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Foundations for the future: thermo-active piling engineering

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Article

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Abstract

The urban subsurface represents a critical underutilized resource for addressing the rising energy and infrastructure demands of modern cities. Among the emerging technologies that use this potential, energy geostructures offer an innovative, sustainable, and cost-effective solution. By integrating geotechnical engineering principles with energy functionality, these systems provide both structural stability and renewable heating and cooling energy for buildings and infrastructure. Over the past three decades, extensive research has advanced the understanding of the behavior of different types of energy geostructures, including energy piles, barrettes, walls, and slabs, and analytical and numerical tools have been developed to support their design and optimization. This study synthesizes a number of these advancements, focusing specifically on building foundations, and emphasizes the transition from theoretical research to practical implementation. Through discussion of key design methodologies and real-world case studies, it highlights the critical role of energy geostructures in reducing fossil fuel dependence, enhancing energy efficiency, and contributing to the decarbonization of the built environment.

1. Introduction

1.1 Energy geostructure technology

Climate change, intensified by the continued rise in greenhouse gas emissions and the depletion of natural resources, underscores the urgency of transitioning toward a more sustainable and low-carbon energy system. In 2022, nearly half of the total energy consumed in buildings was devoted to space and water heating, generating around 2400 Mt of direct and 1700 Mt of indirect CO2 emissions, numbers that showed little improvement from the previous year. Although there is progress in using cleaner and more efficient heating solutions, fossil fuels still account for over 60% of the energy used for heating. At the same time, global cooling demand has surged to more than three times its 1990 level, contributing to increased electricity grid stress, higher greenhouse gas emissions, and the exacerbation of urban heat islands (IEA, 2023).

Over the last three decades, energy geostructures have emerged as a promising solution to such challenges, harnessing the largely untapped thermal energy of the urban subsurface within shallow geothermal systems (e.g., Laloui & Rotta Loria, 2019). These systems integrate geothermal heat exchangers into structures that are in contact with the ground. The technology was initially developed for pile foundations and subsequently extended to various types of earth-contact structures, including walls, slabs, and barrettes. By harnessing the stable, low-enthalpy thermal energy available in the shallow subsurface, energy geostructures can provide renewable heating and cooling for buildings, support domestic hot water production, and offer seasonal thermal storage. They also offer operational benefits, such as preventing ice formation on pavements, bridges, and runways, as well as reducing ventilation requirements in underground infrastructure facilities. While their use is well-established in geothermal heat pump applications, the emergence of fifth-generation district heating and cooling networks presents an opportunity for wider deployment.

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These networks connect multiple energy users, enabling energy geostructures to function as low-temperature, ground-coupled sources and storage systems, thereby enhancing the sustainability, flexibility, and resilience of urban energy systems (Meibodi & Loveridge, 2022).

Energy geostructures are typically constructed from reinforced concrete and incorporate heat exchanger tubes, most often made of high-density polyethylene, that are embedded in drainage paths or attached to the reinforcement cage during construction (Figure 1). These pipes, ranging in diameter from 10 to 40 mm, circulate a heat-transfer fluid, typically water mixed with antifreeze or a salt solution, to facilitate thermal exchange with the surrounding soil. Initial sections of the piping are insulated to reduce climatic impacts and improve overall efficiency. The arrangement of the pipes varies according to the design requirements of the system and influences installation, operation, and maintenance costs. For example, energy walls and slabs interact thermally with both the ground and the ambient air, making their effectiveness highly sensitive to this selected strategy in terms of pipe placement and insulation. By considering such design and integration effects in a careful manner, energy geostructures provide an integrated solution that simultaneously meets structural demands and supports sustainable energy management in buildings and infrastructure (e.g., Laloui & Rotta Loria, 2019).

1.2 Environmental, social, and economic aspects of energy geostructures

Energy geostructures provide a sustainable, economically viable, and socially advantageous approach to supplying thermal energy for buildings and infrastructure. As low-carbon technology, the thermally activated geostructures can substantially reduce CO_2-eq emissions and support global decarbonization efforts. These systems are compatible with international sustainability policies, regulations, and agreements promoting sustainability, and can easily be integrated with other renewable technologies to develop efficient and flexible energy systems. In comparison to conventional gas- or electricity-based heating systems, which emit approximately 200 gCO_2-eq/kWh, renewable heating energy solutions have a much lower environmental impact with typical life cycle emissions ranging between 4 and 46 gCO_2-eq/kWh (Edenhofer et al., 2011). Recent advances in renewable energy technology have further improved life-cycle emissions: polycrystalline silicon photovoltaic panels now emit roughly 12-20 gCO_2-eq/kWh (Louwen et al., 2016), low-temperature solar thermal panels around 5.8 gCO_2-eq/kWh (Pfadt-Trilling et al., 2023), and energy geostructures typically produce around 15 gCO_2-eq/kWh. From an environmental perspective, their implementation requires no additional soil excavation, and embedding the heat-exchanging circuits within the concrete structures reduces risks of pipe damage or groundwater contamination. Concerns about subsurface temperature variations are mitigated, as temperature disturbances in the subsurface are generally limited to depths of 5 to 10 meters. The systems can also capture and store otherwise wasted thermal energy, creating highly efficient energy storage solutions (Laloui & Rotta Loria, 2019). In urban areas affected by subsurface heat islands, shallow geothermal systems can achieve improved heating performance by exploiting excess subsurface heat resulting from human activity (Bayer et al., 2019; Benz et al., 2022; Rotta Loria, 2023; Zhu et al., 2010).

From a societal standpoint, energy geostructures provide a range of advantages that extend beyond energy efficiency only. They enable quieter and cleaner thermal regulation than traditional air-conditioning systems, contributing to stable temperature and humidity control in environments such as museums, and improving personal comfort by delivering radiant heating through building surfaces, including floors and walls (Brandl, 2016).

In addition to their environmental and societal benefits, energy geostructures offer significant economic advantages. They typically provide a reliable return on investment within 2 to 10 years, and their costs are largely

Figure 1. Installation of heat exchanger tubes on reinforcement cages of foundation structures before pouring concrete or integrated into drainage paths (image source: GEOEG, 2025).

unaffected by fluctuations in energy markets (Brandl, 2016; Singh et al., 2019). Their low maintenance requirements further contribute to short payback periods (Brandl, 2016; Singh et al., 2019). Compared to traditional geothermal systems, energy geostructures are more cost-effective because the heat exchangers are integrated into structural elements that are already needed for construction, thereby reducing both excavation expenses and administrative burdens. Long-term studies indicate that operational costs over a 50-year building lifecycle often surpass initial construction costs, highlighting the economic and environmental value of energy-efficient designs (Brandl, 2016). At a national level, the widespread deployment of energy geostructures can lower energy import dependence, reducing vulnerability to external economic pressures and geopolitical uncertainties.

1.3 Synopsis

Extensive research over the past decades has established a rich scientific basis for the conception and design of energy geostructures. These efforts have produced a range of tools that go from simplified calculations to sophisticated computational models. Among the major contributions to the discipline, the work of Laloui & Rotta Loria (2019) stands out for its synthesis of key principles governing the behavior and implementation of these systems.

Building upon these foundations, the present work connects this academic progress with applied engineering practice. It first outlines core approaches for the design and analysis of energy geostructures, emphasizing scientifically grounded methodologies. The discussion then turns to real-world applications, with examples demonstrating how energy geostructures contribute to more sustainable and energy-efficient urban development.

2. Design of energy geostructures

The primary mode of heat transfer for energy piles and barrettes in soil or rock is conduction. Convective heat transfer becomes relevant when significant groundwater flow is present. The mechanical response of these structures is largely governed by axial forces arising from vertical loads and thermal expansion. Figure 2a provides a schematic representation of the heat transfer mechanisms in energy piles, highlighting the axial mechanical behavior and the interaction between the pile and the surrounding ground.

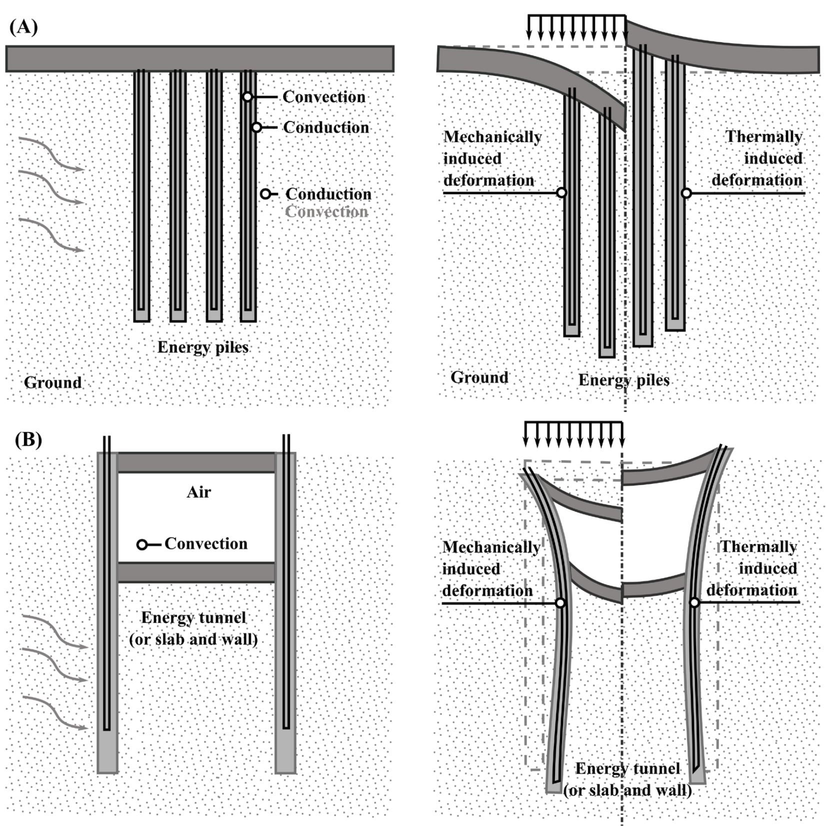

Figure 2. Heat transfer modes and schematic of deformations (for positive temperature variations) characterizing (a) energy piles and barrettes and (b) energy walls and slabs (modified from Rotta Loria (2020)).

In contrast, more complex thermal and mechanical behavior occurs in energy walls and slabs due to their simultaneous interaction with both the ground and the air domain of the underground energy infrastructure. These structures not only capture heat from the surrounding soil but also exchange energy with the air, allowing the collection of both geothermal and aerothermal energy. In these systems, heat is exchanged through both conduction with the ground and convection with the internal air domain, while bending, rather than axial forces, governs the mechanical behavior. The schematic in Figure 2b illustrates the deformation of energy walls and slabs under these combined thermal and mechanical influences, emphasizing the predominance of bending deformation.

Accurate analysis and design of energy geostructures requires a detailed understanding of the thermo-hydro-mechanical interactions that govern both their energy and structural performance. In these systems, heat transfer, fluid movement, and deformation are interdependent phenomena, requiring the solution of constitutive and balance equations that allow the determination of temperature distributions, flow patterns, displacement fields, and stress fields. The governing continuity and momentum equations are respectively presented in Equations 1 and 2, as

$$\rho_f \nabla \cdot \boldsymbol{v_f} = 0 \quad (1)$$

$$\rho_f (\boldsymbol{v_f} \cdot \nabla)\, \boldsymbol{v_f} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{K}] + \boldsymbol{F} \quad (2)$$

where ρ_f is the fluid density, $\boldsymbol{v}_f$ is the velocity vector, p is the pressure, $\boldsymbol{K}$ is the viscous stress tensor, and $\boldsymbol{F}$ is the volume force vector. The energy conservation equation (Equation 3) with both convection and conduction characterizing the heat transfer reads:

$$\rho_f c_{p,f} \boldsymbol{v_f} \cdot \nabla T - \nabla \cdot (\lambda \nabla T) = Q \quad (3)$$

where $c_{p,f}$ is the heat capacity at constant pressure, λ is the thermal conductivity, T is the temperature, and Q is a heat source. Solving Equation 3 alongside the mass conservation equation allows to address conduction-convection heat transfer problems and highlights the thermo-hydraulic coupling between heat and mass transfer. The momentum conservation equation (Equation 4), when simplified by neglecting the influence of body forces, becomes:

$$\nabla \cdot \boldsymbol{\sigma} = 0 \quad (4)$$

where ∇ is the divergence operator and $\boldsymbol{\sigma}$ is the total stress tensor. The stress tensor can be expressed using Equation 5, as

$$\boldsymbol{\sigma} = \mathbf{D} : [\boldsymbol{\varepsilon} + \boldsymbol{\beta}\,(T - T_0)] \quad (5)$$

where $\boldsymbol{D}$ is the elastic stiffness tensor, which contains the material parameters (i.e. Young's modulus, E, and Poisson's ratio, ν), $\boldsymbol{\varepsilon}$ is the total strain tensor, $\boldsymbol{\beta}$ is a vector that comprises the linear thermal expansion coefficient of the material, α, and $T - T_0 = \Delta T$ is the applied temperature variation.

The study and design of energy geostructures can be categorized according to the theoretical frameworks applied to describe their complex behavior. Analytical and semi-analytical approaches provide valuable insight into the thermo-hydro-mechanical behavior of these systems. As projects advance in scale and complexity, however, these simplified models become insufficient to fully capture the coupled processes of heat transfer, fluid movement, and structural deformation. In such cases, numerical modeling techniques become essential, offering the capability to consider all processes that influence the performance of these geostructures (Rotta Loria, 2020). The following sections provide a non-exhaustive summary of the theory that supports understanding of the behavior and performance of energy geostructures, as well as an overview of the current state of knowledge and expertise in this evolving field.

2.1 Analytical methods

Analytical approaches serve as valuable practical tools for exploring key aspects of the behavior of energy geostructures. Their strength lies in their ability to provide efficient and relatively simple solutions for initial assessments, making them particularly suitable for preliminary evaluations and conceptual design stages. These methods enable engineers to gain a first-order understanding of the system's behavior before proceeding to more detailed numerical analyses. The following sections introduce a range of analytical models that address the three interconnected aspects of energy geostructure behavior, i.e., the energy, structural and geotechnical aspects.

From an energy perspective, thermal performance can be assessed using (i) thermal power charts and (ii) thermal resistance models.

Thermal power charts are charts available to estimate the amount of thermal energy that can be extracted from or injected into various types of energy geostructures, including energy piles, barrettes, and walls (Rotta Loria, 2020). These charts often consider important characteristics for the energy geostructure performance, such as specific site characteristics, the pipe configuration, the effective thermal conductivity of the surrounding ground, the magnitude and direction of possible groundwater flow, and the influence of internal airflow in underground infrastructure environments. They provide a useful tool for the preliminary assessment of the energy potential of specific energy geostructure installations (e.g., Batini et al., 2015; Rotta Loria et al., 2023; SIA, 2005; Zannin et al., 2022). An example of a thermal power chart, illustrating the impact of groundwater flow conditions and soil thermal conductivity on the energy performance of an energy wall, is presented in Figure 3 (Zannin et al., 2022). It is worth noting that, because the charts are based on steady-flux energy operating conditions, they provide conservative estimates of the thermal power, representing lower bounds on the energy that can be realistically exploited.

Thermal resistance models represent a more advanced analytical method for assessing the energy performance of energy geostructures by applying the concept of thermal resistance. These models incorporate both time-dependent and time-independent thermal resistance formulations. While traditional thermal resistance approaches were primarily developed for vertical borehole heat exchangers, adaptations have been introduced to address the unique characteristics of other geostructures. In particular, specific thermal resistance models have been proposed for energy piles (e.g., Li & Lai, 2012; Loveridge & Powrie, 2014), and additionally, complementary analytical solutions have been formulated for other geostructures such as energy walls (e.g., Kürten et al., 2015) and tunnels (e.g., Tinti et al., 2017).

Analytical models addressing the structural behavior of energy geostructures include (i) stress charts, (ii) continuum analysis models, and (iii) load-transfer models.

Stress charts originally developed for conventional foundation piles under purely mechanical loading have been adapted to account for the additional thermal effects present in energy piles and barrettes (e.g., Garbellini & Laloui, 2019; Laloui & Rotta Loria, 2019; Rotta Loria et al., 2023). These charts offer estimates of vertical stresses across a range of conditions, considering variations in soil characteristics, geostructure properties, and structural constraints. Accurate assessment of vertical stress is important to ensure they meet the required structural performance.

Continuum analysis models present a more advanced approach for evaluating the structural behavior of energy geostructures, drawing on simplified formulations of continuum thermo-elastic theory (e.g., Laloui et al., 2003; Zannin et al., 2020). Thermal loads develop as a result of temperature variations occurring within and around the geostructures during their geothermal operations. These temperature variations are generally non-uniform and can be conceptualized as consisting of two components: a uniform temperature variation, which induces axial deformation, and a linear distribution of temperature variation, which generates a curvature. For cylindrical geostructures, such as energy piles, analytical models focus only on uniform temperature

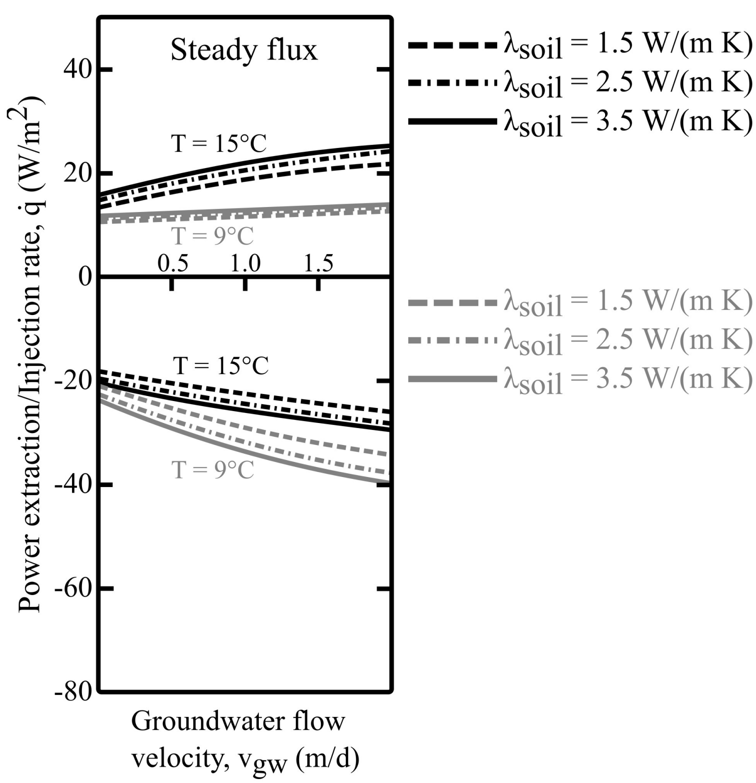

Figure 3. Example of a thermal power chart to estimate the thermal potential of an energy wall with groundwater flow perpendicular to the wall and varying conditions in terms of flow velocities and thermal conductivity of the soil (modified from Zannin et al. (2022)).

variations to capture the resulting axial deformations. In contrast, both uniform and linear temperature variations are incorporated simultaneously in analytical modelling of planar geostructures such as energy walls, to account for the combined effects on axial loads and bending deformation. Preventing these temperature-induced deformations results in axial loads and bending moments, respectively.

The third method in this category, using load-transfer models, provides a method for evaluating the equilibrium of energy geostructures by discretizing the structure into a series of elements. Each element interacts with the surrounding soil through springs governed by a constitutive law, which can be derived theoretically or determined experimentally. Compared to chart-based approaches, load-transfer models thus offer a more detailed representation of the effects of both mechanical and thermal loads. They can be applied to a range of configurations, including isolated energy piles, groups of energy piles, and planar geostructures such as walls and slabs (e.g., Knellwolf et al., 2011; Ravera et al., 2020b; Zannin et al., 2020).

The geotechnical behavior of energy geostructures can be analytically analyzed using (i) displacement charts, (ii) interaction factors charts, and (iii) continuum-based methods:

Displacement charts, similar to the previously discussed stress charts, offer estimates of vertical displacement for energy geostructures (e.g., Rotta Loria et al., 2023; Rotta Loria & Laloui, 2016, 2017). An example of such a chart is shown in Figure 4, which indicates the vertical displacement at the head of a single cylindrical energy pile subjected to a thermal load in an elastic soil mass. The displacement values are normalized per unit of applied thermal load, allowing for straightforward assessment across different loading conditions. Absolute values of thermally induced displacements are reported to represent both heating and cooling effects, reflecting the reversible conditions for the soil.

Interaction factor charts are used to evaluate the interactions that arise when energy piles are arranged in closely spaced groups, providing a means to quantify how the loading of one pile affects neighboring piles under both mechanical and thermal loads. These charts are applicable to both configurations of piles with and without a slab connecting the pile heads (e.g., Ravera et al., 2020a; Rotta Loria & Laloui, 2016, 2017). The level of interaction is expressed through a displacement interaction factor, which represents the effect of a source pile on the displacement response of a receiver pile. Interaction factors are provided in tables for uniform soil conditions as well as for scenarios where a finitely or infinitely rigid bearing layer is present beneath the piles. An example of a chart that presents interaction factors for energy piles subjected to a thermal loading is presented in Figure 5. This analytical tool enables engineers to account for group effects in the preliminary design of energy pile systems.

Continuum analysis models incorporating geotechnical aspects have been developed for groups of energy piles, based on Mindlin's equations (e.g., Rotta Loria et al., 2017). These methods extend earlier formulations for conventional piles to account for temperature-induced effects and allow interaction factors to be defined along the pile length rather than solely at the pile head. At present, such continuum approaches are only available for energy piles.

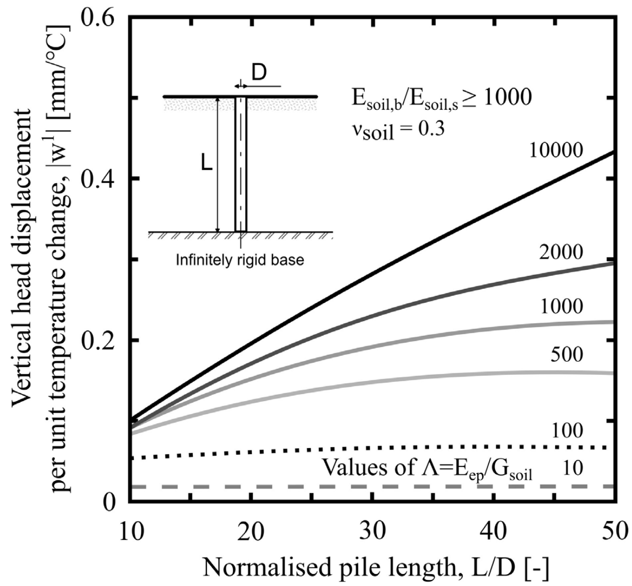

Figure 4. Example of displacement chart showing the vertical head displacement of an individual energy pile resting on an infinitely rigid soil strata for variations of normalized pile lengths and pile-soil stiffness ratio (Rotta Loria & Laloui, 2017).

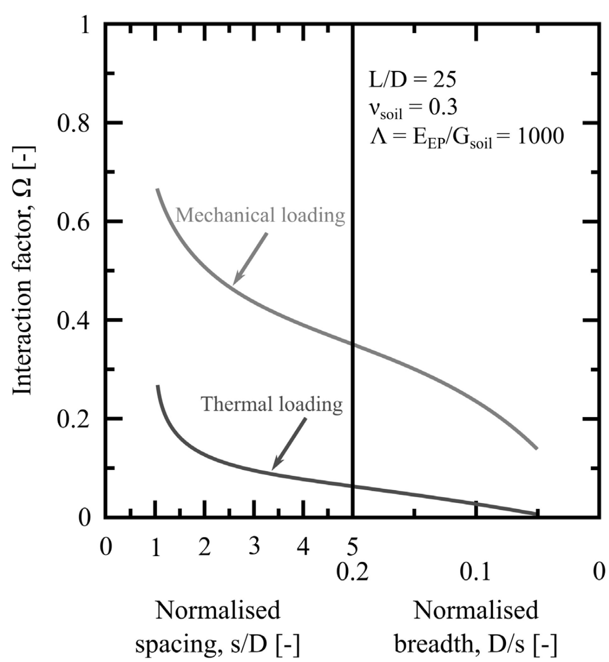

Figure 5. Example of an interaction factor chart showing the interaction factor for a variation of pile spacing (modified from (Rotta Loria & Laloui, 2016)).

Finally, the load-transfer method described in the section on structural aspects for defining stresses also addresses geotechnical aspects by providing information on displacements and soil-structure interface resistance.

2.2 Numerical methods

Numerical analyses represent a more advanced approach for the analysis and design of energy geostructures, as they allow the simultaneous consideration of energy, structural and geotechnical behavior.

To evaluate the energy performance, simulations model heat and mass transfer characteristics, and typically temperature or thermal power variations are applied to the geostructure. Advanced simulation tools can represent embedded pipes and their interactions with surrounding materials in the models. Time-dependent simulations are crucial, as thermal loads in energy systems frequently fluctuate over time.

Structural behavior is modeled by applying forces or prescribing displacements, with either structural elements or simplified stiffness quantifications. While concrete is commonly idealized as a linear thermo-elastic material, advanced analyses may incorporate effects such as thermal creep or tensile resistance. Geotechnical simulations incorporate soil properties to realistically represent heat transfer, mass transfer, and deformation phenomena, with a focus on thermal expansion coefficients to estimate thermally induced deformations and stresses.

3. Application and development of energy geostructures

This section presents two case studies that illustrate the development and implementation of some of the previously discussed methodologies in real-world projects. Both case studies concern building complexes; however, they are situated in distinct environmental contexts. Owing to the differing climatic conditions, the two sites exhibit contrasting operational regimes — one predominantly heating-driven and the other predominantly cooling-driven.

3.1 Energy barrettes in Monaco

An experimental and numerical study on the performance of a large-scale energy geostructure foundation implemented in the Testimonio II building complex in the Principality of Monaco (Rotta Loria et al., 2023) is summarized here. This real estate complex includes a total of 348 housing units in two residential towers, a 50-place nursery, and the new campus of the International School of Monaco, which accommodates around 700 students. The complex also includes multiple levels of underground parking.

The foundation of the Testimonio II building consists of a combination of barrettes, piles, diaphragm walls, and slabs, several of which have been thermally activated to extract and store geothermal energy. This system operates together with a vertical borehole heat exchanger installed beneath the building, forming a hybrid geothermal network. In total, the energy geostructure system comprises 165 energy piles and approximately 9500 m^2 of energy barrettes, which were analyzed, designed and tested to supply the building's energy needs.

During the design phase, experimental field tests and three-dimensional time-dependent thermo-hydro-mechanical simulations were performed for the energy barrettes. The experimental program included thermal performance tests, in which controlled thermal loads were applied to geothermal heat exchangers to evaluate their response under various geometric, site, and operational conditions. The equipment that was used for these tests is shown in Figure 6. The tests evaluated the impact of pipe configuration and the placement of the heat exchangers on-site. The results of the thermal performance tests validated the models used during the design phase of the energy barrettes, as shown in Figure 7.

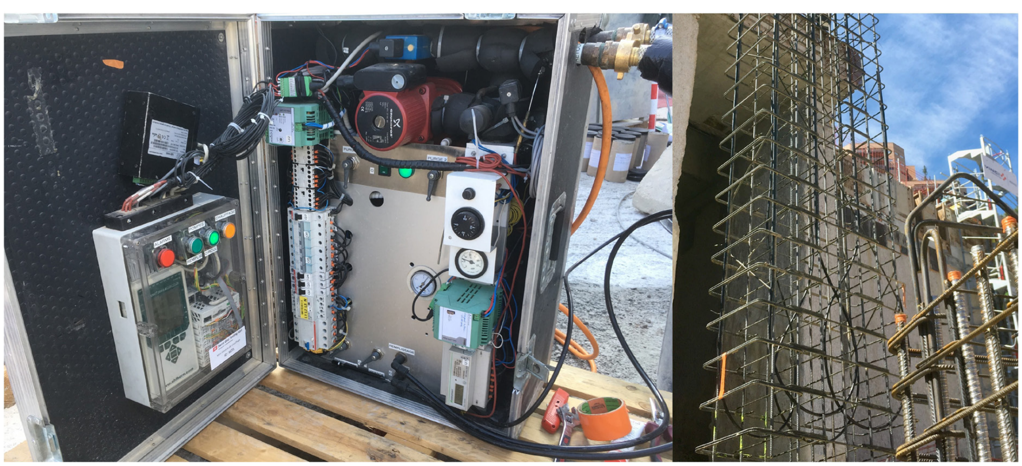

Figure 6. (Left) Testing equipment (image source: GEOEG, 2025) and (right) photograph of one of the energy barrettes supporting the considered building ensemble (Rotta Loria et al., 2023).

The numerical analyses represented the energy geostructures, surrounding soil, and the integrated heat exchanger pipes, providing a detailed understanding of thermal interactions and their influence on overall system performance (Figure 8).

The results provided new insights into the behavior of energy barrettes under various practical conditions, and revealed significant non-uniform temperature fields within and around these structures. These analyses led to the development of the first design charts for this type of energy geostructures (Rotta Loria et al., 2023). It is, however, important to note that while such charts are valuable for preliminary energy assessments, numerical analyses remain essential. Figure 8 illustrates that for cases with complex foundation geometries, accurately evaluating thermal and mechanical interactions requires time-dependent, three-dimensional thermo-hydro-mechanical modeling. Temperature variations are more pronounced where a greater number of thermally activated elements are closely spaced. Neglecting such interactions may result in diametrically opposed performance outcomes for energy geostructures, leading to marked traps, particularly when dealing with the performance of complex energy geostructures (Ravera et al., 2024).

3.2 Energy piles in Dubai

In hot-dominated climates, the interest in using energy pile foundations is to inject heat into the ground and extract energy for space-cooling purposes. The use of energy for space cooling is the fastest-growing electricity demand in buildings worldwide today, and it is predicted that this cooling demand will more than triple by 2050 (IEA, 2018).

The use of energy pile foundations for cooling operations was examined in detail through numerical analyses to assess how this technology can contribute to meeting the increasing demand. This was done in the context of a case study building located in Dubai (Ten Bosch et al., 2024). Three-dimensional, time-dependent simulations were conducted to assess the potential of the building's energy foundation in mitigating cooling demand. The results indicate that the system can effectively supply a substantial portion of the total cooling load, up to approximately 40%, through ground heat exchange. During periods when the heat pump is inactive, auxiliary systems complement the cooling provision. The study also highlights the presence of a markedly unbalanced thermal load characteristic of the hot-dominated climate, with a nearly continuous cooling demand throughout the year (see Figure 9) and limited

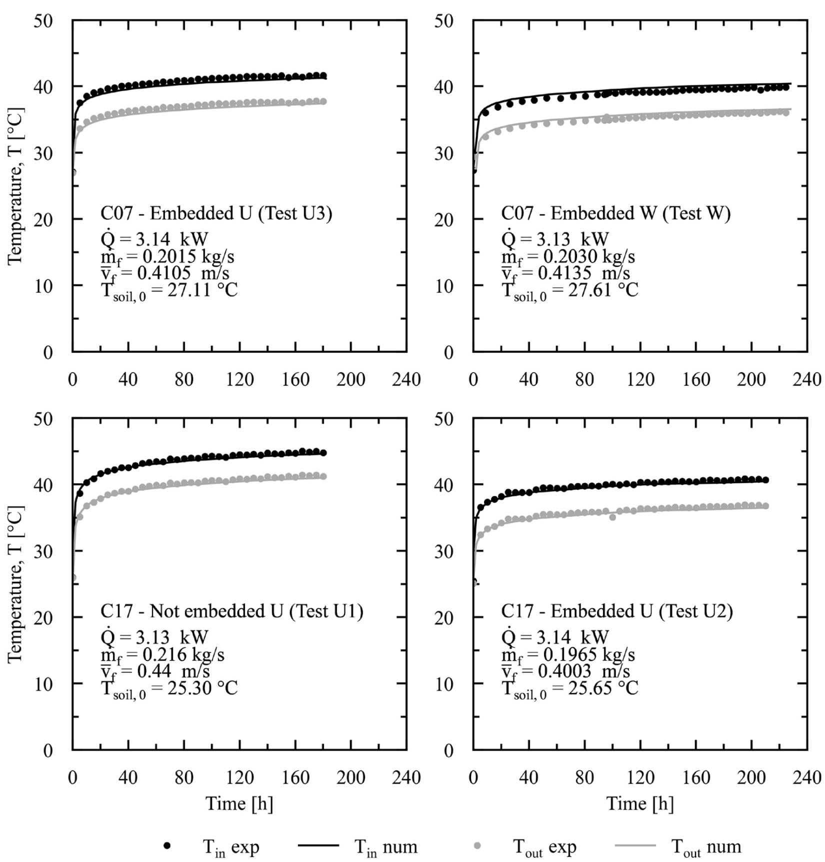

Figure 7. Comparison between the experimental and simulation results for different energy barrette configurations (modified from (Rotta Loria et al., 2023)).

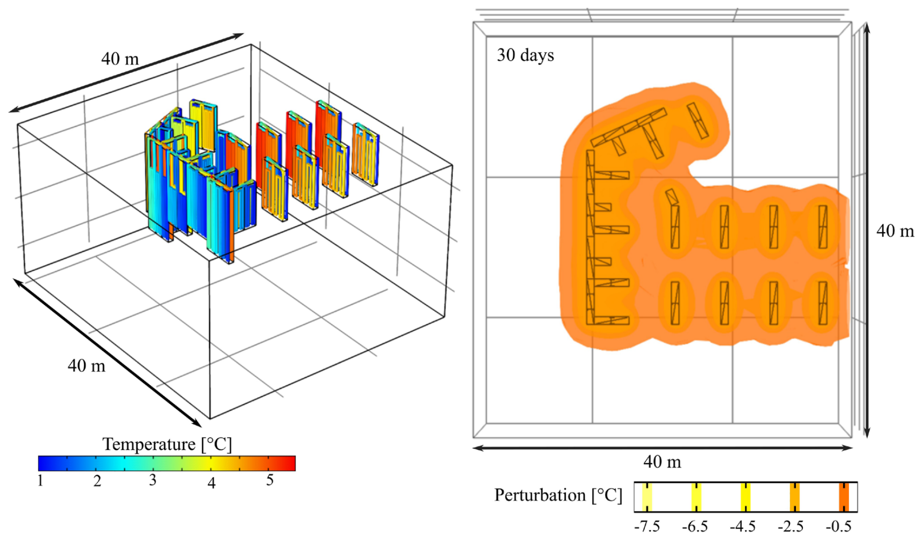

Figure 8. Numerical model used to predict the behavior of selected energy barrettes with (left) temperature profiles in the exchanger tubes and (right) temperature perturbation in the surrounding soil (image source: GEOEG (2025)).

opportunities for natural thermal recovery of the ground over the long term.

The numerical simulations represented the energy dynamics of the energy geostructure over 50 years (Figure 10) and accounted for all the key physical phenomena governing the actual heat exchange process within and around the designed energy system. The simulations also included the ON/OFF operation of the geothermal system, taking into account the functioning of the heat pump.

The modelled long-term behavior, presented in Figure 10 shows that the increase in temperature of the heat circulating fluid due to the constant extraction of cooling energy is largest in the first few years and exhibits stabilization behavior thereafter. The main limitation for such applications stems from the heat pump, which requires the maximum outlet temperature of the heat-circulating fluid coming from the pipes to be respected. For the analyzed case study, the stabilization behavior allowed for respecting this limitation over the period of 50 years. This shows the potential of energy piles to contribute to providing renewable cooling energy in these settings when these systems are properly designed. Such results provide a solid knowledge base on the performance of energy geostructures in hot-dominated climates and highlight their effectiveness in decarbonizing energy supply in buildings via the use of renewable energy sources.

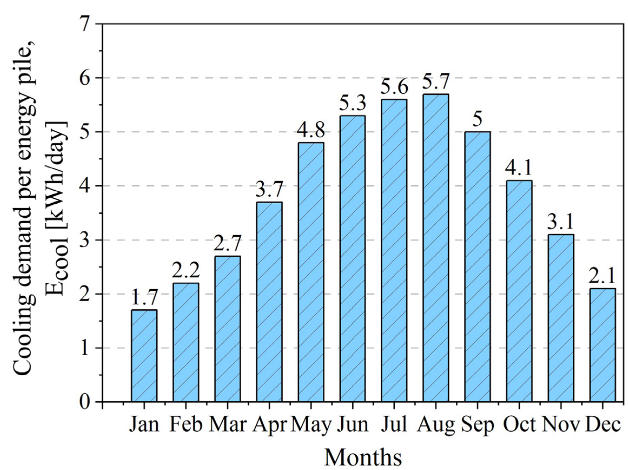

Figure 9. Implemented daily cooling demand per energy pile for the case study in Dubai (modified from Ten Bosch et al. (2024)).

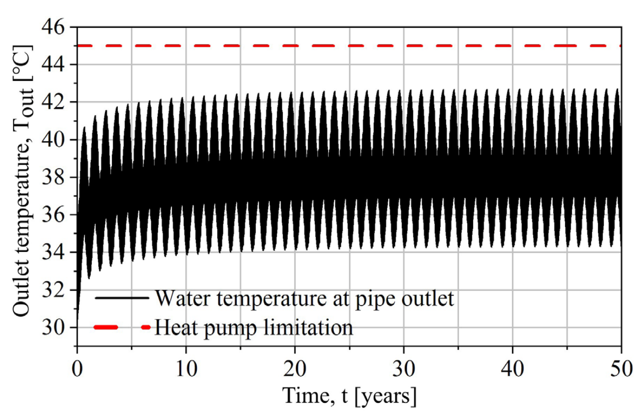

Figure 10. Long-term performance (50 years) of the energy foundation in hot-dominated climates (modified from Ten Bosch et al. (2024)).

4. Closure

Over the past three decades, research on energy geostructures has evolved from an initial focus on energy piles to a broader investigation encompassing various types of earth-contact structures, such as barrettes, walls, and slabs.

The field is thus moving from studies of isolated structural elements toward a holistic understanding of their integrated role within urban environments. This scientific progress has been driven by substantial theoretical, experimental, and computational developments, which collectively allow for an accurate representation of the thermo-hydro-mechanical behavior and performance of these systems under real operating conditions. Importantly, recent studies have expanded the scope of investigation to include diverse climatic contexts and the corresponding operational regimes, ranging from predominantly heating- to predominantly cooling-driven applications. The experimental and numerical findings presented in this work highlight the versatility, practicality, and efficiency of energy geostructures in all their configurations, demonstrating their capability to provide sustainable and effective energy solutions across different climates and urban settings. These achievements confirm that energy geostructures constitute a fully viable and impactful pathway toward developing more sustainable and resilient cities and infrastructure.

Declaration of interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: LL, AFRL, and ER hold shares of GEOEG — an engineering design and innovation firm addressing underground energy solutions. LL and AFRL also hold shares of Enerdrape — a company commercializing the world's first geothermal panel.

Authors' contributions

Lyesse Laloui: conceptualization, supervision, project administration, resources, writing - reviewing and editing. Alessandro F. Rotta Loria: conceptualization, writing - reviewing and editing, visualization. Elena Ravera: conceptualization, writing - reviewing and editing, visualization. Sofie ten Bosch: writing – original draft preparation, visualization.

Data availability

No dataset was generated or evaluated in the course of the current study; therefore, data sharing is not applicable.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of the generative artificial intelligence tool, ChatGPT. The entire process of using this tool was supervised, reviewed, and edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of generative artificial intelligence.

List of symbols

$c_{p,f}$	Heat capacity at constant pressure
p	Pressure
$\boldsymbol{v}_f$	Velocity vector
$\mathbf{D}$	Elastic stiffness tensor
$\boldsymbol{F}$	Volume force vector
$\boldsymbol{K}$	Viscous stress tensor
Q	Heat source
T	Temperature
$\boldsymbol{\beta}$	Thermal expansion coefficient vector
$\boldsymbol{\varepsilon}$	Total strain tensor
λ	Thermal conductivity
ρ_f	Fluid density
$\boldsymbol{\sigma}$	Total stress tensor

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