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Title:

Energy geostructures: a review of analysis approaches, in situ testing and model scale experiments

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Abstract

This position paper was developed by members of the task force on "Energy Geostructures" of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee TC308 on 'Energy Geotechnics'. The article includes a summary and review of some of the most recent analysis approaches, in situ testing, full scale testing and model scale experiments with a focus on energy piles and other energy geostructures. The geotechnics literature in these topics has increased rapidly in the last five years suggesting a surge in this emerging research area. Here complementary lines of research can be distinguished, one focusing on thermal analysis and another focusing on thermo-geomechanical analysis. Limitations, shortcomings and knowledge gaps are identified and needs for further research and development within the geotechnical community are highlighted.

Keywords: geothermal, ground source heat pumps, ground heat exchangers, energy piles, review, state of the art

Table of Contents

1 Introduction

There is an inexorable increase in global energy demand driven by world population growth and the global pursuit of a higher 'quality' of life. As a result, the annual per capita energy consumption has grown exponentially for a century (Glassley 2010). This growing demand may be satisfied by increasing energy supply, for example by finding new ways to exploit oil and gas reservoirs that were previously deemed uneconomical to exploit. However, the long term and more sustainable solution relies on both reducing global energy demand and the use of fossil fuels and increasing the use of energy from renewable sources. Geo-professionals can contribute to the development of a number of different renewable energy sources with low greenhouse gas emissions (Arulrajah et al. 2015, McCartney et al. 2016, Sanchez et al. 2017).

Shallow geothermal energy or ground source heat pump (GSHP) technology can contribute to lowering or flattening peak energy demand through efficient heating and cooling of residential, commercial and industrial buildings (Brandl 2006; Olgun and McCartney 2014; Sanchez et al. 2017). A GSHP system is inherently more efficient that alternative Heating Ventilation and Air Conditioning (HVAC) systems as it exchanges heat with a more stable source/sink: the ground temperature in the upper tens of meters is typically close the mean atmospheric temperature for a given location year-round. Energy geostructures are foundations or other buried geotechnical structures which have been equipped with heat transfer pipes so that they may act as the ground heat exchanger (GHE) part of a GSHP system. Therefore, energy geostructures remove the need for construction of special purpose GHEs, offering opportunities to reduce capital costs for shallow geothermal energy (CIBSE, 2013; Park et al. 2015; Lu and Narsilio 2019; Akrouch et al. 2018).

Piles are the most common type of energy geostructure, having been first constructed in northern Europe in the 1980's (Brandl 2006). Their application has expanded in the subsequent decades (e.g. Amis & Loveridge, 2014), but their numbers are still minor compared to the total GSHP installations worldwide. Demonstration projects using slabs, walls and tunnels as ground heat exchangers soon followed the first pile installations (Adam & Markiewicz 2009). However, these types of energy geostructures are rarer, for several reasons. First, piles clearly have the potential to offer reduced capital costs compared to traditional vertical GHEs (CIBSE, 2013) such as boreholes. Second, as piles have a superficial resemblance to boreholes, there are available thermal design methods which can be adapted for use with piles (e.g., Eskilson 1987; Pahud 2007). There remain limitations of such approaches (Loveridge & Powrie 2013a), but they are readily available. Additional approaches for the geotechnical design of piles subject to thermal changes are under development (e.g. Mimouni & Laloui 2015; Rotta Loria & Laloui 2016a). By contrast, for other structures there are no standard design and analysis approaches and every project must proceed very much on a case by case basis. The development of infrastructure schemes for shallow geothermal utilisation also comes with additional challenges regarding users for the stored thermal energy. While piled foundations are typically constructed to support a building which is then well placed to use the renewable heating/cooling provided, for retaining walls and tunnels the user of the thermal energy may be a third party which places additional logistical and bureaucratic barriers in place for adoption of the technology.

The application of energy geostructures has been summarised in Laloui & Di Donna (2013) and Soga & Rui (2016). However, research in this area has both intensified and broadened in recent years. Work has focused on two mains areas. First, the geomechanical implications of using bearing structures also for heat exchange and storage (e.g., Bourne-Webb et al. 2009, Stewart & McCartney 2012). Second, the development of thermal analysis approaches to assess energy performance and understand how to maximise energy efficiency (e.g. Loveridge & Powrie 2013b, Bidarmaghz et al. 2016a, 2016b, Mikhaylova et al. 2016a). Both these areas have the aim of minimising uncertainty and risk in design, facilitating reduction in capital costs and hence an increase in technology uptake.

This paper reviews recent research on energy geostructures in both these areas, covering analysis approaches and the field and model scale testing that have been used to inform those approaches. The topic of material parameters for energy geostructures is excluded since this is well reviewed by Vieira et al. (2017). This paper will be naturally biased towards piles since these are the most common installation and the area which has seen most research in recent years. However, energy walls in particular have seen a recent increase in interest, and this is reflected in our review. The text is arranged into three main sections covering analysis and design methods (Section 2), full-scale field testing (Section 3) and model scale testing (Section 4). These will be followed by a discussion pertaining to knowledge gaps and a summary of the current state of the practice. The scope of the paper will focus mainly on the in-ground elements, where there is novelty and hence uncertainty due to the more recent adoption of energy geostructures. However, the importance of the mechanical engineering elements must not be underestimated, and some brief comments are made on these aspects in Section 2.1.

2 Analysis of Energy Geostructures

2.1 Thermal Analysis

2.1.1 Overview

The thermal design of energy geostructures involves the use of analyses to estimate the amount of energy that can be readily exchanged with or stored within the ground to fully or partially satisfy the thermal energy loads of buildings. This includes consideration of the best arrangement of heat transfer pipes for energy efficiency, determining the relationship between energy exchanged and temperature changes, and selecting the heat pump and appropriately linking the source side of the energy system (the ground) to the delivery system in the building. This review focuses on the first two elements, but brief consideration of the building and mechanical engineering aspects is given below.

2.1.1.1 Thermal Loads

The nature of the thermal loads applied to a ground source heat pump system has a large impact on its performance (CIBSE, 2013). For example, a system which is dominated by one-way heat transfer due to heat extraction will show decreasing performance over time as the ground (source side) temperature is reduced by that heat extraction. A system that is balanced between heat injection and heat extraction, on the other hand, will act as an inter-seasonal store of heat and will always operate at greater efficiency. Additionally, thermal loads that are "peaky", displaying rapid changes in magnitude, may be most efficiently covered with a combination of a GSHP for the base thermal load and an auxiliary system for the balance.

Ground heat exchanger (GHE) and energy geostructure design is therefore dependent on provision of these thermal loads from the mechanical engineering team. The level of detail provided can be important and requirements will depend on the size and complexity of the heat pump scheme (GSHPA, 2012). Unfortunately, reliable prediction of the heating and cooling demands of buildings is extremely difficult and current approaches often lead to an underestimate of demand, leaving a so called "energy gap" (e.g. Menezes et al. 2012). To mitigate against this effect, designers can assess the risk of underestimation of thermal loads and either include a factor of safety approach to thermal loads or alternatively adopt installation and use of back up auxiliary heating and cooling systems (Garber et al. 2013b; Mikhaylova et al. 2016b).

2.1.1.2 Temperature Limits

It is important to ensure that the GSHP and the energy geostructures operate within acceptable temperature limits. This serves to both, protect the structure from extreme temperature changes which could impact on the geotechnical performance, and ensure that the heat pump is operating within an optimal efficiency range. While the upper bound temperature depends on the particular GSHP specifications (typically 30-40°C) and designer's choice, the lower bound temperature is generally taken as 0°C to 2°C to avoid ground freezing (GSHPA 2002), although lower fluid temperatures can potentially be tolerated (Loveridge et al. 2012).

2.1.1.3 Mechanical Design

The mechanical design aspects of a GSHP scheme are of equal importance to the GHE design. Optimisation of the heat pump and minimisation of the temperature lift are essential factors, as is the pipework and pumping design. GSHP systems are complex, extending from the ground to the heating and cooling delivery systems, via the ground heat exchangers, headers and manifolds, circulation pumps and heat pumps. All aspects need to be properly designed and executed for a system to perform well. Detailed discussion of these elements can be found in, for example, Oschner (2008).

Some integrated building simulation software packages allow analyses of all components of a GSHP system from the in-ground components to the delivery of heating and cooling, e.g. EnergyPlus (Fisher et al. 2006) or TRNSYS (2018). These and other applications are reviewed in Do & Haberl (2010) and are typically aimed at borehole heat exchanger design, but a standalone implementation in TRNSYS for application to energy piles is available (Pahud 2007).

2.1.2 Piles

Typically, analytical solutions are used to determine the fluid temperature changes for a given thermal demand. This allows the available energy within certain temperature limits to be determined. Analytical solutions are preferable to numerical solutions since fast run times are required to process decade's worth of thermal load input data which may vary on an hourly basis. However, closed form solutions are sometimes associated with assumptions that limit their range of application. Furthermore, some numerical tools have been implemented with sufficient computational efficiency that provide reasonable alternatives (e.g. see Section 2.1.2.6).

To simplify the thermal problem most analysis approaches separate the temperature change into a number of zones for which different solutions are applied, with the results then combined by superposition. Thus, the change in circulating fluid temperature, T_f, can be given by:

$$\Delta T_f = \Delta T_{ground} + \Delta T_{pile} + \Delta T_{pipe} \quad (1)$$

When analytical techniques are adopted the ground temperature change is often calculated using a transient temperature response function (G-function or G_g) evaluated at a radial coordinate $r=r_b$, where r_b is the pile radius.

$$\Delta T_{ground} = \frac{q}{2\pi\lambda_g} G_g(t,r) \qquad (2)$$

where λ_g is the thermal conductivity of the ground in W/(mK), q is the applied thermal power in W/m and t is the elapsed time in seconds. The G-function can take a number of different forms (Section 2.1.2.1) as summarised in Table 1.

Traditionally ΔT_{pile} and ΔT_{pipe} are calculated using thermal resistances and assuming a thermal steady state:

$$\Delta T_{pile} = T_p - T_b = qR_c \qquad (3)$$

$$\Delta T_{pipe} = T_f - T_p = qR_p \qquad (4)$$

where R is a lumped thermal resistance (Section 2.1.2.3) in mK/W and T_b and T_p are the average temperatures at the pile edge and pipe edge respectively (see Figure 1). R_c is the resistance associated with the temperature changes within the pile concrete and R_p is that associated with the pipes and the fluid flowing within them. The latter may be further split into the conductive resistance associated with the pipe itself and the convective resistance associated with the fluid, $R_{p\text{-cond}}$ and $R_{p\text{-conv}}$ respectively. Together the individual resistances make up the total resistance, R_b:

$$R_b = R_c + R_{p-cond} + R_{p-conv} \qquad (5)$$

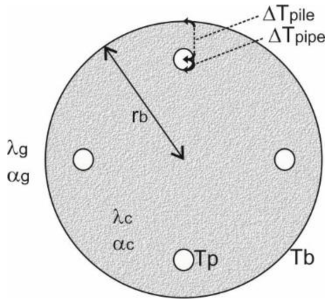


Figure 1 Typical arrangement of an energy pile

2.1.2.1 Classical G-functions

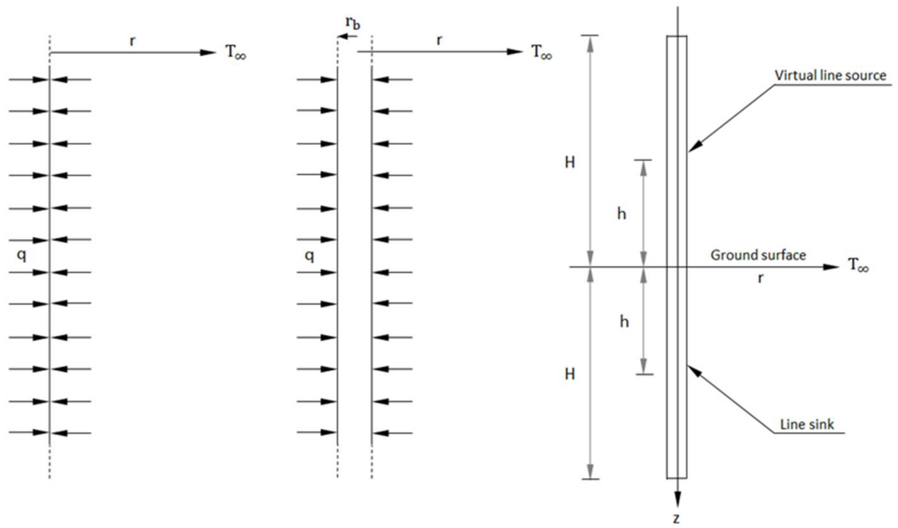
The term G-function was originally used to describe the temperature response functions developed for borehole heat exchangers by Eskilson (1987) using the Superposition Borehole Model (SBM), see also Section 2.1.2.5. However, it has since been adopted more generally to describe any function which relates the temperature change in the ground around a vertical GHE to the applied thermal load, q. Hence the general approach is equally applicable to piles. Most typically G-functions are expressed as a dimensionless form of Equation 2:

$$\Phi = G_g(\mathrm{Fo}, r^*) \qquad (6)$$

where Φ is the dimensional temperature response, $\Phi = \frac{2\pi\lambda_g}{q}\Delta T$, Fo is the Fourier number or dimensionless time defined as $Fo = \frac{\alpha_g t}{r_b^2}$, α_g is the ground thermal diffusivity, and r_b the pile radius, and r^* is a dimensionless geometry factor, often expressed as radial coordinate divided by heat exchanger length (see Figure 1). Sometimes other non-dimensional parameter sets are used, but the concept is the same. The classic analytical solutions of the G-functions are based on the infinite line source (ILS), the infinite (hollow) cylindrical source, and the finite line source (FLS). These geometric configurations used in the analytical solutions are schematically presented in Figure 2, with a summary of these and other solutions listed in Table 1 and illustrated in Figures 3 and 4. Full details of these solutions are not given here since they are readily available in the literature (e.g. Bourne-Webb et al. 2016a, Fadejev et al. 2017).

In the development of the analytical solutions, it is assumed that the ground is homogeneous and isotropic, with no initial temperature gradient nor groundwater flow and fully saturated ground conditions. Such factors are known to affect the temperature changes around vertical GHEs (e.g. Signorelli et al. 2007; Bidarmaghz et al. 2016a) but are more difficult to account for by analytical means.

G-functions are normally plotted for a constant q (Figure 3 and Figure 4), but as q varies in actual routine operation it is necessary to use some form of temporal superposition and/or load aggregation (Claesson & Javed 2012) to determine the overall temperature change, $\Delta T(t)$ resulting from $q(t)$ over the lifetime of a geo-structure.



(a) (b) (c)

Figure 2 Schematic of the classical G-function models: (a) infinite line source (ILS), (b) infinite cylindrical source (ICS), (c) finite line source (FLS). T_∞=far field temperature; H=heat exchanger length; h=depth below ground surface. Adapted from Bidarmaghz 2015.

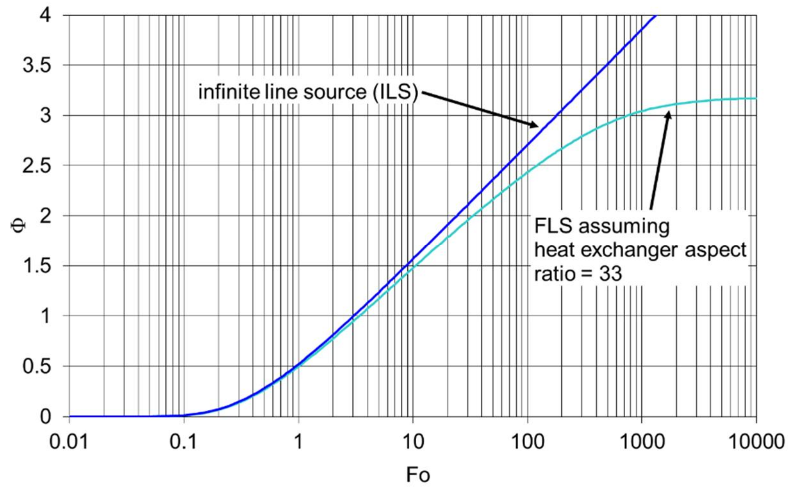


Figure 3 Example G-functions showing development of long-term steady state conditions for heat exchangers of finite length. Aspect ratio = pile length / pile diameter

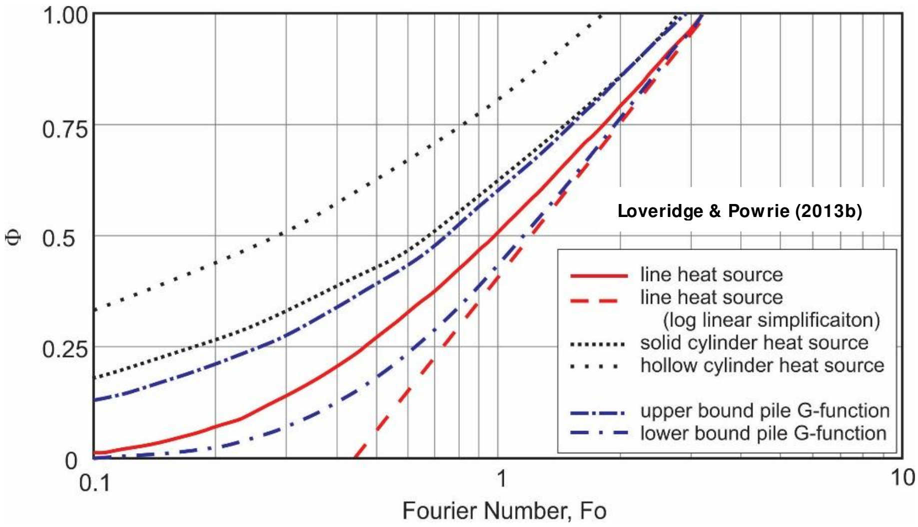


Figure 4 Different G-functions displayed at short time scales. Pile upper and lower bound G-functions after Loveridge & Powrie (2013b)

2.1.2.2 Pile Specific G-functions

The SBM and other FLS approaches are perhaps the most commonly adopted type of G-function, being readily implemented in accessible borehole design software that is sometimes used for piles. However, this type of approach is not validated for piles and may over predict temperature changes (e.g. Wood et al. 2010a). This is due to (i) the short length of piles not being accommodated in routine GHE software which implements these analysis methods; and (ii) the accompanying use of a steady state resistance (see Section 2.1.2.3). However, it should be noted that such approaches remain conservative in terms of energy assessment. This means that a design would be safe, although the danger of over conservatism relates to increased payback times on investment.

The solid cylinder model has advantages for use with piles since it can capture flow of heat into the pile as well as into the ground. Solutions have been published for both the infinite and finite heat source scenarios (Man et al. 2010). However, this approach still requires validation, but it was suggested that it may provide an upper bound for pile behaviour as shown in Figure 4 (Loveridge & Powrie 2013b).

Applying a similar approach to the SBM, Loveridge & Powrie (2013b) derived upper and lower bound G-functions based on pile geometries rather than a line source. While validated on short term thermal response tests of small diameter piles, the approach awaits longer term validation and critical assessment for piles with different length to diameter ratios.

All the finite heat source models described above are illustrated for short time periods in Figure 4. At long time periods the temperature response will converge on that of the finite line source (Figure 3), with the steady state value dependent on the aspect ratio. All these models also suffer some of the same limitations which need to be appreciated. They all assume a constant surface temperature as a boundary condition. This has two drawbacks. First, the near surface temperature distribution is not constant, but fluctuates throughout the year. For short GHEs such as energy piles this may be significant (e.g. Bidarmaghz et al. 2016). Second, most energy piles are buried beneath a building and boundary conditions at the pile head may be better represented as either insulated or as a small net flux representing heat loss from the building (Loveridge & Powrie 2013a). There are few datasets showing pile temperatures under buildings, but initial data from Mikhaylava et al. (2016c) and Habart et al. (2016) show fluctuations at the pile head. These temperature changes suggest some heat exchange with the building. However, uncertainty over the most appropriate boundary conditions also remains a barrier to further development (see also Section 3.1).

Table 1 Main types of G-function for use with piles

Model	References	Description	Comments
Infinite Line Source (ILS)	Carslaw & Jaeger (1959)	Assumes an infinitely long and thin heat source embedded in a homogeneous medium.	Infinite length means that long term steady state behaviour is neglected.
Infinite (Hollow) Cylindrical Source (ICS)	Carslaw & Jaeger (1959); Ingersol et al. (1954); Kakaç and Yener (2008); Bernier (2001)	Assumes an infinitely long hollow cylinder which acts as a heat source embedded in a homogeneous medium.	Infinite length means that long term steady state behaviour is neglected. Gives larger temperature changes than the ILS at short time periods. It is equivalent to the ILS at longer time periods.
Superposition Borehole Model (SBM)	Eskilson (1987)	Uses numerically exact calculation based on a finite line heat source, with superposition for multiple boreholes.	As calculated numerically, to be applied routinely the SBM G-functions must be pre-programmed into software codes for different combinations of multiple boreholes. This approach is widely used and well validated for borehole design (e.g. Cullin et al. 2015).
Analytical Finite Line Source (FLS)	Eskilson (1987) Zeng et al. (2002) Lamarche & Beauchamp (2007) Claesson & Javed (2011)	Using a mirrored virtual line sink approach to simulate the ground surface, these G-functions provide an analytically exact version of SBM.	Zeng et al. (2002) use the mid-depth of the heat exchanger as the reference temperature while later works use an average temperature which provides a better correlation to SBM. The more recent works concentrate on simplifying the mathematics

Model	References	Description	Comments
Solid Cylinder Model (SCM)	Man et al. (2010)	Heat flow into and out of the heat exchanger is simulated. The model has been presented in both infinite and finite forms.	Studies by Loveridge & Powrie (2013b) suggest that the SCM may provide a sensible upper bound for piles, providing the finite version of the model is used.
Pile G-Functions	Loveridge & Powrie (2013b)	Derived numerically in a similar way to SBM, these G-functions are then presented as appropriate upper and lower bound solutions to cater for the wide range of pile sizes and pipe configurations.	The functions typically fall between the SCM and the log linear simplification of the FLS (Figure 4).

2.1.2.3 Thermal Resistances

The pipe thermal resistance R_p can be readily calculated by analytical means as set out in Hellstrom (1991) and Lamarche et al. (2010). Analytical, empirical or numerically based methods can be used to calculate the resistance of the concrete part of the pile, a summary of which is given in Table 2. Claesson & Hellstrom (2011)'s multipole method for calculation of the pile resistance, R_c, has been shown to be the best solution for small diameter vertical GHEs (Lamarche et al. 2010) and is expected to also perform well with larger diameter piles. Such an approach was adopted by the SIA (2005). Additionally, numerically derived means of determining the pile resistance are proposed by Loveridge & Powrie (2014) based on the results of simulations. These correspond well to the multipole method for the two pipe cases.

However, R_c is a steady state parameter and a thermal steady state may not be present during operation of the pile. Except for very small diameter piles a design approach based on a steady state resistance is therefore unlikely to be a sensible assumption and would result in over prediction of the temperature changes (Loveridge & Powrie 2013b) and hence underestimation of energy availability. Consequently, transient methods are to be recommended for pile design where possible.

Table 2 Methods for calculating ground heat exchanger steady state thermal resistance

Approach	References	Description	Comments
Empirical	Paul (1996)	Shape factor approach using empirically derived values for different pipe configurations. Derived from in situ test data.	Empirical for boreholes so will not apply for larger dimeter piles. Determines R_b
Analytical	Hellström (1991)	Direct analytical method based on line source theory. Assumes 2D heat flow.	Theoretical, therefore applicable to any geometry. Determines R_c
Analytical	Bennet et al. (1987); Claesson & Hellstrom (2011)	Line source method with multipole expansion correction. Assumes 2D heat flow.	Theoretical, therefore applicable to any geometry. Determines R_c

Analytical	Hellstrom (1991); Diao et al. (2004a)	Multipole method with correction for quasi-3D heat flow.	Theoretical, therefore applicable to any geometry. It determines R_c. Not significantly different from 2D case in most scenarios.
Numerically derived	Sharqawy et al. (2009)	Empirical method based on 2D numerical simulations for boreholes	Most pile geometries will be outside range of analysis carried out to determine relationships. Determines R_c
Numerically derived	Loveridge & Powrie (2014)	Empirical method based on 2D numerical simulations for piles	Specific for pile geometries. Determines R_c

2.1.2.4 Transient Pile Models

There are several alternatives to using a steady state pile resistance. Loveridge & Powrie (2013b) proposed adopting temperature response functions, like G-functions, to replace the constant value of R_c. They suggested upper and lower bound functions based on a range of numerical simulations.

Alternative transient analysis can be carried out which considers the ground and the pile concrete in one analysis. Li & Lai (2012) proposed composite G-functions based on superposition of several line sources (each representing a pipe) installed in a two-material medium containing the ground and the pile. These functions are an important step forward but would need pre-programming for a range of likely scenarios (as is done for SBM when implemented in popular borehole software tools).

2.1.2.5 Numerical Simulations

Despite the fact that analytical solutions have been developed to capture the thermal performance of GHE, most of the assumptions bring limitations. In response to these difficulties, numerical models solving the governing heat transfer equations have surged. This includes 1D finite difference models (e.g. Gehlin & Hellstrom 2003; Shonder & Beck 1999, 2000) and Finite Element (FE) models in 2D (e.g. Austin, 1998; Sharqawy et al. 2009) and 3D (e.g. Bidarmaghz 2015; Ozudogru et al. 2015; Raymond et al. 2011; Signorelli et al. 2007; Wagner et al. 2012). In the following section, selected 1D, 2D and 3D numerical models are briefly explained, with a focus on illustrating the main approaches taken. Several the examples have been developed for boreholes rather than piles, but the techniques used are equally as applicable in the latter case.

Eskilson developed pioneering work on numerical simulation of GHEs for boreholes, which has gone on to underpin much of current practice (Eskilson 1987; Eskilson & Claesson 1988) for both boreholes and piles. Numerical computation on a 2D radial-axial coordinate system was used to determine the temperature distribution around a single borehole with finite length and diameter. The mirror image method has been used to account for the constant temperature on the ground surface, as per the finite line source method. The temperature distribution in the ground region for a number of thermally interacting boreholes is then obtained by superimposing the temperature response of a single borehole in space. This is the basis of the Superposition Borehole Model (SBM) and led to the first G-functions, examples of which are given in Figure 5. However, by neglecting the detail of the GHE, the model is not suitable for use at short timescales.

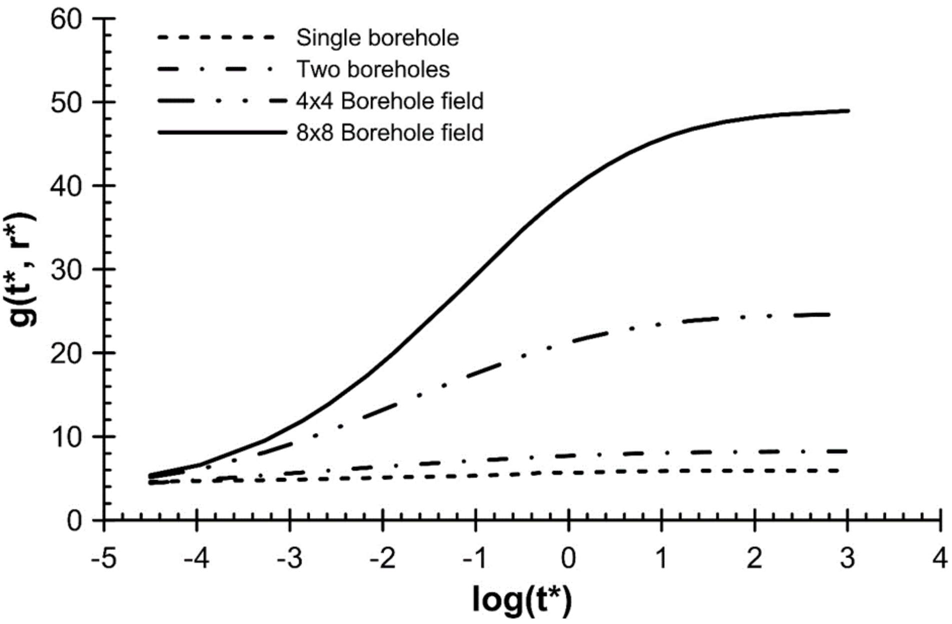


Figure 5 Example G-functions for different arrangements of boreholes (Bourne-Webb et al. 2016). t* is the ratio of the elapsed time and time to steady state; r* is the non-dimensional radial coordinate.

Based on Eskilson's g-functions, Yavuzturk et al. (1999) developed a 2D finite volume numerical model that overcomes the short time step issues in Eskilson's model. Therefore, the thermal resistance and capacitance effects of the heat exchanger components are considered in this model. A constant heat flux per unit depth of the borehole was assumed for the pipe wall as the boundary condition due to the restriction of the code used. The fluid in the pipes is not explicitly modelled. Several other 2D models have been proposed for borehole heat exchanger fields (e.g., Muraya et al. 1996; Lazzari et al. 2010).

Two dimensional models have also been employed to understand pile thermal behaviour. Some of the more notable cases include the 2D slice models of Loveridge & Powrie (2013b) and Loveridge & Powrie (2014) who used the results of their finite element (FE) simulation to develop pile specific G-functions and thermal resistance relationships. The models do not explicitly consider the pipes and apply a constant heat flux at the pipe outer boundary. Similar techniques were also used by Alberdi-Pagola et al. (2018) when interpreting thermal response tests of quadratic section energy piles.

Dupray et al. (2014) built a 2D model in the vertical plane to consider the potential thermal storage available for a group of piles beneath a building. This type of simplification is unusual in GHE analysis and reflects the adoption of plane strain for the coupled geomechanical part of the analysis. In the model the authors used a slab of fixed temperature underlain by a low conductivity insulating layer to represent the base of the building. The heat source was rather crudely incorporated throughout the area of the piles within the 2D domain. However, Sailer et al. (2018a) show this 2D plane approach to overestimate the temperate change that occurs. While this will be conservative, Sailer et al. (2018a) go on to develop conversion factors for 2D plane analysis to improve predictions made from this approach.

A transient 3D finite element model to simulate the thermal behaviour of the ground and the GHEs was developed by Marcotte et al. (2010) and Marcotte & Pasquier (2008). The model is limited in depth to the length of the GHE. The carrier fluid, the U-pipes and the grout are considered in this model, but instead of including an explicit pip bend at the base of the GHE, the pipes are simply continued to the base of the model. The fluid temperature profile is obtained after integrating the bottom horizontal face of the downward pipe, information that is then used as a boundary condition for the lower face of the upward pipe. Despite being a 3D model, axial effects related to geometry (as opposed to fluid flow) are ignored since the upper and lower boundaries are insulated. Therefore, the model is only appropriate for short timescales.

Bidarmaghz, Narsilio and co-workers developed a truly 3D finite element model for both boreholes and energy piles. This model explicitly considers the flow and heat transfer in the pipes embedded in the GHE. The fluid flow within the pipes is modelled either in 3D or 1D and is fully coupled to the heat diffusion in the concrete and the ground. The model has been validated against full scale experimental data covering a range of conditions and then used to investigate optimisation (Bidarmaghz 2015, Bidarmaghz et al. 2012, Bidarmaghz et al. 2016a, 2016b, Narsilio et al. 2012, Narsilio et al. 2018). Using similar techniques, Ozudogru et al. (2015) also developed a 3D numerical model for simulating vertical U-tube borehole GHEs.

Various authors have also applied 1D line or pipe elements to energy piles, including Choi et al. (2011), Cecinato & Loveridge (2015), Batini et al. (2015) and Caulk et al. (2016). Rees & He (2013) took an alternative approach to simplifying the pipe details within a borehole heat exchanger model. They used a single layer of cells to represent the fluid within the U-tube. The thermal properties of the material in these cells must be adjusted to make this representation appropriate.

Other numerical simulations have considered different physical processes in the soil surrounding energy piles and geothermal heat exchangers to evaluate coupling between heat transfer and water flow processes. For example, Wang et al. (2015a) evaluated the impact of coupled heat transfer and water flow on the behaviour of an energy pile in unsaturated silt and compared results with those from centrifuge physical modelling tests. Baser et al. (2018) evaluated the roles of enhanced vapour diffusion and phase change in the coupled heat transfer and water flow in unsaturated soils surrounding a borehole heat exchanger and found that consideration of these two variables leads to a faster heating response and larger zone of influence of the heat exchanger. Further, heating of unsaturated soil was found to lead to permanent drying that may cause changes in the transient response during cyclic heating and cooling. Specifically, the drying effect leads to a decrease in thermal conductivity and specific heat capacity of the unsaturated soil.

2.1.2.6 Hybrid Models

The Duct Storage Model (DST) was developed to consider an underground thermal store constructed of many identical vertical GHE installed within a cylindrical area (Hellstrom 1989). The model superimposes three solutions: a finite difference model for the long-term heat transfer between the thermal store and the surrounding ground, a second finite difference model for the heat transfer between GHEs and the ground within the store and finally an analytical model for the steady heat transfer within the heat exchangers. Despite numerical implementation the model runs fast enough for routine application. It has been implemented in the building energy software TRNSYS for borehole applications and as a standalone application called PILESIM (Pahud 2007). PILESIM is commercially available and one of the few tools validated for use with piles. The validation is based on the Zurich Airport case study (Pahud & Hubbach 2007). However, many of the assumptions in the DST are not appropriate for piles, which are typically installed on an irregular grid and may comprise different sizes and lengths. The DST also assumes a steady state resistance which has been shown to overestimate temperature changes.

Another technique which has proved successful is that of simulating the energy pile and the ground as a series of resistances and capacitances using an electrical analogy. This approach has been adopted by Zarrella et al. (2013) who initially developed a model for boreholes (De Carli et al. 2010, Zarrella & De Carli 2013) and then extended it to be applicable to energy piles. The pile version uses an equivalent U-tube simulation to account for a larger number of U-pipes connected in parallel. The "electrical" circuit is 3D to include axial effects and is computed numerically but is dependent on input parameters in term of values of the resistances that depend on the pile and pipe geometry. These needed to be determined separately in advance and is usually done by application of a discretised model based on the finite difference or finite element methods. A similar approach is presented for piles with four pipes, without the U-tube simplification, by Maragna & Loveridge (2019).

2.1.2.7 Pipe Arrangements and Pile Geometry

Numerical simulation is a productive tool for sensitivity analysis and several authors have addressed the issues of pipe arrangements and pile geometry (e.g., Makasis et al. 2018a, 2018b). Initial studies (e.g. by Gao et al. 2008) focused on the relative efficiency of U, UU (parallel connection) or W (series connection) shaped pipes being installed within the piles. However, more recent work by Cecinato & Loveridge (2015) shows that the most important factor for maximising energy exchange in piles is to install a greater number of pipes, hence either UU or W shaped arrangements will always be preferable to a single U tube. The authors showed that following pipe numbers, the pile length was the next most influential factor, followed by the pile thermal properties. The importance of pile length is consistent with work by Batini et al. (2015), who also studied the influence of aspect ratio and other factors on thermal and mechanical performance.

Recently there has been significant interest in the use of helical (or "spiral coil") pipe arrangements rather than standard vertical pipe installed as U-tubes (e.g. Park et al. 2013; Go et al. 2014; Man et al. 2011). Comparative studies have shown helical pipe arrangements to potentially offer greater heat transfer rates compared to standard energy pile arrangements (Zarrella et al. 2013; Yoon et al. 2015). At least some of this advantage is due to the greater pipe lengths that can be accommodated within the pile using the spiral arrangement.

Contiguous flight auger (CFA) piles with short steel cages which prevent full depth installation of heat transfer pipes have also given rise to an alternative pipe layout. In these cases, to permit a full depth pipe installation U-tubes are attached to a separate steel bar and plunged centrally into the concrete following insertion of the short cage (Amis et al. 2014). However, due to the closer proximity of the pipes such central arrangements of pipes will always be less energy efficient than a standard arrangement (Loveridge & Cecinato 2016).

Further discussion of pile types and pipe arrangements is considered from a field data perspective in Section 3.1.1.1.

2.1.3 Energy Walls

2.1.3.1 Overview

The last five years has seen an increased interest in energy retaining walls. These are most typically diaphragm walls, but also include piled walls. These embedded retaining walls may be constructed to support building basements, metro stations or shallow cut and cover tunnels. Depending on the end use of the excavation space in front of the wall, their thermal behaviour may vary and consequently it is important to correctly understand the nature of this space and what boundary conditions it may impose on the energy wall. This additional boundary condition is the most important difference when considering the thermal performance of energy walls as opposed to piles which are surrounded by the ground. Consequently, some consideration is given to determining this condition before looking specifically at analytical and numerical methods applied to thermal analysis for energy walls.

2.1.3.2 The Excavation Space

Building basements may be subject to damped seasonal variations if they are not temperature controlled, or they could approximate constant temperature environments if they are subject to climate conditioning. On the other hand, metro stations or shallow tunnels may exhibit strong convective conditions due to the movement of trains or other vehicles, and there might be sources of heat, like train braking or passengers. When undertaking such an analysis, the excavation space therefore needs thermal characterisation. The space may be represented by one of three boundary conditions. An adiabatic condition suggests that there is no heat transfer to this space and is potentially conservative in the long term if the space is considered a positive source of energy. However, the space can also be a sink and reduce efficiency due to heat losses, in which case this assumption may not be conservative. The alternative extreme is a constant (or time varying) temperature boundary condition. This will give the highest heat transfer rates. Finally, a convective condition may be assumed, with use of a heat transfer coefficient to determine the magnitude of the heat transfer occurring within the excavation space. Very high heat transfer coefficients, applicable to scenarios with high air flow conditions, will approximate a temperature boundary.

Bourne-Webb et al. (2016b) studied the difference between a temperature and a convective boundary using a 2D steady state finite difference simulation. They showed a potential four-fold difference in heat transfer rates from 20 W/m^2 to 80 W/m^2 between the extreme conditions. However, the steady state analysis may not be representative of long-term behaviour. Transient analysis over two months by Piemontese (2018) showed a much smaller discrepancy between these conditions, generally less than 5 W/m^2.

Current experience shows a variety of approaches taken to the excavation space boundary condition. Many analyses have assumed a constant (or time varying) temperature condition, for example the basement applications considered by Kürten et al. (2015a), Kürten (2014) and Sterpi et al. (2017), and the metro stations studied by Soga et al. (2014), Rui & Yin (2018) and Rammal et al. (2018). Heat transfer coefficients representing a convective boundary have been used more rarely, notably by iC Consulten (2005) when assessing metro stations and tunnels and by Bourne-Webb et al. (2016b) in their sensitivity study. More recently, adiabatic conditions have been assumed for metro station studies in Torino (Barla et al. 2018) and Melbourne (Narsilio et al. 2016a, 2016b).

Field data with which to validate analysis approaches remain relatively rare (see also Section 3). Angelotti & Sterpi (2018) used data from a diaphragm wall forming a basement wall in northern Italy to validate their numerical simulations. They found that a time varying temperature boundary was appropriate over the four months of data available. To provide the best fit they applied a damping coefficient to reduce the fluctuations of air temperature in the locality to an appropriate value to approximate conditions within the basement. The constant temperature approach used by Kurten et al. (2015a) during numerical simulation was also validated, but this time with reference to model test data (refer to Section 4). No longer-term validations are available.

2.1.3.3 Numerical Simulations

Numerical simulation is the most common approach for analysis of the thermal capacity of energy walls. Several different approaches have been applied. Bourne-Webb et al. (2016b) used 2D steady state finite difference analysis with fixed temperature values on the pipe boundary conditions. Rammal et al. (2018) approximated the heat transfer process by assuming a constant temperature in the energy wall in the 3D finite difference analysis. More common, however, is the use of 1D line elements to simulate the heat transfer pipes within a 3D finite element analysis, for example in the studies of Sterpi et al. (2017), Di Donna et al. (2016a), Narsilio et al. (2016a, 2016b) and Barla et al. (2018). 3D finite volume analysis was carried out by Shafagh & Rees (2018), including meshed pipe detail.

Not all the approaches are fully validated by field data. Di Donna et al. (2016a) used the published short-term thermal performance test data from Xia et al. (2012) to validate their model. Sterpi et al. (2018) and Shafagh & Rees (2018) both use longer data sets. The former from 4 months of monitoring from a real case in Italy and the latter from a 38-day multi-stage thermal response test in Spain.

2.1.3.4 Analytical Methods

While numerical simulation is a common research tool, and has also been used by researchers supporting practice (e.g. Narsilio et al. 2016a, 2016b; Rammel et al. 2018), more accessible analytical techniques for analysis of energy walls have yet to be fully developed for routine deployment

First Sun et al. (2013) proposed the first analytical solution based on heat conduction. The model contains many familiar assumptions from the analysis of energy piles, with the addition of a convective heat transfer boundary condition for the inside face of a retaining wall. The model was tested against full numerical simulation and the thermal performance test data from the Shanghai Museum of Nature History (Xia et al. 2012). However, poor fit was found at short time periods (<12 hours) suggesting the details of the heat exchanger are insufficiently well captured.

Subsequently, Kurten et al. (2015b) used an electrical analogy to develop a thermal resistance model for energy walls. They took account of pipe positioning and used a numerical model to compute the resistance. The approach was then validated against full numerical simulation and model scale laboratory tests. More recently Shafagh & Rees (in review) have developed a more general resistance model for a rectangular shape with an irregular hole. The truly analytical approach, which assumes either isothermal or convective boundary conditions, would be application to energy wall applications.

While the thermal resistance models deal only with the internal heat transfer within the wall, a composite model has also been developed by Shafagh & Rees (2018) based on the Dynamic Thermal Network (DTN) approach. The network describes the relationship between temperature and fluxes at surfaces, with these surfaces specified as the ground, the excavation space and the heat transfer pipes. DTN is a response factor method and therefore represents transient conduction in terms of the surface fluxes and temperature variables only. In this approach the current state is expressed entirely in terms of the current and past temperatures (Rees & Fan, 2013). Each transient heat flux is dependent on weighed averaged nodal temperatures which are calculated using weighting factors. Shafagh & Rees (2018) calculated these weighting factors using their finite difference model. However, once the weighting factors are pre-determined based on the geometry then the run time is fast. The model was then validated against a long-term thermal response test.

2.1.3.5 Pipe Arrangements

Various sensitivity analyses have shown the benefit of W as opposed to U shaped pile installations within the walls (Xia et al. 2012, Barla et al. 2018) based on field and numerical testing (Figure 6). However, slinky-like arrangements, where many turns are made to maximise the amount of pipe included in the wall are also popular in some countries, and analyses show these may have the greatest benefit in terms of heat transferred (Sterpi et al. 2017). Reducing the pipe spacing or increasing the length of pipe attached to a given wall panel will also often increase energy efficiency (Kurten 2011, Di Donna et al. 2016a, Barla et al. 2018). However, pipe length alone is an insufficient measure and pipe arrangement must also be considered in combination (Sterpi et al. 2017).

The above pipe optimisation studies were mostly are short-term analyses. The statistical based parametric analysis by Di Donna et al. (2016a), on the other hand, suggests that the importance of pipe spacing and arrangement will decrease in the longer term. As more time progresses, the temperature difference between the ground and the excavation space becomes of prime significance instead. This is consistent with the steady-state analysis of Bourne-Webb et al. (2016b) and the long-term transient analyses of Narsilio et al. (2016a). Again, this highlights that the temperature response of the structure (and hence the energy exchanged) to be highly dependent on this internal excavation space boundary condition. Finally, the temperature difference between the heat transfer fluid and the soil is key for determining the heat transfer rate (Xia et al. 2012, Piemontese 2018), Figure 6. This confirms the importance of balancing thermal loads to maintain maximum temperature differences during operation (e.g., Narsilio et al. 2016a).

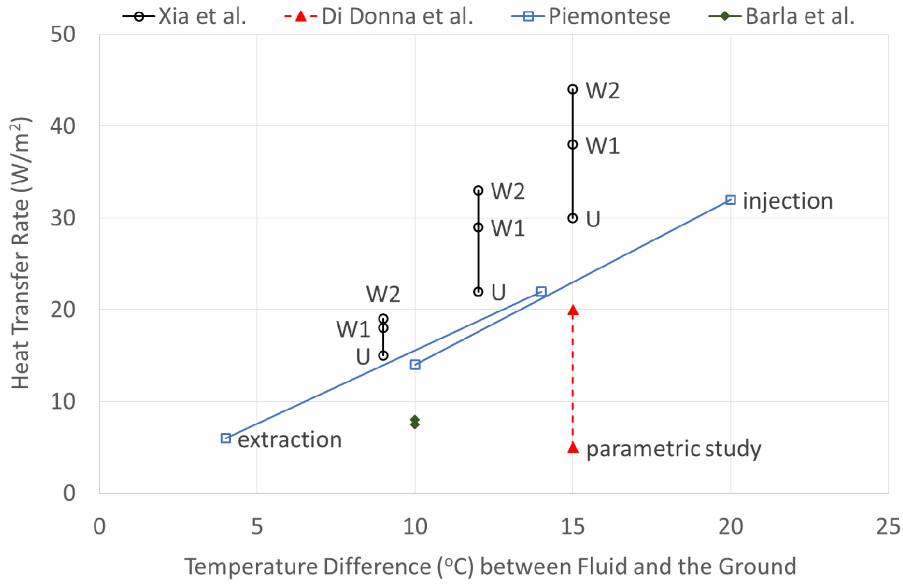


Figure 6 Effect of pipe arrangements and temperature difference between fluid and the ground on the heat transfer rate obtained from energy walls. (U = single U tube; UU = two U-tubes connected in parallel; W1 or W2 = two U-tubes connecting in series; parametric study includes both U and UU arrangements).

2.1.4 Energy Tunnels

2.1.4.1 Overview

Like retaining walls acting as heat exchangers, tunnel linings equipped with heat transfer pipes are relatively rare and there is still no routinely adopted design and analysis practice, although some guiding principles have been offered in the literature (e.g., Frodl et al. 2010, Nicholson et al. 2014a, Tinti et al. 2017). Figure 7 shows a schematic example of an energy tunnel. However, there is an increasing interest on the potential use of energy tunnels, driven by sustainability and innovation requirements found in large infrastructure projects. Pilot and trial tunnel sections are most typically encountered in metro rail projects, with pipe heat exchangers embedded on the tunnel linings shortly after shotcreting or in tunnel segments. Depending on the primary intended end-use of the tunnel heat exchangers, that is, to exchange heat with the ground or to exchange heat with the tunnel air space (i.e., providing heating or cooling to the tunnel space), their thermal behaviour may vary and consequently it is also important to correctly understand the nature of this use and the boundary conditions that are to be prescribed on the energy tunnels models. Like with energy walls, the boundary condition against the air space of the tunnel is the most important difference with borehole ground heat exchangers and energy piles, and due consideration must be given in any analytical or numerical analysis for energy tunnels. The role of groundwater flow and its predominant direction also impact on the thermal energy yield.

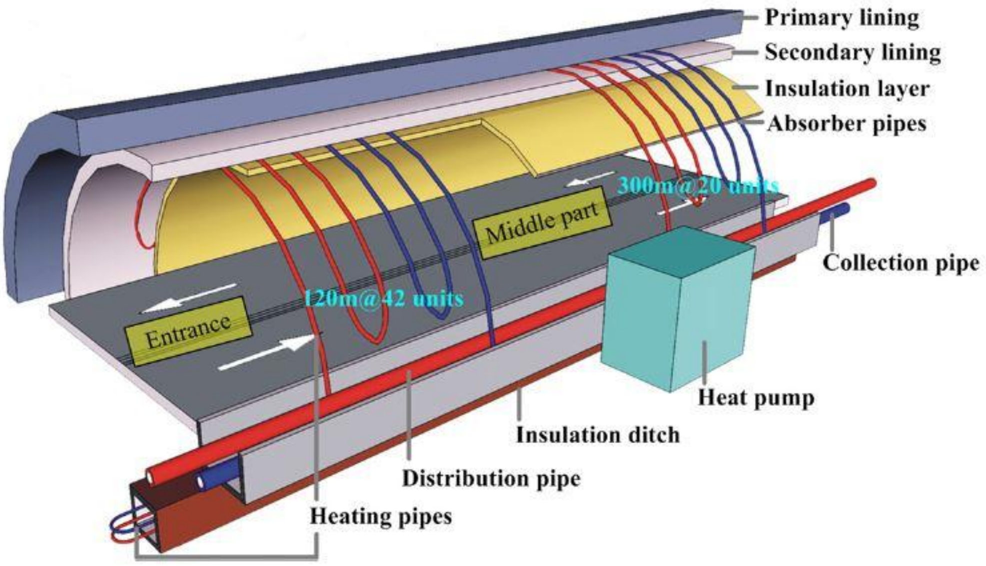


Figure 7 Schematic view of a energy tunnel. Absorber pipes are embedded into the tunnel lining (adapted from Zhang et el. 2013, reproduced with permission, Licence Number 4585510080214)

2.1.4.2 The Tunnel Space

Like with energy walls, the tunnel space needs careful thermal characterisation. The environmental conditions of the tunnel air space vary on a case by case basis. They are typically not subjected to climate conditioning; however, ventilation is common in metro and vehicle tunnels. Unventilated or "hot" tunnels also exist, such as those in the London Underground (Nicholson et al. 2013; Stephen, 2016, Mortada et al. 2018). These conditions are important when considering thermally activating the tunnels. Even in hot tunnels, convective conditions may exist due to the movement of trains or other vehicles, and additional sources of heat arising from train braking or passengers may also exists. In sewage tunnels (liquid as oppose to gas, air) convection is also important.

The tunnel space may be represented by one of three boundary conditions. When there is no heat exchange with this space, an adiabatic condition shall be considered. This boundary condition implies thermal insulation has been incorporated in the tunnel lining, which is not typically the case for tunnels and carries additional material and construction costs (and in the case of metro, passengers and cargo tunnels, materials must be fire resistant as well). For the common case of no thermal insulation, the tunnel air space can also be a heat sink or source, and the analysis can be carried either modelling the space air convective-conductive heat transfer (most comprehensive) or by (un-conservatively) prescribing a constant or time varying temperature boundary condition. The latter approach under- or over-estimate the heat transfer of the thermally activated tunnel lining, scenarios with high air/sewage flow convention, will approximate a temperature boundary.

2.1.4.3 Numerical Simulations

Full scale data with which to validate analysis approaches remain relatively rare (see also Section 3). Bidarmaghz et al. (2017) and Bidarmaghz and Narsilio (2018) used data from an energy tunnel pilot project in Germany summarised in Buhmann et al. (2016) to validate their numerical simulations. Lee at al. (2016) and Zhang et al. (2013, 2016a, 2017) performed field scale and laboratory scale thermal performance tests to validate and extend their own numerical and analytical models respectively. They found that a constant or time varying temperature boundary was appropriate for highly ventilated tunnels or for short term testing, but this is an area of active research in which longer-term validations and representativeness of the boundary conditions adopted are still under investigation.

While the published literature on energy tunnels is still quite limited, one can see that numerical modelling has been adopted to undertake technical feasibility studies and or better understand results from laboratory and field testing (e.g., Nicholson et al. 2014a, Narsilio et al. 2016a, 2016b, Barla et al. 2016, Baralis et al. 2018). Numerical simulations are used to assess temperature changes in the ground and the tunnel space, and heat transfer rates. Studies have been conducted in both two (Franzius & Pralle 2011) and three dimensions (Nicholson et al. 2014a). Again, the structure internal boundary condition is very important. Zhang et al. (2014) have observed the importance of the air inside the tunnel as a heat source, with subsequent analysis linking tunnel air speed and heat transfer rates (Zhang et al. 2016a, 2017). This is reflected in the study of Nicholson et al. (2014a) where the trains running within the tunnel were positively taken as a source of heat. However, Franzius & Pralle (2011) neglected heat transfer into the tunnel which is a significant over simplification. Di Donna & Barla (2016), Barla et al. (2016), Lee et al. (2016), Bidarmaghz et al. (2017) and Bidarmaghz and Narsilio (2018) have also used 3D numerical simulations with 1D pipes to reduce computational effort to perform parametric studies, including the effect of ground and groundwater conditions on the energy efficiency of energy tunnels.

2.1.4.4 Analytical Methods

An analytical solution has also been proposed by Zhang et al. (2013) based on a model in radial coordinates. This accounted for the internal boundary condition via a sinusoidal varying temperature condition determined from monitoring of road tunnels. The model was successfully validated against field data, but only over a limited time frame. In addition, empirical models have been used by Tinti et al. (2017) for high level estimations of thermal yields for sections of tunnels linking Italy and Austria.

Analytical methods offer much quicker alternatives for the analysis and design of energy tunnels than detailed finite element simulations, the most common numerical technique adopted to date for this purpose (previous section). Clearly, research on analytical techniques for energy tunnels is underdeveloped at present.

2.1.4.5 Pipe Arrangements

As it is the case for other types energy geostructures, pipe arrangements must suit constructability and minimise or avoid overall construction program delays. Currently, there are three main means to embedded absorber pipes into tunnels, with similar pipe configuration arrangements. These are also reflective of the excavation method:

- Installation of absorber pipes between the outer and inner (shotcrete or other) lining or in the inner lining. This solution is best suited to be used in drill and blast or punctual mechanised excavation systems. Examples included the pilot geothermal system of Stuttgart's Fasanenhof underground station in Germany (Geimer 2013, Buhmann et al. 2016) and of Yakeshi's Linchang tunnel in Inner Mongolia (Zhang et al. 2014).

- Installation of precast energy textile or energy fleece, also suitable for drill and blast excavations (Lee et al. 2016). The first application of this type can be found in Vienna's Lainzer tunnel (2003) in Austria (Adam and Markiewicz 2009).
- Installation of absorber pipes within precast lining segments: suitable for Tunnel Boring Machine (TBM) excavations. The first GSHP system using thermally activated lining segments was installed in Austria, in the Stuggart-Jenbach tunnel (Frodl et al. 2010; Franzius & Pralle 2011).

In all three cases, absorber pipes are placed in a meandering fashion, with the pipes either predominately parallel to the main axis of the tunnel (longitudinal meandering) or perpendicular to it (transverse meandering). The slinky pipe arrangement has only been tested in prefabricated energy textiles (see Figure 8).

Adam & Markiewicz (2009) and Brandl et al. (2010) placed heat exchanger pipes on a geotextile between the primary and secondary tunnel lining for a Vienna metro tunnel constructed using the New Austrian Tunnelling Method (NATM), Schneider & Moorman (2010) incorporated geothermal heat exchangers into panels in a Stuttgart metro tunnel that were connected with coupling joints that provide both mechanical interlocking and hydraulic connections, and Nicholson et al. (2014a) incorporated heat exchanger tubing into segmental panels for the London Crossrail tunnel.

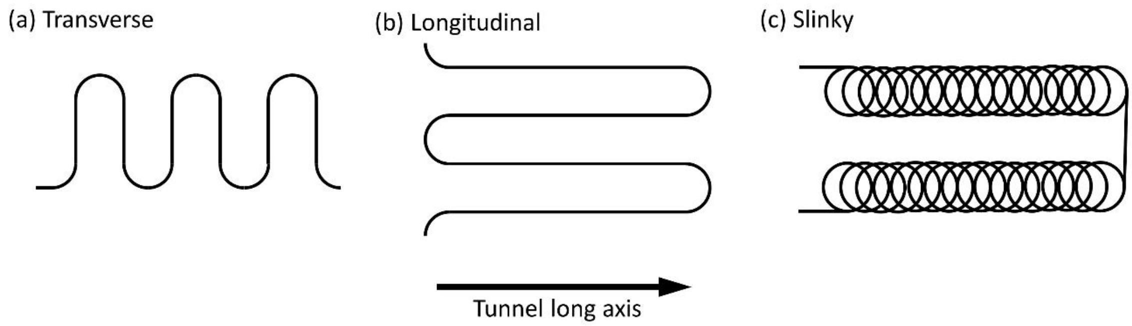


Figure 8 Typical layout of absorber pipes in energy tunnels: (a) longitudinal meandering pipe, (b) transverse, and (c) slinky (only found in energy textiles to date).

2.1.5 Other Geotechnical Structures

Energy ground anchors have been suggested and in one case successfully trialled (Adam & Markiewicz 2009, Mimouni et al. 2014). Analysis to date appears to be mainly based on numerical simulations, although their axisymmetric nature would mean they are well suited to similar design approaches applied to energy piles. Energy base slabs have also been constructed (e.g. Brandl 2006) and design approaches would be similar to retaining walls. However, because slabs do not have the benefit of the embedded part of retaining walls, which are surrounded by soil on both sides, they will always have lower rates of heat transfer. Recent in situ monitoring of walls and slabs by Angelotti & Sterpi (2018) show almost three times lower heat transfer rates for the slabs, in the range of 3 to 9 W/m^2. This compares well to the average rate of 5 W/m^2 reported from various sites by Kipry et al. (2009).

Excavations for shallow foundations have also been utilised for ground heat transfer and storage. In Korea, heat transfer pipes have been trialled at the base of concrete shallow foundations, with subsequent numerical simulation validated against experimental data (Nam & Chae 2014). In the

United States, Oak Ridge National Laboratory led a project to place horizontal pipes within the excavations already being made for shallow foundations for domestic house (Hughes & Im 2013), so called Foundation Heat Exchangers. The project was supported by analysis by Oklahoma State University and others who developed numerical simulation and implemented the results in the software EnergyPlus for routine application (Cullin et al. 2014, Xing et al. 2012, Spitler et al. 2011).

Shallow geothermal systems can also be used to prevent snow accumulation and/or ice formation on bridges, roads, sidewalks, and similar structures. For example, geothermal systems for bridge de-icing generally envisage energy piles for the bridge foundation, loops embedded in the abutment embankment for additional heat exchange with the ground, and loops in the bridge deck that will maintain the surface warm to prevent ice formation (e.g. Olgun & Bowers, 2013). A brief review on geothermal energy for bridge deck and pavement de-icing is presented in Yu et al. (2016). Detailed numerical analyses and feasibility studies are presented elsewhere (e.g. Ho and Dickson, 2017; and Han and Yu 2018).

2.2 Geomechanical and Structural Analysis

2.2.1 Overview

The geotechnical design of energy geostructures focuses primarily on both ensuring their ultimate capacity to safely exceed building loading demands, and their long-term serviceability in terms of deformation response. In the case of energy piles, depending on the restraints provided by the overlying superstructure and the mobilised side shear stresses and end bearing stresses specific to the subsurface stratigraphy, temperature changes associated with geothermal heat exchange may lead to thermally-induced changes in axial stress and deformations. The thermally-induced changes in axial stress may increase the building loading demands on the energy pile, while the thermally-induced deformations may lead to changes in the long-term serviceability. Furthermore, depending on the magnitude of the axial stress before heat exchange processes commence, cyclic heating and cooling may lead to permanent deformations that need to be characterised. Accordingly, it is critical to accurately estimate the thermally-induced changes in axial stress and deformations expected for an energy pile under the site-specific end-restraint boundary conditions and subsurface stratigraphy. For other energy geostructures such as tunnels and walls, a similar design philosophy may be adopted, but it is expected that the restraint boundary conditions will differ from those encountered for energy piles.

2.2.2 Piles

The two major approaches to predict the thermally-induced axial stresses and deformations in energy piles are load transfer analysis and FE analysis. Load transfer analysis is a simplified approach to consider axial soil-structure interaction phenomena that relies upon assumed shapes of the mobilised side shear stress and end bearing stress versus deformation curves (Coyle & Reese 1966). Although semi-empirical, this approach permits characterisation of nonlinear soil-structure interaction that may be difficult to consider in finite element analyses. However, a challenge in this analysis is the definition of the head restraint boundary conditions and the role of radial stresses. Load transfer analysis has been used successfully to represent the observed mechanical and thermo-mechanical behaviour of energy piles in the field and centrifuge by Knellwolf et al. (2011), McCartney (2015) and Chen & McCartney (2016). It has also been used to evaluate the role of cyclic heating and cooling (Pasten &

Santamarina 2014; Suryatriaystuti et al. 2014). It is important to note that there has not been sufficient experimental data collected to validate these predictions. These studies did identify that piles that are loaded closer to their ultimate capacity will show greater amounts of permanent deformations due to ratcheting effects. Ouyang et al. (2011) used a hybrid load transfer analysis that combined the axial stress-strain response of individual energy piles obtained from a load transfer analysis with an elastic continuum solution to model interaction between energy piles.

Finite element analyses have been widely used to study the thermo-mechanical behaviour of energy piles, considering a range of different constitutive relationships for the energy pile, soil, and interface, as well as considering different physical processes such as heat flow and thermally-induced pore water flow. Although FE analyses can consider the impacts of more complex phenomena, they require more parameters for the constitutive relationships. Although the focus of many energy pile designs is on the pile performance considering the soil-pile interface, the behaviour of the surrounding soil may have long-term implications on the energy pile performance. Laloui et al. (2014) and Coccia & McCartney (2016a, 2016b) provided a review of different constitutive relationships that can be considered for the thermo-mechanical behaviour of soils and soil-pile interfaces. Several constitutive relationships used in FE analyses of soils do not consider thermo-mechanical behaviour but account for different ways to incorporate soil nonlinearity during mechanical loading. Specifically, Suryatriyastuti et al. (2016) used a hyperbolic model to represent the behaviour of the soil without consideration of temperature effects. Saggu & Chakraborty (2015), Olgun et al. (2014) and Ozudogru et al. (2015) used an elasto-plastic formulation with the Mohr-Coulomb yield criterion, while Ng et al. (2015) used an incremental nonlinear hypoplastic model specific to sand. On the other hand, fewer models have incorporated thermo-elasto-plastic soil behaviour. Specifically, Rotta Loria & Laloui (2016a) used a linear thermo-elastic model for the soil, Laloui et al. (2006) used a thermo-elasto-plastic model with the Drucker-Prager yield criterion, and Di Donna et al. (2016b) used a thermo-elasto-plastic model with the Mohr-Coulomb criterion. It was not possible to validate whether the soil constitutive model influenced the axial soil-structure interaction predictions, but all the constitutive models used in the previous studies still resulted in good matches in terms of the predicted axial stresses and strains in the energy piles. Laloui et al. (2006), Laloui and Nuth (2006), and Rotta Loria & Laloui (2016a) assumed that the pile and soil were rigidly connected (a perfectly rough interface), Suryatriyastuti et al. (2012) and Ozudogru et al. (2015) used an elastic-perfectly plastic soil-pile interface element, Saggu & Chakraborty (2015) and Ng et al. (2015) used an interface friction angle smaller than that of the soil and a refined mesh near the interface, while Suryatriyastuti et al. (2016) used a bounding surface plasticity formulation for the interface. Gawecka et al. (2016, 2017) used a full-coupled thermo-hydro-mechanical FE model to model the impact of transient heat transfer and water flow on soil-structure interaction in energy piles and found that thermally-induced stresses in energy piles dissipate with time as the surrounding subsurface reacts to the changes in pile temperature. Cyclic effects have been considered in several finite element analyses, with plastic deformations obtained through the constitutive model of the soil (Ng et al. 2015) or through the soil-pile interface constitutive model (Suryatriyastuti et al. 2016). Many of the models mentioned above were validated using field data from Laloui et al. (2006) or Bourne-Webb et al. (2009), although Rotta Loria et al. (2015a, 2015b) found that FE analyses could also be validated using centrifuge modelling results.

A significant advantage of FE simulations over load transfer analyses is the ability to consider heat flow analyses and their impacts on the thermo-hydro-mechanical response of the subsurface surrounding the energy pile. Laloui et al. (2006) was able to predict the deformations of the soil surrounding an energy pile while Di Donna et al. (2016b) and Rotta Loria & Laloui (2016a) were able to characterise the thermal and thermo-mechanical interactions between pile groups. Wang et al. (2015a) simulated the coupled flow of heat and water away from a centrifuge-scale energy pile in unsaturated silt, while Akrouch et al. (2016) simulated coupled heat and mass transfer in unsaturated soil away from laboratory-scale energy piles. In both cases, the changes in degree of saturation surrounding the energy pile will lead to a change in effective stress and a corresponding change in the ultimate side shear stress at the soil-pile interface, similar to that observed experimentally by Goode and McCartney (2015). Changes in saturation also lead to changes in the soil thermal properties and heat transfer from the energy pile.

Different methods of analyses have been used to consider the behaviour of energy pile groups than those used for individual energy piles. Rotta Loria et al. (2016a) used a modified interaction factor approach to consider group effects, while Suryatriyastuti et al. (2016), Di Donna et al. (2016b), and Rotta Loria & Laloui (2016b) used FE analyses. The interaction factor approach can be used readily in design calculations, while finite element analysis requires more in-depth site-specific testing to determine material properties. The critical variables in the design of energy pile groups are the spacing and diameter of the energy piles, and the relative stiffness of the pile, soil, and overlying slab which may lead to changes in thermal and mechanical interaction. Although these studies identify that there may be differential movements or changes in the stresses in the overlying slab if one of the energy piles operates while the others do not, this effect is lessened when the temperature changes of the energy piles are the same. It may not be possible to achieve similar changes in pile temperature in practice, so some differential displacements or stresses are expected. Thermal interaction may lead to a decrease in the thermal efficiency of the energy piles in terms of a balanced seasonal heat exchange, so it is still important to have an adequate spacing between energy piles in groups if possible.

Several analyses have been conducted quite recently focused on the behaviour and performance of groups of energy piles (i.e. Rotta Loria and Laloui 2016a, 2016b, 2017a, 2017b, 2017c). It was shown that the vertical displacement of energy piles can increase because of thermally-induced group effects induced by the interactions among piles (Rotta Loria and Laloui, 2017b; Rotta Loria and Laloui, 2017c).

New challenges in the analysis of energy piles may arise when they are applied in soft soil, expansive soil, or unsaturated soil settings, during lateral loading of energy piles, or when different materials are used in the construction of energy piles. For example, McCartney & Murphy (2017) presented 6 years of monitoring results from a pair of energy piles in saturated claystone that may have expansive characteristics and observed a long-term dragdown effect superimposed atop the thermo-mechanical behaviour of the energy pile. This dragdown could have been due to the natural settlement of the soils on site under the building load, but they may also have been induced by the ground temperature changes. Ghaaowd et al. (2018) evaluated the impact of heating on the pullout response of energy piles from soft clays and observed an increase in pullout capacity that corresponded with a decrease in void ratio of the clay surrounding the energy piles. This was attributed to the impact of permanent contraction during drained heating of the clay on the undrained shear strength, which was characterized experimentally for the same clay by Samarakoon et al. (2018). Analyses of these new challenges will undoubtedly require the use of advanced finite element software for the long-term design of energy piles.

2.2.3 Other Energy Geostructures

The thermo-mechanical response of energy walls is expected to be similar to energy piles, with an exception that the lateral expansion at the ends of the wall will induce a 3D stress field that may be more complex to evaluate than in energy piles (Soga et al. 2015). Further, structural restraints in the case of basement walls may lead to differential thermal volume changes that are not observed in the 1D axial analysis of energy piles. While it may be possible to use load transfer analyses for energy walls, it is expected that FE analyses would be required to evaluate their thermo-mechanical response. However, Nicholson et al. (2014a) found that the temperature changes within the space enclosed by a tunnel have a much greater effect than the temperature changes in the wall due to typical levels of heat extraction.

As described in Section 2.1.4.5, different methods have been proposed to incorporate geothermal heat exchangers into tunnel linings to extract heat from both the interior of the tunnel as well as from the surrounding ground, depending on the method of tunnel construction. These different designs may have different thermo-mechanical performance due to the geometry of the concrete section surrounding the energy pile. The FE analyses developed for energy piles can be adapted to study energy tunnels, with the main technical difference expected would be a change in the hoop stresses and strains in the tunnel during heat extraction along with the tensile stresses around the heat exchangers and between joints (Nicholson et al. 2014a). The surrounding subsurface may provide a different restraint to thermal strains than in energy piles, and thermal deformations may affect arching and stress distributions around the tunnel, although these changes likely already occur in the tunnels without the incorporation of heat exchangers due to changes in ambient tunnel temperature (Nicholson et al. 2014b). Sailer et al. (2018b) used FE analyses to compare hydro-mechanical FE analyses where an energy wall expands and contracts during temperature changes without temperature effects on the soil, and thermo-hydro-mechanical FE analyses where an energy wall expands and contracts during temperature changes considering temperature effects on the soil. The changes in pore water pressure of the soil in the latter analysis were found to have major effects on the stress state in the soil and led to differences in the axial forces in the wall and the vertical displacement of the wall. Barla et al. (2018) used FE analyses to study the thermal and thermo-mechanical behaviour of energy walls and also found that the bending moment and horizontal displacement increase at the top of an energy walls during heating, but with magnitudes within acceptable structural limits.

3 Field Scale Testing

3.1 Pile Thermal Tests

3.1.1 Thermal Performance Tests

In this discussion thermal performance tests, which aim at obtaining the energy capacity of a system, are differentiated from thermal response tests, which have their origin in the need to determine the soil thermal conductivity in situ. Thermal performance tests have been further subdivided into short term tests, usually conducted over a few days, and longer-term observations, typically conducted during full operation of a system. This distinction is important, since short term tests commonly provide an overestimate of energy capacity compared with operational conditions. Short term tests nonetheless can be useful, especially for making comparisons of design aspects such as pile types and configurations.

3.1.1.1 Short Term Tests

In this context short term test are defined as those where the duration of the experiment is no more than three months (although typical such tests are less than one week long). The performance of the pile heat exchanger is tested by circulating fluid, usually entering the pile at constant temperature, through the heat transfer pipes and recording the resulting outlet temperature. From the outlet temperature and knowledge of the fluid flow rate and thermal properties it is possible to calculate the heat transferred to the heat exchanger and the ground. Seven examples of this type of test have been identified for a variety of different piles as summarised in Table 3. The resulting heat exchange rates, expressed in W/m, vary substantially and depend on a range of factors including the pile construction, the number and arrangements of pipes, the flow rate, the ground conditions, the temperature difference between the fluid and the ground and the test duration. Complete information is not always available about all these factors, but nonetheless some overarching trends can be identified.

Table 3 Summary of pile thermal performance tests

Reference	Pile Type	Pile Diameter (mm)	Pipe No & Arrangement*	Flow Rate (L/h)	Temperature Difference^{+} (°C)	Heat Transfer Rate (W/m)
Jalaluddin et al. (2011)	Steel screw pile, sand filled	140	U	120, 240, 480	10	37 - 55
Hamada et al. (2007)	Hollow pre-cast concrete, mortar filled	300	U, UU	244, 263	9 - 10	54 - 69
Morino & Oka (1994)	Steel, water filled	400	Direct use	1800	15 - 25 5 – 12 (extraction)	120 – 140 70 - 85
Nagano et al. (2005)	Steel, water filled	400	U, UU, direct use	300 – 1800	7 - 14	14 - 95
Gao et al. (2008)	Concrete, cast in situ	600	U, UU, W	171, 342, 684	17	55 - 115
Colls (2013)	Concrete, cast in situ	600	U, UUU	726 - 1242	3 - 16	4 – 8
Katsura et al. (2009)	Hollow steel, water filled	267, 400, 600, 800, 1200	U	480, 960, 1440	9 - 14	70 - 90
Murphy et al. (2015)	Concrete, bored cast in situ	610	U, W, UUU	381 - 1249	1.3 – 8.8	90 – 139
Brettmann & Amis (2011)	Concrete, continuous flight auger (augercast)	300, 450	UU	N.R.	N.R.	73 - 80
Ooka et al. (2007)	Concrete, bored cast in place	1500	8 U	N.R.	N.R.	100 - 120
Singh et al. (2015)	Concrete, bored cast in place	600	U	600	~4	

+ between the fluid inlet temperature and the undisturbed ground temperature
* Notes on pipe arrangements:
U = single U-tube (2 pipes); UU = two U-tubes in parallel (4 pipes); UUU = three U-tubes in parallel (6 pipes); W = two U-tubes in series (4 pipes); Direct use = two open ended pipes inserted into the water filled pile, water infill part of circulation system.
N.R. = Not reported.

Several studies show increasing heat transfer with both increasing flow rate and increasing heat exchanger diameter (Gao et al. 2008, Katsura et al. 2009, Jaluddin et al. 2011, Nagano et al. 2005). However, when the pile capacity is normalised by temperature difference between the inlet fluid and the undisturbed ground, the trends in flow rate are less clear due to scatter relating to other factors (Figure 9). The study of Gao et al. (2008) also illustrates how an increasing number of U-tubes in series will increase the heat transfer capacity for the same flow rate. This verifies numerical studies by Cecinato & Loveridge (2015). However, Gao et al. (2008) also show that using multiple U-tubes in parallel is not necessarily advantageous unless the total flow rate to the pile is also increased so that the same flow rate to each U-tube can be maintained. The type of heat exchanger is also important. The highest rates of heat transfer in Table 3 are both associated with the direct use of infill water in steel piles as part of the heat exchanger (Morino & Oka 1994, Nagano et al. 2005). This is not surprising since this type of pile will be able to exploit any thermally driven convection within the water contained inside the steel pile. What is perhaps more surprising is that the cases of closed loop U-tube installations within water filled steel piles also reported by Nagano et al. (2005) have a much lower unit extraction rate compared to other installations (Figure 9). Overall, most pile exhibit a heat transfer rate in the range of 3 to 6 (W/mK). The effect of intermittent and continuous operating modes on the thermal behaviour of a full-scale geothermal energy pile was investigated by Faizal et al. (2016a, 2016b).

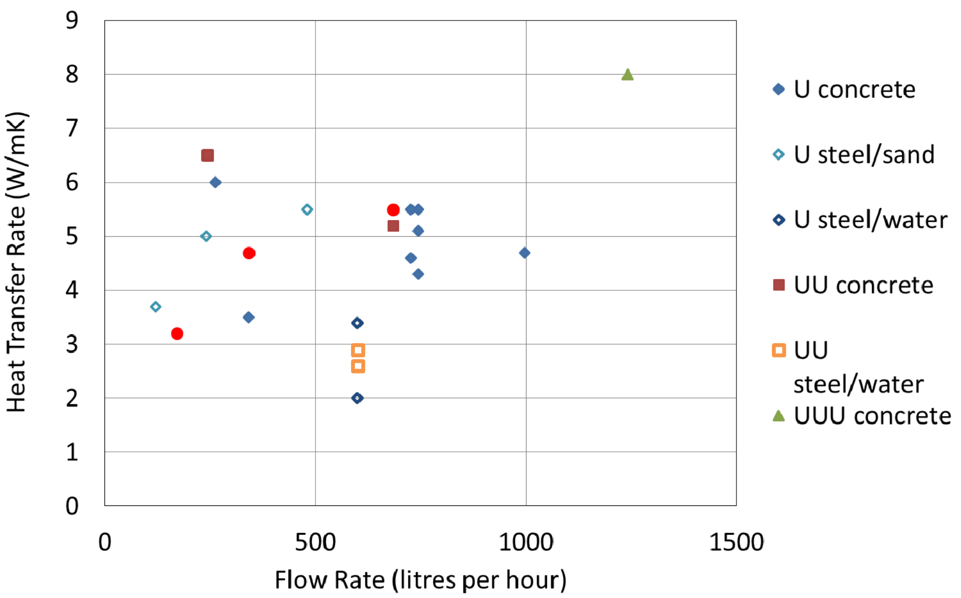


Figure 9 Unit heat exchange rates from short term performance tests of piles. Data taken from the sources listed in Table 3.

3.1.1.2 Long Term Tests and Operation

Long term monitoring data for operational energy pile schemes is relatively rare. Six cases where heat transfer rates have been recorded over periods of months or years are included in Table 4. One notable factor is that most long-term studies consider concrete piles that have been bored and cast in situ, whereas many of the thermal performance tests were conducted to examine other types of piles, especially steel piles. Four of the case studies (Wood et al. 2010a,2010b; Kipry et al. 2009; Pahud 2007; Pahud & Hubbach 2007; Henderson et al. 1998) show significantly lower heat exchange rates than shorter term tests, in the range 15 to 35 W/m. This is to be expected and is in line with recommended ballpark figures (e.g., SIA, 2005). More surprising are the two studies with higher heat exchange rates (Murphy & McCartney 2015; Sekine et al. 2007) of 90 to 220 W/m which fall outside of expected ranges. However, it must also be noted that without full information about the thermal loads at all the sites, as well as the temperature differences between the fluid and the ground it is not possible to make full comparisons between the case studies. Generally enhanced heat transfer rates would be expected where the thermal load is highly intermittent and includes a balance of heat injection and extraction, where the temperature difference between source and sink is high and where the ground has beneficial thermal properties.

Other notable observations from the studies include relatively uniform temperature profiles with depth down the piles (Murphy & McCartney 2015; McCartney and Murphy 2017) and the favourable comparison between piles and boreholes forming part of a combined system (Henderson et al. 1998). The first point suggests that largely radial heat flow is occurring (at least within the two-year timescale of the study), although the authors do note that the influence of ambient conditions is noticeable for the instrumented pile closest to the building edge. In the second study, Henderson et al. (1998) were able to compare the energy exchanged by an approximately equal total length of borehole and pile heat exchangers. They found the piles beneath their building to be supplying 56% of the heating and 70% of the cooling, which they attributed to the absence of interaction with ambient conditions due to the building positioned above the pile heat exchangers.

Table 4 Summary of operational pile performance

Reference	Pile Type	Pile Diameter (mm)	Pile Length (m)	No Pipes	Monitoring Period	COP / SPF*	Heat Transfer Rate (W/m)
Henderson et al. (1998)	Steel tubes with concrete infill	200	26	2	12 months		16.4 extraction 18.3 injection
Wood et al. (2010a, b)	Bored cast in situ	300	10	2	7 months		26
Murphy and McCartney (2015); McCartney and Murphy (2017)	Bored cast in situ	910	15, 13	4, 8	6 years		91, 95

Pahud & Hubbach (2007)	Bored cast in situ	900 - 1500	26 - 27	10	24 months	2.7 to 3.9 (SPF)	15 extraction 16 rejection
Sekine et al. (2007)	Bored cast in situ	1500	20	8	15 months	3.2 extraction (COP) 3.7 injection (COP)	120 extraction 100 – 220 rejection
Kipry et al. (2009)	Various schemes					3 to 6.5 (SPF)	<30 extraction <35 injection

* COP = coefficient of performance and is the ratio of useable energy to the electricity supplied to the heat pump; SPF = seasonal performance factor and is the ratio of the useable energy to the electricity supplied to the heat pump and associated circulation pumps used in the system.

3.1.2 Thermal Response Tests

Thermal response testing is an in-situ technique designed to characterise the thermal properties of the ground heat exchanger and the surrounding soil or rock to enable appropriate values to be used in design. The technique as it is commonly deployed now, using mobile tests rigs, was developed for borehole heat exchangers in the 1990's by two groups working independently, one at Oklahoma State University (Austin, 1998) and the other at Lulea University of Technology in Sweden (Gehlin 2002). Both groups developed an idea first proposed by Mogensen (1983) which proposed applying a constant rate of heating or cooling to a GHE via the circulating fluid and using the resulting temperature change to determine both the ground thermal conductivity and the borehole thermal resistance. The test is directly analogous to a pumping test in groundwater engineering to determine aquifer properties.

For the case of borehole heat exchangers, the test has now become relatively routine and there are a number of relevant national and international standards for its implementation and interpretation (Sanner et al. 2005; IGSHPA 2007, 2009; GSHPA 2011; Banks 2012). Additionally, Spitler & Gehlin (2015) provide a useful review of the development of the test method and equipment as well as a review of interpretation methods and uncertainties. The most commonly used analytical model for interpretation of the test remains the simplified infinite line source. In this model the relationship between change in temperature and time is log-linear which makes interpretation straight forward. The thermal conductivity can be determined from the gradient of the straight line and the thermal resistance from the intercept on the temperature change axis. The thermal conductivity can therefore be determined independently of the thermal resistance, which is not possible in other more sophisticated parameter estimation techniques. However, the simplified infinite line source approach has a key disadvantage when applied to pile heat exchangers. For the log-linear relationship to be valid a certain amount of time must have elapsed, usually taken as $5r_b^2/\alpha$ where r_b is the heat exchanger radius and α is the soil thermal diffusivity. This ensures that the mathematical simplification behind the log-linear relationship is valid, and that the heat exchanger is at a thermal steady state (i.e. the thermal resistance is constant). While this criterion is typically a few hours for boreholes, it may be days or weeks for piles given the dependence on the square of the radius. The consequence of this is that longer test times or different interpretation techniques are required for large diameter piles (Loveridge et al. 2014a). Longer test times mean greater expense and reliable alternative interpretation techniques for large diameter piles are still under development (e.g. Loveridge et al. 2015).

The following sections summarise the work that has been done on thermal response testing for piles in recent years, as well as reporting published test datasets.

3.1.2.1 Case Studies

Seven notable pile thermal response test case studies are highlighted in Table 5 below. Other tests have been performed but those summarised in the table are more comprehensively reported and contain some alternative measure of the ground thermal conductivity with which to compare the in-situ results. In almost all cases the in-situ results for thermal conductivity are higher than those measured in the laboratory (Figure 10). There are several factors which may be causing this effect. First assuming the inlet temperature is typically higher than the ambient air temperature, thermal response tests can lose heat to the atmosphere between the application of the heat input and the point at which the circulation fluid enters the ground. This can cause overestimation of the applied thermal power and hence over estimation of the thermal conductivity and/or thermal resistance (see e.g., Jensen-Page et al. 2018). This effect can be minimised by reducing the distance between the test rig and the GHE, by better insulating hoses, and by positioning the fluid temperature sensors as close to the ground as possible. Of course, underestimation of the power is also possible when tests are conducted in the peak of summer or in particularly warm climates. Secondly, real temperature response functions for piles are expected to have reduced gradients compared with the idealised ILS model (Figure 4). Therefore, fitting of the ILS will lead to artificially low line source gradients and hence overestimations of thermal conductivity.

Furthermore, samples taken from sites will have lost confining stress and also potentially lost moisture before they are tested. Both these factors could result in underestimation of thermal conductivity from laboratory tests. Consequently, quality of thermal response test and quality of soil sample can both affect the accuracy of laboratory – field comparisons. Similar comparisons from borehole thermal response testing have shown that better comparisons can be achieved when appropriate care is taken with respect to quality (Witte et al. 2002, Breier et al. 2011). However, it is likely that the larger diameter and shorter length of piles will contribute to potential errors in thermal response tests results due to additional divergence from line heat source theory. Recently, Akrouch et al. (2015) proposed the 'thermal cone test' to determine in-situ the thermal properties of soils. This technique upgrades the well-known cone penetrometer test (CPT), typically used to determine the geotechnical engineering properties of soils to gather their thermal properties as well. Finally, it is also worth highlighting the two orders of magnitude difference in scale between needle probes often used in the laboratory and in situ tests.

Table 5 Summary of pile thermal response tests

Reference	**Pile Type**	**Pile Dia. (mm)**	**Pile Length (m)**	**No Pipes**	**Test Duration**	**Field Thermal Conductivity (W/mK)**	**Laboratory Thermal Conductivity (W/mK)**	**Comments**
Hemmingway & Long (2013)	Bored cast in situ	250, 350	14.5	2	13 hours	3.2/3.5 (line source injection & recovery) 5.8 (GPM)	3.2 (needle) ~ 2.3 (literature)	Sands and gravels; tests curtailed due to overheating

Reference	Pile Type	Pile Dia. (mm)	Pile Length (m)	No Pipes	Test Duration	Field Thermal Conductivity (W/mK)	Laboratory Thermal Conductivity (W/mK)	Comments
		300	6	2	20 hours	2.9/2.6 (line source injection & recovery) 2.9 (GPM)	~ 2.2 (literature)	
Alberdi-Pagola et al. (2018)	Square, precast concrete	300	15	2	96 hours	2.4 (simulation) 2.1 (line source)	~ 2.0 (literature)	Two test sites, one in organic clay and sand, one in fill over till.
Loveridge et al. (2014b); Low et al. (2015)	Cast in situ	300	26	2	72 hours	2.5/2.7(line source injection & recovery) 2.4/2.9 (G-function injection & recovery)	1.3 (needle)	London Clay; extended time period between sampling and lab testing
Loveridge et al. (2015)	Bored cast in situ	300, 450	18	2, 4	70 – 100 hours	2.6 – 2.7 (line source) 3.1 ±10% (G-functions)	3.0 (needle)	Silty and sandy clay over dense sand; see also Brettmann et al. 2010, 2011
Park et al. (2015)	Hollow concrete cylinder, grout fill	400	13, 14	4, 6	13 hours	2.2 (simulation)	2.0 (needle)	Residual soil, over weather and unweathered gneiss.
Bouazza et al. (2013)	Bored, cast in situ	600	16	2 6 6	3 days 9 days 52 days	4.2 (line source) 5.0 (line source) 3.8 (line source)	2 to 3 (needle)	Dense sands; power variations may have effected results
Murphy et al. (2014)	Bored cast in situ	610	15	6	20 days	2.0 (line source)	1.2 (needle)	Sandstone; field thermal conductivity corrected for pipe run out length

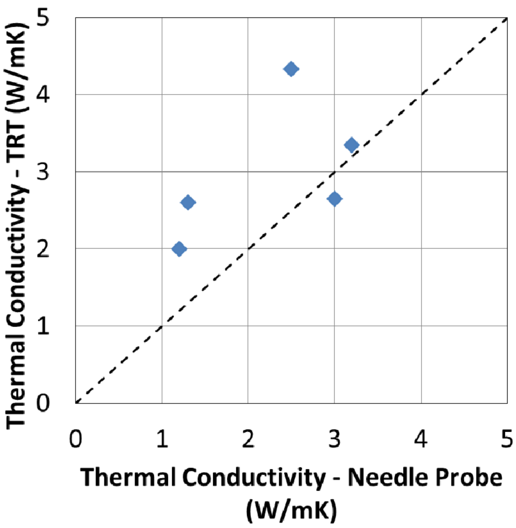


Figure 10 Comparison of Thermal Conductivity derived from Laboratory Testing and Thermal Response Testing (TRT) on Energy Piles. Laboratory values from the needle probe, using a weighted average where different soil units are present. TRT results from line source interpretations, average where there are multiple tests or injection and recovery values.

3.1.2.2 Recommendations

Given the test results in Table 5 it is clear that due care is required in the interpretation of pile thermal response tests. Some better results have been obtained from smaller diameter piles and given the costs of long tests on larger diameter piles it is recommended that practical application be restricted to smaller diameters until better interpretation methods are available. Loveridge et al. (2014a) and Loveridge et al. (2015) have suggested that to limit test durations to 100 hours, then pile diameters should be kept to 300mm or possibly 450mm at the most. Routine pile thermal response testing also has project programme implications since time must be provided in the construct schedule for the concrete heat of hydration to dissipate, which will take longer in larger diameter piles. An alternative approach is to use a borehole for thermal response testing at site investigation stage. However, this has its own drawbacks given that the pile lengths are unlikely to be known this early in the project planning. Further research in this area would therefore assist with providing better guidance, especially for larger diameter piles.

3.2 Pile Geomechanical Tests

3.2.1 Single Piles

Several tests have been performed on full-scale energy piles in the field, including both individual energy pile tests before construction of the building (Laloui et al. 2003; Laloui et al. 2006; Bourne-Webb et al. 2009; Amatya et al. 2012; Akrouch et al. 2014; Wang et al. 2015b; Bouazza et al. 2011; Laloui 2011; Sutman et al. 2014) as well as tests on energy piles beneath constructed buildings (Brandl 2006; McCartney & Murphy 2012; Murphy et al. 2015; Murphy & McCartney 2015; Faizal et al. 2018a, 2018b). Quantitative observations from these studies have been summarised in recent review papers (e.g., Olgun & McCartney 2014; Bourne-Webb et al. 2019), so this discussion focuses on the range of conditions that were investigated in these studies. Although most of the field-scale pile tests were on the compression response of bored cast-in place (drilled shaft) energy piles or augercast energy piles, Akrouch et al. (2014) investigated the application of tensile loads to energy micropiles. The soil profiles in most of the cases were heavily overconsolidated clays or weak rock, which are the best suited for bored pile installation. There were not any studies in soft clay, but Akrouch et al. (2014) evaluated the response of energy piles in highly expansive clay and observed a pronounced creep effect during application of tensile loads. Most of the individual loading tests on energy piles included a loading frame at the ground surface using other pipes for reaction support, while Bouazza et al. (2011) presented the only study on an energy pile that used an Osterberg cell embedded at the toe to push upward and measure side shear stresses and end bearing independently. A wide range in instrumentation has been used in the piles, including thermistors and fiberoptic sensors for temperature changes, vibrating wire strain gages and fiberoptic sensors for axial and radial strain changes, and load cells for axial stress changes. The fiberoptic sensors have a significant advantage of being able to monitor continuous profiles of strain and temperature, permitting evaluation of the impacts of individual subsurface strata on the axial thermo-mechanical response of energy piles.

3.2.2 Pile Groups

Consistent with conventional pile groups, there are relatively few full-scale case histories on energy pile groups. Two relevant studies have been performed by Mimouni & Laloui (2015) and Rotta Loria and Laloui (2016b). Rotta Loria & Laloui (2016b) assessed the impact of stresses imposed on other piles during of a single pile beneath a building load, while Mimouni & Laloui (2015) evaluated the response of piles without a head restraint and restrained in a group by a slab and investigated heating of all the piles as a group. Heating all the piles doubled the degree of freedom and led to greater upward pile heave during heating. However, this also corresponded to lower differential displacements and associated stresses.

3.3 Energy Walls

There have now been a number of energy walls constructed around the world. These include at least four diaphragm walls for commercial buildings and two other embedded retaining walls for rail infrastructure in Austria (Brandl, 1998, 2006), two building basements in the UK (Amis et al, 2010, Nicholson et al, 2014b), metro station applications in London and Paris (Soga et al, 2015, Delerablee et al, 2018), a public building in Shanghai (Xia et al, 2012) and a recent commercial building in Northern Italy (Angelotti & Sterpi, 2018). However, by contrast to piles, few of these case studies report on the thermal capacity or performance. Those that are published also tend to be reported with fewer details making it harder to learn broader lessons. The sections below identify relevant data that are available.

3.3.1 Thermal Performance

The only true short-term thermal performance test for an energy wall is the case of the Shanghai Natural History Museum. Xia et al. (2012) present the thermal performance test results for the constructed diaphragm wall with heat transfer pipes installed on both the front and rear sides of the panel. Three different types of pipe arrangements were tested at three different inlet water temperatures. Two of the arrangements involved four pipes with two each on the excavated and retained sides, while the third arrangement included only the two pipes on the retained side. The experiments also investigated the effects of flow rate and intermittent operation. The results are presented in terms of energy exchanged per metre of installed heat transfer pipe and range between 30W/m and 150 W/m depending on the conditions tested. As would be expected the four pipe arrangements, intermittent operations, higher temperature differences and higher flow rates all lead to greater heat exchange.

Table 6 converts the results of Xia et al. (2012) to exchanged power in W/m^2 and compares them with the operational case of Angeloltti & Sterpi (2018) and numerical experiments reported in the literature. Angeloltti & Sterpi (2018) present four months of data for heat extraction from a diaphragm wall in Tradate in Northern Italy. Each 2.4m wide panel contain a single loop of pipe but arranged in three overlapping coils at the back of the wall to maximise pipe lengths. The heat transfer rates for this operational case are 12 – 15 W/m^2 based on monthly averages and correspond to the lower range of data presented by Xia et al. (2012). This is unsurprising since longer term studies would be expected to have lower heat transfer rates. The numerical studies also presented in Table 6 have a similar lower bound to the field data. However, many studies include the effects of groundwater flow which theoretically give a substantial increase in available power.

Total energy obtained from two notable bored pile wall case studies are reported by Brandl (2006) and Nicholson et al. (2014b). These operational schemes in are located in Vienna and Oxford respectively. In the Vienna scheme the bored pile wall forms part of a railway tunnel, where 59 piles of 17 m length are connected to the energy system and used to heat an adjacent school. One heating period yielded 214 MWh of thermal energy. In Oxford 61 bored piles of 450mm in diameter were equipped with heat transfer pipes. Heating of an associated building was achieved with a COP of 5.8 for cooling and 3.9 for heating.

Table 6 Summary of wall thermal performance

Reference	Approach (Field / Simulation Type / Excavation BC)	Wall Type	Excavation Space	Dimensions	Retained Height	Pipe No & Arrangement*	Flow Rate (L/h)	Temperature Difference+ (°C)	Duration	Heat Transfer Rate (W/m²)
Xia et al. (2012)	Field Thermal Performance Test	Diaphragm wall	Open to air when tested	2.25m long x 1m wide x 38m deep	18.5m	U or W	706	+9 +12 +15	50 hours	15 (U); 18 – 19 (W) 22 (U); 29 – 33 (W) 30 (U); 38 – 44 (W)
Angelotti & Sterpi (2018)	Operational Case	Diaphragm wall	Building basement	0.5m wide x 2.4m long x 15.2mm deeo	10.8m	1 loop with 3 overlapping coils in 0.8m width	NR	NR	4 months (Winter)	12 – 15 (extraction)
Bourne-Webb et al. (2016b)	2D steady state FDA; Constant temperature or convection	Diaphragm wall	NR	0.8m wide	Not modelled	U UU	Not modelled	+15	Steady state	13 – 22 20 - 80
Di Donna et al. (2016a)	3D FEA; Constant Temperature	Diaphragm wall	NR	Variable width, 20m deep	Variable	U or UUU	353 - 2121	+8	60 days	5 – 20
Makasis et al. (2018c)	3D FEA & Machine Learning; Varying thermal load; thermally insulated wall	Diaphragm wall	Metro station, basement	13m long x 1m wide x 22m deep	Variable: 5, 10, 20, and 30m	Meandering (W)	330	NR	5 years, monthly analysis	4 – 22 (NR, personal communication)
Piemontese (2018)	3D FEA; Constant Temperature or convection	Diaphragm wall	NR	2.5m long x 1m wide x 20m deep	10m	W	469	+10 to +20 -4 to -14	30 days	14 – 32 (injection) 6 – 22 (extraction) (up to 48 with gw flow)
Rammal et al. (2018)	3D transient FDA; Adiabatic	Diaphragm wall	Metro station	1.2m wide x 32.5m deep	22m	Not modelled	Not modelled	+11 (summer) -5 (autumn) -9 (winter) +7 (spring)	3 year seasonal analysis	12 (100 with gw flow)

Reference	Approach (Field / Simulation Type / Excavation BC)	Wall Type	Excavation Space	Dimensions	Retained Height	Pipe No & Arrangement*	Flow Rate (L/h)	Temperature Difference+ (°C)	Duration	Heat Transfer Rate (W/m²)
Barla et al. (2018)	3D transient FEA; Adiabatic	Diaphragm wall	NR	0.8m wide x 15.5m deep	9.5m	W Slinky	706	-10	30 days	7.5 8
Barla et al. (2018)	3D transient FEA; Adiabatic	Diaphragm wall	NR	0.8m wide x 15.5m deep	9.5m	Slinky	291	+13 to -13 (seasonal sinusoidal)	6 years seasonal analysis	7 – 20 (extraction) 10 – 25 (injection) (up to 50 with gw flow)

FEA = finite element analysis; FDA = finite difference analysis; FVA = finite volume analysis.
N.R. = Not reported.
\+ between the fluid inlet temperature and the undisturbed ground temperature
* Notes on pipe arrangements:
U = single U-tube (2 pipes); UU = two U-tubes in parallel (4 pipes); UUU = three U-tubes in parallel (6 pipes); W = two U-tubes in series (4 pipes); Slinky = 1 loop with meandering pipes
Heat transfer rates in absence of groundwater (gw) flow unless stated.

3.3.2 Thermal Response Tests

Few thermal response tests have been reported on energy walls. This may be because the absence of easily applied analytical solutions for their interpretation means that generating meaningful results from a wall thermal response test more challenging. Equally, given these challenges, there may be simpler methods of obtaining site specific design parameters, including borehole thermal response tests and laboratory testing.

A number of test have been carried on diaphragm walls constructed as part of the Crossrail project in London, although the data is not publicly available. As part of the GEOTECH project, an extended thermal response test was carried out on a 17m deep diaphragm wall constructed to support a 6.5m deep basement in Spain. Four loops were installed at 0.4m spacing to a depth of 15.6m. Multiple thermal tests were carried out consecutively at an applied power of 2kW with pulses of varying durations from a few hours to several days. In total the experiment ran for over one month. The data is reported in Shafagh & Rees (2018) where it is used for model validation purposes rather than for explicit determination of the ground thermal properties. Nonetheless, in the absence of other soil information, fitting their Dynamic Thermal Network model to the test data did allow derivation of the wall and ground thermal properties. It is worth noting that the analyses used fully transient techniques to capture the thermal behaviour, which, like piles, would be essential for avoidance of model errors related to the capacitance of the heat exchanger.

3.4 Energy Tunnels

Similarly to energy walls, there have now been a few pilot and testing energy tunnels constructed around the world and a few operational energy tunnels. These include notable test sections constructed in Austria and Germany at the Katzenburg, Lainzer and Jenbach tunnels (Schneider & Moormann 2010; Adam & Markiewicz 2009; Franzius & Pralle 2011); a tunnel heat exchanger constructed in Inner Mongolia to transfer heat from deeper within the tunnel to the tunnel portal regime where there is a risk of freezing during cold winter conditions (Zhang et al. 2013), and a series of energy geotextile installed inside a disused tunnel in Korea (Lee et al. 2012).

Typically, thermal performance tests are conducted. Although the construction of the above structures has been well reported, details of their thermal performance is just becoming available and complement other numerical (or model scale) results being published. The scarcity of published data in this emerging field of research makes it hard to generalised broader lessons. Nevertheless, the sections below identify relevant data that are available.

3.4.1 Thermal Performance Tests

A number of thermal performance tests have been carried out and reported on a 200 m section of the Linchang tunnel in the city of Yakeshi in Inner Mongolia, starting from about 2013. Results have been used by the same research group conducting the tests and others to assist with validation of analytical models for heat transfer around the tunnel (Zhang et al. 2014) as well as to validate and contrast against results of various numerical models (e.g., Barla et al. 2016; Barla and DiDonna 2018). A number of constant temperature inlet tests were carried out, each over about two-day period. These showed a linear relationship between the inlet temperature and the heat exchanged, with resulting rates of 24 to 60 W/m length of the heat exchange pipes, depending on the temperature difference and flow rate used. Not surprisingly, these figures are similar to those obtained for diaphragm walls.

Longer thermal performance tests were conducted on the Stuttgart's Fasanenhof tunnel, where two blocks of 10 m each were thermally activated by imbedding meandering absorber pipe between outer and inner shotcrete linings. Tests were run for about half a year at constant inlet temperature with flow rates kept constant for 5 months and them almost doubled for a further 2 months. The heat transfer rates were found to be between 30W/m^2 and 5W/m^2 of activated tunnel depending on operational conditions (Buhmann et al. 2016,). These results were used by others to validate numerical models and explore the impact on nearby borehole ground heat exchangers (Bidarmaghz et al. 2017) and the impact of groundwater flow (Barla and DiDonna 2018, Bidarmaghz and Narsilio 2018). The results from these field scale tests in Fasanenhof are consistent with the average heat transfer yield reported for the 54m long energy tunnel segmental lining of Stuttgart's Jenbach tunnel, of about 15 W/m^2 on average (Frodl et al. 2010; Buhmann et al. 2016).

Short term and longer-term tests were also performed on six variants of energy geotextiles attached to the abandoned tunnel in South Korea, near Seocheon. The pipe arrangement included similar pipe lengths of both transverse and longitudinal meandering pipe (see Section 2.1.4.5) and greater lengths of pipe in slinky configuration, and also tested proximity of the absorber pipes to the tunnel space. Both constant power and varying inlet temperature to represent operational conditions. The heat transfer rates were found to be up to around 40W/m^2 of geotextile on average, with higher yield rendered by the slinky configurations. Again, this is similar to conditions found for diaphragm walls. The field data gathered from the tunnel lining also showed clearly that the air temperature inside the tunnel had a large impact on the temperatures in the circulating fluid, emphasising the importance of understanding this boundary condition. This has been also flagged by the German-Austrian experienced.

While not explicitly addressed by the current field scale energy tunnel literature, numerical simulations built upon these experimental results strongly suggest that the groundwater flow velocity and the degree of tunnel air ventilation and thermal insulation have a significant impact on the thermal yield of energy tunnels. Table 7 summarises such observations and provides more details of field and full-scale testing, as well as other means to assess the thermal aspects of energy tunnels.

Table 7 Summary of tunnel thermal performance

Reference	Approach (Field / Simulation Type / BC)	Heat Exchanger Type	Tunnel Location	Dimensions	Equivalent Tunnel Diameter (m)	Pipe No & Arrangement*	Flow Rate (L/h) (per pipeline)	Temperature Difference$^+$ (°C)	Duration	Heat Transfer Rate (W/m^2)
Zhang et al. 2014	Field Thermal Performance Test	Cast in situ - Fixed between outer and inner tunnel lining	Linchang tunnel, Yakeshi city, Inner Mongolia	NR (~70 m^2 estimated) (8 m long)	7.7	Longitudinal meandering, 1m and 0.5m pipe spacing	487 to 1250	2 to 6	42 hours	25 to 50
Buhmann et al. 2016	Field Thermal Performance Test	Cast in situ - Fixed to outer tunnel lining	Stuttgart–Fasanenhof, Germany	360 m^2 (20 m long)	9.6	Longitudinal meandering	580 (5 months) to 1085 (2 months) (Re 2400 to 4330)	3.6	6 months (Summer)	30 to 5
Frodl et al. 2010; Buhmann et al. 2016	Field Thermal Performance Test / Operation	Tunnel segmental lining	Stuttgart–Jenbach, Germany	2,200 m^2 (54 m long)	13	Transversal Meandering	500	4.6	2 months (Winter)	15
Lee at al. 2016	Field Thermal Performance Test (and Numerical model)	Cast off site - Fixed on inner tunnel lining	Abandoned railroad tunnel, Seocheon, South Korea	~90 m^2	NR	6 types: including longitudinal meandering, transverse and slinky	30 to 60 (heating) | 90 to 120 (cooling)	4 to 5 (heating) and 12 (cooling)	2.5 months (heating) + 2 months (cooling)	Transverse: 4-6 (Heating) and 24-34 (Cooling) Longitudinal: 5-10 (Heating) and 24-28 (Cooling) Slinky: 11 (Heating) and 37 (Cooling)

Reference	Approach (Field / Simulation Type / BC)	Heat Exchanger Type	Tunnel Location	Dimensions	Equivalent Tunnel Diameter (m)	Pipe No & Arrangement*	Flow Rate (L/h) (per pipeline)	Temperature Difference⁺ (°C)	Duration	Heat Transfer Rate (W/m²)
Zhang et al. 2016a; Zhang et al. 2017	Laboratory TRT	Cast in situ - external to outer lining	Laboratory study (1/20th scale)	NR (~20 m² estimated scaled up) (18 m long scaled up)	8 (scaped up, 0.4 m in model)	Longitudinal and transverse meandering, 1m (scaled up) pipe spacing	360 to 1800 (estimated equivalent)	7, 12, 17	1 to 4 days	30 to 60
Zhang et al. 2013	Analytical model	Cast in situ - Fixed between outer and inner tunnel lining	Linchang tunnel, Yakeshi city, Inner Mongolia	NR (~3,500 m2 estimated) (200 m long)	12	Meandering	290 to 1470 (750 recommended)	varies	2 to 90 days	~12 (average, estimated)
Tinti et al. 2017	Analytical (empirical) model	Cast in situ - Fixed between outer and inner tunnel lining	Mules Access Tunnel of the Brenner Base Tunnel (BBT) system, Eastern Alps, Italy	~37,000 m² (1,265 m long)	9.5	Meandering	800	10 (varies)	NR	11 to 32
Nicholson et al. (2014a)	FEM Numerical model	Within tunnel lining	Cross-rail London, UK	~4800 m² (33 rings) (250 m long)	6.3	Longitudinal Meandering	216 to 432	2 to 10 (varies)		10 to 30
Barla et al. 2016; DiDonna & Barla 2016; Barla & DiDonna 2018	3D FEM Numerical model	Tunnel segmental lining	Metro Torino line 1, Italy	~30,000 m² (1350 m long)	7.4	Transversal Meandering	600	3 to 4	1 month	53 (Winter) to 74 (Summer)
Bidarmaghz and Narsilio 2018; Bidarmaghz et al. 2017	3D FEM Numerical model	Within tunnel lining	Stuttgart–Fasanenhof, Germany	240 m² (10 m long)	10	Longitudinal meandering, 0.4m pipe spacing	560	NR	5 years	12 to 40

3.5 Other Energy Geostructures

The use of basement slabs as heat exchangers is well known from the literature (e.g. Adam & Markiewicz, 2009, Katzenbach et al. 2014), but there are few details of well recorded case studies providing details of thermal performance. Katzenbach et al. (2014) suggest that slabs are less thermally effective compared to other geostructures, but that they nonetheless remain attractive due to their low installation costs. These points are supported by recent in situ monitoring of walls and slabs by Angelotti & Sterpi (2018) and Kipry et al. (2009), as discussed in Section 2.1.5.

Large diameter sewer pipes adapted as energy geostructures have also been successfully trialled at full scale. As reported by Adam & Markiewicz (2009), the heat transfer pipes are placed in the material of the base of the pipe. Initial results of a trial section showed dependency of the peak power obtained on the effluent level in the sewer, its flow rate and temperature.

4 Model Scale Testing

Although field-scale testing of energy piles permits consideration of the effects of actual construction techniques and real soil conditions, there are limitations to this type of testing. In addition to issues with expense, time, and site coordination, there are many uncertainties in the field that may not permit a comprehensive understanding of the thermal or thermo-mechanical process of interest. Model testing in either laboratory-scale or centrifuge-scale provides an opportunity to understand the mechanisms of energy pile behaviour under carefully controlled conditions (material properties, geometric features), and dense instrumentation arrays can be used to detect heat transfer, water flow, and changes in stress or strain. Furthermore, boundary conditions can play a critical role in both the thermal and thermo-mechanical evaluation of energy piles and other energy geostructures. From a thermal perspective, boundary conditions at the surface, far field, and within the embedded heat exchangers can affect the heat transfer process and should be well-characterised. From a geomechanical perspective, the restraint provided at the head and toe of the structure have major effects on the magnitude and location of the thermally-induced stresses. In the field, it is often difficult to ensure that the toe of the foundation is completely clean, which may result in a softer restraint at the toe than expected from the characteristics of the intact material (Murphy et al. 2015). In addition, it is difficult to assess the restraint provided to the top of the foundation by an overlying slab or beam. For example, the head deformations of energy piles will affect the response of other energy piles in a group. The thermal and mechanical boundary conditions in laboratory-and centrifuge-scale testing can be carefully controlled, which provides them with a major advantage over field testing. Finally, the parameters governing the failure of a foundation may play an important role in the prediction of the thermo-mechanical soil-structure interaction behaviour. Axial or lateral loading tests to failure are relatively simple to perform in the laboratory or centrifuge (e.g., McCartney & Rosenberg 2011; Wang et al. 2011, 2012a; Yavari et al. 2014a; Goode et al. 2014a; Goode and McCartney 2015), while they may be very complex in the field.

Due to the advantages mentioned above, the information gained for model scale testing can potentially be used to provide trust-worthy calibration or validation data for numerical or analytical models describing energy geostructure behaviour. Of these model testing options, laboratory-scale testing permits realistic simulation of heat transfer processes and can potentially be used to study thermo-mechanical effects for some soil types. Centrifuge testing is more suited for evaluation of thermo-mechanical soil-structure interaction due to scaling issues with heat flow that will be discussed later. However, some thermo-hydro-mechanical processes that depend on the stress state such as thermally-induced excess pore water pressure during undrained heating may be considered in centrifuge testing. All the model scale testing conducted by researchers so far has been limited to energy piles except for the work by Kurten (2011), who assessed the thermal behaviour of energy walls, and the work by Zhang et al. (2016b), who performed an experimental study of nonisothermal tunnel linings.

4.1 Model Test on Piles

4.1.1 Laboratory Scale Tests (1-g)

4.1.1.1 Overview

Laboratory-scale testing in tanks permits both careful control of the preparation of soil layers, use of different heating sources and loading mechanisms for energy piles, and potentially visualisation of different phenomena. A summary of the different laboratory-scale tests that will be discussed in this section is presented in Table 8. Most laboratory-scale experiments on energy piles have been performed on reduced-scale models, typically ¼ to ½ scale systems. In many cases the scaled diameter of the model energy pile can be similar to energy piles in the field, but the length is typically shorter than in the field. Although there has not been a detailed evaluation of scaling relationships for reduced-scale energy piles tested under self-weight conditions (1-g), there have been studies in the earthquake engineering field that may provide some insight into potential scaling relationships. Most work on this topic has built upon the scaling relationships of Rocha (1957) and Lai (1988). The main concept of their relationships is that the constitutive relationship that governs the mechanical response of the soil should be scaled, and thus both stresses and strains (strain which is already dimensionless) in the model are linearly related through a scalar scaling parameter. This approach was proposed because many soils when tested under low effective stresses will exhibit dilative, strain softening behaviour. By using a looser soil in the scaled model, the stress strain curve under lower effective stresses will have a closer shape to that expected in the full-scale model. They found that their scaling relationships work well for small-strain behaviour where the soil can be considered as an elastic body. A similar scaling conflict for heat flow to that encountered in centrifuge modelling, which will be discussed later, may be encountered as the length is scaled in their approach. Nonetheless, the scaling conflict may have less of an effect than in centrifuge tests. Further research is needed to evaluate scaling relationships for laboratory testing of energy piles, either through re-interpretation of available data or through numerical modelling of physical models (Ko 1988).

4.1.1.2 Evaluation of Heat Transfer in Laboratory-scale Tests

One of the earliest laboratory-scale tests to consider the role of heat flow around an energy pile was performed by Ennigkeit & Katzenbach (2001), who evaluated heat flow processes. They developed a solution to the heat equation assuming that the primary mode of heat transfer is conduction and were able to obtain a good match to their data. Their work showed the utility of incorporating dense instrumentation arrays around a carefully prepared soil layer to validate analytical models. Thermal tests on scale-model energy piles have since been performed by Kramer and Basu (2014a, 2014b) and Kramer et al. 2015), who processed their heat flow results to interpret the heat flux from the energy pile into the soil. Akrouch et al. (2016) performed a coupled heat transfer and water flow analysis for energy piles in unsaturated clay and found that heating of the energy pile results in a drying effect of the soil surrounding the energy pile. This drying effect also served to lead to a slight reduction in the thermal conductivity of the soil. An innovative technique to study heat flow in laboratory-scale models developed by Black & Tatari (2015) involves the use of transparent soils and digital image analysis. Transparent soils consist of particles saturated with a fluid having a compatible refractive index that leads to transparent conditions and have been used together with lasers and digital image analysis to study deformation problems in geotechnical engineering. Black & Tatari (2015) found that temperature changes led to a change in the refractive index and a loss of optical clarity of the fluid, which can be used as a beneficial attribute of transparent soil to study heat transfer processes around energy piles.

4.1.1.3 Evaluation of Soil-structure Interaction in Laboratory-scale Tests

Several studies have been performed on energy piles in laboratory-scale tanks. Wang et al. (2011, 2012a) performed tests at various temperatures on small-scale steel energy piles, with an innovative setup that permits the pile to be loaded upward from the base after heating. This approach permits the role of the side shear stress to be isolated. They evaluated the behaviour of the model energy piles in loosely-compacted, dry N50 fine sand, partially saturated N50 fine sand, and partially saturated 300WQ silica flour. During heating, the authors observed no change in shaft resistance with the dry sand and a decrease in shaft resistance with the partially saturated sand and with the partially saturated 300WQ silica flour. The changes in shaft resistance may be due to some mobilisation of side friction during the thermal expansion of the steel, which led to less additional axial stress required to reach the ultimate capacity of the energy pile during mechanical loading.

Kalantidou et al. (2012) performed a thorough evaluation of a multi-stage test on an aluminium model-scale energy pile in a dry sand layer. They tracked the head displacement of the energy pile during heating-cooling cycles, and during mechanical loading after heating to different temperatures. They observed a hysteretic response during heating and cooling, which indicates that some plastic deformations occurred at the soil-pile interface during the temperature changes. This effect is likely overemphasised due to the relatively large thermal expansion of the aluminium, which has a coefficient of thermal expansion that approximately double that of most soils and reinforced concrete. Tang et al. (2014) performed similar tests to Kalantidou et al. (2012) but focused on the role of the applied load on the foundation head. Application of a greater foundation load will lead to a greater initial mobilisation of side shear resistance and end bearing, which can influence the subsequent thermo-mechanical response. However, the magnitude of thermal stress will depend on the restraint provided by the overlying structure (i.e., the head stiffness) more than the applied load on the foundation head. Yavari et al. (2014a) performed complimentary tests to those of Kalantidou et al. (2012) using similar a similar dry sand, but incorporated strain gages to infer soil-structure interaction behaviour. They were able to measure strain profiles that are consistent with those measured in full-scale energy piles. Subsequently, Yavari et al. (2014b) performed a simplified finite element analysis of the energy pile tests and found good agreement between the calibrated model and the laboratory-scale results. Marto & Amaludin (2015) performed tests on aluminium energy piles in compacted Kaolinite and observed similar compression curves for different temperatures. However, their model scale energy pile and soil container were relatively small compared to other laboratory-scale tests.

The characteristics of the energy pile can have a major effect on the soil-structure interaction response because the displacement required to mobilise the side shear resistance may be relatively small. Accordingly, tests on reinforced concrete will provide closer response to actual energy piles in the field. Kramer & Basu (2014b) and Kramer et al. (2015) reported results from small-scale tests on a precast concrete pile tested under 1-g using F50 Ottawa sand and observed a slight increase in pile capacity at increased temperatures. Although a relatively large layer of sand must be prepared in their tank-scale tests, their results permit the evaluation of the failure conditions of energy piles in addition to their thermal response. Di Donna et al. (2015) performed direct shear tests under different temperatures to evaluate the effects of cyclic temperature changes on soil-structure interaction mechanisms. They found that a sand–concrete interface was affected by cyclic degradation (i.e., deformations induced by temperature changes) but not affected directly by temperature. Conversely, the response of a clay–concrete interface changed at different temperatures. They observed an increase of interface strength with increasing temperature because of clay volume changes associated with the changes in temperature.

Laboratory-scale tests have provided interesting insight into energy pile behaviour in some settings, which have also matched well with modelling results. However, the scaling relationships of Rocha (1957) have not been considered when extrapolating the trends from laboratory-scale (low stress) conditions to full-scale piles that are also influenced by installation effects. Although 1-g tests have not been performed on saturated clays, pore water pressure development and thermal consolidation in saturated clays can alter the stress state and result in deformations around a heat exchanger pile. In energy piles, the rate of heating and the rate of dissipation of excess pore water pressures must be carefully considered. Fast heating may lead to undrained heating and pore water pressure increases that may cause a decrease in pile capacity. Slow heating may lead to drained heating and thermal consolidation that may cause an increase in pile capacity. The role of the initial effective stress state is an important issue to consider in these conditions (Ghaaowd et al. 2017), which may not be completely captured in a tank scale test.

A different approach was followed Eslami et al. (2017) to study the effect of the temperature on the variation on the bearing capacity of thermo-active piles. A mini-pressuremeter test was conducted in the laboratory in in a container with controlled temperatures ranging from 1 to 40 C. It was observed that as temperature increased, the pressuremeter modulus (E_p) slight decreased, and both, the limit pressure (p_l) and creep (p_f) significantly decreased. Murphy and McCartney (2014) developed a thermal borehole shear device to evaluate the impact of temperature on the soil-concrete interface shear behaviour in-situ and found negligible effect of temperature on the frictional behaviour of the interface with a sandy soil. This negligible impact of temperature on the drained interface shear strength in cohesionless is consistent with the negligible increase in ultimate capacity of energy piles in sands with increasing pile temperature observed by Goode and McCartney (2015).

Table 8 Summary of laboratory-scale tests on energy piles

Study	**Tank dimensions**	**Pile/heater material**	**Pile type**	**Soil type**	**Purpose**
Ennigkeit and Katzenbach (2001)	1 m diameter, 2.4 m height	Aluminum	Heating rod	Dry sand	Heat flow analysis
Wang et al. (2011, 2012a)	0.272 m diameter, 0.15 mm height	Steel	End-bearing	Moist sand, silica flour	Upward loading for side shear evaluation
Kalantidou et al. (2012), Tang et al. (2014)	0.57 m diameter, 0.85 m height	Aluminum	Semi-floating	Dry sand	Cyclic heating and cooling, loading to failure
Yavari et al. (2014a)		Aluminum	Semi-floating	Dry sand	Cyclic heating and cooling
Kramer and Basu (2014a, 2014b); Kramer et al. (2015)	1.83 m × 1.83 m square, 2.13 m height	Reinforced concrete	Semi-floating	Dry sand	Heating, effect of temperature of load-settlement curve

Study	Tank dimensions	Pile/heater material	Pile type	Soil type	Purpose
Black & Tatari (2015)	0.6 m × 0.5 m rectangle, 0.4 m height	Aluminum	Semi-floating	Transparent soil	Heat flow visualization
Marto and Amaludin (2015)	0.27 m diameter, 0.25 m height	Metal	Semi-floating	Compacted clay	Effect of temperature on pile head displacement

4.1.2 Centrifuge Tests on Energy Piles (N-g)

4.1.2.1 Overview

Because soil properties are very sensitive to self-weight conditions, laboratory-scale tests may not accurately capture the soil behaviour that may affect the thermo-mechanical response of a full-scale energy pile. This is particularly the case in sands, where a change in the mean effective stress can change the shape of the shear stress-strain curve and volumetric strain response significantly, potentially converting from contractive, strain-hardening behaviour at high mean effective stress to a dilative, strain-softening behaviour at low mean effective stress. Accordingly, a geotechnical centrifuge can be used to increase the self-weight of a soil layer, and more accurately consider the role of mean effective stress in the soil layer. A summary of the different centrifuge tests that will be discussed in this section is presented in Table 9.

Centrifuge physical modelling is based on the concept of geometric similitude. In this case, the lengths of geometric features in a model L_m can be scaled down from the lengths of geometric features in a full-scale prototype L_p, as follows:

$$L_m = \frac{L_p}{N} \tag{7}$$

where N is the acceleration ratio, defined as follows:

$$N = \frac{\omega^2 r}{g} \tag{8}$$

where g is the acceleration due to earth's gravity, ω is the angular velocity of the centrifuge, and r_e is the effective radius (typically at the centre of the energy pile). Using the concept of geometric similitude, the effective stresses in a centrifuge-scale model σ_m can be shown to be the same as those in a prototype σ_p, as follows:

$$\sigma_m = \rho g N z_m = \rho g N \left(\frac{z_p}{N}\right) = \rho g z_p = \sigma_p \tag{9}$$

where r is the density of the soil and z_m and z_p are the depths from the surface of the soil layer in the model or prototype. Similarly, the strains in a centrifuge-scale model ε_m are also equal to those in a prototype ε_p, as follows:

$$\varepsilon_m = \frac{\Delta L_m}{L_m} = \frac{\Delta L_m}{N}\frac{\mathrm{N}}{L_m} = \frac{\Delta L_p}{L_p} = \varepsilon_p \tag{10}$$

Accordingly, the stress and strains in a centrifuge-scale model are expected to be the same as those in a prototype. This also includes the thermal axial strains in an energy pile, as the coefficient of thermal expansion of an energy pile is not expected to depend on self-weight.

Although the centrifuge is effective at increasing the self-weight of the soil layer, and thus affecting any aspect of soil behaviour that is stress-dependent, it is not effective at scaling other features that do not depend on self-weight, such as heat flow and diffusion-based flow processes. Experimental evaluations of heat flow in the centrifuge will be discussed in the next section, but an implication of the fact that heat flow does not scale is that the zone of influence of heat flow in the centrifuge will be greater than that in the prototype. Another way of considering this is that during heating for a certain time period, heat will have travelled over a greater scaled distance in the centrifuge model than in the prototype. Accordingly, most engineers use a scaling factor for the time in the centrifuge scale model t_m compared with the time for heat flow in the prototype t_p. This scale factor can be assessed using Fick's law as follows:

$$\frac{dT_m}{dt_m} = \alpha_m \frac{d^2T_m}{d{z_m}^2} \tag{11}$$

where T_m is the temperature in model scale, z_m is the length in model scale, and α_m is the thermal diffusivity. Using a similar equation for the prototype, the following relationships between the times in model and prototype scales can be derived:

$$t_m = \left(\frac{z_m}{z_p}\right)^2 t_p = N^2 t_p \tag{12}$$

where z_p is the length in prototype scale. Accordingly, when scaling results from a centrifuge model to prototype scale, heat will be transferred N^2 times faster than in the actual prototype soil layer.

An implication of temperature scaling is that a greater volume of soil surrounding the model-scale foundation will be affected by changes in temperature. Soils change in volume with temperature, so if a greater zone of soil around the foundation is affected then the effects of differential volume change of the foundation and soil may be emphasised. From this perspective, centrifuge modelling will provide a worst-case scenario. A solution to address the scaling issue is to calibrate numerical simulations of the tests using the data from model scale. However, if the goal of testing is to evaluate the impact of temperature on the load-settlement curve of the foundations, time should be provided to reach steady-state conditions. However, if the goal is to evaluate the impact of temperature on the axial strain distribution in the foundation, tests can be performed until strains stabilize while the foundation temperature is held constant. This amount of time depends on the soil type.

4.1.2.2 Evaluation of Heat Transfer and Water Flow in Centrifuge-scale Tests

One of the earliest uses of centrifuge modelling for the evaluation of the thermo-hydro-mechanical response of soil surrounding a heat source was performed by Maddocks & Savvidou (1984), who were interested in the disposal of nuclear waste canisters in soft clay deposits offshore. The study was complimented by an assessment of scaling relationships for heat and water flow in the centrifuge by Savvidou (1988) and the development of an analytical solution for coupled heat flow and thermal consolidation by Booker & Savvidou (1984; 1985). Although this experimental situation is perhaps the most complex setting that can be encountered by an energy pile in the field, the lessons learned from these studies are still useful for understanding different processes that may occur in soil surrounding an energy pile. As the study was focused on soft clay soils, it was found that heating of a cylindrical source will lead to diffusive heat flow due to conduction, which is affected by the scaling issue mentioned in the previous section. However, they also observed the generation of excess pore water pressures during undrained heating. These will dissipate with time leading to volume changes. Furthermore, Savvidou (1988) observed that for soils with high Rayleigh numbers (i.e., soils with relatively high hydraulic conductivity) such as saturated sand, convective heat flow may occur due to buoyancy driven flow of water in the soil layer, this phenomenon has been also observed in numerical simulations (Bidarmaghz & Narsilio 2016; Diao et al. 2004b). Because convective heat flow is associated with the flow of water, this process can lead to non-similar conditions between a model and prototype. This behaviour is not expected for dry sands or lower permeability soils (i.e., clays or unsaturated soils). Because of complexities that may be encountered in some soil layers (e.g. because of volume change or convection), the approach suggested by Ko (1988) can be used to confirm the scaling relationships proposed by Savvidou (1988) when conducting tests in the centrifuge involving heat transfer. Specifically, soil layers having different thicknesses and energy piles with different diameters can be tested in the centrifuge container at different g-levels so that each model represents the same prototype system. As each model is theoretically similar to the same prototype, they should have the same behaviour in prototype scale if the scaling relationships are valid.

The geotechnical centrifuge is an ideal setting for the evaluation of the change in pore water pressure encountered during undrained heating of saturated soils. Centrifuge modelling not only permits formation of a NC clay deposit that has a similar stress state to a prototype soil layer in the field (zero effective stress at the surface and increasing effective stress with depth), but also permits a dense instrumentation array to characterize the heat transfer and water flow processes and extensive in-situ characterization to evaluate thermo-hydro-mechanical processes. Because studies such as Ghaaowd et al. (2017) showed that the magnitude of excess pore water pressures induced in saturated soils is closely linked with the initial effective stress, the effective stress profile in the centrifuge model will ensure that the pore water pressures that develop with depth will be closer to those expected in the field than in laboratory-scale consolidation chambers under constant mean stress.

Several centrifuge studies have been performed on energy piles in dry sand. In these soil layers, the heat flow is expected to be insensitive to the g-level. This was confirmed by the study of Krishnaiah & Singh (2004) who performed spatial and temporal measurements of temperature in dry quartz sand surrounding a cylindrical heat source during centrifugation at different g-levels. Their results confirm that centrifugation does not lead to a change in the heat flow process, and that application of geometric similitude to the model measurements will lead to a greater zone of influence of the heat source. However, dry sands are not expected to undergo a significant thermal volume change during heating and cooling, so this greater zone of influence may not have a major effect. Rosenberg (2010) presented results from heat flow around an energy pile in unsaturated silt, and subsequent analyses by Kaltreider et al. (2015) using model-scale dimensions confirm that conduction was the primary mode of heat transfer.

4.1.2.3 Evaluation of Soil-Structure Interaction in Centrifuge-Scale Tests

There are several experimental studies which investigated the temperature effects on the load-displacement curve and soil-structure interaction response of centrifuge-scale energy piles. McCartney et al. (2010) and McCartney & Rosenberg (2011) performed early centrifuge-scale on reinforced-concrete, semi-floating energy piles in unsaturated, compacted silt, focusing on changes in the load settlement curve after a heating-cooling cycle and after monotonic heating to steady-state conditions, respectively. McCartney et al. (2010) found that the capacity of the energy pile after a heating-cooling cycle was greater than that of an unheated energy pile. McCartney & Rosenberg (2011) found that the capacity of the energy pile increased with temperature. Although the observations of McCartney & Rosenberg (2011) were initially proposed to be due to radial expansion of the energy pile, leading to a change in normal stress on the sides of the pile, later tests found that heating of the energy pile led to thermally-induced water flow in the unsaturated silt and a corresponding increase in effective stress. The compaction of the soil around the foundations may have led to an initially high radial stress that may not be representative of energy piles in the field.

A later series of centrifuge tests were performed in a layer of the same compacted silt but with an end-bearing energy pile having embedded strain gages (Stewart & McCartney 2012, 2014). Stewart & McCartney (2014) provided an interpretation of the thermally induced strains, stresses, and displacements in the energy pile. Although, the concrete mix design of the energy pile evaluated by Stewart & McCartney (2012, 2014) led to a relatively low Young's modulus and coefficient of thermal expansion, the trends in the results corresponded well with those observed in full-scale energy piles (McCartney 2013). Stewart & McCartney (2014) also observed a reduction in water content near the test pile due to thermally induced water flow. McCartney (2013) reported the results from a semi-floating energy pile having the same Young's modulus as that of Stewart & McCartney (2014) and observed lower compressive stresses in the energy pile due to the lower restraint provided by the relatively compressible soil at the toe of the semi-floating pile. Small-scale testing also presents opportunities to evaluate different technologies to assess soil-structure interaction effects. For example, Khosravi et al. (2012) performed non-destructive load-response tests on the scale-model, end-bearing energy pile developed by Stewart & McCartney (2014) in compacted silt and found that a slight increase in the speed of a compressive wave was observed due to the greater restraint of a heated energy pile.

Goode et al. (2014), Goode & McCartney (2014) and Goode & McCartney (2015) developed a new pair of end-bearing and semi-floating energy piles with a slightly larger diameter than that evaluated by Stewart and McCartney (2014) that permitted a stiffer concrete mix design that had thermo-mechanical properties close to that expected in an energy pile in the field. The centrifuge tests performed by Goode et al. (2014) and Goode & McCartney (2015) on semi-floating energy piles in dry Nevada sand indicate that the shape of the compression curve does not change significantly with temperature. They also observed that the thermal axial strains in the pile were close to the free-expansion strain due to the relatively low restraint provided by the medium-dense sand. A null point near the centre of the energy pile was observed from an integration of the strains with depth. Goode and McCartney (2014) evaluated the role of head restraint (load control and stiffness control) for an end-bearing energy pile in dry Nevada sand, and found that stiffness control conditions lead to higher thermal axial stresses due to the greater restraint provided for the energy pile. Goode & McCartney (2015) also compared the behaviour of semi-floating and end-bearing energy piles in dry sand and compacted silt and found that higher stresses were observed in the compacted silt. The strain distributions in the energy piles in compacted silt were more nonlinear with depth, likely due to greater side shear stresses. Goode and McCartney (2015) also performed loading-unloading tests on an end-bearing energy pile in dry sand after heating to different temperatures and did not observe a noticeable change in the slope of the recompression curve.

Ng et al. (2014) and Ng et al. (2015) performed centrifuge tests on aluminium energy piles in saturated clay and saturated sand layers, respectively, focusing both on the impact of cyclic heating and cooling and on the role of temperature on the compression curve. Different from the observations of Goode et al. (2014) for semi-floating energy pile tests in dry sand, Ng et al. (2015) observed an increase in the ultimate bearing capacity of semi-floating energy piles in saturated sand heated to higher temperatures.

The effect of cyclic temperature-induced changes in energy pile performance is another area of research. During its lifetime, an energy pile is exposed to daily and seasonal temperature changes which result in expansion and contraction of the pile itself. These relative deformations between the soil and the pile can induce slip at the soil-pile interface which can affect the shear stress transfer between the soil and the pile. Further, ratcheting mechanisms may occur for semi-floating foundations that lead to continued thermally-induced settlements or heave after multiple cycles. In addition, the soil surrounding the energy pile is exposed to temperature changes which can induce excess pore pressures, volume changes and degradation of the strength of the soil at the pile interface. Progressive migration away from energy piles in unsaturated soils can reduce the thermal conductivity and cause desaturation of the soil at the pile interface. The role of cyclic heating and cooling has been studied by studied by Stewart and McCartney (2014) and Ng et al. (2014). Little permanent head displacements were noted by Stewart and McCartney (2014) for an end-bearing energy pile in compacted silt. However, Ng et al. (2014) observed that continued downward displacements were observed for a semi-floating energy pile in saturated clay, albeit approaching a shakedown behaviour after several cycles. Further tests need to be performed to evaluate whether ratcheting conditions may occur during cyclic heating of energy piles in over-consolidated clay or dense sand.

In addition to help clarify the role of different variables (soil type, saturation conditions, cyclic loading, restraint at the head or toe of the energy pile), the results from the centrifuge modelling are also useful to calibrate and validate numerical simulations. Wang et al. (2012b, 2015) used a coupled thermo-hydro-mechanical model to evaluate the thermal axial stresses and strains in the energy pile results presented by Stewart and McCartney (2014). A good match between the calibrated model and the experimental results was obtained when the model was performed using model-scale results. Rotta Loria et al. (2015) used a finite element model with the Mohr-Coulomb failure criterion to evaluate the centrifuge results for semi-floating energy piles in sand presented by Goode et al. (2014), and a good match between the model and experimental results was obtained. The promising match between the observations from centrifuge data and numerical simulations emphasizes the usefulness of centrifuge modelling in the development of new numerical simulation tools.

Table 9 Summary of centrifuge-scale tests on energy piles

Study	**Pile/heater material**	**Pile/heater type**	**Soil type**	**Purpose**
Maddocks & Savvidou (1984)	Steel	Thin heating rod	Saturated clay	Thermo-hydro-mechanical process characterization
Krishnaiah & Singh (2004)	Steel	Thin heating rod	Dry sand	Heat flow evaluation at different g-levels
McCartney et al. (2010)	Reinforced concrete	Semi-floating	Compacted silt	Temperature effects on load-settlement curve
McCartney & Rosenberg (2011)	Reinforced concrete	Semi-floating	Compacted silt	Temperature effects on load-settlement curve
Stewart and McCartney (2012, 2014)	Reinforced sand-cement	End-bearing	Compacted silt	Soil-structure interaction, cyclic effects
Khosravi et al. (2012)	Reinforced sand-cement	End-bearing	Compacted silt	Dynamic load-response test
McCartney (2013)	Reinforced sand-cement	Semi-floating	Compacted silt	Soil-structure interaction

Study	Pile/heater material	Pile/heater type	Soil type	Purpose
Goode et al. (2014)	Reinforced concrete	Semi-floating	Dry sand	Soil-structure interaction, temperature effects on load-settlement curve
Goode & McCartney (2014)	Reinforced concrete	End-bearing	Dry sand	Role of head restraint
Goode & McCartney (2015)	Reinforced concrete	Semi-floating and end-bearing	Dry sand and compacted silt	Soil-structure interaction, temperature effects on load-settlement curve
Ng et al. (2014)	Aluminum	Semi-floating	Saturated clay	Soil-structure interaction, cyclic effects
Ng et al. (2015)	Aluminum	Semi-floating	Saturated sand	Soil-structure interaction, temperature effects on load-settlement curve
Ghaaowd et al. (2018)	Aluminum	End-bearing anchor	Saturated clay	Temperature effects on load-settlement curve

4.2 Model Scale Tests on Other Energy Geostructures

Kurten et al. (2015a) present results of energy performance testing carried on a model energy wall. Constructed within a sand box of dimensions 3m x 3m x 2m the model walls contained both U and W shaped pipe arrangements. It was possible to control the temperature conditions on both sides of the wall. The results showed the overall pipe length to be more important than the actual pipe arrangements, with heat exchange rates of between 20 W/m and 100 W/m of pipe. These short-term results are compatible with the full-scale, short-term tests performed by Xia et al. (2012). Overall energy outputs from the model tests were quoted as 36 W/m^2 to 150 W/m^2.

Zhang et al. (2016b) completed a model scale sand box experiment on a geothermal tunnel lining subjected to cross flow of groundwater (see Table 7). The experiment was 1/20th scale and construction within a 1.4 m x 1.2 m x 1.2 m tank. The authors investigated both the spacing and nature of the arrangement of the heat transfer pipes, the temperature difference between the inlet temperature and the ground and the role of groundwater based on sensitivity to Darcy velocity. The issue of scaling was not addressed in detail, but it was noted that the groundwater flow velocity in the model is 20 times that in the prototype and hence values were chosen with this factor in mind. Overall the results showed that significant groundwater flow both lowers the temperature change at the tunnel and spreads the temperature increment over a wider area. It also reduces the time to steady state and increases the degree of recovery during intermittent operation. Instrumentation within the tunnel also showed the significant heat transfer occurring between the model geostructure and the air within the tunnel, again showing the importance of this boundary condition. It is commented that the results of the model test are consistent with those from the full-scale tests carried out by the same authors (Zhang et al. 2016b, Zhang et al. 2014).

5 Discussion

It follows from the preceding material that geoprofessionals indeed contribute to the development of GSHP technology and the dual use of geostructures as load bearing and as heat exchanger elements (as well as the thermal optimisation of borehole GHEs). By doing so, peak energy demand is lowered and/or flatted via this efficient heating and cooling of residential, commercial and industrial buildings. Moreover, using geostructures remove the need for construction of (or minimise the number of) special purpose GHEs, further contributing to reduce capital costs for shallow geothermal energy systems.

The GSHP technology has been primarily driven by colleagues specialising in Mechanical Engineering and the Heating, Ventilation and Air Conditioning (HVAC) industry with limited input from Geotechnical Engineering. This situation is rapidly changing. While there is still further research and development opportunities for the design and installation of borehole GHEs, there exist today a swathe of thermal design approaches developed for boreholes. In contrast, much fewer guidelines are available for the design and construction of energy piles and for other energy geostructures such as retaining walls or tunnel linings. When it comes to thermal analyses for geostructures, particularly for energy piles, a number of lessons can be imported, albeit with limitations, from existing knowledge for GSHP systems that use boreholes, as highlighted in Section 2.1.2. However, regarding thermo-geomechanical considerations, the existing GSHP literature developed for boreholes is of limited use.

For thermal analysis and design of energy piles (and other geostructures) appropriate analytical models are still required. An analytical solution which is solved transiently in radial coordinates has been proposed by Javed & Claesson (2011). The model was developed for boreholes but is potentially suitable for adaption for piles. One aspect which would require reconsideration is the simplification of the pipe details to an annulus to permit adoption of radial coordinates. In addition, the model has a uniform surface boundary temperature and assumes homogeneous and isotropic ground conditions which for 'short' piles (relative to typical deeper boreholes) poses issues. Regardless of the model employed, in energy piles analytical models dealing with the short term transient behaviour are yet to be effectively developed. Numerical simulations (Section 2.1.2.5), hybrid models (Section 2.1.2.7) or other novel techniques such as Machine Learning (Makasis et al. 2018c, 2018d) may guide these analytical developments in the view of the current limited access to full scale and model scale testing data.

For the thermo-geomechanical analysis of energy piles (and other geostructures), ensuring that their ultimate bearing capacity is not exceed by the combined building and thermally induced forces, and that their long-term serviceability is maintained have driven the core of the research by geoprofessionals. Although published long term experimental data is lacking in general, Sections 2.2, 3 and 4 and the long-term experience from Switzerland and Austria (e.g., Brandl's work) suggest negligible or manageable thermo-mechanical effects arising from GSHP system operations. However, special attention and further research is needed when dealing with soft, normally consolidated and/or unsaturated soils.

In all cases, there has not been sufficient experimental data collected to validate predictions. This situation is also changing. The largest field instrumented program in shallow geothermal research is believed to be running in Australia (Johnston et al. 2014, Narsilio et al. 2014, Aditya et al. 2018), but it mostly accounts for borehole GHEs and the GSHP industry there is not as developed as in other parts of the world. Although not in a systematic and coordinated manner as in the Australian case, a number of other isolated monitored full scale tests were conducted and are being conducted around the globe, particularly in North America, parts of Europe (e.g., Switzerland, UK, Spain) and parts of Asia (e.g., Korea, China). These testing account for borehole GHEs and energy piles mostly. Not only a larger dataset is still needed, but also other energy geostructures are required to be tested to advance knowledge and validate and calibrate numerical and analytical models, alongside constructability. The absence of standard thermal performance testing makes generalisations hard to be derived, which is also compounded by the incomplete site characterisation and knowledge of soil conditions.

Similar limitations and difficulties arise in *in situ* thermal response testing for determining soil conditions. Perhaps more importantly are the limitations of the test itself, initially developed for slender boreholes, when attempted on energy piles or retaining walls, with vastly different geometrical ratios and more subjected to influences from the elements (e.g. Bidarmaghz et al. 2016b, Jensen-Page et al. 2018). For the log-linear relationship to derive in situ thermal parameters at steady state conditions to be valid, it may be days or weeks for energy piles (as oppose to 1-2 days for boreholes), or different interpretation techniques are still required, with a few currently just under development (e.g. Loveridge et al. 2015).

Model scale testing offer good opportunities to overcome the disadvantages of field scale testing as highlighted in Section 4. However, there still exist scaling issues and scaling compatibility amongst the different physical processes involved. Materials' thermo-mechanical mismatches with prototypes, for example on the materials used for energy pile centrifuge models, have been generally overlooked, and while still providing useful information, there are opportunities to perform more realistic model testing (e.g. Minto et al. 2016).

Clearly practical tools for geoengineers and practitioners are still required. GSHP technology and energy geostructures are starting to be implemented more widely and seriously considered in large scale infrastructure projects (e.g. Cross Rail in London, Metro extensions in Melbourne, Paris and Torino). Tools for design as well as for management and constructability of energy geostructure are desperately required alongside guidelines, which would eventually lead to standards. While some solid research bases have been already developed perhaps for a first generation 'practical' design tool, there is still much to learn for a routine application of GSHP technology. Even more so, when larger scale implementation of the technology is sought (see for example, Nicholson et al. 2013, Ryżyński & Bogusz 2016, Mortada et al. 2018). The development and implementation of guidelines for the structural and geotechnical design of energy geo- structures is another critical component of this activity that need more work. Perhaps the first effort in this area corresponds to the SIA-D0190 (2005) Swiss guide that deals with the design of energy piles. A similar standard was developed in the United Kingdom by the Ground Source Heat Pump Association (GSHPA 2012). Most recently the 'CFMS/SYNTEC INGENIERIE/SOFFONS-FNTP' (2017) was proposed in France. Following the Eurocodes, the French guidelines consider a performance-based design approach, which is a significant difference respect to the Swiss and British standards, which are basically prescriptive approaches. Undoubtedly more effort and advances are necessary in this area as well.

6 Summary

An overview on the most relevant and recent advances on energy geo-structures was presented in this paper. Aspects covering the design and analysis of thermo-active geostructures were discussed in this contribution with particular attention to the influence of temperature changes on pile, surrounding soils and other components of the system. Analytical functions and approaches (e.g. G-functions, thermal resistances) generally used in the design of energy piles were presented and analysed in detail together with numerical solution typical used to tackle this type of problem. The discussion did not limit to energy piles, because other energy geostructures were also considered, including, retaining walls, tunnels and bridges (i.e. deck de-icing). The paper also reviews recent developments in terms of laboratory and field testing associated with thermo-active structures, encompassing, lab 1-g tests, centrifuge experiments; and large-scale/field tests. Finally, the discussion focused on highlighting the main findings and progress in the last few years in this very active area, as well as on identifying present and future challenges related to the interaction between energy geostructures and the ground.

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List of Tables

List of Figures