Analysis and Design of Energy Geostructures
Theoretical Essentials and Practical Application

LYESSE LALOUI
Soil Mechanics Laboratory, Swiss Federal Institute of Technology, Lausanne, Switzerland

ALESSANDRO F. ROTTA LORIA
Mechanics and Energy Laboratory, Northwestern University, Evanston, IL, United States
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Urban systems present an enormous demand for innovative solutions to meet human activity needs. In many situations, these needs require built environments and are associated with substantial amounts of energy requirements. While it is a critical challenge to develop buildings and infrastructures whose energy requirements are supplied with a limited impact on the environment, employing renewable energy sources is essential for this purpose. So-called energy geostructures represent a breakthrough multifunctional technology for the sustainable development of present and future urban systems.

A substantial amount of renewable geothermal energy is readily available in the ground. Geostructures, including foundations and general earth-contact structures, are essential means for the structural support of built environments through the ground. By leveraging the previous concepts, energy geostructures represent integrated earth-contact structures and thermal energy carriers for all built environments. Energy geostructures particularly explicate a multifunctional role for buildings and infrastructures: reinforce soils and rocks for their structural support and, at the same time, extract or store thermal energy from or in the subsurface for the supply of their heating and cooling energy requirements.

An extraordinary interest has risen over the past 20 years in both the scientific and practitioner communities about energy geostructures. The capabilities of this technology are unique in serving the structural support and renewable energy supply of built environments. However, the analysis and design of energy geostructures can be daunting, inappropriate or even unsuccessful without a sound understanding of their behaviour and performance by means of the relevant theoretical essentials and the appropriate practical application.

Many and complex are the phenomena associated with the multifunctional operation of energy geostructures that need to be considered in analysis and design (e.g., energy, geotechnical and structural). The competence required for such purpose is strongly multidisciplinary, gathering theoretical essentials that govern heat and mass transfers, and the mechanics of geomaterials and structures, as well as practical knowledge about performance-based design and detailing. Some competence on the previous subjects may be acquired through educational paths that include energy engineering, civil and environmental engineering, mechanical engineering and architecture. More advanced yet fragmented competence addressing unique features that characterise energy geostructures may be acquired through the scientific literature. However, at the present time, the competence required to develop the analysis and
design of energy geostructures is not available in a unified framework. This book resolves such a challenge for the first time, by gathering the available theoretical and experimental competence to develop the analysis and design of energy geostructures.

Structured in 5 parts and 16 chapters, this book provides the broad training that is required to understand, model and predict the behaviour and performance of energy geostructures, as well as to carry out the related analysis and design from energy, geotechnical and structural perspectives. Part A presents an introduction to the scope of energy geostructures. Part B summarises the theoretical essentials allowing the understanding of the phenomena governing the behaviour of energy geostructures. Part C provides experimental evidence about the referenced behaviour. Part D covers analytical and numerical approaches to analyse the behaviour of energy geostructures. Part E provides elements to design energy geostructures and assess the related performance. At the end of each chapter, theoretical questions and practical application exercises are proposed.

The book has been designed with civil engineers in mind, but targets energy engineers, environmental engineers, geologists, architects and urban project managers as well. By covering theoretical and practical aspects as homogeneously and comprehensively as its scope permits, the book targets readers who have no experience with energy geostructures as well as audiences who have already been involved in the analysis or design of energy geostructures. Particularly useful for university students at the graduate level, this book aims to inspire and prepare current and future generations of scientists and practitioners to positively revolutionise urban environments.

A substantial amount of the content of this book is based on research and development activities carried out over the past 20 years at the Swiss Federal Institute of Technology in Lausanne (EPFL). Various theoretical frameworks and results proposed by colleagues in the scientific and technical literature are also included in an effort to make this treatise as comprehensive as possible. While the scientific community is acknowledged for making available relevant knowledge that helped to broaden the scope of this book, a particular vote of thanks is devoted to current and past collaborators of the authors for their valuable contributions to this treatise.

The following collaborators are acknowledged for revising some chapters, preparing a number of figures and tables, developing some exercise solutions and sharing fruitful discussions during the preparation of this book: Margaux Peltier, Benoît Cousin, Elena Ravera, Jose Antonio Bosch Llufriu, Jacopo Zannin, Eleonora Crisci, Niccolò Batini, Louise Copigneaux, Christopher Gautschi, Aldo Madaschi, Chao Li, Simon Caldi, Laurette Rohrbach, Francesco Di Bari, Etienne Cassini, Alberto Minardi, Patrick Dubey, Francesco Parisio, Patrycja Baryla, Roba Houhou and Carlo Gaffoglio. The following colleagues are thankfully acknowledged for sharing photographs of construction sites of energy geostructures that enriched the content of the introductory part of the book: Tony Amis, Sebastian Homuth and Stefan Wehinger.
The following colleagues and collaborators are acknowledged for contributing to this book by means of the work and discussions developed across generations of research projects at the graduate and undergraduate levels, PhD theses and postdoctoral research: Alice Di Donna, Thomas Mimouni, Hervé Péron, Christoph Knellwolf, Mathieu Nuth, Bertrand François, Cane Cekerevac, Alessio Ferrari, Laurent Vuillet, Melis Sütman, Fabrice Dupray, Aurélien Vadrot, Matteo Bocco, Cristiano Garbellini, Hani Taha, Pia Hartmann, Lea Kaufmann, Aymen Achich, Thibaut Duparc, Etienne Dominguez, Perrine Ratouis, Qazim Llabjani, Samuel Kivell, Stefano Cingari, Alain Kazangba, Marianna Adinolfi, Dimitrios Terzis, Claire Silvani, Sarah Dornberger, Matteo Moreni, Gilbert Steinmann, Gangqiang Kong, Gunter Siddiqi, Tomasz Hueckel and Gilbert Gruaz.

Last, but not least, the continued and special support provided by Claire, Sinan and Inès to the first author as well as by Giorgia to the second author are gratefully acknowledged.

*Ly esse Laloui*¹ and *Alessandro F. Rotta Loria*²

¹Soil Mechanics Laboratory, Swiss Federal Institute of Technology, Lausanne, Switzerland;
²Mechanics and Energy Laboratory, Northwestern University, Evanston, IL, United States

April 2019
PART A

Introduction
CHAPTER 1

Energy and geotechnologies

1.1 Introduction

Since the 18th century energy consumption and supply have contributed to a marked increase in environmental pollution. Many are the ways and frameworks that can be accounted for restraining environmental pollution, but a development that meets human activity needs and progress goals with a limited impact on the environment can undoubtedly contribute to such a challenge.

In the construction sector, national and international policies, directives and regulations are increasingly requiring, or promoting, the use of so-called “environmentally friendly” technologies that involve a limited impact on the environment. This result can be achieved, for example through technologies that supply buildings and infrastructures with energy drawn from sources that can renew themselves at a sufficient rate in human time frames and cause low environmental pollution. In a growing number of countries, new buildings must be constructed with such technologies.

This chapter expands on energy sources and technologies that can sustain human activity needs with a limited impact on the environment. Among the various energy sources and technologies available, attention is devoted to geothermal energy (from the Greek roots geo, meaning earth and thermos, meaning heat) and geotechnologies because of their unique features for addressing the previously mentioned challenge.

With this aim, world anthropogenic development and the energy question are first expanded: in this context the goal is to describe the interplay between the trend in the world’s population and the exploitation of energy sources, the related effect on the environment, and the perspectives that need to be considered in the building sector to contribute to a development of low environmental impact. Next geothermal energy is addressed: the objective of this part is to discuss the origin and the features of the considered energy source as well as to establish acquaintance with the principles that govern the operation of geotechnologies (and associated technological systems) harvesting this energy source. Then geothermal systems are discussed: in this context the purpose is to provide a classification of geothermal systems, to describe their features and uses, and to highlight the technology of energy geostructures. Finally questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.
these systems are for district heating, but heating of large industrial or agricultural con-
structions can also be conveniently achieved.

_Petrothermal systems_ also extract groundwater through open wells, but from deeper
depths than hydrothermal systems (from a depth of $z = 4000–6000$ m). The tempera-
ture and thermal energy present in the water at these depths can be used for large-
scale electrical power production and supply.

References


CHAPTER 2

Energy geostructures

2.1 Introduction

Along with the ancient use of soils and rocks as heat reservoirs, the employment of geostructures (e.g. piles, walls and tunnels) as structural supports represents an effective historical means to meet human activity needs. Energy geostructures are an innovative technology that couples the structural support role of conventional geostructures to the heat exchanger role of shallow geothermal systems for any type of built environment.

This chapter addresses the technology of energy geostructures as a breakthrough means for contributing to the sustainability of human activity needs via the establishment of low-carbon buildings and infrastructures. Features, uses and capabilities of energy geostructures are addressed, examples of applications worldwide are presented, and an overview of the phenomena governing the behaviour of this technology is proposed.

To this aim, the energy geostructure technology is described first: in this context the purpose is to highlight the roles of energy geostructures, the materials involved and other relevant features of this technology. Next energy geostructure operation modes are presented: the purpose of this part is to illustrate possible uses of energy geostructures for heat exchange and storage purposes. Then so-called ground source heat pump systems and underground thermal energy storage systems are described: in this framework the aim is to propose relevant aspects related to the composition and operation of such systems. Afterward the application and development of energy geostructures are discussed: the aim of this part is to propose typical features characterising applications of such technology and expand on three energy geostructure projects that involve an energy pile foundation, energy tunnel linings and energy walls. Later physical phenomena and approaches to analysis and design are expanded: in this section the aim is to highlight key physical phenomena that characterise energy geostructures and to propose approaches for describing such phenomena in analysis and design. Finally questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.
a fluid mechanics perspective, while those involved in the latter class of problems are usually addressed from a geomechanics and structural mechanics perspective. The referenced approach involves the mathematical relations employed for investigating the considered aspects being expressed differently for convenience, and using the same formulations may thus hinder their comprehension.

References

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PART B

Fundamentals
CHAPTER 3

Heat and mass transfers in the context of energy geostructures

3.1 Introduction

Heat and mass transfer phenomena arise because of the gradient of variables and may be considered independently from each other. Heat transfer characterises the thermal behaviour of materials and is often associated with the influence of thermal loads. Mass transfer characterises the hydraulic behaviour of materials and is often associated with the influence of hydraulic loads. However, heat and mass transfers are coupled phenomena: one phenomenon (i.e. the flow) can be triggered by the gradient of the variable typically associated with the other phenomenon. That is heat transfer can trigger mass transfer and the opposite is true.

Heat and mass transfer phenomena crucially characterise energy geostructures through the thermohydraulic response of the materials involved. Understanding the physical principles governing heat and mass transfers, and accounting in a suitable way for the coupling between these phenomena in the analysis and design of energy geostructures is crucial.

This chapter presents a theoretical treatment of heat and mass transfers in the context of energy geostructures. The topic is addressed by focusing on the features of heat and mass transfers that may be considered for the characterisation of the thermohydraulic behaviour of materials and the related analysis and design of energy geostructures. Comments on the coupling between heat and mass transfers are also provided.

To this aim, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of the conceptual descriptions and hypotheses that are employed for describing heat and mass transfer phenomena. Second, principles of heat transfer are described: the purpose of this part is to characterise the physical phenomenon of heat transfer in the context of the analysis and design of energy geostructures. Third, conduction, convection and radiation are addressed: the purpose of this part is to discuss salient features of the considered modes of heat transfer. Next, the energy conservation equation and the associated initial and boundary conditions are presented: in this framework, the aim is to propose mathematical expressions that allow the modelling of any given heat transfer problem together with the use of initial and boundary conditions. The principles of mass transfer are subsequently discussed: the purpose of this section is to describe the fundamentals of the considered physical phenomenon.
Later, *laminar and turbulent flows* and the problem of *seepage flow* are addressed: the purpose of this part is to expand on the regimes that govern mass transfer as well as on the phenomenon of groundwater flow. Then, the *mass conservation equation* and the associated *initial and boundary conditions* are presented: the goal of this digression is to progress with the understanding and mathematical modelling of mass transfer. Next, *boundary layers in flow problems* are discussed: the aim in this context is to characterise the considered subjects in view of their influence on the operation of energy geostructures. Afterward, the *momentum conservation equation* is considered: the aim of this section is to complete the mathematical description of mass transfer phenomena for situations in which the equilibrium of the moving fluid is accounted for. Finally, *questions and problems* are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 3.2 Idealisations and assumptions

Different materials characterise energy geostructure applications. These materials include, for example (1) the soil or rock surrounding energy geostructures, (2) the concrete constituting energy geostructures, (3) the steel reinforcing energy geostructures, (4) the plastic material constituting the pipes embedded in energy geostructures, (5) the heat carrier fluid circulating in the pipes and (6) the air in a built environment adjacent to energy geostructures.

In principle all of the aforementioned materials can be characterised by different constituents and are heterogeneous at all scales, that is characterised by properties that vary in space. Geomaterials such as soil, rock and concrete contain solid particles and pores typically filled with water and air, with the solid particles consisting of different solid components that may differ, for example in size, shape, mineralogy and behaviour. Reinforcing steel and plastic pipes are characterised by impurities in the form of pores filled with air. The heat carrier fluid circulating in the pipes of energy geostructures and the air flowing in an adjacent built environment can be characterised by impurities in the form of solid particles.

In practice, heterogeneous materials can be modelled via the *continuum medium idealisation* as if they were *homogeneous*, that is characterised by properties that do not vary in space. The main advantage of this approach is that governing equations and constitutive equations can be applied to describe the behaviour and phenomena characterising such materials from a continuum perspective, with reference to an elementary volume (see, e.g. Timoshenko and Goodier, 1951; Lai et al., 2009).

An approach for describing the behaviour and phenomena characterising materials from a continuum perspective, without being influenced by their actual heterogeneities, relies on the concept and the definition of a so-called ‘*Representative Elementary Volume*’ (REV). The REV concept, originally proposed by Lorentz (1952), is defined
References


CHAPTER 4

Deformation in the context of energy geostructures

4.1 Introduction

Deformation and heat transfer phenomena arise because of the gradient of physical variables and may be considered independently from each other. Deformation characterises the mechanical behaviour of materials and is often associated with the influence of mechanical loads. Heat transfer characterises the thermal behaviour of materials and is often associated with the influence of thermal loads. However, deformation and heat transfer are coupled phenomena, similar to heat transfer and mass transfer. That is, heat transfer can influence the deformation of materials and the opposite is true. This fact implies that the thermal and mechanical behaviours of materials are coupled.

Deformation phenomena under nonisothermal conditions characterise energy geostructures through the thermomechanical response of the materials involved. Understanding the physical principles governing deformation phenomena under nonisothermal conditions and accounting in a suitable way for these phenomena in the analysis and design of energy geostructures is paramount.

This chapter presents a theoretical analysis of deformation phenomena that can occur under nonisothermal conditions associated with heat transfer processes in the context of energy geostructures. The topic is addressed by focusing on the essentials of the theories of thermoelasticity, plasticity and thermoplasticity that may be considered for the characterisation of the thermomechanical behaviour of materials and the related analysis and design of energy geostructures. Comments on the coupling between deformation and heat transfer are also provided.

To this aim, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of the conceptual descriptions and hypotheses that are employed for describing deformation phenomena under nonisothermal conditions. Second, the concepts of strain, compatibility and stress are addressed: the purpose of this part is to expand on fundamental variables and principles governing the description of the mechanical response of materials. Third, the momentum equilibrium equation and boundary conditions are presented: the purpose of this part is to define the equations governing the equilibrium of materials under loading. Next, generalities about stress—strain relations are introduced: the goal of this section is to elaborate on mathematical expressions relating strains to stresses and the opposite. Later, thermoelasticity is
addressed: in this context, the aim is to characterise the reversible mechanical behaviour of materials through the essentials of the theory of thermoelasticity. Afterward, plasticity and thermoplasticity are addressed: in this part, the objective is to characterise the irreversible mechanical behaviour of materials through the essentials of the theories of plasticity and thermoplasticity. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

4.2 Idealisations and assumptions

As highlighted in Chapter 3, Heat and mass transfers in the context of energy geostructures, the materials constituting energy geostructures, soils and rocks are discrete in nature. However, mathematical models based on the continuum medium idealisation and the concept of Representative Elementary Volume (REV) allow describing, predicting and analysing key aspects of the behaviour of materials (discrete in particular). In the following, the continuum idealisation and the REV concept are employed to model the mechanical behaviour of materials, by further assuming that they are isotropic and homogeneous unless otherwise specified (cf. Fig. 4.1A). According to the continuum medium idealisation, the heterogeneous nature of geomaterials is neglected, and, in the simplest case, the presence of at least one fluid phase in addition to the solid phase constituting the structure of materials is also neglected. The consideration of at least one fluid phase in addition to the solid phase in the structural characterisation of materials involves challenges in the analysis of deformation phenomena. These challenges are discussed in Appendix B for both isothermal and nonisothermal conditions while providing the essentials of a framework for the hydromechanical and thermohydromechanical modelling of geomaterials.

Among the various theories that may be considered for describing the mechanical behaviour of materials (and general structural systems) subjected to perturbations (e.g. loads) under nonisothermal conditions, the theories of thermoelasticity, (isothermal) plasticity and thermoplasticity are addressed in the following because of their relevance for the analysis and design of energy geostructures. The mathematical formalisation of the theory of thermoelasticity has been developed by Duhamel (1835), based on the classical (or isothermal) theory of elasticity (see, e.g. Hooke, 1678; Navier, 1821; Cauchy, 1823; Lamé and Clapeyron, 1831; Saint Venant, 1870). In a similar way, the theory of thermoplasticity has been expanded by Prager (1958), based on the unified framework characterising the theory of isothermal plasticity (see, e.g. Prager, 1949; Drucker and Prager, 1952).

The theories of elasticity and thermoelasticity address a reversible mechanical behaviour of materials (and general structural systems) by neglecting and considering sensitivity to temperature variations for this behaviour, respectively. In the former
4.10.10 Constitutive modelling of materials involved with energy geostructures

In the context of the modelling of the mechanical behaviour of materials for the analysis and design of energy geostructures, the reinforced concrete that often characterises such structures can be described in most situations as linear thermoelastic. In contrast, the mechanical behaviour of the soil and rock surrounding energy geostructures is often described as either (1) thermoelastic, (2) thermoelastic, perfectly plastic, (3) thermoelastic, plastic with hardening or (4) thermoelastic, thermoplastic with hardening. Linear or nonlinear stress–strain relations are employed for the previous purpose, and the choice of accounting for plasticity depends on factors such as the stress state and the stress history characterising the modelled materials.

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PART C

Observations
CHAPTER 5

Thermohydromechanical behaviour of soils and soil—structure interfaces

5.1 Introduction

The ground represents the medium through which loads arising from energy geostructures are to be equilibrated by means of a transfer through the interfaces with such structures (i.e. soil—structure interfaces). Because of the multifunctional role of energy geostructures, thermal and mechanical loads are applied to soils and soil—structure interfaces. In this context, the multiphysical nature of the applied loads, together with the couplings that govern the behaviour of materials, makes the thermohydromechanical behaviour of soils and soil—structure interfaces paramount for the analysis and design of energy geostructures. Not only does this behaviour influence the deformation and capacity of energy geostructures depending on the material properties, but it also characterises the heat that can be exchanged via such structures. Understanding the behaviour of soils and soil—structure interfaces is thus critical to address the analysis and design of energy geostructures.

This chapter focuses on the experimental analysis of the thermohydromechanical behaviour of soils and soil—structure interfaces based on the results of laboratory tests. The behaviour of soils and soil—structure interfaces is expanded with a focus on their deformation and strength under nonisothermal conditions, and the influence of aspects that govern such behaviour are highlighted.

To address the aforementioned aspects, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of the conceptual descriptions and hypotheses that are employed for describing the behaviour of soils and soil—structure interfaces under nonisothermal conditions. Second, the characterisation of soils is treated: the objective of this part is to summarise concepts for the characterisation of the behaviour of fine- and coarse-grained soils. Third, the deformation and strength of soils under nonisothermal conditions is discussed: in this context, the purpose is to address the influence of thermal and mechanical loads on the response of the considered materials. Next, the thermally induced effects on soil parameters are treated: in this framework, the purpose is to discuss the influence of thermal loads on parameters that describe the thermohydromechanical behaviour of soils. Afterward, the characterisation of soil—structure interfaces is discussed: the purpose of this part is to expand on features of interfaces with soils that can be employed to describe the related response to loading.
Then, the strength of soil–concrete interfaces under nonisothermal conditions is considered: in this context, the purpose is to comment on the response of interfaces between fine- and coarse-grained soils and concrete to thermal and mechanical loads. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 5.2 Idealisations and assumptions

A key aspect related to the development of laboratory tests on core samples of soil, similar to other materials, is the representativeness of the obtained results with respect to the heterogeneities that characterise the tested material and the problem itself across scales. Based on the considerations proposed in Part B of this book, the concept of Representative Elementary Volume (REV) is employed in the following. The REV concept allows describing the behaviour of heterogeneous materials such as soils, rocks and concrete as if they were homogeneous, with the possibility to account for heterogeneities at greater scales than the scale characterising the REV.

In this context, the addressed materials are assumed multiphase systems characterised by one solid phase and one fluid phase. The previous assumption involves neglecting materials under partially saturated conditions [the thermohydromechanical behaviour of soils under partially saturated conditions has been investigated, for example by Bolzon and Schrefler (2005), François and Laloui (2008) and Gens (2010)] and accounting for soils that are either dry or fully saturated with water. When soils fully saturated with water are investigated, drained conditions are assumed upon thermal loading. These conditions are the result of testing procedures that do not cause excess pore water pressures upon thermal loading, despite the water present in the pores of soil matrices having a thermal expansion coefficient that is approximately 10 times greater than that of the solid particles and involving interactions with the solid phase. The considered conditions are representative of most energy geostructure applications because of the sufficiently slow rates of thermal loads applied to such structures that ensure drainage of the water embedded in the soil pores and negligible pore water pressure build-ups (Rotta Loria and Laloui, 2017).

Yet while the deformation and strength of soils and soil–structure interfaces under nonisothermal conditions is commented hereafter for temperature levels between 2°C and 90°C, temperature values between 2°C and 45°C should be considered representative for energy geostructure applications (Rotta Loria, 2019). In other words, results referring to temperature variations higher than 45°C are not representative of current energy geostructure applications, but they provide additional information on the subject matter treated herein.
with sand while globally appears to be on the safety side for interfaces with clay because it increases the interface strength (Di Donna et al., 2015).

When calculating the capacity of geostructures in terms of effective stress, the angle of shear strength of the interface is included while the adhesion is neglected. Therefore, a decrease of the strength of interfaces with fine-grained soils for an increase in temperature would arise from capacity formulations due to the decrease in the angle of shear strength of such interfaces. However, the actual increase in the shear strength of the considered interfaces with temperature by means of the contribution of the adhesion supports the use of a constant value of interface angle of shear strength (e.g. determined at ambient temperature) in capacity formulations.

A cyclic mechanical degradation of the interface shear stress induced by the thermoelastic expansion and contraction of the structural material at the interface with the soil may be observed. This effect is similar to the cyclic degradation phenomenon caused by cyclic mechanical loads applied to interfaces with conventional structures. It is typically more pronounced for coarse-grained soils compared to fine-grained soils because of the more significant volumetric cyclic contraction of the interface in the former case compared to the latter. In the case of interfaces with initially NC fine-grained soils, the cyclic volumetric contraction is even reduced by the increase in temperature, as the soil first undergoes a thermal collapse thus reducing the soil potential of collapse during shearing (Di Donna et al., 2015). Cyclic degradation effects may be considered in the analysis and design of energy geostructures. These effects are assumed to play a central role in the characterisation of the deformation of energy geostructures, especially for situations in which significant mechanical loads are applied. The reason for this is that, together with subsequently applied cyclic thermal loads, significant mechanical loads (even if approximately constant over time) may involve noteworthy degradation effects. When cyclic effects are considered limited in magnitude or absent, they can be omitted in the analysis and design of energy geostructures.

References


CHAPTER 6

Thermomechanical behaviour of single energy piles

6.1 Introduction

Energy pile foundations, similar to conventional pile foundations, consist of two components: a group of piles and a pile cap (the latter being intended as the general structural element connecting the piles to the superstructure). Addressing the response of the piles in a group is crucial for a comprehensive understanding of the behaviour of any pile foundation. At the same time, in many practical cases, considering the piles as single isolated elements represents the starting point of any analysis and design. This approach is considered hereafter for energy piles subjected to the mechanical and thermal loads associated with their structural support and geothermal heat exchanger roles.

The application of mechanical and thermal loads to energy piles introduces novel aspects in the mechanical response of such foundations compared to that characterising conventional piles typically subjected to only mechanical loads because of their sole structural support role. The reason for this is because, as a consequence of the coupling between the heat transfer and the deformation of materials previously treated in Part B of this book, thermal loads induce thermal expansions and contractions of both the piles and the surrounding soil as well as modifications of the stress state. Understanding the influence of thermal loads, applied alone or in conjunction with mechanical loads, is key to address the thermomechanical behaviour of energy piles.

To investigate the response of single energy piles to mechanical and thermal loads, various approaches can be employed. Full-scale in situ tests, model-scale laboratory tests and centrifuge tests are example of experimental approaches. In general, more remarkable financial expenditures are required to run full-scale in situ tests compared to model-scale laboratory tests and centrifuge tests. Despite this limitation, the capability of full-scale in situ tests to provide data unaffected by scale effects that can potentially characterise the results of model-scale laboratory tests and centrifuge tests can make such an approach preferable for analysis and design purposes.

This chapter presents an analysis of the response of single energy piles subjected to mechanical and thermal loads based on the results of full-scale in situ tests. A focus is devoted to energy piles subjected to mechanical and heating thermal loads, although the influence of cooling thermal loads can be inferred from the results presented.
To address the aforementioned aspects, *idealisations and assumptions* are presented first: in this context, the objective is to propose a summary of the assumptions made to interpret the response of energy piles subjected to mechanical and thermal loads. Second, the *classification of single energy piles* is treated: the objective of this part is to summarise a characterisation of the types of single energy piles. Third, the *temperature variations* in energy piles are discussed: in this context the purpose is to expand on the thermal field characterising energy piles. Next, the *thermally induced vertical and radial strains* characterising energy piles are treated: in this framework the purpose is to discuss the influence of thermal loads on the deformation of energy piles. Afterward, the *thermally and mechanically induced variations in vertical displacement, shear stress and vertical stress* characterising energy piles are discussed: the purpose of this part is to expand on the variation of the considered variables along energy piles and to highlight crucial differences between the influence of thermal loads compared to mechanical loads. Then, the *variations in degree of freedom* are considered: in this context the purpose is to comment on the response of energy piles depending on the restraint provided by the ground and the superstructure characterising such foundations. Finally, *questions and problems* are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 6.2 Idealisations and assumptions

As previously highlighted in Part B of this book, the materials constituting energy geostructures, soils and rocks are nonhomogeneous. However, in many cases, an effective analysis approach can resort to the continuum medium idealisation while considering the materials isotropic and homogeneous. This approach is again considered for the forthcoming interpretation of the thermomechanical behaviour of energy piles (cf. Fig. 6.1A).

While in practice piles are not often exactly characterised by a cylindrical shape and the surrounding soil layers are not fully horizontal, assuming the considered conditions markedly simplifies the analysis of pile response. Accordingly, these hypotheses are accounted for the following developments (cf. Fig. 6.1B).

Thermal and mechanical loads involve nonuniform variations of the temperature, stress, strain and displacement fields within (and around) energy piles (*Abdelaziz and Ozudogru, 2016; Caulk et al., 2016; Rotta Loria and Laloui, 2017*). Despite a fine analysis of the response of energy piles would require consideration of the actual non-uniform nature of the considered fields, in the following it is assumed that the reported variations in temperature, stress, strain and displacement are uniform and representative of the energy pile response (cf. Fig. 6.1C). The validity of this hypothesis increases at successive stages of the geothermal operation of energy piles and for more uniform pipe configurations within the cross-section of energy piles.
this phenomenon can be attributed to the overall progressive increase of the stiffness characterising the pile–soil–superstructure system. The stiffness at the head of energy piles varies locally depending on their position within the foundation. This fact indicates that comparable energy piles subjected to the same thermal load in a given soil deposit but in different locations of a foundation are characterised by different degrees of freedom.

In all usual situations where the thermal expansion coefficient of the soil is (significantly) lower than or (at least theoretically) equal to that of the piles, it results in $0 \leq DOF \leq 1$. However, because of the previously mentioned role of the thermally induced soil deformation in the rare cases in which the thermal expansion coefficient of the soil is higher than that of the piles, it can result at successive stages of geothermal operation that $DOF > 1$.

**References**


CHAPTER 7

Thermomechanical behaviour of energy pile groups

7.1 Introduction

Energy pile foundations can involve mixed groups of conventional and energy piles, or uniform groups of energy piles for the purpose of a partial or entire geothermal heat operation of such elements, respectively. In either case, energy pile foundations do not consist of a single energy pile but of a group of energy piles that function as structural supports and geothermal heat exchangers.

Pile groups can be divided into two classes: widely and closely spaced. In widely spaced pile groups, the piles are located far enough from each other that their individual responses can be considered independent. In closely spaced pile groups, the piles are close enough to each other that their individual responses are influenced by the presence of and loadings on the neighbouring piles. Therefore while in widely spaced pile groups the individual pile responses can be associated with the response of a single isolated pile, the individual pile responses in closely spaced pile groups differ from that of an isolated pile.

The influences between the individual pile responses of any energy pile foundation represent interactions (thermal and mechanical) between the piles, the connecting structural element and the surrounding soil. These interactions characterise the deformation and flows (e.g. of thermal energy and mass) governing the considered geostuctures and manifest through so-called group effects. Understanding the significance and influence of group effects and interactions among energy piles is crucial to comprehensively address the thermohyrdomechanical behaviour of such foundations.

This chapter presents an analysis of the response of energy pile groups subjected to mechanical and thermal loads based on the results of full-scale in situ tests. A focus is devoted to energy pile groups subjected to heating thermal loads, although the influence of cooling thermal loads can be inferred from the results presented.

To address the aforementioned aspects, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of the assumptions made to interpret the response of energy piles subjected to mechanical and thermal loads. Second, the classification of energy pile foundations is treated: the objective of this part is to summarise a characterisation of the types of energy pile foundations. Third, the temperature variations in energy pile groups are discussed: in this context, the purpose is to
expand on the thermal field characterising the energy piles and the surrounding soil. Later, the pore water pressure variations characterising energy pile groups are considered: the aim of this section is to highlight the influence of thermal loads on the variation of the pore water pressure in the soil deposits surrounding energy piles. Next, the thermally induced vertical strain and stress variations characterising energy pile groups are treated: in this framework, the purpose is to discuss the influence of thermal loads on the deformation of energy piles. Afterward, the effect of number of loaded energy piles on the vertical strain and stress variations are considered: in this context, the purpose is to comment on the response of energy piles depending on the number of foundations subjected to thermal or mechanical loading. Then, the key aspects governing the behaviour of energy pile foundations are discussed: the purpose of this part is to expand on the design variables and parameters that play the major role in the variation of energy pile group response subjected to mechanical and thermal loads. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

7.2 Idealisations and assumptions

The idealisation and assumptions made in this chapter coincide with those presented in Chapter 6, Thermomechanical behaviour of single energy piles. The quoted considerations find due justification in the referenced chapter and are only summarised for completeness in the following.

A continuum medium idealisation of the materials constituting energy pile foundations is employed while considering the materials isotropic and homogeneous. The piles are assumed to be characterised by a cylindrical shape. Layered (i.e. nonuniform) soil deposits are considered to be composed of fully horizontal layers. Uniform variations of the temperature, stress, strain and displacement fields within (and around) energy piles are considered. Contractive strains, downward displacements, compressive stresses and increases in angles in the anticlockwise direction are considered to be positive.

7.3 Classification of energy pile foundations

The rationale of pile foundations in the support of structures can be (1) to provide sufficient bearing capacity to a superstructure by transferring a load to a relatively deep and competent ground, (2) to reduce the deformation of a superstructure to an acceptable level, or (3) both of the previous purposes. In this regard, only the piles, only the cap or both the piles and the cap can be considered to address the requirements of structural support and deformation control. Based on the employed design
operation of the piles due to the typical thermal insulation of the pipes. Nothing more unusual than the surface conditions may be expected to affect the interplay between the deformation of the slab and the underlying shallow soil. This phenomenon minimally contributes to the overall deformation of the system because, as in most applications, thermal insulation may be assumed between the slab floor and the upper environment. In any case, the influence of surface conditions may be considered negligible when compared to the effect of the geothermal operation of the energy piles on the deformation of the slab and soil.

References


PART D

Analysis
CHAPTER 8

Analytical modelling of steady heat and mass transfers

8.1 Introduction

The heat and mass transfer phenomena associated with the operation of energy geostructures certainly do depend on time, that is they are time-dependent. The temperature changes applied to energy geostructures continuously vary together with the thermal loading and boundary conditions. Heating and cooling loads of superstructures typically vary depending on the changes in weather and occupation from an hourly to an annual basis. Boundary conditions such as the temperature in the shallowest portion of the ground vary depending on the weather conditions over the day as well as throughout the day—night and seasonal cycles.

However, there are some reference time (and space) scales that allow considering the heat and mass transfer phenomena as time-independent. These timescales are generally associated with so-called steady conditions and involve a time independence of the heat and mass transfer phenomena allowing for a relatively straightforward analysis of the problems involved. For example in the context of the analysis of the heat transfer characterising a body surrounded by a larger domain, under steady conditions (1) the capacity effect of the body becomes negligible, (2) the heat transfer phenomenon becomes a purely resistance process and (3) two distinct subprocesses can be considered to characterise the heat transfer. The first subprocess concerns the heat transfer occurring within the body and may be modelled via a time-independent approach. The second subprocess potentially refers to the heat transfer occurring in the domain around the body and may be modelled through a time-dependent approach. The considered body may typically be a pipe, a geothermal heat exchanger or a relevant zone of the ground surrounding the heat exchanger.

This chapter presents analytical approaches to characterise the time-independent heat and mass transfer phenomena governing energy geostructures under steady conditions. The analysis of these phenomena is treated for pipes, energy geostructures and the surrounding ground in an attempt to comprehensively characterise the operation of the investigated technology.

To address the aforementioned aspects, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of assumptions that allow for expedient yet rigorous analyses of energy geostructures and other geothermal heat
exchangers. Second, an analysis of the heat and mass transfers in pipes is proposed: the objective of this part is to determine relevant temperature changes, the flow rate and the convection heat transfer coefficient for heat carrier fluids circulating in pipes, such parameters representing the basis to characterise the heat transfer within energy geostructures. Third, the concept of thermal resistance is defined by referring to bodies with no internal heat energy generation and with known temperature distribution: in this framework the purpose is to remark how thermal resistance describes heat transfer in the same way electrical resistance does for electric current flow. Next, the concept of thermal resistance is used for the time-independent analysis of the heat transfer within energy piles and other circular heat exchangers, as well as within energy walls and other plane heat exchangers: in this context the purpose is to show how plain and stratified cylindrical and planar geometries can be used to analyse problems involving energy geostructures of varying complexity, and to illustrate the case of internal heat generation for cylindrical and planar geometries. Afterward, approaches to estimate the heat transfer and storage capacities of energy piles are presented: the goal of this section is to highlight the importance of the heat transfer capacity for analyses devoted to assessing the heat extraction potential of cylindrical heat exchangers such as energy piles, while investigations into heat storage capacity aimed to assess the injection potential of such elements. Then, a digression on the required thermally active dimension of energy geostructures and the effectiveness-NTU analysis method for energy geostructures is proposed, with the goal of summarising the impact of various design solutions on the thermohydraulic behaviour of energy geostructures. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

8.2 Idealisations and assumptions

In the analysis of the heat transfer, considering reference times, \( t^* \), allows critical considerations to be made. For time intervals \( t \leq t^* \), the heat transfer within a considered body cannot be associated with steady conditions and requires a time-dependent modelling approach to be described. In contrast, for time intervals \( t > t^* \), the heat transfer within a considered body can be associated with steady conditions and may be meaningfully described through a time-independent modelling approach. In general, for \( t > t^* \), steady-flux conditions (not steady-state conditions) can be considered to characterise the heat transfer. Steady-flux conditions are situations in which the variation of the potential variable governing a given phenomenon (e.g. temperature for heat transfer) is a result of quantities that evolve with time but are characterised by a constant difference over time. Steady-state conditions are situations in which the variation of the relevant potential variable is a result of quantities that are constant with time.
with

$$\epsilon_{ghe} = f(NTU) = f \left( \frac{1}{mc_p} \frac{L}{R_{ghe}} \right)$$

There is one main advantage associated with the use of the effectiveness—NTU method for the analysis of energy geostructures: the thermal power at the surface of the geostructure can always be considered to be coherent with the temperature variation of the fluid, \( \overline{T_{in}} - \overline{T_{out}} \). The reason for this is that the outlet fluid temperature is imposed to be always greater or lower than the temperature at the soil—pile interface depending on the heat flux direction for the cooling or heating mode of the energy geostructure, respectively. This fact allows the avoidance of inconsistent analysis results that may arise as a consequence of the use of the mean temperature in terms of local direction of heat transfer (e.g. \( \overline{T_{out}} < \overline{T_{s-p}} \) when \( \overline{T_{f}} > \overline{T_{s-p}} \) and \( \dot{Q} > 0 \)) because of the small temperature drop between the fluid and the ground (Conti et al., 2016). The \( \epsilon_{ghe} - NTU \) method is a powerful tool for performing sensitivity analyses on the impact of different design solutions on the thermohydraulic behaviour of energy geostructures.

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Analytical modelling of steady heat and mass transfers

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CHAPTER 9

Analytical modelling of transient heat transfer

9.1 Introduction

The continuously varying energy requirements of built environments, together with the weather conditions, can cause different magnitudes and frequencies of temperature changes in the subsurface. These temperature changes vary over time and can be classified in two types: (1) high-frequency temperature changes occurring within hours to days (i.e. for relatively short-to-medium timescales) of small magnitudes (from 5°C to 10°C) and (2) low-frequency temperature changes occurring throughout seasons and years (i.e. for relatively long timescales) of remarkable magnitudes (from 10°C to 30°C).

Based on the previous evidence, the heat transfer phenomena occurring in the subsurface and characterising energy geostructures also vary with time, that is they are time-dependent. The time-dependence of unsteady or transient heat transfer typically is the result of a variation in the boundary conditions in a system and lasts until a steady-state temperature distribution is reached. Understanding and modelling time-dependent heat transfer phenomena is crucial to characterise the transient thermohydraulic behaviour of energy geostructures as well as to comprehensively understand the functioning of both Ground Source Heat Pump Systems and Underground Thermal Energy Storage Systems. In fact, both high- and low-frequency temperature changes have a direct impact on the response of heat pumps and thus significantly influence the overall system behaviour. Although a time-independent modelling of the heat transfer phenomena involved with energy geostructures can provide important insights for analysis and design purposes, time-dependent investigations must thus be carried out for a sound characterisation of the thermohydraulic behaviour of energy geostructures and the associated energy systems. The rationale of the time-dependent modelling of heat transfer phenomena is to address the temperature distribution in bodies during a transient process as well as the heat transfer between such bodies and their surroundings. Typical problems of interest can involve the determination of the temperature variation with time or the analysis of the temperature variation with both location and time. In the context of energy geostructure applications, the latter problem is often of primary interest and analytical models can be employed for such purpose.
This chapter presents analytical approaches to characterise the time-dependent heat transfer phenomena governing energy geostructures under transient conditions. The analysis of these phenomena focuses on the influence of low-frequency temperature changes characterising energy geostructures over relatively long timescales, but the influence of high-frequency temperature changes associated with small-to-medium timescales is also treated in an attempt to comprehensively characterise the operation of the investigated technology.

To address the aforementioned aspects, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of assumptions that allow for expedient yet rigorous analyses of energy geostructures and other geothermal heat exchangers. Second, the analysis approaches are proposed: the objective of this part is to present two effective approaches allowing for the time-dependent modelling of heat transfer problems to be carried out. Next, the Duhamel's theorem is presented: in this context, the purpose is to expand on the superposition principle and the ways superposition can be considered over time and in space to address complex problems. Next, the concept of thermal resistance for the time-dependent analysis of heat transfer is expanded: in this framework, the purpose is to complement previously addressed knowledge about the concept of thermal resistance for a comprehensive time-dependent modelling of the heat transfer. Afterward, analytical solutions for the time-dependent analysis of the heat transfer around energy piles and other circular heat exchangers, as well as around energy walls and other plane heat exchangers are considered: in this context, the purpose is to show analytical solutions that can effectively capture the heat transfer characterising relatively simple geometries representative of geothermal heat exchangers such as energy geostructures. Then, the analysis of heat transfer at short-to-medium timescales is presented: the goal of this section is to highlight analytical solutions that can address the response of geothermal heat exchangers subjected to high-frequency temperature fluctuations at the timescales addressed. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 9.2 Idealisations and assumptions

In the following time-dependent modelling of the heat transfer characterising geothermal heat exchanger such as energy geostructures, the same idealisation and assumptions presented in Chapter 8, Analytical modelling of steady heat and mass transfers, are accounted for unless otherwise specified. The quoted considerations find due justification in the referenced chapter and are only summarised for completeness in the following prior to the detailed description and justification of additional hypotheses.

The ground is considered to be infinite or semiinfinite in extent. A uniform initial temperature is assumed in any modelled domain. Constant flux or constant
with
\[
F_0 = \frac{\alpha_{d,\text{ghc}}}{R^2}
\]
(9.59)
\[
\tilde{R}^* = \frac{r}{R}
\]
(9.60)
\[
\tilde{R}^* = \frac{r'}{R}
\]
(9.61)
\[
A_d = \sqrt{\frac{\alpha_{d,\text{ghc}}}{\alpha_{d,\text{soil}}}}
\]
(9.62)
\[
A_l = \frac{\lambda_{\text{soil}}}{\lambda_{\text{ghc}}}
\]
(9.63)
\[
\varphi_n(\nu) = A_d A_l J_n(\nu) \frac{dJ_{B,n}}{d\beta^*}(A_d \nu) - \frac{dJ_{B,n}}{d\beta^*}(\nu)Y_{B,n}(A_d \nu)
\]
\[
\psi_n(\nu) = A_d A_l Y_{B,n}(\nu) \frac{dY_{B,n}}{d\beta^*}(A_d \nu) - \frac{dY_{B,n}}{d\beta^*}(\nu)J_{B,n}(A_d \nu)
\]
\[
f_n(\nu) = A_d A_l Y_{B,n}(\nu) \frac{dY_{B,n}}{d\beta^*}(A_d \nu) - \frac{dY_{B,n}}{d\beta^*}(\nu)Y_{B,n}(A_d \nu)
\]
\[
g_n(\nu) = A_d A_l Y_{B,n}(\nu) \frac{dY_{B,n}}{d\beta^*}(A_d \nu) - \frac{dY_{B,n}}{d\beta^*}(\nu)Y_{B,n}(A_d \nu)
\]
(9.64)

where \(J_{B,n}\) and \(Y_{B,n}\) are the Bessel functions of the first and second kind of order \(n\), respectively.

References


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CHAPTER 10

Analytical modelling of capacity and deformation of single energy piles

10.1 Introduction

Estimating the response of single energy piles subjected to the mechanical and thermal loads associated with their structural support and heat exchanger operation represents the starting point for any comprehensive analysis of energy pile foundations. In this context, two key aspects must be addressed for any characteristic pile constituting energy pile foundations: the pile capacity and the pile deformation. Addressing the capacity of energy piles involves determining the maximum load that is likely to be associated with an inadmissible state in the soil (or in the pile) and may cause the collapse or failure of the structure or its components. Addressing the deformation of energy piles involves assessing the maximum load that is likely to be associated with an inadmissible state in the soil (or in the pile) and may cause the loss of functionality, appearance and durability of the structure or its components. The referenced ‘maximum load’ for the previous considerations may in principle consist of a unique load, but in the majority of cases it consists of a combination of loads.

While the capacity of piles markedly depends on their method of installation, the deformation of such foundations is crucially characterised by the adopted construction details. However, both of these aspects are a function of the properties of any considered site. In this context, understanding and being capable of describing the load-transfer relationship between the pile and the surrounding ground is essential to address the thermomechanical behaviour of such foundations. Experimental evidence obtained from full-scale field tests can yield the most realistic information on the load-transfer relationship of energy piles. Particularly rigorous theoretical analysis approaches such as the finite element method are accessible to tackle this problem as well. However, analytical approaches can in many cases represent an effective solution to address the load-transfer relationship of energy piles, with the advantage of being expediently applicable in sensitivity analyses for even large pile foundations, potentially via relatively simple computer software.

This chapter focuses on analytical and semianalytical approaches to characterise the capacity and the deformation of single energy piles subjected to mechanical and thermal loads. Attention is given to the influence of axial (e.g. vertical and compressive) mechanical loads as well as to both heating and cooling thermal loads.
The analysis of the influence lateral loads can be considered separately and is not treated in the following.

To address the aforementioned aspects, idealisations and assumptions are presented first: in this context the objective is to propose a summary of the assumptions made to model the response of energy piles subjected to mechanical and thermal loads. Second, the generalised axial capacity formulation for energy piles is treated: the objective of this part is to define mathematical expressions that can be employed to investigate the failure of such foundations. Third, the capacity in coarse-grained soil, fine-grained soil and rock is analysed: in this context the purpose is to expand on approaches for estimating the capacity of energy piles in many of the situations that are likely to be encountered in practice. Next, the generalised axial deformation formulation characterising energy piles is treated: in this framework the purpose is to define mathematical expressions governing the deformation of such foundations. Afterward, thermomechanical schemes for energy piles are described: the purpose of this part is to expand on theoretical diagrams describing the influence of axial mechanical loads and thermal loads on the response of energy piles. Then, displacement charts are presented: in this context the aim is to provide charts summarising the vertical head displacement of single energy piles caused by mechanical and thermal loads in various situations. Later, the load-transfer analysis approach is discussed: the objective of this part is to provide the essentials of a powerful method for the analysis of the failure and deformation of energy piles. In addition to this, a discussion about the modelled and observed response of energy piles is proposed: in this framework, the aim is to expand on the capabilities of the foregoing theoretical approaches in modelling the actual response of energy piles. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 10.2 Idealisations and assumptions

Most of the idealisation and assumptions made in this chapter coincide with those presented in Chapter 7, Thermomechanical behaviour of energy pile groups. The quoted considerations find due justification in the referenced chapter and are only summarised for completeness in the following, prior to a detailed description and justification of additional hypotheses.

A continuum medium idealisation of the materials constituting energy pile foundations is employed while considering the materials to be isotropic and homogeneous. The piles are assumed to be characterised by a cylindrical shape. Layered (i.e. nonuniform) soil deposits are considered to be composed of fully horizontal layers. Uniform variations of the temperature, stress, strain and displacement fields within energy piles are assumed.
Young’s modulus and the Poisson’s ratio of the soil as well as to the slab dimensions of $L_{slab} = 26$ m and $B_{slab} = 10$ m. In the estimation of the average Young’s modulus and Poisson’s ratio of the soil no account was made of the properties of the molasse layer. The previous value of head stiffness resulted in a head restraint of $K_h = 4313.9$ MPa/m applied to the head of the modelled pile. (2) According to the hypothesis of an infinitely rigid plate representing the slab, a vertical mechanical load calculated as the average of the mechanical loads applied to the piles in the foundation of $P = 495$ kN was considered.

Fig. 10.55 shows the measured and computed evolutions of the degree of freedom, $DOF = \frac{\varepsilon_{th}}{\varepsilon_{th}}$, along the normalised along depth, $z^*/L$, of the single energy pile. The results of two different sets of simulations associated with different values of the Menard pressuremeter modulus for the molasse layer are reported.

The predictions capture the overall evolution of the experimental data. An increasing difference between the experimental and modelling results in correspondence with the shallower portion of the energy pile is observed for successive stages of its geothermal operation, that is when temperature variations of $\Delta T = 15^\circ C$ and $20^\circ C$ are considered. This difference is attributed to the incapability of the present load-transfer analysis approach in capturing the effects (e.g. stress redistribution) associated with the more pronounced thermally induced deformation of the soil (the molasse layer) than the deformation of the pile that was observed by Rotta Loria and Laloui (2017b) at the considered stages of the experimental test. Values of $DOF \neq 1$ are meaningfully observed at the pile head because of the presence of the head restraint.

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CHAPTER 11

Analytical modelling of capacity and deformation of energy pile groups

11.1 Introduction

Estimating the response of energy pile groups subjected to the mechanical and thermal loads associated with their structural support and heat exchanger operation represents a crucial complementary point to the characterisation of the single pile responses for any comprehensive analysis of energy pile foundations. Two key aspects must be addressed for energy pile groups: the group capacity and the group deformation. Addressing the capacity of energy pile groups involves investigating the potential failure of the individual piles composing the group and that of the pile group as a block. Addressing the deformation of pile groups involves considering the vertical displacement — differential and average — of the piles in the group and the load redistribution among the piles in the group.

The rationale for distinguishing the analysis of the capacity and deformation of energy pile groups from that characterising single energy piles is related to the presence and influence of group effects. Considering these phenomena may be omitted when dealing with widely spaced energy pile groups. However, these phenomena and the related analysis should be considered for closely spaced energy pile groups because of the different response to loading that characterise the piles in the group with reference to the same piles in a single isolated case. No analysis and design of closely spaced energy piles can be considered complete without addressing the behaviour of piles as both isolated elements and in a group. In this context, understanding and being capable to describe the potential interactions characterising energy pile groups is essential to address the thermomechanical behaviour of such foundations.

This chapter focuses on analytical and semianalytical approaches to characterise the capacity and the deformation of energy pile groups subjected to mechanical and thermal loads. Attention is given to the influence of axial (e.g. vertical and compressive) mechanical loads as well as to both heating and cooling thermal loads. The analysis of the influence of lateral loads can be considered separately and is not treated in the following.

To address the aforementioned aspects, idealisations and assumptions are presented first: in this context, the objective is to propose a summary of the assumptions made to model the response of energy piles subjected to mechanical and thermal loads.
Second, the generalised axial capacity formulation for energy pile groups is treated: the objective of this part is to define mathematical expression that can be employed to investigate the failure of such foundations. Third, the capacity in coarse-grained soil and fine-grained soil is analysed: in this context, the purpose is to expand on approaches for estimating the capacity of energy pile groups in many of the situations that are likely to be encountered in practice. Next, the generalised axial deformation formulation characterising energy pile groups is treated: in this framework, the purpose is to comment on the mathematical formulation expressing the vertical equilibrium of energy piles in a group and to present a summary of the approaches that can address the axial deformation of such foundations. Afterwards, the interaction factor method based on charts and analytical models is described: the purpose of this part is to expand on a simplified yet effective analysis approach addressing the deformation of energy pile groups subjected to axial mechanical loads and thermal loads, based on the analysis of a single energy pile. Then, the equivalent pier method is presented: in this context, the aim is to present a second method addressing both the axial failure and deformation of energy pile groups, based on the analysis of a single solid element representative of the group. Later, a comparison with rigorous solutions is discussed for a number of predictions obtained with the discussed analysis approaches: the objective of this part is to expand on the capabilities of the considered theoretical methods in modelling the response of energy pile groups to loading. In addition to this, a discussion about the modelled and observed response of energy piles is proposed: in this framework, the aim is to expand on the capabilities of the foregoing theoretical approaches in modelling the actual response of energy pile groups. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

11.2 Idealisations and assumptions

Most of the idealisation and assumptions made in this chapter coincide with those presented in Chapter 7, Thermomechanical behaviour of energy pile groups, and Chapter 10, Analytical modelling of capacity and deformation of single energy piles. The quoted considerations find due justification in the referenced chapters and are only summarised for completeness in the following prior to a detailed description and justification of one additional hypothesis.

A continuum medium idealisation of the materials constituting energy pile foundations is employed while considering the materials isotropic and homogeneous. The piles are characterised by a cylindrical shape. Layered (i.e. nonuniform) soil deposits are considered to be composed of fully horizontal layers. Uniform variations of the temperature, stress, strain and displacement fields within energy piles are assumed. Mechanical loads applied to energy piles are modelled via a prescribed force to their
The diameter of the equivalent pier was determined according to the expression proposed by Poulos (1993) for end-bearing piles. The slopes $K_{s,\text{eq}}$ and $K_{b,\text{eq}}$ of the elastic branches of the load–displacement functions proposed by Rotta Loria and Laloui (2018) were determined with reference to the spacing of $s = 4.67D$. The shaft and base capacities of the equivalent pier were determined by multiplying the shaft and base capacities of the single isolated piles multiplied by the number of piles in the group. The previous value of head stiffness resulted in a head restraint of $K_h = 1078.5$ MPa/m applied to the head of the equivalent pier. A value of mechanical load of $P = 1980$ kN was assumed to be applied to the equivalent pier based on the mechanical loads applied to the four energy piles represented by the pier. The equivalent Young’s modulus was calculated considering an average value of soil Young’s modulus with depth referring to all the soil layers except the bottom molasse layer.

Fig. 11.65 shows the measured and computed evolutions of the degree of freedom, $DOF = \varepsilon_{\text{th}}/\varepsilon_{0,\text{th}}$, along the normalised depth, $z^*/L$, of the equivalent pier, whereby $z^*$ expresses the depth from the head of the piles and pier. The relative depth $z^*$ is normalised by the pile length $L$. The results of two different sets of simulations associated with different values of the Menard pressuremeter modulus for the molasse layer are reported.

The predictions capture the overall evolution of the experimental data. An increasing difference between the experimental and modelling results in correspondence with the deeper portion of the energy piles is observed for successive stages of their geothermal operation, that is when temperature variations of $\Delta T = 15^\circ \text{C}$ and $20^\circ \text{C}$ are considered. This difference is attributed to the incapability of the present load-transfer analysis approach in capturing the effects (e.g. stress redistribution) associated with the more pronounced thermally induced deformation of the soil (the molasse layer) than the deformation of the piles that was observed by Rotta Loria and Laloui (2018) at the considered stages of the experimental test. Values of $DOF > 1$ are meaningfully observed in correspondence with the soil layer expanding more than the piles because of the greater thermally induced deformation of the piles compared to the one associated with free thermal expansion conditions by referring to the linear thermal expansion coefficient of the pile and the applied temperature variation to the pile. Values of $DOF \neq 1$ are meaningfully observed at the pile head because of the presence of the head restraint.

References


CHAPTER 12

Numerical modelling of energy geostructures

12.1 Introduction

The analysis of the thermohydromechanical behaviour of energy geostructures requires the consideration of the relevant heat transfer, mass transfer and deformation phenomena that characterise the subsurface throughout the geothermal and structural support operation of such technologies. These phenomena take place within and around energy geostructures, and are associated with a different thermohydromechanical behaviour depending on the intrinsically different geometrical features, heat transfer potential and construction methods characterising such geostructures.

From the perspective of the geothermal heat exchanger role of energy geostructures, the following noteworthy aspects can be highlighted. The different geometrical features and related heat transfer potential involve energy piles representing an effective means for energy harvesting at the building scale, while energy tunnels and energy walls can be considered for energy harvesting from the building to the city scale (e.g. via district heating networks). Energy piles are in most applications completely bounded by an interface with a soil or rock deposit. In contrast, energy tunnels and energy walls are also characterised by an interface wherein airflows are encountered. The presence of an interface with air involves the possibility of harvesting aerothermal energy in addition to geothermal energy. This feature makes the energy exploitation achievable through energy tunnels and walls particularly flexible yet challenging, because different heat sources can be employed for the energy harvesting. Based on the previous aspects, the energy harvesting achievable via energy geostructures can involve (1) heat and mass transfer by convection in the built environment adjacent to the energy geostructure, (2) heat transfer dominated by conduction within the filling material of the geostructure and across the wall of the pipes, (3) heat and mass transfer dominated by convection within the pipes of the geostructure and (4) heat transfer dominated by conduction in the ground, unless a significant groundwater flow leads to convection dominated heat transfer. Phenomena (1)–(4) typically characterise energy geostructures such as energy tunnels and energy walls. Phenomena (2)–(4) usually characterise energy geostructures such as energy piles.

From the perspective of the structural support role of energy geostructures, the following aspects can be noted. The mechanics of energy geostructures such as energy
piles is typically characterised by a predominant axial character. In contrast, the mechanics of energy geostructures such as energy walls is characterised by a predominant flexural character. Strong perturbations of the stress and displacement fields can characterise the ground surrounding all types of energy geostructures because of the loadings associated with their construction or operation. These perturbations can cause reversible or irreversible deformations (e.g. in the ground surrounding energy geostructures). However, the relative significance of mechanical loads to thermal loads that is associated with the construction and operational phases of energy geostructures is much more pronounced for energy tunnels and walls compared to energy piles, for example.

Various critical aspects of the thermohydromechanical behaviour of energy geostructures can be effectively captured through analytical and semianalytical modelling approaches. However, with the progress of the analysis or design process, numerical modelling approaches become essential to obtain comprehensive information on the heat transfer, mass transfer and deformation phenomena that characterise the behaviour of energy geostructures.

This chapter focuses on the numerical modelling of the thermohydromechanical behaviour of energy geostructures for typical technical solutions and site conditions that can characterise such applications. The analysis resorts to the results of finite element and computational fluid dynamics simulations, and is devoted to expanding on the influence of factors that can significantly characterise the response of energy geostructures.

To this aim, idealisations and assumptions are presented first: in this context the objective is to propose a summary of the conceptual descriptions and hypotheses that can be employed for the numerical modelling of the heat transfer, mass transfer and deformation phenomena that occur within and around energy geostructures. Next, the thermohydromechanical behaviour of energy piles, energy tunnels and energy walls is addressed: the purpose of this part is to investigate the response of such geostructures for a variation in typical technical solutions and site conditions. Later, the modelled and observed response is commented: the objective of this part is to propose a summary of currently available numerical simulations of the observed behaviour of energy geostructures. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 12.2 Idealisations and assumptions

The numerical modelling of the thermohydromechanical behaviour of energy geostructures typically differs depending on the following aspects: (1) the choice of the relevant modes of heat and mass transfers that are assumed to characterise energy
12.6 Modelled and observed response

Many different numerical approaches can be employed to simulate the thermohydro-mechanical behaviour of energy geostructures and the literature presents various comparisons between modelled and observed responses of energy geostructures. To date, the most significant proportion of experimental results obtained by means of full-scale field testing, centrifuge testing or laboratory testing is available for energy piles (see, e.g., Laloui et al., 2003; Bourne-Webb et al., 2009; Akrouch et al., 2014; Wang et al., 2014a; You et al., 2016; Sutman et al., 2018; Ng et al., 2014, 2015; Stewart and McCartney, 2012; Goode and McCartney, 2015; Kalantidou et al., 2012; Yavari et al., 2014, 2016; McCartney and Murphy, 2012; Murphy and McCartney, 2015; Mimouni and Laloui, 2015; Rotta Loria and Laloui, 2017, 2018; Nguyen et al., 2017). A markedly less developed amount of experimental results characterises other energy geostructures such as energy tunnels (Adam and Markiewicz, 2009; Buhmann et al., 2016; Barla et al., 2019) and energy walls (Xia et al., 2012; Sterpi et al., 2018a). Because of the previous evidence, the largest amount of numerical simulations currently available focuses on modelling aspects involved with the structural support and geothermal operation of energy piles rather than with other energy geostructures such as energy tunnels and energy walls.

The numerical simulation of the observed behaviour of energy piles has been addressed, for example, by Laloui et al. (2006), Wang et al. (2014b), Rotta Loria et al. (2015a,b), Saggu and Chakraborty (2015b), Di Donna et al. (2016) and Gawecka et al. (2016). The numerical simulation of the observed behaviour of energy walls has been addressed, for example, by Di Donna et al. (2017) and Sterpi et al. (2018b).

Due to the significant challenges and limited knowledge associated with energy tunnels and energy walls, the numerical analysis of the considered structures is expected to increase in the future.

References


PART E

Design
CHAPTER 13

Performance-based design in the context of energy geostructures

13.1 Introduction

Nowadays it is established that energy geostructures have major capabilities to provide energy supply and structural support to the built environment. To date, the energy requirements of various constructions have been met via energy geostructures and no examples showing the lack of structural support requirements have been documented. Based on the previous fact, the performance of energy geostructures, that is the feature to verify a given requirement while interacting with general perturbations, may be considered satisfactory.

However, the absence of applications of energy geostructures characterised by a lack of required performance (e.g. energy, geotechnical and structural) is often not representative of an adequate design. In contrast, the previous evidence is the consequence of a design created (at least theoretically) to overly conservatively tackle the challenging multiphysical phenomena associated with the structural support and geothermal operations of energy geostructures. Designs of structures aimed at achieving a trouble-free performance instead of an optimal performance have the marked limitation of being uneconomical. Only by understanding any problem in a theoretical and empirical sense and by developing analysis tools and design methodologies can adequate and economical designs can obtained.

So-called performance-based design approaches are key methodologies to achieve adequate and economical designs. The reason for this is that, compared to so-called prescriptive design approaches that resort to deterministic specifications and are consequently of limited applicability, performance-based design approaches resort to statistical concepts and provide verifications of broad applicability to ensure an optimal performance.

In the context of the design project of constructions, various norms rely on a performance-based design approach. For example a framework for the structural and geotechnical performance-based design of structures has been available for several decades in the European Union and is detailed in norms often called the Eurocodes. In relatively recent years, integrations to the previous normative framework have been proposed to address the optimal geotechnical and structural design of energy geostructures, based on three main reasons: (1) the different nature of thermal actions applied to energy geostructures compared to that of thermal actions typically applied to more
conventional structures and infrastructures; (2) the shortcomings described in prescriptive design guidelines about the influence of thermal actions, applied alone or in conjunction with mechanical loads, on the actual response of energy geostructures; and (3) the lack of appropriate performance-based design methodologies addressing the influence of thermal actions applied to energy geostructures.

This chapter presents the theoretical essentials constituting the performance-based design of general geostructures drawing from the Eurocodes framework, with a focus on novel aspects and practical approaches to address the geotechnical and structural performance-based design of energy geostructures. While not claiming to be comprehensive of all design situations that may characterise energy geostructures and to be valid for all normative contexts, this analysis is aimed at expanding on key aspects characterising the geotechnical and structural design of many energy geostructures.

To this aim, holistic integrated design considerations are proposed first: the objective of this part is to summarise essential features of the design project of constructions and to focus on key aspects characterising the design of energy geostructures. Second, the available design recommendations for energy geostructures are summarised: in this context the purpose is to expand on currently available guidelines for the design of the considered structures. Next, the Eurocode Programme is introduced: the purpose of this part is to expand on features of norms available in the European Union for the common performance-based design of structures. Then, the concepts of limit states and design situations as well as the classification of actions characterising general structures are presented: in this framework the aim is to propose essential features characterising the performance-based design of structures. Afterward, the verification of requirements through a partial factor method, the performance-based design approach for energy geostructures and the combinations of actions at ultimate and serviceability limit states are described: the aim of this part is to highlight typical steps constituting the performance-based design of structures as well as to propose an appropriate design approach for energy geostructures drawing from the Eurocodes. The design data for some materials are subsequently summarised: the purpose of this section is to report design data for concrete and reinforcing steel, based on the rationale that these materials characterise most energy geostructures. Later, the design for ultimate and serviceability limit states is discussed: the goal of this part is to present theoretical essentials and practical design approaches to tackle typical design problems in the framework of the Eurocodes. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

**13.2 Holistic integrated design considerations**

The design project of buildings and infrastructures is certainly complex and a holistic integrated approach is required for achieving the features desired for any construction.
(4) degree of slip between the foundation and the ground, and (5) building configuration, should be considered.

Information on the severity of cracking damage for buildings is given by Day (2000), who also concluded that the following relationship, first suggested by Skempton and MacDonald (1956), is reasonable for estimating the relationship between the absolute value of differential settlement $\Delta_{\text{max}}$ and the angular distortion $\Delta w/l$ to cause cracking:

$$\Delta_{\text{max}} \approx 8900 \frac{\Delta w}{l} \text{[mm]}$$  \hspace{1cm} (13.80)

**References**


CHAPTER 14

Determination of design parameters for energy geostructures

14.1 Introduction

Various input data are required to carry out the analysis and design of energy geostructures. These data allow developing qualitative and quantitative characterisations of any planned energy geostructure application and include, without being limited to, material properties and material parameters. In principle, a clear distinction between the terms parameters and properties exists. Material properties are quantities that are independent of the state conditions. Material parameters are quantities that change with the state conditions. In practice, as is often made in the scope of energy geostructures, the two aforementioned terms are used as synonyms. The same approach is considered here.

Investigations must be performed to determine parameters serving analysis and design processes. These investigations are carried out considering the features and goals of the analysis or design to be performed, and can be empirical or theoretical. Empirical approaches include experimental full-scale in situ tests, laboratory tests and centrifuge tests. Theoretical approaches include literature surveys and analytical calculations. In principle, theoretical or experimental investigations can be employed for analysis and design purposes. In practice, no analysis or design can be considered comprehensive without resorting to parameters defined through detailed experimental tests.

Experimental in situ tests have the advantage to allow the ground or the geostructure to be tested under full-scale conditions and thus to inherently include the peculiarities of any site (e.g. stress state, groundwater flow, undisturbed ground temperature). Laboratory tests and centrifuge tests have the advantage to allow comprehensive experimental campaigns to be carried out and to be quicker and cheaper compared to in situ tests. With particular reference to the stress state, centrifuge tests have the advantage of allowing for a replication of the in situ conditions through the use of appropriate scaling factors and experimental methodologies. No preferable experimental approach should be stipulated. The choice of the experimental approach may often be driven by temporal and economic availabilities as well as by the targeted comprehensiveness of the analysis or design to be performed. Determining the parameters required for the analysis and design of energy geostructures and understanding the features of the experimental tests that can address the previous purpose is paramount for successful applications of this technology.
This chapter addresses the parameters required for the design of energy geostructures, with a focus on their determination through experimental approaches. In this context, specific reference is made to parameters required for design purposes, but the same parameters may be considered for analysis activities. Yet, while a focus is given to full-scale in situ tests and laboratory tests, centrifuge tests are disregarded.

With this aim, the characterisation of sites is discussed first: the objective of this part is to summarise key features of energy geostructure applications and to link these features to the behaviour (e.g. thermal, hydraulic and mechanical) and performance (e.g. energy, geotechnical and structural) of the considered structures. Second, design parameters are summarised: in this context the goal is to propose categories of parameters allowing the previous types of behaviour and performance of energy geostructures to be addressed. Next, testing methods are presented: the aim of this digression is to summarise experimental approaches for determining the highlighted parameters. Then, guarded hot plate testing as well as oedometer, triaxial and direct shear testing under nonisothermal conditions are addressed: the aim of this part is to expand on the considered experimental laboratory tests. Afterwards, thermal response testing and load testing under nonisothermal conditions are described: the purpose of this part is to discuss key features of the addressed in situ tests. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 14.2 Characterisation of sites

Any energy geostructure project presents specific features that characterise the multiphysical behaviour and performance of such structures. Addressing these features is paramount for analysis and design purposes. Several features characterising energy geostructure applications have been summarised by Brandl (2006). A modified and expanded list of these features is as follows:

1. Geothermal features of site:
   a. Thermal properties;
   b. In situ temperature field,
2. Aerothermal features of site (where applicable):
   a. Significance of airflow in underground built environment (e.g. flow condition);
   b. Features of velocity and thermal boundary layers;
   c. Presence and significance of heat sources.
3. Hydrogeological features of site:
   a. Depth of groundwater table;
   b. Presence and significance of seasonal fluctuation of groundwater table;
   c. Presence and significance of groundwater flow (e.g. flow velocity, flow direction).
geostructures as well as to address the mechanical response of such structures through the understanding of the sensitivity to loading (e.g. thermal) of the deposit.

Piezometers and thermistors allow temperature and pore water pressure variations in the ground to be measured. The piezometers PWS with stainless steel filters from Roctest and thermistors TH-T from Roctest are two types of these sensors. Both the piezometers and thermistors can be deployed in boreholes filled with a mixture of coarse- and fine-grained soil. Thermistors must be used with the piezometers because the latter employ vibrating wire transducers that require temperature corrections due to the nonisothermal conditions involved with the geothermal operation of energy geostructures. The pore water pressure variations can be calculated as

\[
\Delta p_w = A^* \frac{K_g^2}{1000^2} (F^4 - F_0^4) + B^* \frac{K_g^2}{1000} (F^2 - F_0^2) - C^*(T - T_0) \tag{14.34}
\]

where \(A^*, B^*\) and \(C^*\) are calibration factors that are provided by the sensor supplier.

### 14.10.6 Displacement determination in the soil

Assessing the magnitude of displacements caused by the loading of the energy geostructures is another key point for addressing the thermohydromechanical behaviour of such structures. Displacements of primary interest are usually those of the geostructure itself. However, ground displacements can also be of interest.

LVDTs can be employed to measure the displacement of energy geostructures. Extensometers allow ground displacements to be measured. The borehole extensometers BOR-EX from Roctest are one type of these latter sensors. Extensometers can be put in place via boreholes to be filled with adequate material. Rebar anchors located at different depths and linked to a reference plate (e.g. made of stainless steel rods) may be used to measure the displacements (Mimouni and Laloui, 2013).

### References


Determination of design parameters for energy geostructures


CHAPTER 15

Performance-based design of energy piles

15.1 Introduction

The coupled application of thermal and mechanical loads to energy piles due to their multifunctional operation represents a challenge. From a design perspective, such a challenge is primarily related to the fundamentally different nature of thermal and mechanical loads, which yields to diverse effects on the mechanical (stress and deformation) response of energy piles. These effects must be considered in the geotechnical and structural design of energy piles via performance-based design approaches.

Thermal loads can be idealised as imposed deformations. These loads cause expansion and contraction of the energy piles and the surrounding ground. While energy piles expand upon heating and contract upon cooling, soils can expand or contract upon heating, and contract upon cooling. In most cases, a portion of the thermally induced deformation of energy piles is restrained by the surroundings and causes thermally induced stress in such foundations. The significance of the observed thermally induced strains and stresses depends on the end-restraint conditions and the ratio between the thermal expansion coefficient of the ground and that of the energy piles. Both of these aspects also characterise the vertical displacement and shear stress variations within energy piles. Energy piles subjected to thermal loads generally displace in opposite directions from the so-called null point of the vertical displacement and mobilise shear stress at the pile shaft to ensure equilibrium from the so-called null point of the shear stress. The locations of the referenced null points are generally different and can vary throughout loading. The stress, strain and displacement variations characterising energy piles can critically vary because of the influence of group effects associated with thermal loads. These effects are responsible for a greater group deformation than that of a single isolated pile under the same average load.

Mechanical loads can be idealised as prescribed forces. These loads typically cause stress and strain variations that decrease along the depth of the energy piles and the surrounding ground. In most cases, the evolutions with depth of the variations caused by mechanical loads are more uniform than those caused by thermal loads and are associated with displacement variations in a unique direction. The end-restraint conditions also govern, in this context, the significance of the
stress, strain and displacement variations, together with group effects caused by mechanical loads.

Much theoretical and empirical knowledge and many analysis tools have been made available to characterise the response of energy piles subjected to thermal and mechanical loads as well as to address the geotechnical and structural performance of such geostructures. In relatively recent years, design recommendations have been proposed and studies addressing performance-based design approaches have been carried out. Along with the previous developments, a performance-based design methodology for the considered geostructures is essential.

This chapter focuses on the performance-based design of energy piles subjected to axial mechanical loads and thermal loads. The considered subject is addressed via the proposition of a dedicated framework with particular reference to the Eurocodes. Nonetheless, the proposed developments may be extended to other performance-based standards and frameworks via potential modifications. Particular attention is given to energy piles made of reinforced concrete, as well as to the influence of compressive mechanical loads applied in conjunction with thermal loads to such foundations.

To address the aforementioned aspects, performance-based design principles for general pile foundations are presented first: in this context the objective is to highlight norms and relevant limit states that may be considered for the design of pile foundations. Second, a performance-based design methodology for energy pile foundations is proposed: the objective of this part is to define design criteria, problems and verification approaches to address the performance-based design of such foundations. Then, the design for ultimate and serviceability limit states is addressed: in this context the purpose is to expand on key steps characterising the design of energy piles at the considered limit states. Finally, questions and problems are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

15.2 Performance-based design principles for general pile foundations

15.2.1 General

Principles and provisions for the performance-based design of pile foundations can be found in the EN 1997 (2004). Particular attention to the action of axial loads on pile foundations is given in the EN 1997-1 (2004). The considered provisions apply to piles installed by driving, boring, jacking and screwing, with or without grouting, and characterised by either a predominantly friction or end-bearing character. These provisions should not be applied to the design of piles that are intended as settlement reducers (e.g. applications of piles in some piled raft foundations).
The minimum cover should be increased to 75 mm where (1) piles penetrate soft soil and are constructed without a casing; (2) an exposure class associated with attack of freeze/thaw cycles with or without de-icing agents is encountered [class 5 in accordance with the DD ENV 206 (1992)]; (3) submerged placement of concrete when a dimension of maximum aggregate is out-dated; and (4) reinforcement is installed subsequent to concrete placement or the borehole walls have even surface (EN 1992, 2004). A minimum cover of 80 mm for dense concrete is essential, but greater cover is advisable (BS 8004, 2015).

Bored piles may typically be equipped with recommended values of minimum longitudinal reinforcement \( A_{r,\text{min}} \) depending on the concrete cross sectional area \( A_c \). Recommended values of minimum reinforcement drawing from the previous considerations are reported in Table 15.6 with reference to the EN 1992 (2004). It should always be ensured that the previous (or other) provisions ensure ductility (Rotta Loria et al., 2019). The minimum diameter for the longitudinal bars should not be less than 16 mm and at least six longitudinal bars should be considered (EN 1992, 2004). The clear distance between bars should not exceed 200 mm measured along the periphery of the pile (EN 1992, 2004). Spacing of longitudinal bars should always be maximised in order to allow proper flow of concrete but should not exceed 400 mm (EN 1992, 2004).

The minimum diameter of 6 mm should be considered for transverse reinforcement represented by links, hoops or helical reinforcement, while the diameter of 5 mm should be considered for wires of welded mesh (EN 1992, 2004).

### Table 15.6 Recommended minimum longitudinal reinforcement area in bored piles.

<table>
<thead>
<tr>
<th>Pile concrete cross section, ( A_c )</th>
<th>Minimum area of longitudinal reinforcement: ( A_{r,\text{min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_c \leq 0.5 \text{ m}^2 )</td>
<td>( A_r \geq 0.005 \ A_c )</td>
</tr>
<tr>
<td>( 0.5 \text{ m}^2 &lt; A_c &lt; 1.0 \text{ m}^2 )</td>
<td>( A_r \geq 25 \text{ cm}^2 )</td>
</tr>
<tr>
<td>( A_c &gt; 1.0 \text{ m}^2 )</td>
<td>( A_r \geq 0.0025 \ A_c )</td>
</tr>
</tbody>
</table>


(EN 1992, 2004). The minimum cover should be increased to 75 mm where (1) piles penetrate soft soil and are constructed without a casing; (2) an exposure class associated with attack of freeze/thaw cycles with or without de-icing agents is encountered [class 5 in accordance with the DD ENV 206 (1992)]; (3) submerged placement of concrete when a dimension of maximum aggregate is out-dated; and (4) reinforcement is installed subsequent to concrete placement or the borehole walls have even surface (EN 1992, 2004). A minimum cover of 80 mm for dense concrete is essential, but greater cover is advisable (BS 8004, 2015).

Bored piles may typically be equipped with recommended values of minimum longitudinal reinforcement \( A_{r,\text{min}} \) depending on the concrete cross sectional area \( A_c \). Recommended values of minimum reinforcement drawing from the previous considerations are reported in Table 15.6 with reference to the EN 1992 (2004). It should always be ensured that the previous (or other) provisions ensure ductility (Rotta Loria et al., 2019). The minimum diameter for the longitudinal bars should not be less than 16 mm and at least six longitudinal bars should be considered (EN 1992, 2004). The clear distance between bars should not exceed 200 mm measured along the periphery of the pile (EN 1992, 2004). Spacing of longitudinal bars should always be maximised in order to allow proper flow of concrete but should not exceed 400 mm (EN 1992, 2004).

The minimum diameter of 6 mm should be considered for transverse reinforcement represented by links, hoops or helical reinforcement, while the diameter of 5 mm should be considered for wires of welded mesh (EN 1992, 2004).

### References


CHAPTER 16

Design of details for construction of energy geostructures

16.1 Introduction

One practical basic feature distinguishing energy geostructures from conventional geostructures is the presence of noteworthy amounts of pipes that need to be installed for the sake of the energy harvesting of such technology. In relatively small energy geostructure projects, kilometres of pipes may have to be installed.

While precise specifications and plans are needed during the construction of energy geostructures about supply, potential stock, installation, verification and testing, quality control and maintenance of materials, products and components, various details must be defined from the analysis and design phases of any project. These details typically involve determining the configuration of the pipes to be installed in an energy geostructure, in what manner and quantity these pipes should be installed, how the piping network may be connected and tested, and what materials or components would need a quality control following specific verifications. All of these aspects play a crucial role for the expedient yet effective application of energy geostructures as well as for their optimal operation and performance. In this context, designing the details characterising the construction of energy geostructures appears of comparable importance to the aspects characterising the energy, geotechnical and structural designs of such geostructures.

This chapter focuses on the design of details for the expedient yet effective construction of energy geostructures. The analysis is based on the available recommendations at the national level in Switzerland, United Kingdom and France as well as on practical experience in this scope, and focuses on the features characterising the piping network installed within and between energy geostructures.

To address the aforementioned aspects, the pipe features and bending are presented first: in this context the objective is to highlight possible materials that may be employed for the pipes characterising energy geostructure applications as well as the details that should be accounted for bending the pipes within energy geostructures. Second, the pipe fixing to the reinforcing cage of general energy geostructures is treated: the objective of this part is to define the methods through which pipes may preferably be installed within energy geostructures. Next, the energy geostructure installation is analysed: in this context the purpose is to expand on approaches for the effective
construction of energy geostructures. Afterward, the *piping network and connections* are treated: in this framework the purpose is to comment on the features that should be considered to connect the pipes installed between energy geostructures. Then, aspects related to *quality control* are described: the purpose of this part is to expand on verifications aimed at ensuring durability and performance of a number of components constituting energy geostructures. Finally, *questions and problems* are proposed: the purpose of this part is to fix and test the understanding of the subjects covered in this chapter by addressing a number of exercises.

### 16.2 Pipe features and bending

Restrictions for the minimum and maximum depth that should be considered for equipping energy geostructures with pipes are mostly driven by the aim of limiting the influence of the surface conditions on the thermohydraulic behaviour and energy performance of the geostructures, and by practical construction considerations linked to the installation of both the pipes and the geostructures, respectively. According to the *SIA-D0190 (2005)*, a minimum depth of \( z = 10 \) m in order for an energy geostructure project to be economically sustainable as well as a maximum depth of \( z = 60 \) m for a relatively straightforward installation of the energy geostructure may be considered. While the former specification may be considered in many situations for all types of energy geostructures, the latter specification should be considered for general energy geostructures except energy tunnels, which can be constructed relatively easily also at greater depths.

In the horizontal direction, the number of pipes that can be installed in an energy geostructure typically depends on its geometry. For energy piles, *Tomlinson and Woodward (1993)* suggest a typical value of four loops to be installed within piles with a diameter of \( D = 60 \) cm, whereas the *CFMS-SYNTecsOFFFFONS-FNTP (2017)* prescribe the number of pipes to be chosen as a function of the pile diameter: for \( D \leq 40 \) cm, one loop should be considered; for \( D > 40 \) cm, one additional loop may be considered for a successive increase of 20 cm in the pile diameter. For a 60 cm diameter energy pile, this latter approach would yield a maximum of three loops, which approximately agrees with the value given by *Tomlinson and Woodward (1993)*. For other energy geostructures, such as energy walls, slabs and tunnels, similar recommendations are currently unavailable. However, the *CFMS-SYNTecsOFFFFONS-FNTP (2017)* suggest that an energy wall may contain several cages with pipes. Therefore looking at each cage individually, similar considerations may be made as for energy piles, with reference to a rectangular section. A minimum spacing of 15 cm between the pipes may generally be considered (*SIA-D0190, 2005; CFMS-SYNTecsOFFFFONS-FNTP, 2017*).
The duration of the pressure tests detailed by the SIA-D0190 (2005) should be of at least 4 hours and a pressure drop of up to 0.5 bar may be allowed. This pressure drop is noticeably higher than the pressure drop of 0.1 bar allowed, for example by the CFMS-SYNTÉC-SOFFONS-FNTP (2017). According to the SIA-D0190 (2005), all pressure tests should also be registered in a logbook that must be handed over to the client once the system is completed. Because the height of junctions and valves can vary up to 1 m from the designed position, the displacement of the cage during and after concreting should be carefully overseen to avoid having to rebuild the connections after trimming.

Experience gives some critical steps at which pressure tests as described in the SIA-D0190 (2005) should be performed:
1. after mounting of pipework in the reinforcement cage;
2. after concreting;
3. after trimming of pile heads;
4. after installation of horizontal networking;
5. after final coating of pipes in the sand (pipes under the invert) or before concreting of the invert (pipes inside the invert);
6. before installation of the manifolds.

References
Appendix A: Survey about energy geostructure projects worldwide

A.1 Summary
This appendix presents the questionnaire that was submitted as a part of the international survey reported in Chapter 2, Energy geostructures, with the aim of estimating the number of applications and the features of energy geostructures worldwide, as well as the best practice methods employed to design and construct such structures by practitioner companies.

A.2 Questionnaire
The following questions concern information that we would need about the projects involving energy geostructures that were designed/built by your company. These questions are grouped into two sets: a general part and a more specific part. We would be grateful if you could answer to as many questions as possible and send this survey back to us. The addition of any material that you could share with us would be greatly appreciated.

I. General part
1. How many projects involving energy geostructures were realised by your company (please specify the name and the location of such project(s))?
2. For these projects, how many elements/surfaces of these geostructures were equipped as a geothermal heat exchanger (e.g. number of energy piles, surfaces of energy walls)?
3. In general, in which type of soil do you realise energy geostructures (e.g. coarse-grained soil, fine-grained soil or rock)?
4. Based on your experience, in which type of soil do you observe the greatest energy performances?
5. In general, what is the operation of the realised energy geostructures (e.g. heat exchange operation for cooling and/or heating, or heat storage operation with solar thermal panels)?
6. What were the types of constructed energy piles (e.g. floating piles, end-bearing piles) and the employed construction method?
7. What were the types of constructed energy walls (e.g. diaphragm wall, sheet pile wall and slurry wall) and the employed construction method?
8. What were the types of constructed energy tunnels (e.g. cut and cover, segmental lining) and the employed construction method?
Appendix B: Thermohydromechanical modelling in the context of energy geostructures

B.1 Summary

This appendix proposes a coupled mathematical formulation addressing the thermohydromechanical behaviour of materials to characterise the influences between heat transfer, mass transfer and deformation, which occur, for example in the context of energy geostructures. The considered developments resort to an analysis of the influences between mass transfer and deformation, and the proposition of a coupled mathematical formulation addressing the hydromechanical behaviour of geomaterials under isothermal conditions. This latter formulation completes the paired analysis of heat transfer, mass transfer and deformation phenomena with the theory treated in Chapters 3, Heat and mass transfers in the context of energy geostructures, and Chapter 4, Deformation in the context of energy geostructures, and serves as a basis for the understanding of the core subject of this appendix.

B.2 Hydromechanical modelling

B.2.1 General

The analysis of the interactions between mass transfer and deformation through mathematical formulations that link the key variables governing the considered phenomena represents a typical example of hydromechanical modelling. Hydromechanical modelling is particularly relevant to address the behaviour of geomaterials such as soils and rocks as a consequence of the interactions between the solid matrix and the fluid(s) contained in the material pores. These interactions are related to the fact that the deformation of porous materials affects the flow of the fluid(s) contained in the pores of their structure, and the fluid pressure influences the mechanical behaviour of these structures. In fact, both the solid matrix and the fluid(s) in the pores support the load acting on porous materials. This hydromechanical coupling influences the expansion or contraction of the deforming matrix, and the pressure gradient of the diffusing pore fluid(s). A thorough understanding of hydromechanical interactions is key to model problems involving consolidation as well as the general (isothermal) loading of geomaterials, and is relevant for the analysis and design of geostructures, for example.

The foundations of the hydromechanical modelling of geomaterials can be addressed to the works of Biot (1941, 1956). The theory of consolidation proposed by Terzaghi (1923) represents a particular case of the general framework characterising the problem addressed (Vulliet et al., 2016). Detailed information on the
References


Appendix C: Advanced Constitutive Model for Environmental Geomechanics-Temperature effects

C.1 Summary
A framework allowing for the modelling of the reversible and irreversible mechanical behaviour of materials has been presented in Chapter 4, Deformation in the context of energy geostructures. However, no specific reference to mathematical formulations for modelling the elastoplastic behaviour of any particular material and account for the influence of nonisothermal conditions on this behaviour has been reported. Various mathematical formulations can be employed for the considered purpose. The features of these formulations depend on the mechanical behaviour of the modelled material because they are generally tailored to capture key aspects of such behaviour depending on the purpose and the aimed accuracy of the investigation.

In the following, the Advanced Constitutive Model for Environmental Geomechanics, with Temperature effects included (ACMEG–T) is presented to capture advanced aspects of the behaviour of geomaterials such as soils. The model can characterise the thermoeelastic, thermoplastic behaviour of soils in the framework of the critical state theory (Schofield and Wroth, 1968) and may be used in the analysis and design of energy geostructures to capture the mechanical response of soils under nonisothermal conditions through an advanced approach. The isothermal part of the model is based on the work of Hujeux (1979). The nonisothermal part of the model has been developed to address monotonic and cyclic loading conditions through successive studies by Laloui (1993), Modaressi and Laloui (1997), Laloui and Cekerevac (2008), Laloui and Francois (2009) and Di Donna and Laloui (2015). Further improvements have been presented by Vilarrasa et al. (2016).

C.2 Stress–strain behaviour and elastic relations
The increment of total strain reads

\[ d\varepsilon_{ij} = \frac{1}{3} d\varepsilon_{\nu}\delta_{ij} + de_{ij} \]  

(C.1)

with

\[ d\varepsilon_{\nu} = \text{tr}(d\varepsilon_{ij}) \]  

(C.2)
References


Further reading

Analysis and Design of Energy Geostructures
Theoretical Essentials and Practical Application

Analysis and Design of Energy Geostructures: Theoretical Essentials and Practical Application gathers a unified framework of the theoretical and experimental competence available on energy geostructures: innovative multifunctional earth-contact structures that can provide renewable energy supply and structural support to any built environment. The book covers the broad, interdisciplinary and integrated knowledge required to address the analysis and design of energy geostructures from energy, geotechnical and structural perspectives. This knowledge includes (Part A) an introduction to the technology; (Part B) the fundamentals of heat and mass transfers as well as of the mechanics of geomaterials and structures required to address the unprecedented behaviour of energy geostructures; (Part C) the experimental evidence characterising the considered geostructures; (Part D) various analytical and numerical modelling approaches to analyse the response of energy geostructures and (Part E) the performance-based design and detailing essentials of energy geostructures. Designed with civil engineers in mind, this book targets energy engineers, environmental engineers, geologists, architects and urban project managers as well.

Key Features
- Proposes the theoretical and practical application essentials required to address the analysis and design of energy geostructures from energy, geotechnical, and structural perspectives
- Presents a substantial amount of resolved exercises on key aspects governing the behaviour and performance of energy geostructures to be considered in analysis and design
- Summarises and discusses the most recent scientific and technical knowledge about energy geostructures, including energy piles, energy tunnels and energy walls

About the Authors
Lyesse Laloui
Lyesse Laloui, PhD, is a chaired professor at the Swiss Federal Institute of Technology in Lausanne, EPFL, Switzerland. He is also an adjunct professor at Duke University, United States, and an advisory professor at Hohai University, China. His main research interests are in Geomechanics as well as Environmental and Energy Sustainability. He has written and edited 12 books, authored over 300 refereed scientific papers and is the editor-in-chief of the international journal Geomechanics for Energy and the Environment. He has served as a keynote speaker and honorary lecturer at more than 40 leading international scientific events and he has also delivered training courses for practitioners and scientists on various topics including the analysis and design of energy geostructures. He has cofounded the GEOEG engineering company, providing integrated solutions for energy geostructures for prominent architectural and engineering projects around the world.

Alessandro F. Rotta Loria
Alessandro F. Rotta Loria, PhD, is an assistant professor at Northwestern University, United States, and a qualified professional civil and environmental engineer of the Italian Order of Engineers. His main research interests are at the interface of Geomechanics, Structural Mechanics and Energy. He is an editorial associate of the international journal Geomechanics for Energy and the Environment and is actively involved in many international scientific events as invited lecturer and presenter. Over the past 5 years, he has received various prizes and honours for excellence in scientific research, among which the 2019 Zeno Karl Schindler Prize for key contributions in the field of environmental sustainability, and he has also delivered training courses for practitioners and scientists on the analysis and design of energy geostructures. He has cofounded the GEOEG engineering company, providing integrated solutions for energy geostructures for prominent architectural and engineering projects around the world.