New European guidelines to unlock shallow geothermal energy resources via energy geostructures

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ABSTRACT

Energy geostructures offer an alternative way to access shallow geothermal energy. Heat transfer pipes for a closed loop ground heat exchange system are embedded within the foundation or support elements of structures or other buried infrastructure, such as tunnels. These pipes can then be connected via manifolds and header pipes to individual ground source heat pump systems, or even connected into heating and cooling networks. However, there is significantly less practical experience of construction and operation of energy geostructures compared with traditional ground source heat pump systems. Therefore, building and infrastructure clients may seek assurance that the primary function of the structure is not compromised, and designers may not know how to assess the full capacity of these systems.

Consequently, there is a need for better guidance and knowledge sharing around the energy geostructure technology to accelerate uptake of these solutions. A Working Group of the European Large Geotechnical Institutes Platform has collaborated with participants of past COST Action GABI TU1405 and the current Cost Action FOLIAGE (FOstering Large-scale Implementation of energy GEostructure) to produce a set of guidelines for the design and construction of energy geostructures. The document, to be published in 2026, will cover feasibility, outline and detailed design for energy piles, walls and tunnels, as well as execution of energy geostructures. Recommendations are made to ensure integrity of the heat exchange pipework, and for monitoring and environmental impacts assessment.

1. INTRODUCTION

Energy geostructures were first developed in the 1980's, with pioneering work conducted in Austria (Brandl 2006). At this time heat transfer pipes were installed in base slabs, deep piled foundations, piles used as retaining walls and diaphragm retaining walls. Use of these and other types of energy geostructure in combination with ground source heat pumps (GSHP) has increased since then (Amis and Loveridge 2014, Di Donna et al 2017), but their usage remains limited in comparison to traditional GSHP system using borehole heat exchangers.

Energy geostructures should be an attractive alternative to borehole heat exchangers because they offer potential cost savings compared with traditional closed loop borehole heat exchanger systems by the removal of the need for special purpose drilling (Di Donna et al 2017, Akrouch et al 2020). The foundation elements are already being constructed for their primary purpose, so integrating the heat exchanger within these in-ground structures means no additional rig mobilisation. Energy geostructures also have the potential to offer access to other sources of heat that not otherwise be available with traditional ground heat exchangers. This includes train breaking near metro stations, or from the transportation of wastewater in cities sewerage tunnels.

However, despite these advantages barriers remain to uptake of energy geostructures (Barns et al 2023). There may be cost savings compared with other GSHP systems, but extra capital costs may still be accrued compared to other heating/cooling systems. In addition, some Clients seek additional assurance about integrity of the solution and importantly of the primary purpose of the structure component. This is to ensure that the foundations continue to support overlying structures without reduction in safety factors or performance. Combined with the fact that thermal design methods are not subjected to standardisation, and that the energy installation can suffer damage if sufficient care is not taken during execution, this has led to a skills gaps within the construction sector workforce.

In response to this need to share knowledge, increase confidence and spread confidence throughout Europe, the first pan-European guidelines for design, construction and monitoring of energy geostructures are currently under production. This paper describes how these guidelines came about and covers their scope and key findings.

2. EUROPEAN COOPERATION

European cooperation on energy geostructures started with the COST Action TU1405, a European network for shallow geothermal energy applications in buildings and infrastructures (GABI), which ran between 2015 and 2019. This collaboration commenced work on the production of European guidelines for energy geostructures, but as the appropriate design methods were still under development, was not able to complete the tasks. Currently a Working Group of the European Large Geotechnical Institutes Platform (ELGIP) is finalising the recommendations, with additional collaboration with some members of the current COST Action, CA21156, a European network for FOstering Large-scale ImplementAtion of energy GEostructure (FOLIAGE). Due to this widespread collaboration, the ELGIP team has access to various national documents, including those currently under development (for example in France and Italy) as well as the forthcoming inclusion of energy geostuctures in the upcoming revision to the CSA/ANSI standard C448 on design and installation standards for ground source heat pumps systems which will include a new chapter on Energy Foundations for the first time.

3. SCOPE AND STRUCTURE OF THE GUIDELINES

The recommendations document covers the use of piles, retaining walls, foundation slabs and tunnels as ground heat exchangers as part of ground source heat pump systems. The whole project cycle from conceptualisation through to execution and monitoring is included (Table 1).

Table 1: The main contents of the new European Recommendations for the conceptualisation, design and construction of energy geostructures.

Chapter	Contents
1	Introduction
2	Context in terms of sustainable development
3	Design data in terms of site characterisation and use of thermal demand data
4	Thermal design recommendations for piles, walls, slabs and tunnels, from feasibility to detailed design
5	Recommendations for Thermo-mechanical design of energy geostructures for piles, walls, slabs and tunnels, from feasibility to detailed design
6	Environmental impacts including thermal interferences
7	Execution of energy geostructures, including monitoring and performance
Appendix	Case studies

4. KEY RECOMMENDATIONS

The following sub-sections provide key highlights from the new recommendations.

4.1 Site Characterisation

The design of energy geostructures requires consideration of a number of different aspects, for which different input parameters are required.

Soil thermal properties are required to understand the energy available and while there are some important similarities to determining properties for other shallow geothermal systems, there are also important differences. In particular thermal response tests undertaken on energy geostructures require adaption from those typically used with borehole heat exchangers. Or alternatively additional boreholes testing is required (Jensen-Page et al 2019).

In-situ hydrogeological conditions to assess potentially for long term sustainability are of utmost important to understand and may not be routinely determined for building and infrastructure projects. Understanding groundwater flow conditions can be particularly important for some energy geostuctures.

One aspect that is especially important for energy geostructures lies in the potential for thermo-mechanical behaviour change due to heating and cooling cycles of the foundation or sub-structure. For this reason estimation of the relative volumetric thermal expansion of the different materials involved (e.g. soil, water, concrete) is important to be able to carry out the subsequent design.

4.2 Thermal Design

At the preliminary stages of thermal design the available energy is often assessed by rules of thumb or based on past project experience and the recommendations include a number of examples which can be used for this initial scoping. In some cases design charts are available in the literature (e.g. see Figure 1) and these are included for such outline assessments.

However, thermal behaviour depends on the interplay of the energy demand, and short term and long term transient response of the ground heat exchanger, as for more traditional systems. Where energy geostructures differ is that there are fewer and less developed analytical approaches for detailed design, and few bespoke software tools for energy analysis. This means that design either needs to occur using tools developed for other applications like borehole heat exchangers, to make bespoke analytical calculations or to resort to numerical modelling.

The recommendations document presents a range of possible analytical approaches for the design of energy piles and critically examines the advantages and limitations of these depending on the specific situation. Some initial tools are presented for energy walls and slabs, but in the most part these planar structures, and also energy tunnels are usually designed using numerical approaches.

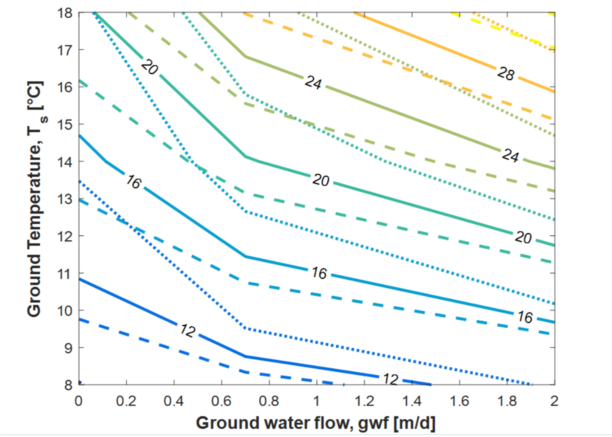

Figure 1: Example design chart for heat extraction from energy walls subject to groundwater flow. Ground conductivity of 3.9 W/mK (dashed line), 2.26 W/mK (solid line), 0.9 W/mK (dotted line). After Di Donna et al (2021).

4.3 Thermo-mechanical design

In addition to the thermal design which is required for any ground source heat pump system, an important difference with energy geostructures is the need to consider the potential changes in stress and strain imposed on the structure due to its thermal operation (Figure 2).

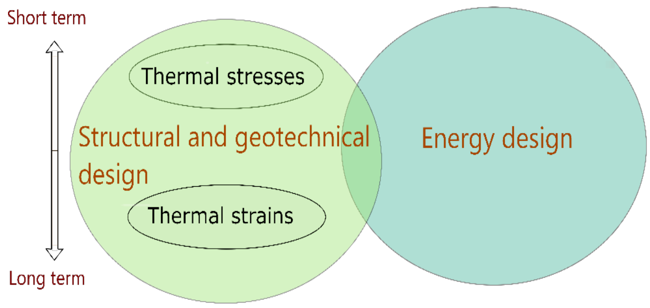

Figure 2: Design aspects for energy geostructures (Vieira et al 2022).

The thermo-mechanical design of energy geostructures addresses the interaction between structural performance and thermal activation, ensuring geotechnical safety under seasonal temperature fluctuations.

Among core principles of energy geostructures behaviour is that while serving their primary structural roles they also experience additional mechanical effects due to thermal cycling. These effects stem from the thermal expansion and contraction of concrete elements embedded in soil. Temperature variations generate stress states that depend on the level of constraint imposed by the surrounding soil and superstructure.

The design approach and complexity of the thermo-mechanical design depends on the stage of the project from feasibility to detailed design phases. The feasibility study estimates potential thermal effects and ensures that preliminary constraints are understood. Later on, the detailed design requires numerical or analytical modelling of the induced thermal strains and stresses, and their interaction with existing static loads. The effect of thermo-mechanical loads should be understood differently depending on the type of the energy geostructure, their roles and support conditions.

In the case of energy piles used as foundation systems, these types of structures are especially sensitive to axial thermal effects depending on their vertical geometry and embeddedness. The interaction between the pile and the ground results in distributed frictional restraint along the shaft. Design must account for type of constraints and non-uniform thermal profiles. Finite element modeling or simplified analytical approaches (e.g., uniform axial loading or thermal ratcheting concepts) are recommended, depending on the stage of the project.

Unlike piles, energy walls can develop bending moments due to asymmetric pipe placement and exposure to different thermal boundaries (e.g., ground on one side, air or excavation on the other). Numerical modeling is often required to capture these effects, especially in the case of energy diaphragm walls exposed to complex interactions with adjacent structural elements.

Energy tunnel linings present a combination of axial and flexural responses under thermal cycling. The placement of pipes on the extrados or intrados can cause temperature gradients that lead to ovalization or bending. Given their large extent and constrained geometry, the design stage of energy tunnels must include numerical modeling of both longitudinal and circumferential thermal effects.

Thermo-mechanical design is not an optional add-on but an important component of energy geostructure design. The guidelines encourage robust modeling, informed simplifications, and site-specific analysis to ensure that structural integrity is maintained under combined thermal and mechanical actions.

4.4 Environmental impacts

The design of an energy geostructure cannot ignore site-specific conditions. In particular, thermal and hydraulic interferences with other pre-existing (thermal or non-thermal) groundwater uses are of importance. Possible interferences with underground structures are also to be evaluated. These thermal and hydraulic interferences are most likely to occur in urban areas, where there is typically a greater concentration of anthropogenic structures.

The recommendations document debates on the reason of these possible interferences together by providing some general instructions on the best practices for their management.

4.5 Execution guidelines

The design of energy geostructures has interactions with many steps of the design procedure for a building, a structure or an infrastructure and including it from the initial stages of a project is crucial. The recommendations document details the points during the construction sequence when particular care must be taken to complete reliable execution of energy geostructures. During construction, opportunity should be taken to ensure a maximum number of heat exchanger pipes are installed. Later on, when the exact thermal design is known, it is too late to add pipes. It is always possible not to activate a pipe which is installed, but it is not possible to install additional pipes when construction has progressed too far.

The recommendations document mainly deals with cast in place geostructures for which the heat exchanger have a bigger impact on the execution feasibility. However, precast elements like piles and tunnel linings are also possible and encouraged. Here factory level quality control may be more easily applied.

It is also recommended that checking the integrity of heat exchanger pipes should be done at every stage of the construction and commissioning of the structure. Actions that can be taken in case of test failure are also provided. Finally, recommends are made to monitor the energy geostructure during its realisation and during its early life to ensure it is functioning as anticipated and its energy capacity can be optimised. This will also provide confidence that any structural function is not being compromised.

5. PUBLICATION

The publication of the recommendations will be handled by ELGIP. The publication will be open access and full availability is expected by beginning of 2026.

6. CONCLUSIONS

Where underground construction is already occurring, energy geostructures offer an attractive alternative to traditional ground heat exchangers for ground source heat pump systems. There are potential cost savings to be made and additional energy opportunities associated with underground infrastructure. However, the approach is still uncommon and one of the challenges to deployment is lack of standardisation which can lead to lower confidence in the solutions. To help reduce such barriers and encourage implementation of shallow geothermal energy via energy geostructures, a Working Group of the European Large Geotechnical Institutes Platform will publish open access technical guidelines in 2026. These guidelines cover the full design life of energy geostructures from conception to execution and operation, and both thermal and thermo-mechanical aspects of their analysis and design.

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