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ANALYSIS and DESIGN METHODS for ENERGY GEOSTRUCTURES

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ABSTRACT:

Based on discussions at the international workshop on “Thermoactive geotechnical systems for near-surface geothermal energy”, hosted at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland (http://www.olgun.cee.vt.edu/workshop/), this article attempts to provide a broad overview of the analysis methods used for evaluation of systems that use either boreholes or geo-structures for heat exchange. It identifies commonalities where knowledge transfer from the former to the latter can be made, and highlights where there are significant differences that may limit this cross-fertilization. The article then focusses on recent developments and current understanding pertaining to the analysis of the thermo-mechanical interaction between a geostructure and the ground, and how this may be incorporated into the geotechnical design of energy geostructures.

KEYWORDS:

Shallow geothermal, boreholes, foundations, underground structures, analysis, design,

NOTATION:

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BHE	Borehole Heat Exchanger
CTE	Coefficient of Thermal Expansion
DFI	Deep Foundations Institute
DST	Duct Ground Heat Storage
EGS	Energy Geostructure(s)
FEA	Finite Element Analysis
GSHP	Ground Source Heat Pump
HDPE	High Density Polyethylene
MLS	Moving Line Heat Source
PHE	Pile Heat Exchanger
RTD	Return Time Distribution
SBM	Superposition Borehole Model
SGE	Shallow Geothermal Energy

SPF	Seasonal Performance Factor
TBM	Tunnel Boring Machine
THM	Thermo-Hydro-Mechanical
UTES	Underground Thermal Energy Storage

SYMBOLS

MW_{th}	Mega-Watts thermal
H	borehole length
Q_k	Action effect
$\dot{q}_b$	heat flux
r_b	borehole radius
r^*	dimensionless geometry factor
T	Temperature (of borehole wall) at time t
T_0	Initial temperature (of borehole wall)
T_{in}	Inlet fluid temperature
T_{out}	Outlet fluid temperature
ΔT	Temperature change in pile
t^*	dimensionless time factor
α	soil thermal diffusivity
α_T	linear coefficient of thermal expansion of pile
ε	strain
ε^e	elastic strain
ε^{th}	thermal strain
λ	ground thermal conductivity
ψ_i	variable action factors

1. INTRODUCTION

The use of the ground as a means for managing the thermal loads within buildings is a well-established technology and borehole heat exchange systems have been used for several decades, especially following the "oil shocks" of the 1970s.

Worldwide installed Ground Source Heat Pump (GSHP) capacity is estimated to have increased nearly twenty-fold between 1995 and 2010, from about 1854 MW_{th} to 35236 MW_{th} and more than doubled from 15384 MW_{th} in 2005 [1]. To the end of 2012, installed capacity of GSHP and Underground Thermal Energy Storage (UTES) systems in Europe, was estimated to total approximately 16500 MW_{th} [2]. Lund et al. [1] annualise the growth in this period to a rate of about 20% and Antics et al. [2] suggest that growth within the geothermal energy sector in Europe, which is dominated by GSHP systems, was estimated to be about 30% in the two years to 2015.

While the borehole heat exchange technique is well established, continuing research and development is focussed on reducing installation costs, i.e. speed/ease of installation, improved borehole heat transfer and heat pump efficiency, and more refined models for use in design [3, 4, 5].

The GSHP and UTES installations referred to in the above figures are entirely borehole based systems; increasingly, however, designers and developers are looking to use engineering structures where heat absorber pipes are integrated within structures in contact with the ground, as the means for providing thermal exchange with the ground. These applications have been referred to variously as energy foundations, thermo-active ground structures [6], geothermal piles, heat exchanger piles and energy geostructures [7] - this latter will be used here.

Potentially, this use of energy geostructures (EGS), that are in any case needed to support buildings (i.e. raft/mat foundations, piles) or the ground itself (i.e. retaining walls and tunnels), Figure 1, can help to facilitate the implementation of GSHP technology on confined urban sites and reduce the initial capital costs of installation, by eliminating borehole construction [6].

The first application of heat exchange via foundation elements was in Austria and Switzerland; shallow foundation elements such as ground bearing slabs and shallow basement walls were first utilised for energy exchange, and these were quickly followed by bearing piles (mid-1980s), diaphragm walls (mid-1990s) and then tunnels (early-2000s) [6, 8]. Subsequently, and in particular since the late 1990s, many projects have been completed in Germany, the United Kingdom, and an increasing number of other countries in Europe and around the World. No collated figures are available; however, the thermal capacity of EGS currently installed is a small fraction of the total shallow geothermal installed – maybe in the range of 100 to 200 MW_{th}, or less than 1% of total installed capacity.

While this application for heat exchange with the ground is proving compelling on a number of grounds and has already been used in a number of differing configurations, its uptake has been impeded by many of the same factors that have affected the uptake of borehole heat exchangers – initial capital cost, a lack of visibility amongst potential end-users, legislators and design professionals, a need for a more fundamental understanding of material and component response to thermal loading, and a lack of validated analysis and design procedures.

These problems were highlighted and explored during an international workshop on "Thermoactive geotechnical systems for near-surface geothermal energy", hosted at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland in March 2013 (http://www.olgun.cee.vt.edu/workshop/). About 70 individuals from both research and industrial backgrounds attended the workshop, and this paper results from the discussions relating to the issue of the validation of design tools for energy geostructures, see [9] for a report on this particular session and the same issue of the DFI Journal for reports on the other sessions of the workshop.

This article attempts to provide a broad overview of the analysis methods used for evaluation of both borehole heat exchanger (BHE) and EGS heat exchange systems, to identify commonalities where knowledge transfer from the former to the latter can be made, and to highlight where there are significant differences that may limit this cross-fertilization. The article then focusses on recent developments and current understanding pertaining to the analysis of the thermo-mechanical interaction between the geostructure and the ground, and how this may be incorporated into the geotechnical design of EGS.

2. ANALYSIS OF HEAT EXCHANGE WITH THE GROUND

2.1. Overview

Design analysis for BHE systems has chiefly involved the use of analytical and semi-analytical solutions within which assumptions have been made that allow the heat exchange calculations to be carried out in a manageable timeframe. This is particularly important for the increasing use of hourly time steps for heat pump system analysis in routine practice. Such short time intervals would lead to excessive computation demands and timeframes for full numerical simulation. The analytical methods, outlined in Section 2.3, have been implemented in a number of easy to use programmes, the validation of which is considered in Section 2.3.7.

Thermal design analysis for energy geostructures presents new challenges. Pile heat exchangers (PHE) comprise the most common form of EGS and current design analysis tends to assume that the thermal response of PHE is equivalent to that of BHE (Section 2.4). However, PHE can be constructed in a number of ways (Figure 2) and can vary in size from 15 cm to 3 m diameter and from 10 to 60 m in length with larger diameters and smaller length-to-diameter ratios compared to BHEs.

A number of other types of EGS have been suggested and applications using retaining walls and tunnels have been installed (Section 2.5). Clearly, these types of systems deviate far from the simple rotational symmetry assumptions made for BHE, although the planar nature of retaining walls and the cylindrical nature of tunnels can still be exploited by analytical methods. Ground anchors have also been proposed and trialled as a means for heat exchange with the ground however, in principle, these will function in a similar manner to piles.

2.2. Considerations in the analysis of heat exchange

Energy geostructures can take a number of forms depending on whether they are installed within piled foundations, retaining walls, tunnels or other structures in contact with the ground.

The following sections provide an overview of the general considerations required of a complete solution for heat exchange with the ground.

2.2.1. Heat transport in the soil

Heat transfer in the ground will be dominated by conduction and available analytical solutions assume this is the only mechanism for heat flow. Groundwater flow can influence heat transfer by additional advection but for the case of thermal energy storage, flows must be substantial for this effect to be significant, as the advection merely shifts the position of the underground thermal store [10]. Nonetheless, analytical solutions for simplified cases of forced convection do exist [11] and these are discussed in Section 2.3.7, although it is perhaps more common to use numerical techniques in these cases.

2.2.2. Heat transport within the ground heat exchanger body

Similarly, heat transfer within the heat exchanger is usually considered to be a diffusive process (i.e. dominated by conduction). Some solutions solve the diffusion equations directly, but it is more common to instead use a thermal resistance [12]. Thermal resistance is often regarded as the inverse of thermal conductivity, but also includes the influences of the geometry of the heat exchanger. If the heat exchanger can be assumed to be at a thermal steady state then the thermal resistance can be taken as constant. This represents a constant temperature difference between the absorber pipes and the structure edge and is a useful simplification. However, the greater the cross-sectional area of the heat exchanger, the less valid this assumption becomes as it can take considerable time to reach thermal steady state.

2.2.3. Heat transfer and transport within the absorber pipes

Heat transfer in the absorber pipe systems can also be calculated with the help of thermal resistances, which is common in all analytical methods [6, 13, 14]. Here, heat conduction in the pipe walls as well as the heat convection in the fluid inside the pipe has to be considered. Due to the high flow rates in the pipes, heat conduction in the fluid can be neglected. The formulation of the thermal resistance can be developed from the thermo-mechanical basis for tube flow [6].

2.2.4. Surface boundary conditions

The temperature at the ground surface is influenced by seasonal fluctuations. Generally, it can be said, that the ground temperature “follows” the air temperature with a temporal phase shift. Furthermore, there is a damping effect such that below a depth of about 10 m to 20 m, no significant temperature fluctuation occurs as a result of diurnal and seasonal surface temperature changes. EGS are normally constructed entirely or partially within this zone, and whether these temperature fluctuations should be taken into account depends on whether there is a structure directly overlying the EGS, e.g. the building the piles are supporting, or whether the surface is open to the air, e.g. as can be the case behind a retaining structure.

The surface temperature fluctuation may be modelled as either a time-varying temperature boundary condition (i.e. Dirichlet condition) [6], or a time-varying heat flux (i.e. Neumann condition). The latter condition can be calculated with the help of the energy balance at the ground surface, which ensures thermal equilibrium is maintained between global and solar radiation, reflection, evaporation and transmission [15, 16].

Alternatively, if a building or other structure is present at the ground surface then alternative boundary conditions need to be considered. Field studies have shown that a small heat flux may exist between buildings and the ground and also that seasonal variations in atmospheric temperature only affected the soil mass within the first few metres from the edge of the building [17].

For numerical applications, the use of a temperature boundary condition at the surface is recommended for stability reasons. The time sequence of the surface temperature can be calculated with the help of the energy balance at the ground surface. The components of the energy balance can be calculated using the climatic parameters for the location of the energy geostructure (e.g. air temperature, global radiation, wind velocity, humidity, etc.).

EGS are normally constructed within cities or urban areas. Therefore, additional heat sources in the ground such as buildings, tunnels or sewers have to be considered [18]. Furthermore, the urban heat island effect can lead to very high background temperature in the ground [19]. Consequently, the initial ground temperature and its variation due to the presence of potential sources/sinks has to be determined according to the particular conditions applicable at a given site.

2.2.5. Geostructure thermal boundary conditions

Many analytical models developed for use with BHE assume either a constant temperature or constant heat flux conditions at the borehole wall. A constant flux condition is perhaps more common and this is often adopted with PHE as well. However, it is known that the actual flux is likely to depend on the depth and ground conditions [20, 21].

Environmental conditions inside tunnels or other air-voids such as basement rooms are an important factor for the calculation of heat exchange and the choice of boundary condition will have a major influence on the predicted heat flow. For example, analysis has shown that the heat flow from the tunnel air is about 30% of the total heat flow available for exploitation [22].

2.2.6. Geometric effects

Many of the classical analytical solutions (see Section 2.3.1) make the assumption that the heat exchanger is of infinite length in order to simplify the mathematics involved. However, axial effects are of increasing importance with shorter heat exchangers such as PHE and end effects need to be taken into account, especially in the long term.

2.2.7. Thermal interactions

Many analytical methods are developed for a single heat exchanger. However, vertical BHE typically exist in fields (groups) and it is necessary to use superposition to determine the group effect of many heat exchangers. An important aspect of relevance for geostructures is that the arrangement of PHE and other structures are not necessarily regular and hence symmetry cannot always be relied upon to simplify superposition.

Thermal interference can also occur between the individual pipes within a heat exchanger [23]. This will be particularly important at small pipe spacing, lower flow rates and longer heat exchangers [12]. Depending on the geometry of the geostructure and installed pipes, taking account of this effect may be important.

2.2.8. Load aggregation

Applied thermal loads are never constant in real operating GSHP systems. If every change in load was accounted for computation timescales would increase to unmanageable levels. Hence, some form of load aggregation is normally carried out. A useful review of techniques in this area is provided in [24].

Each of the considerations discussed above require different modelling scales. For calculations of the temperature change and heat transport in the ground a large scale is necessary (metre range). For describing the heat transfer between EGS, the soil and the pipe system a smaller scale (centimetre scale) has to be employed. There exist analytical approaches for the individual aspects mentioned above however and these can be implemented in numerical solutions, so the computational times can be reduced for most practical applications.

2.3. Borehole Heat Exchangers

We commence first with a review of relevant methods for BHE analysis as these are often adopted or modified for use with PHE. For the analysis methods reviewed in this section, no mathematical expressions are given in the text. Readers are instead referred to more specialised literature, e.g. [25, 26, 27], for precise mathematical formulation and inter-model comparison of these methods.

2.3.1. Classical Analytical and semi-analytical methods

Classical analytical models for designing and analysing BHEs include line-source [28] and cylindrical-source [29] solutions. The classical line- and cylindrical-source models provide solutions to the radial transient heat transfer problem in the ground:

- The line-source model treats the radial heat transfer in a plane perpendicular to the vertical borehole. The borehole is assumed to be a line source of constant heat output and of infinite length surrounded by an infinite homogeneous ground.
- The cylindrical-source model assumes the borehole to be an infinitely long hollow cylinder surrounded by homogeneous ground and having constant heat-flux across its outer boundary.

Various discrepancies occur when applying these two classical solutions to model borehole heat transfer. These solutions not only ignore the end-effects of their heat sources (i.e. finite length of BHE), but also do not account for the thermal properties of the borehole components (fluid, pipe circuit, borehole infill). Consequently, they must be combined with a series of thermal resistances to account for these aspects of the heat transfer.

A further consequence of these underlying assumptions regarding geometry of the heat sources is that both these solutions are inaccurate when determining the short-term response of a borehole heat exchanger. This inaccuracy becomes important when either short time step analysis (e.g. hourly) is carried out or when the capacitance of the heat exchanger is large (e.g. in large diameter piles).

Nevertheless, many practitioners and researchers have used the classical line- and cylindrical-source models for design and analysis of BHE systems.

2.3.2. ASHRAE Handbook Method

The ASHRAE Handbook method to design BHEs is based on the approach of [30]. This relatively simple method uses a set of equations derived from the cylindrical source model to size the ground loop. The model assumes constant heat flux across the borehole outer boundary, ignores the end effects of the borehole, and disregards the thermal capacities of the circulating fluid and the grouting. Another limitation is that the estimation of thermal short-circuiting inside a borehole and thermal interactions between boreholes is quite ambiguous and has not been able to be independently validated by other researchers [31, 32]. Generally the method does not perform well compared to other approaches (Section 2.3.8). Some of these issues of the ASHRAE method have been recently addressed by [33].

2.3.3. Superposition borehole model

The Superposition Borehole Model (SBM) [34] is one of the mostly commonly used models in design and analysis of BHEs. The SBM solves transient radial-axial heat transfer in a borehole heat exchanger using the finite difference numerical technique. The model is based on a finite line-source approach and develops thermal response solutions to a stepped heat pulse.

The non-dimensional form of thermal response functions, obtained from the SBM, are more commonly known as g-functions. The model obtains g-functions for multiple BHEs (Figure 3) in a numerically exact way. The thermal interactions between adjacent boreholes are accounted for by spatial superposition of numerical solutions with radial-axial heat transfer for each borehole. The main limitation of the numerically calculated g-functions lies in the fact that due to an absence of borehole geometry detail in the model, they are only valid for times greater than 200 hours [35].

Another practical aspect of the g-functions is that these functions need to be computed numerically, which is a time-consuming and computationally-intensive task. Hence, these functions are pre-computed for various borehole geometries and configurations and then stored as databases in building energy analysis software.

The SBM has been implemented in several stand-alone programs and simulation software including Earth Energy Designer (EED) and the Ground Loop Heat Exchanger Program (GLHEPro), among others. Both design tools determine the long-term response of the BHE to the monthly heating and cooling loads using the above-discussed g-function approach. Short-term response due to the peak loads is calculated differently in each program however.

Building energy simulation software with the SBM implemented includes HVACSIM+, eQuest, EnergyPlus, TRNSYS and Polysun. Some of these programmes have also extended the g-functions obtained from the SBM to short time steps. The implementation of the SBM in building energy simulation software differs from the BHE field design tools in that it uses hourly values of heating and cooling loads instead of monthly aggregated values. This allows for a more detailed and accurate thermal analysis of the BHEs.

2.3.4. Analytical g-functions

Analytical g-functions have been developed to address the flexibility issue of numerically computed g-functions from the SBM. [34] developed an analytical g-function expression, which was later adopted by [36]. These methods use a constant value of borehole wall temperature, taken at the middle of the finite line-source. Alternative analytical g-functions have been developed using the integral mean temperature along the finite line-source [37]; this provided a better match to the numerically calculated g-functions, but requires the solution of a complicated double integral. Simplifying the problem to a single integral [38] present a closed form formula for analytical g-functions and extend the analytical finite line-source approach to model multiple boreholes. Using the finite line-source solution and SBM boundary conditions [39] have also developed semi-analytical g-functions.

2.3.5. Duct ground heat storage model

The Duct Ground Heat Storage (DST) model [40] is another widely used numerical model for design and thermal analysis of underground energy storage systems with borehole heat exchangers. The DST model solves the heat transfer problem of BHEs placed uniformly within a cylindrical underground thermal energy system. The model uses spatial superposition of three different heat transfer solutions to determine the ground temperature. The first solution accounts for the long-term heat transfer between the storage volume and the undisturbed ground. The second solution considers the short-term heat transfer of each borehole to its surrounding ground inside the storage volume. The third solution accounts for steady-flux heat transfer between circulating fluid in a borehole and the ground surrounding the borehole. The first and second solutions are determined numerically using the finite-difference method, while the third solution is determined analytically.

The DST model was originally distributed as a FORTRAN program, which is still available. Later, it was implemented in TRNSYS [41] and is now distributed commercially as Type 557 [42]. A stand-alone TRNSED application of the DST model, called PILESIM2 also exists and is available commercially (see also Section 2.4.3) [43]. Despite its complex mathematical formulation, software implementations of the DST model are computationally very efficient even for large-sized systems. A significant limitation of the model lies in its inability to model irregular borehole-field configurations and non-uniform borehole lengths.

2.3.6. Short-Time Analysis

Temperature response functions (g-functions) have been extended to short time-scales [44]. As with the SBM's g-function approach, the temperature response functions of [44] also needed to be pre-computed for individual cases and then stored in design and simulation software as databases.

Using a radial numerical model [45] also developed temperature response functions for short time-scales. The model accounts for thermal properties of circulating fluid, pipe, grout, and the surrounding ground and is a major improvement on existing analytical models. A purely analytical method to determine borehole fluid temperature for time scales from minutes to decades was obtained by combining the short- and long-time temperature response functions [45]. The method uses superposition of heat pulses in a similar manner to the SBM; however, it removes the important limitation of having to use a constant or steady state resistance. The principal limitation of the method lies in its assumption of having uniform heat flux in all boreholes. More recently, a new analytical method to the problem addressed by [45] has also been presented by [46].

2.3.7. Influence of groundwater flow

The Line and Cylinder Source models, as well as SBM and analytical g-functions are all based on heat transport by conduction. If significant groundwater flow exists, convection and an additional heat transport occur. For consideration of this additional heat transport a higher thermal conductivity value could be used [47, 48]. This is however a significant oversimplification because the characteristic timescales for conduction and convection are very different.

A model for the prediction of the thermal resistance of a borehole in contact with groundwater was developed by [49, 50]. The model is based on Moving Line heat Source (MLS) theory and was coupled with the infinite line source theory. Further developments were presented by [11] where the MLS was coupled with the finite line-source model in order to include axial effects.

The software PILESIM and implementation of the DST model includes the effects of groundwater by making two simple two-dimensional approximations. The first approximation is to the global problem of heat transfer into and out of the heat store, where the maximum convective energy is then limited to that which would be released by changing the temperature of the heat store to that of the undisturbed groundwater temperature. PILESIM then also implements increased heat transfer due to convection at the local level surrounding each duct in the store by using the steady state heat transfer for a cylinder at given temperature in a saturated porous media [51]. It must be stressed however that although both these groundwater approximations are included within the software, [42] indicates that the accuracy of the underlying assumptions has not been checked.

2.3.8. Validation of Borehole Design Tools and Approaches

Although a number of models and design tools for sizing and modelling of borehole heat exchangers have been developed over the years, only a few have been validated at all, and even fewer have been validated against actual field data. Most validation efforts have focused on inter-model comparison. Analytical g-functions have been compared favourably with SBM by a number of authors [52, 53, 54, 39]. Common design tools have been evaluated using measured data from different installations to calibrate the DST model [55, 56]. The calibrated model was then used as a benchmark for comparing the design tools. This showed that borehole design lengths varied by between ±8% and ±16%, respectively, among different design programs.

The SBM-based design tool GLHEPro and the ASHRAE handbook method have been validated using operational data from four different installations in the USA and Europe [57]. Actual on-site parameters, real thermal loads, and temperature constraints obtained from the experimental measurements taken over several years were used for the validation. For all four cases, the GLHEPro design tool predicted the borehole lengths to within 6% of the actual borehole depths. However, the ASHRAE handbook method resulted in design borehole depths ranging from -21% (undersized) to 103% (oversized) of the actual depths, Figure 4.

2.3.9. Numerical thermal analysis of BHE

Full numerical thermal analysis of BHE should in theory be able to deliver a completely general solution to the problem that takes into account each of the considerations detailed in Section 2.2. Each individual component and its respective thermal properties can be represented, fluid transport in the pipes can be modelled, correct initial temperature and boundary conditions applied, thermal exchanges to the ground below and at the ground surface can be captured along with real ground variation.

However, full three-dimensional (3D) analysis is computationally expensive and most early work was either based on a two-dimensional (2D) slice approach [58, 35, 44] or carried out on a 2D radial-axial plane, as was the case for the derivation of the SBM [31]. The horizontal slice approach was applied to an instrumented GSHP pilot project in Hong Kong [59] where, in spite of the simplifying assumptions, comparisons with the measured temperatures on the walls of the heat exchange pipes were generally within about ±6%.

To undertake a complete 3D analysis of the problem, in addition to the problem geometry, the solution should involve the coupling of the fluid flow problem within the heat exchange pipes with the heat transfer problem throughout the remainder of the problem domain. To deal with this problem various approaches have been used to approximate the fluid flow and associated heat transfer to the remaining elements forming the BHE, i.e. the heat exchanger pipe walls, grout infill and surrounding soil/rock mass. Primarily, this focuses on reducing the dimensions of either the heat exchanger pipes or the entire borehole such that they can be represented as a one-dimensional (1D) element within the numerical model.

1D representations of the BHE have been used within a 3D representation of the remaining components within the problem domain [60, 61]. In a similar approach, the heat exchanger pipe was replaced by a 1D element that solves the fluid flow and heat transfer equations for the heat exchanger pipe, to yield the surface temperature of the pipe which is coupled to the heat flow problem in the main solution domain [62].

Alternatively, a single layer of cells can be used to represent the fluid circulation within the heat exchanger pipe with the thermal properties of the cells adjusted to ensure that the full thermal mass of the fluid within the pipe is represented [21]. Again, this is a 1D representation of the problem and the authors showed that there was an unavoidable, mesh dependent error of 7% to 10% in the Return Time Distribution (RTD) due to the 1D representation that is likely to also be present in other 1D models. This appears to have little effect in the steady-state where the model was able to estimate borehole thermal resistance to within 0.1% of an analytical solution based on the multi-pole method.

Taking the simplification process a step further, the entire BHE can be reduced to a line element [63, 64]. Not only is the fluid flow and associated heat exchange approximated; in this element, the interactions between the heat exchanger pipes and the borehole wall via the grout are included. The approach has been developed further to include only a single a term that accounts for the thermal capacity of the grout body [65, 66]. The proposed method has been validated against a fully discretized finite element model where in terms of predicted heat flow, the new model is in agreement with the full simulation in a period of time from 15 minutes to three hours [67].

2.4. Pile Foundations

2.4.1. Overview

In practice, analytical approaches used for the assessment of the thermal capacity of pile foundations are commonly based on the methods developed for borehole heat exchangers [68]. This is due to the superficial similarity between the two types of heat exchanger and also due to an absence of many validated alternatives. However, it is important to understand that piles are different to boreholes in a number of important respects:

- As discussed in Section 2.1, different boundary conditions may be required,
- Piles may be installed on a semi-regular, or irregular grid to suit structural column requirements,
- Not all piles installed in a given scheme will necessarily be of the same length,
- The aspect (length to diameter) ratio will be different. For boreholes this is typically between 500 and 2000, while most constructed piles fall between 15 and 50 [69]. The consequence of the smaller aspect ratio is that axial effects will become important at shorter time periods.
- The larger diameter of most pile foundations compared to boreholes also has important consequences. The larger cross section of the heat exchanger means the potential for inclusion of more heat transfer pipes and more options for how these are arranged. These details will influence the early time temperature response of the heat exchanger, making short time step analysis more important. This is particularly pertinent as the greater volumes of concrete means that the heat exchanger is rarely at a thermal steady state and consequently there is significant short term thermal storage of heat within the pile concrete.

As is the approach for BHE, the temperature changes in the ground associated with PHE are often calculated by some kind of g-function; either one of those described in Section 2.3 or a bespoke function for piles, see below. In most cases the pile is accounted for by using a thermal resistance, an assumption that is known to be conservative [70, 71] and better approaches are needed.

2.4.2. Analysis methods

The only commercially available tool for pile foundation thermal analysis is the software PILESIM [46]. This tool is based on the DST Model described in Section 2.3.5, and assumes a large number of identical piles installed in a regular array to form a cylindrical store. It is unclear however what errors result from smaller or less regular pile group arrangements that are more representative of typical foundation layouts.

Other analysis methods are mostly based on the g-function approach. [72] propose a solid cylinder model which differs from the hollow cylinder model by assuming heat flow both into the pile and into the ground from the circumference of a cylinder. Numerically derived pile g-functions have been developed that provide upper and lower bound solutions for typical PHE geometries and fall between the line-source and the solid cylinder model in the short term, Figure 5 [62]. In the long term, the pile response is equivalent to the SBM and is controlled by the aspect ratio [62].

[73] have proposed composite g-functions based on superposition of infinite line sources in two media, the concrete and the ground. However, these two-region analytical models are complicated

and the superposition must be derived for each and every arrangement of pipes. This would be a barrier to their routine adoption in design. They are also only applicable in the short-term due to the infinite length of the heat source.

An alternative approach to cover the short term transient aspects is suggested by [70], who present upper and lower bound pile and concrete g-functions, which describe a step pulse response in the concrete. In this way, they account for the short term storage of heat within the pile concrete and consequently the validity of the analysis does not depend on the heat exchanger having reached a thermal steady state. Pile g-functions describing the temperature change in the ground surrounding the pile (Figure 5) are then combined with the concrete g-functions by superposition to obtain the total temperature response of the system.

Finally, models have been developed based on resistance-capacitance models using an electrical analogy and capture the short term storage of heat within the pile concrete [74, 75].

2.4.3. Validation of PHE Models

Only the DST which underpins PILESIM has been validated against operational energy pile data. Initially, however, the DST was validated against field data for small diameter (<50 mm) borehole thermal stores in Sweden [76]. It was only later that the approach was implemented for use with piles, and then validated using field data from Zurich Airport [77]. The validation focused on the overall heat exchange capacity of the system. Subsequently, independent analysis using finite element models was carried out suggesting that for regular arrangements of piles, the results provided by PILESIM are reasonable, Markiewicz, R. (2010, Pers. Comm.).

The pile and concrete g-functions proposed in [74] have now been tested successfully against thermal response test data but await longer timescale validation [78]. Performance data for a plot of 300 mm diameter energy piles against the software EED was tested by [68]. This approach, based on SBM, over-predicted the fluid temperature changes. This discrepancy is due to the short length (10 m) of the piles and the assumption of constant thermal resistance.

2.4.4. Numerical thermal analysis of PHE

In terms of examining the thermal behaviour of PHE, very limited examples of the application of any type of continuum numerical analysis are available. This is perhaps because the focus has been on the thermo-mechanical impact of these elements where somewhat more effort has been expended (Section 3.2.2).

When looking at PHEs in comparison with the BHE problem discussed earlier, the same basic issues associated with full 3D numerical analysis occur, with significant geometric contrasts between the diameter and length of the heat exchanger. In this case, as noted in Section 2.4.1, the length issue is not so great as most piles are less than about 30 m long but the diameter may vary between 0.15 m and 3 m, and the number of heat exchanger pipe loops varies with the pile size. For example, the pile and concrete g-functions developed by [70] were developed on the basis of 2D & 3D FEA, considering 0.3, 0.6 & 1.2 m diameter, piles with 2, 4 or 8 heat exchanger pipes respectively and length to diameter ratios of 15, 25, $33^1/_3$ & 50.

Thermal storage response of a piled building foundation has been studied using a 2D plane strain idealization of the problem domain [79, 80]. Considering various heating scenarios [79] examined the development of the temperature field within and adjacent to the foundation system, over a period of 5 years, and confirmed thermal losses to the surrounding soil mass were similar to borehole systems examined in other studies. [79] and [80] both explore the evolution of temperature in the piles and show that with time and with uniform annual thermal demands, the temperature profiles in the piles tend to equilibrate.

One-dimensional line elements are also now being adopted in PHE simulations [55, 81, 82, 83]. The authors showed that the approach compared favourably to the finite line-source approach and [82] also validated the approach against PHE field data. Both [82] and [83] then use the approach to investigate the influence of pile and pipe geometries on the pile thermal behaviour.

2.5. Other energy geostructures

2.5.1. Overview

The use of pile foundations for heat exchange remains the most common application however a number of other geostructures including retaining walls and tunnels have been used or are being investigated for use in providing the means for heat exchange with the ground.

The walls of shallow, cut-and-cover tunnels and other underground structures are formed using concrete piled and diaphragm walls, and sheet-pile walls that along with other earth-contact elements such as base slabs can be thermally-activated. The first “Energy tunnel” was a section of cut-and-cover tunnel built in Vienna (Lainzer Tunnel), installed to test the concept and provide heating to a local school adjacent to the railway [6]. Other, full-scale applications have been constructed including Keble College, Oxford [84], four stations of the U2 metro extension in Vienna [85] and the Knightsbridge Palace Hotel, London [86]. In a further development, RWTH Aachen University has developed and is trialling, high density polyethylene (HDPE) protection panels with absorber pipes attached which can be used for the thermal activation of shallow basement walls that are in contact with groundwater [87].

Deep tunnels may be formed by mining or using tunnel boring machines (TBM). The first test application for a mined tunnel was again on the Lainzer Tunnel project where a section of tunnel was thermally-activated using an “energy geotextile” developed at the Vienna University of Technology [8]. Further test sections using a similar technique have been installed in Germany [88] and China [89], and an operational system was installed adjacent to one station of the U2 metro extension in Vienna [90]. For the thermal-activation of tunnels formed by TBM, the companies Ed. Züblin AG and Rehau AG+Co developed the “Energietübbing®” system [91]. In this system, the absorber pipes are attached to the reinforcement cage inside each precast tunnel lining segment and each segment is connected via a fusion joint located in a small recess in the front face of the segments. The first application of the Energietübbing® system is a trial section in Austria (Jenbach railway tunnel).

2.5.2. Analytical solutions

As EGS other than piles remain rare there are few analytical solutions available for these cases. Those that do exist are often very much simplified. [6] highlights how solutions of the diffusion equations for the cases of a semi-infinite body, and infinite body with cylindrical gap and an infinite body with a spherical gap could be applied in the analysis of available energy and temperature change prediction around EGS. Such solutions could potentially be applied to the cases of slabs or retaining walls, piles or tunnels, and pile toes respectively. However, most real application scenarios are more complicated; for example, by the significance of heat flux boundary conditions within tunnels and underground structures, and therefore alternative approaches are usually adopted.

A simple thermal resistance model was developed for an energy tunnel for determining the energy potential for the tunnel projects of “Stuttgart 21” [22]. In this model, heat transfer in the soil is based on conduction only, so no groundwater flow could be considered. [89] also developed a conduction only model for tunnel lining ground heat exchangers. The model was verified using the results of a thermal response test carried out in the Lichang tunnel, China and for times greater than 10 hours of operation there was good agreement between the predicted and observed outlet temperature, Figure 6. The discrepancy seen prior to the 10 hour mark was attributed to the model not capturing all aspects of the lining construction.

A conductive heat transfer model for energy diaphragm walls has been developed [13]. The model was verified by comparison with numerical simulations and field data from the Shanghai Museum of Natural History. In terms of heat exchange rate, good agreement was found between the observed values and those predicted for running times beyond about 14 hours, Figure 7. However, the comparison in terms of predicted temperatures within the wall were not as consistent but were considered adequate [13]. Again, the discrepancy in the solution during the early stages of the test is most likely due to the simplifications made in the calculation model.

In both [89] and [13], it should be noted that the test data used is of very limited duration (2 days) and that the longer term suitability of the proposed models has yet to be fully verified.

2.5.3. Numerical analysis

In most cases, EGS (other than piles) are modelled with numerical methods. Most of them are based on heat conduction. To reduce computational time, often the heat exchange system is not modelled in detail; a simple temperature or flux boundary condition is applied where the pipes are located, or at the edge of the geostructure.

As part of the development of a thermally-activated segmental tunnel lining, finite-difference calculations were performed to estimate the energy potential of a tunnel and its associated temperature field [91, 92]. The one-dimensional model assumed, that the temperature field around the tunnel is axially symmetric . This model assumes the tunnel is sufficiently deep that the surface boundary does not play a significant role and there is no groundwater flow. For conditions with groundwater flow, finite element calculations were carried out with the absorber system simplified to a constant temperature boundary condition. In these models, heat transfer into the tunnel was neglected [92].

[93, 94, 8] have modelled different EGS types. Their models again only considered heat conduction and depending on the size of the problem the heat exchange pipes were modelled using either a module that calculates heat and mass transfer or as a constant temperature boundary condition.

[14] developed a model for thermally-activated HDPE protection panels, which has similarities with the duct storage model. The processes in the heat exchange system are described via thermal resistance with the relationship for the “structure resistance” based on a model for concrete core activation. Heat flow to both the ground and into the basement room is modelled. The model calculates the effect of both conduction and convection due to groundwater flow while also accounting for seasonal temperature fluctuations. The model has been verified using full numerical simulations and laboratory tests, Figure 8.

[95, 96] present results from 2D plane strain FEA for a shallow, cut-and-cover type tunnel structure where the thermal and thermo-mechanical behaviour was examined, Figure 9. Heat flow to the tunnel dominated and was critically dependent on the assumption made regarding the boundary condition on the tunnel wall surface. Defining suitable thermal parameters for this interface is not straightforward and requires further consideration; otherwise, overly optimistic estimates for heat exchange may be calculated.

3. ANALYSIS OF THERMO-MECHANICAL SOIL-STRUCTURE INTERACTION

3.1. Introduction

The primary function of an EGS will always be to safely carry loads (e.g. building loads on piles and slabs, external and ground loads on retaining walls and tunnels) without unacceptable movement or damage to the structure itself or neighbouring structures. A concern that therefore arises from the use of engineering structures for heat exchange is what potential is there for the thermal loads to impact on the performance of the structure either in terms of serviceability or safety. Thus, there is a need for analysis to be undertaken to assess whether the proposed secondary use of the EGS as a heat exchanger will prove acceptable, or to confirm what changes are necessary within the structure to ensure that the EGS operation can be implemented safely.

Broadly, the impact of an EGS operation requires the study of three major issues:

(i) Deformation of the building supported by the EGS.
(ii) Stress variations in the EGS induced by constrained thermal expansion and contraction.
(iii) Possible changes in the available load resistance of the EGS.

Few detailed thermo-mechanical numerical analyses examining the behaviour of energy geostructures have yet been published. This probably reflects the similar lack of case histories covering differing soil conditions and geostructures against which they could be verified. Also, in addition to the considerations outlined for thermal analysis in Section 2.4.2, a full thermo-hydro-mechanical analysis needs to consider additional aspects such as the thermo-hydro-mechanical (THM) constitutive behaviour of constituent materials, initial geological stress conditions (including pore water pressures), mechanical boundary conditions, material parameters and construction sequence. Modern geotechnical analysis based on numerical methods, is of necessity, highly nonlinear and it is not unusual, especially in large complex projects, for models to extend to multi-millions of degrees-of-freedom and to take several days or even weeks to complete. Obviously, such analysis is only justifiable in research and for big budget, complex construction projects, and therefore the development of simpler methods that can be used on smaller projects is desirable.

A great deal of care is also required in the implementation of these types of analysis because all aspects of the modelling process from choice of constitutive models to the numerical solution procedures used will affect the outcome. A number of benchmarking exercises for isothermal geotechnical problems have been undertaken to understand these effects and it has been found that even when the problem has been tightly defined and even though the analyses were largely undertaken using the same software (if by differing organisations), the final results showed significant variation [97, 98].

In the following sections, THM analysis of pile foundations will first be discussed, as this is where the greatest level of effort has been expended to-date and simplified analytical methods have been developed (Section 3.2.1), and then THM analysis of other EGS will be examined.

3.2. Pile Foundations

3.2.1. Load Transfer Method

Load transfer methods are widely used in geotechnical engineering practice to estimate the axial response of isolated piles. This method is based on a one-dimensional finite element representation of the pile with the interaction between the pile and soil being represented by discrete load-transfer (t-z) functions along the shaft and at the base of the pile. In this type of model, the inclusion of thermal effects is achieved by adding a thermo-elastic term to the deformation response of the pile such that the total deformation ε consists of an elastic part ε^e and a thermal part ε^{th}, Equation [3].

$$\varepsilon = \varepsilon^e + \varepsilon^{th} \qquad [3]$$

where the thermal part ε^{th} is introduced assuming that any change of temperature, ΔT is homogeneous throughout the pile and thus,

$$\varepsilon^{th} = \alpha_T . \Delta T \qquad [4]$$

where α_T is the linear coefficient of thermal expansion (CTE) of the pile.

Two important assumptions are implicit in the definition of the thermal deformation, ε^{th} in this model:

1) The ground is assumed to be thermally inert. This is unlikely to be the case except in rather particular situations and thus may not be valid generally.
2) Thermal effects on the mechanical properties of the soils can be neglected. In granular and very stiff, moderately to highly over-consolidated clayey soils this may be a reasonable approximation but in normally to lightly over-consolidated clayey materials this may not be true because heating may induce thermal consolidation of the soil.

A spring can be introduced at the pile head to mimic the restraining effect of an overlying structure, and a full range of restraint from zero to fully fixed can be imposed; however, the determination of an appropriate stiffness to utilise in such a calculation is not a simple exercise. To model groups of piles, the model is not directly applicable however other assumptions can be introduced to approximate the effect of mechanical and thermal interaction with adjacent piles.

A number of groups have developed methodologies for applying the load transfer method to the analysis of thermally-activated piles. A calculation method based on the load transfer approach was presented by [99], validated using two field tests [100, 101], and applied to some generic scenarios to illustrate how heating & cooling might affect different pile types.

A load transfer solution that incorporates hyperbolic functions as the “t-z” curves was proposed by [102] and used to fit the results of thermally-activated pile tests undertaken in a centrifuge. [103] have adapted an elastic foundation analysis method that uses the load transfer approach to model pile-soil interaction to incorporate thermal loading in the pile response. This method also uses hyperbolic “t-z” curve functions but recognises that thermal loads are cyclic and introduces a modification that stiffens the initial “t-z” response when the load reverses. To reproduce the thermally induced changes in pile behaviour seen in a field test [101], it was necessary to change the soil stiffness associated with the interface response from that required to reproduce the response under iso-thermal mechanical loading. [104] have developed a load transfer approach to the analysis of thermally-activated piles that utilise “t-z” curves broadly similar to those used by [99], and [105] adapted this model to include a function that permits cyclic degradation at the pile-soil interface, so that the potential impact of such loss of resistance on the performance of thermally-activated piles may be explored.

Broadly, the load transfer method appears to be able to capture the changes in behaviour that have been observed in tests of thermally-activated structures and may find use in day-to-day design applications, so long as its underlying assumptions and therefore basic limitations are well understood. Further evaluation of the method is necessary to demonstrate its general applicability and to provide guidance regarding the specification of load-transfer curves and their parameters.

3.2.2. Full numerical analysis of single piles and pile groups

The finite element and finite difference methods of analysis have been applied to the analysis of PHE either to back-analyse field & laboratory tests [100, 106, 107] or to evaluate the behaviour of particular aspects, i.e. cyclic loading [108], soil thermal response [109, 110, 111], or the behaviour of groups of piles [79, 80, 112, 113].

In trying to reproduce the observed response of field tests, both [100] and [101] report good agreement in terms of the observed and calculated pile head movement throughout the modelled sequence, Figures 10 and 11. However, both cases, comparisons in terms of other parameters such as internal axial stress and strain were less convincing. The analysis by [100] under-predicted the axial stress/strain response in the upper part of the pile, and the maximum response is slightly underestimated in relation to that inferred from the field observations, Figure 10. And, in the analysis by [106], large changes in the axial strain at the pile head were predicted suggesting some additional restraint has been included in the model that was not present in the field test, Figure 11. Clearly, there were some details within the models that are not particularly representative of the actual conditions however in qualitative terms the analyses appear to have captured the thermo-mechanical response of the pile.

An interface element which allows for cyclic load degradation of the pile-soil interface shearing resistance was introduced by [108] into a thermally-activated pile model they had described previously, [109]. The results show how cyclic degradation effects could be considered in the design of pile EGS and more work is needed to define if and when it should be considered.

Axisymmetric FEA was used by [110, 111] to examine the response of an isolated pile of varying length subjected to thermal loading. The soil CTE was varied on the basis that in heavily over-consolidated clays the CTE could be several times larger than that for concrete. The results highlight that the temperature field around the pile, in combination with the thermal characteristics of the pile and soil play a major part in determining the final pile-soil interaction response, Figure 12. The simplified nature of the analyses notwithstanding, this result has important implications for the use of e.g. the load transfer method which implicitly assumes the soil to be thermally inert, and in the interpretation of field tests where the surface temperature boundary differs from the operational situation under a building.

Considering normally consolidated clay, [80] showed that under uniform cyclic thermal loading, settlement of a pile group increased gradually but eventually stabilized, Figure 13(a). Thermal consolidation of the soil in response to the changes in thermal loading also led to a gradual increase in pile axial load, Figure 13(b) which is equivalent to downdrag which is often seen in piles installed through soft clays that subsequently undergo consolidation [114]. This is a quasi-permanent loading effect that like the settlements stabilises after a period of time and around which the stresses in the pile would likely oscillate during heating and cooling.

For the case of a thermally-elastic stiff over-consolidated clay, [79] illustrated that stronger heating, when all piles in a group are thermally loaded, leads to larger pile axial stress changes, Figure 14(a) and when only one pile was heated, the other piles restrained the thermal expansion of the pile and the change of axial stress was several times larger than when all the piles were heated, Figure 14(a). The authors also examined the changes in stress state within the soil mass (mid-way between piles) for differing values of hydraulic conductivity, Figure 14(b). Pore water pressures, vertical and horizontal effectives stresses all cycled, with the predicted response being highly dependent upon the value of the hydraulic conductivity. Horizontal effective stress changes, Figure 14(b), of about 4 kPa (medium to high perm.) and 11 kPa (low perm.) were predicted. These values lie between about 10% and 20% of the initial stress, and may be important in terms of the resistance that is available at the pile-soil interface, and for low permeability soils, the effect may be significant.

3.3. Other Energy Geostructures

While a number of thermal studies relating to energy walls and tunnels have been published (see Section 2.5), reporting of the analysis of the THM response of such structures is largely absent from the literature – again, this may also be due in part to the absence of case history data.

[115] present the results of 3D FEA for a thermally-activated deep circular tunnel lining. No substantive details of the modelling are presented except that it is said that a THM coupled soil model was used in the analysis. Rather small changes in hoop (circumferential) stresses of less than 10% are reported.

[95, 96] present results from 2D plane strain FEA for a shallow, cut-and-cover type tunnel structure where the thermal and thermo-mechanical behaviour was examined. The authors based their tunnel loosely on that used in the Lainzer tunnel, Austria, as described by [6] and [93] in order to be able to compare the numerical results with observations, and test the structure under stronger thermal loads than those reported in [6]. In spite of larger temperature changes being applied to the wall, the numerical results broadly confirm the observations; the changes in wall response are dominated by climatic temperature changes while any changes due to heat exchange are negligible.

4. DESIGN OF ENERGY GEO-STRUCTURES

4.1. Existing design codes and guidance

In the absence of official Standards, a number of professional and industry organisations across Europe have produced guidance documents that establish procedures for planning, design and installation of ground energy systems that utilise foundation elements, principally piles:

- German Guideline VDI 4640 Part 2 [116] provides no detailed information for the design of EGS. It is only said, that an energy pile can be treated as borehole heat exchanger; referring back to Section 2.2.1, this statement is questionable and is being reconsidered for the next version of the guideline. For other EGS a case-by-case analysis is required.
- Swiss Guideline SIA D0190 [117] gives more information for the design of EGS, especially for thermally-activated piles. There is guidance regarding construction details (e.g. pipe arrangement, materials, etc.) and design considerations such as accounting for any additional

load and the effect of differential movement when not all piles are used for heat exchange. The guideline refers to the use of the program PILESIM for the calculation of the thermal performance of an energy pile installation (see Section 2.2.1). Detailed information for other EGS are not provided.

- In the United Kingdom, the Ground Source Heat Pump Association has published “best practice” guidance [118] covering design, installation and materials standards for projects incorporating thermally-activated piles. In terms of design, the guidance discusses the roles and responsibilities of the various parties involved in the project, and key aspects of both the thermal and geotechnical analysis of the thermally-activated pile foundation system.
- In France, a design process and tools that take into account the mechanical impact of the thermal variations in the design of geothermal piles is in development; a process that will be certified by the Centre for Building Science & Technology (CSTB). In this process, the geothermal designer takes responsibility for assessing the all thermal effects in the piles (energy supply and pile-soil interaction effects) and the piling contractor dimensions the piles appropriately based on the effects defined by the geothermal designer [119].

For the design of other energy geostructures, some numerical studies based on particular projects have been published [88, 94, 115, 120, 121] which although they cannot be generalized completely, provide some guidance on the aspects that need to be considered.

4.2. Considerations

In any design, two main issues – behaviour when in service and the possibility of failure need to be considered. Serviceability covers aspects associated with the operational performance of a system, e.g. movement of a structure, delivery of design thermal requirements. Failure involves the complete loss of function/collapse of a system be it the structure or the energy system. In the following, the key considerations relating to the design of EGS both thermally and mechanically are discussed.

4.2.1. Thermal serviceability and failure

None of the standards listed above offer any indication on how the performance of an operation system should be measured and what failure criteria may be appropriate. However, there are potentially a number of ways in which performance can be considered and these are outlined in Table 1.

4.2.2. Geotechnical serviceability and failure

Temperature variations in EGS lead to complementary responses that need to be considered in design – the structure's response to changes in temperature will take the form of both alterations in dimension (expansion/contraction) and internal forces (compression/tension). Where the former is restricted, the latter will increase and vice versa. There are however limits to this behaviour that can be defined on the basis of the element being either completely unrestrained (maximum movement) or perfectly restrained (maximum internal load change) with respect to any imposed thermal loading (Table 2).

4.3. From analysis to design

Temperature variations cannot be directly interpreted as force variations and they cannot be considered as a "real" variable action such as wind or snow. They induce contractive or expansive strains which require designers to consider the interaction between the structure and the soils (see Section 3).

While the methods described in Section 3 are well established calculation tools for isothermal mechanical analyses and thermal only analyses, their application to the thermo-mechanical analysis of EGS specifically is a relatively recent development. A limited number of studies applying these methods to the analysis of EGS have been reported and a number of interesting results have come from these that will inform future work. However, the reliability of these methods has not been fully explored with regards to this application and there is a lack of robust case study data that can be used to undertake such validation. As a consequence, there remains a lack of guidance regarding how such analysis should be implemented and the results integrated in design.

Any design also needs to consider the interactions between the geotechnical and the thermal analysis as shown in Figure 16. In the simplest case, temperature limits are applied to both the geotechnical and thermal design streams. However, these limits must first be agreed upon and may also require refinement during the design process.

4.4. Integration with design codes

Temperature variations in EGS are not currently taken into account by any design codes. The primary issue is the integration of these temperature induced load variations in load combinations appropriate for the verification of serviceability limit states (SLS) and ultimate limit states (ULS). There is also the question of which limit states that this effect is relevant for; SLS certainly however in terms of ULS while the changes in internal forces may lead to there being insufficient margin with respect to the structural resistance of the element, it is not necessarily the case that a geotechnical limit state can occur. In relation to pile foundations, [128] conclude that as a result of the mode of deformation of the pile as it expands or contracts about a neutral point (i.e. there is always a point on the pile where deformation relative to the surrounding ground is zero) then failure in terms of plunging of the pile cannot occur.

To combine the effect of temperature variations with other permanent and transient action effects, values for accompanying variable action factors ψ_i have to be determined according to the principles of [129]. This means that a combination value $\psi_0 Q_k$ needs to be defined for the ULS, and a frequent value $\psi_1 Q_k$ and a quasi-permanent value $\psi_2 Q_k$ need to be defined for the SLS (ψ_i have values less than or equal to 1 and Q_k is the action effect associated with a characteristic temperature variation, ΔT_k.

Based on the temperatures monitored in operational thermally-activated piles, [104] suggest that the following factors could be proposed: $\psi_0 = 0.6$, $\psi_1 = 0.5$ and $\psi_2 = 0.2$. These values are broadly consistent with those used elsewhere in the Eurocode system where for thermal loading of buildings, [130] specifies values of 0.6, 0.5 and 0.0 for ψ_0, ψ_1 and ψ_2 respectively, and for bridge thermal loading 0.6 for ψ_0 and ψ_1, and 0.5 for ψ_2.

5. SUMMARY & FINAL REMARKS

There is an increasing interest across the World in the potential for using civil engineering structures constructed in contact with the ground as a means for allowing heat exchange with the ground within shallow geothermal systems. Doing so opens up congested urban sites for such systems and presents potential savings in the initial capital costs because costly deep boreholes can be either eliminated, or reduced in number. There is however an ongoing need to demonstrate the efficacy of these types of system with respect to both the potential for heat exchange and also the impact of heat exchange operations on the structure itself.

In terms of heat exchange, there is a substantive existing base of experience with respect to the use of conventional borehole heat exchange systems that can be applied to EGS. There are a number of particular characteristics of EGS which also limit this potential knowledge transfer however – in the case of piles, the short lengths and greater thermal mass compared to boreholes, and in other structures, the lack of geometrical symmetry allowing simplified solutions to be readily applied. There is an ongoing research effort to fully understand and to provide suitable interfaces with existing design tools that can account for these differences.

Thermal analysis of EGS is an area of current active research and collaboration. Because potential EGS vary widely in terms of layout, dimension generally and possible distribution of heat exchanger pipes, the development of universal analytical tools will likely prove problematic.

Consequently, at least for the time being, analytical techniques are only likely to be applied to pile EGS. Here it is recommended that analysis proceeds using either the validated adaption of the DST [43, 77] or one of the methods which fully captures the thermal capacity of the pile concrete, e.g. [71, 73, 74, 75].

For the majority of other EGS, through necessity, the use of full 3D numerical analysis will be more commonplace than is the situation with BHE where robust analytical models have been established. The development and validation of 1D elements similar to those used to represent BHE, to model heat exchangers embedded within EGS will however reduce the computational resources required for such analysis and is recommended as a practical approach in these cases.

It is apparent that the correct definition of thermal boundary conditions in these types of problem is crucial if realistic and conservative predictions of heat exchange potential are to be made. Consequently, for less common EGS, such as tunnels and basements, there is a need for more information regarding the internal environmental conditions that would dictate the heat flow potential.

One barrier to the development and implementation of further analytical and numerical methods is the scarcity of datasets for validation of analysis methods. Partnerships between industry and academia to develop such datasets on operational schemes will be key to future developments and hopefully encourage uptake on EGS systems in the future. A number of short term thermal response test type datasets are becoming available and longer term datasets are starting to be captured [71]. However, much remains to be done to move to fully validated analysis tools.

In addition, it is essential that tools developed in research, are made available in a practice ready format. This will involve the development of modules for existing building simulation software so that EGS can be integrated into the building energy design process, or it may involve development of further stand-alone software packages.

The thermal actions associated with heat exchange will impose deformation and/or additional internal forces on the geostructure. There is very little existing experience of the observation of these effects in either experimental or operational energy geostructures to provide insight into the mechanisms and likely magnitude of these effects. Again, this is a field of active and rapidly developing research and a number of studies currently in progress will expand this knowledge base in the near-future.

As is the case with solely thermal analysis of EGS, the development of techniques and methodologies for the thermo-mechanical analysis of EGS is an area of active research and collaboration. Likewise, the efficiency of such analyses will benefit from e.g. the implementation of 1D elements to represent the heat exchange pipes and its development is hindered by the lack of robust data sets against which the calculations can be validated.

The few articles that have been published where these types of structure have been modelled numerically have highlighted a number of issues that will require clarification in the future, e.g. the role of the temperature field, whether the soil thermally consolidates or is thermally expansive, the potential effect of cyclic loading and changes in effective stresses.

Currently, there are no clear design guides that provide a methodology for establishing thermal actions or how they should be dealt with in terms of safety and serviceability of the energy geostructure. A number of studies utilising numerical analysis have been undertaken and these have highlighted a number of aspects of the behaviour of these systems that should be attended to by both designers and researchers planning and undertaking field studies.

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Table 1. Thermal performance criteria

1. Energy delivered	An EGS scheme will be designed to deliver a certain proportion of the overlying buildings heating and cooling requirements and if this is not achieved then it may be considered to have failed. The consequences of failure will be greatest when no backup system is available. A suggested recommended approach would be to consider a 10% margin between required and expected energy supply as a starting value and then to revise it on a project-by-project basis depending on the specific conditions that occur [119].
2. Efficiency of system	The seasonal performance factor (SPF) gives the measured efficiency of an installed heat pump system. It is the ratio of the heat delivered for space heating and hot water and the electricity used to run the system. Under EU Renewable Energy Sources Directive [124], heat pumps are considered renewable if their SPF is greater than 2.5. This could also be a convenient measure of acceptable serviceability performance of EGS.
3. System temperatures	More work is required to establish guidance on operational temperature limits for EGS. Current practice tends to recommend that the lower limit on the heat transfer fluid temperature in BHE & EGS should be kept above freezing with a 2°C margin of error [125, 117, 118]. This is to ensure the ground does not freeze. It has been shown both theoretically and in practice, that for large diameter piles, temperatures lower than 0°C can be sustained within the heat transfer fluid for short periods and have no detrimental effects on the ground [126, 71]. Similar conclusions were reached by [6] but do not seem to have been acted upon in general practice. Due to the impact of high temperatures on pump efficiency and thus SPF, the circulating fluid is usually kept below 40°C, although values as high as 60°C are used [117].
4. Environmental	The development of SGE and EGS systems in the future will increasingly need to consider interactions with adjacent systems and/or the potential for heat to propagate outside site boundaries and thus, compromise future developments. Currently, there is no guidance or regulation relating to this issue.

Table 2. Mechanical performance criteria

1. Deformations	Field observation of pile thermal expansion and contraction gave measured pile head movement in the range of 40% to 60% of the theoretical maximum values, i.e. that of a free-standing column [101]. As a serviceability issue, this is only likely to require specific consideration if either very long piles are to be used, and/or large temperature changes are likely to be imposed. Limiting criteria for assessing the acceptability of such movements would have to be defined on a case-by-case basis, as is generally the case for structural movement limits currently.
2. Overstress	Field observations of the internal stress changes in PHE suggest values between 50% and 100% of the theoretical value for a perfectly restrained column may occur [127]. Such stress changes could lead to the compressive stress in a pile exceeding the maximum value allowed in some design codes. Tensile forces have also been observed during cooling [101]; in many design codes, the tensile strength of concrete is often ignored and thus, tensile reinforcement would be required. In addition, stress variations in reinforced concrete geostructures can induce cracking phenomena that may reduce concrete durability and this effect is often countered by the addition of extra reinforcing steel. While failure is unlikely consideration is required to ensure an adequate margin is maintained between the expected stresses in the EGS and the ultimate resistance of the constituent material.
3. Resistance	Strength and volume change characteristics of the ground may be altered due to temperature change, and cyclic expansion and contraction may lead to further alterations in the available resistance and stiffness. In some soil conditions, it will be necessary to verify, by means of specific tests, how the mechanical properties of the ground may vary with temperature change. Experience from offshore pile installations suggests that when initial static loading represents a large proportion of the available pile resistance, cyclic loading effects can have an important influence on stability. Until application specific guidance is developed for PHE, this experience can be used as an indicator of the need for consideration of cyclic thermal loading effects. This issue requires further investigation to provide complete understanding of the actual risk and how this should be accommodated in design.

FIGURES

Figure 1. Examples of heat exchange systems utilizing geo-structures – pile foundations, retaining wall and tunnels.

Figure 2. Common Types of PHE: a) small diameter driven piles; b) precast hollow concrete piles; c) rotary bored piles; d) contiguous flight auger piles.

Figure 3. Eskilson's [31] g-functions for various borehole configurations

Figure 4. Comparison of SBM based design tool to AHSRAE Handbook Method based on data from four monitored buildings (data from [60])

Figure 5. Derived pile g-functions for a single 30 m long pile heat exchanger assuming $\alpha = 1 \times 10^{-6}$ m^2/s: a) 1 m diameter pile; b) 300 mm diameter pile

Figure 6. Outlet temperature observed during thermal tunnel trial, [92]

Figure 7. Heat exchange rate observed during thermal tunnel trial, [13]

Figure 8. Inlet (T_{in}) and outlet (T_{out}) fluid temperatures versus time (hours) from model wall tests and from the thermal-resistance model, [90]

Figure 9. Heat flow from thermally-activated wall panel to tunnel void and across the wall-soil interface, [98]

Figure 10. Comparison of FEA model and observed thermally-activated pile response, [102]

Figure 11. Predicted and observed a) pile head displacement and b) pile axial strain during thermal pile test, [108]

Figure 12. Effect of temperature field and soil CTE on pile axial stress response during heating and cooling for a) adiabatic ground surface and b) constant temperature ground surface, [112]

Figure 13. Effect of cyclic thermal loading on a) settlement and b) pile internal stress response for pile foundation in normally consolidated clay, [83]

Figure 14. Effect of thermal loading on a) pile axial stress for two heating modes and two pile head restraint conditions and b) horizontal effective stress changes for pile foundation in thermo-elastic soil, [82]

Figure 15. Alteration of wall mechanical response due to changes in thermal boundary conditions and heating of wall panels, [98]

Figure 16.The interactions between the geotechnical and thermal design processes

Figure 1

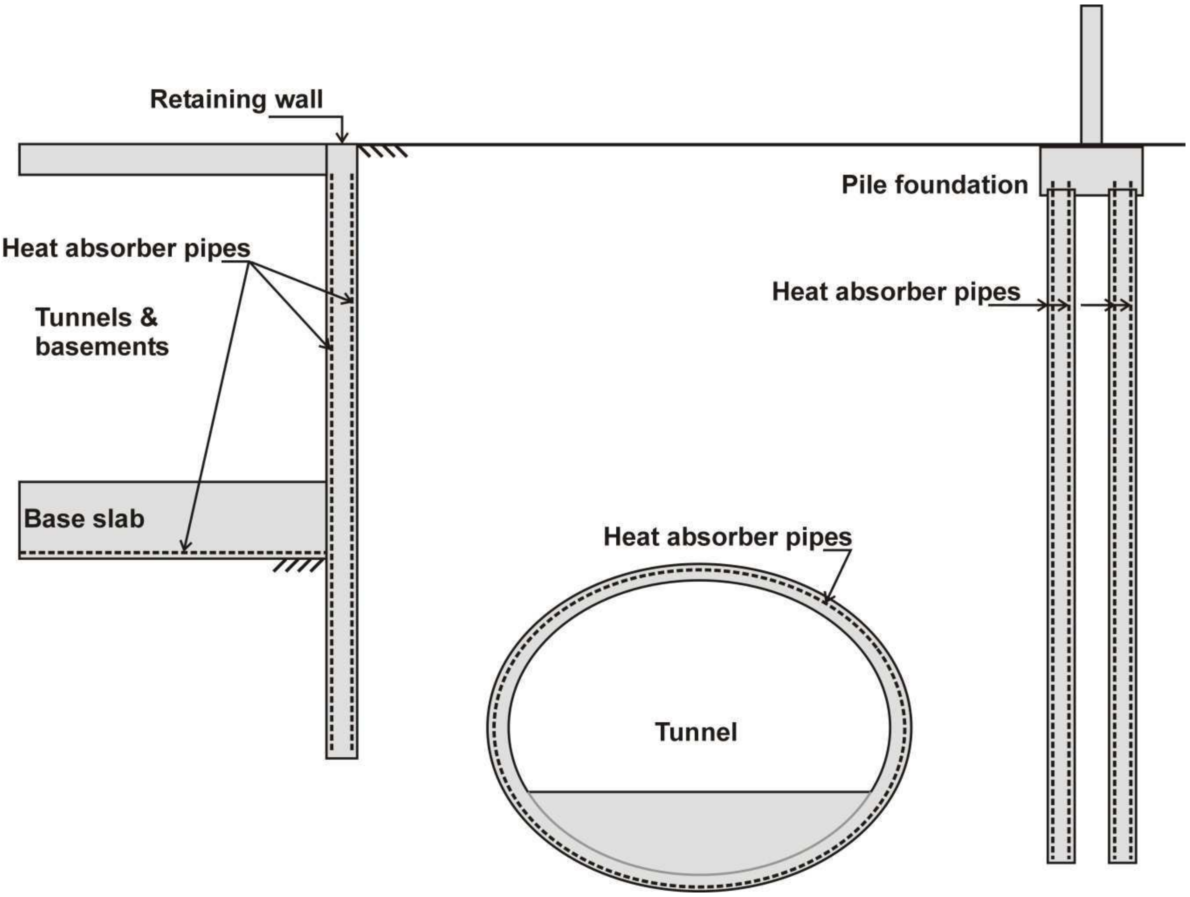


Figure 2

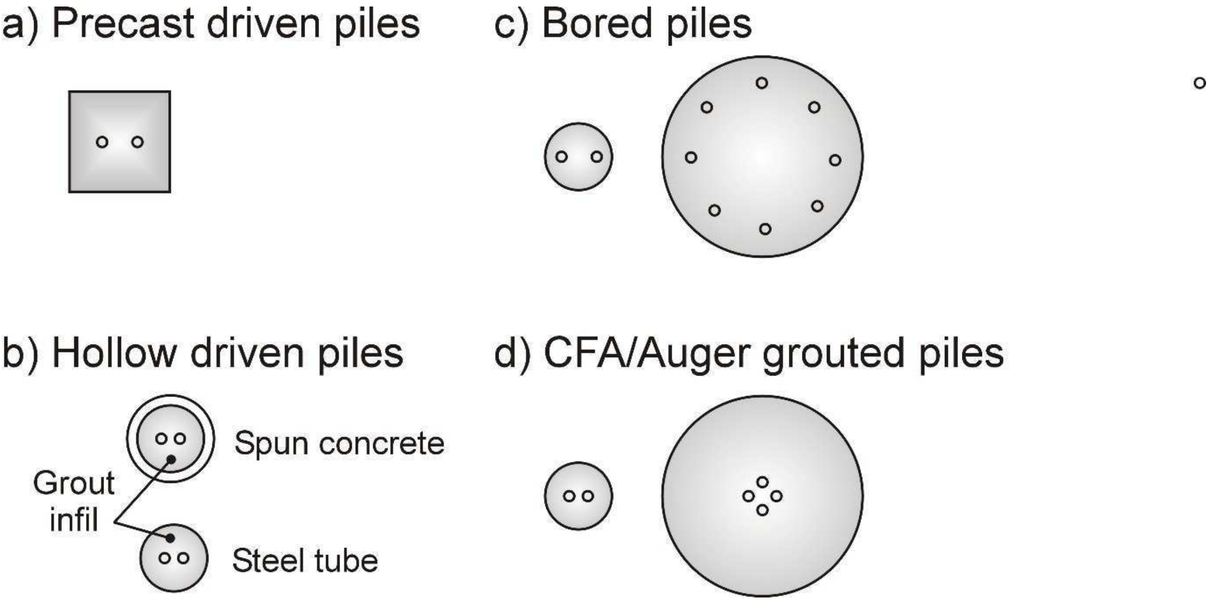


Figure 3

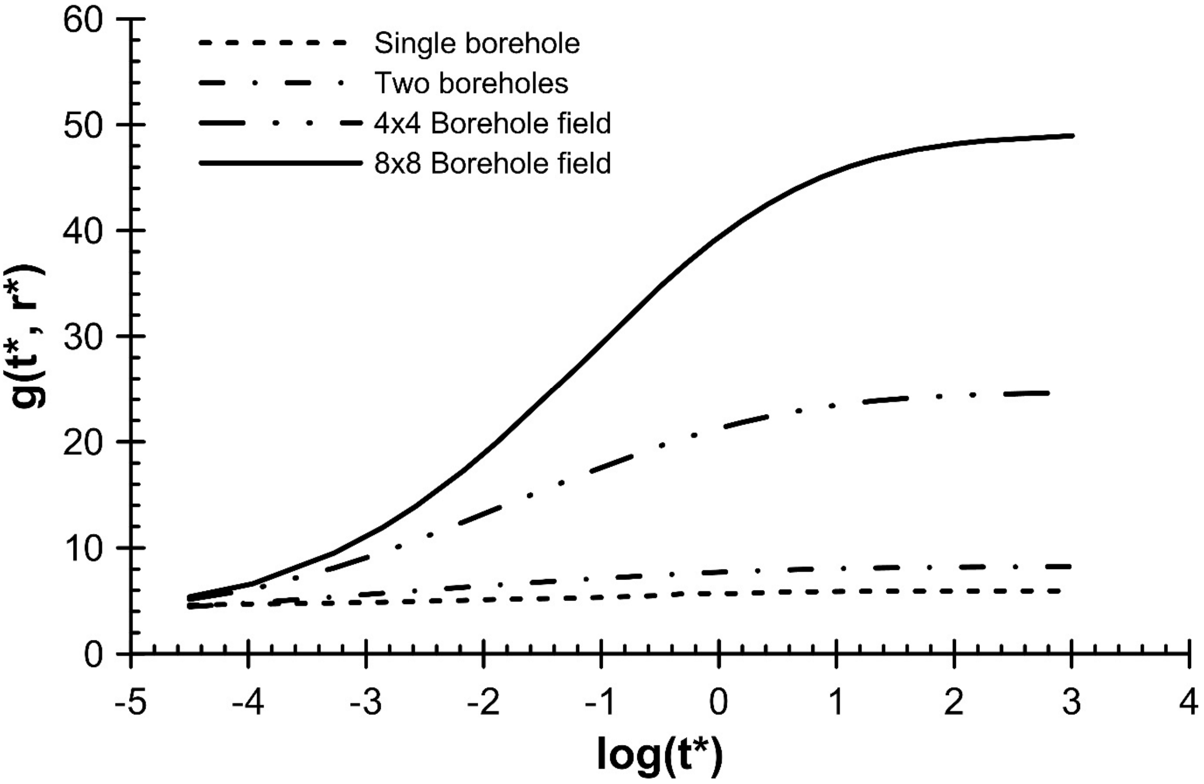
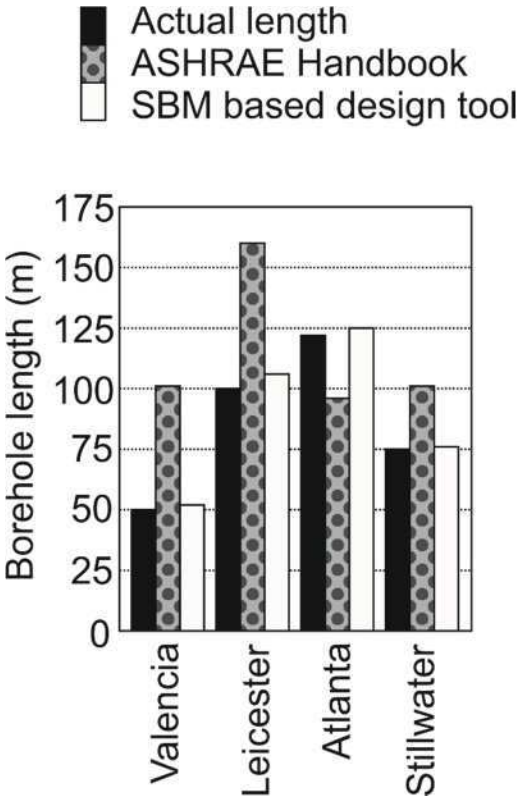


Figure 4



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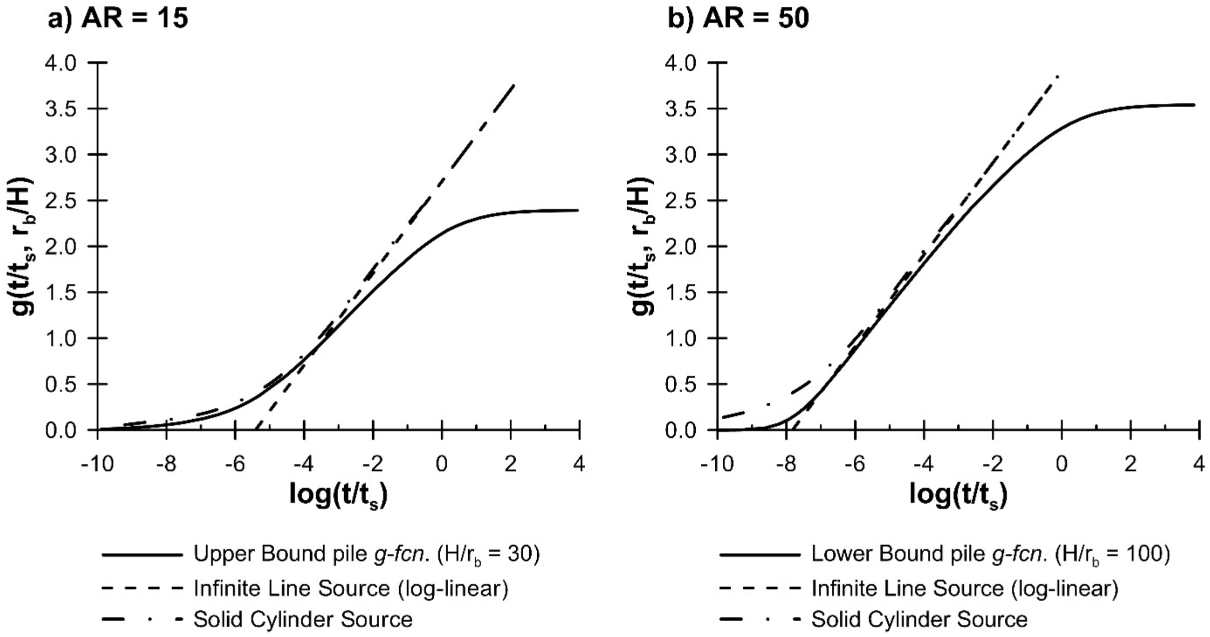

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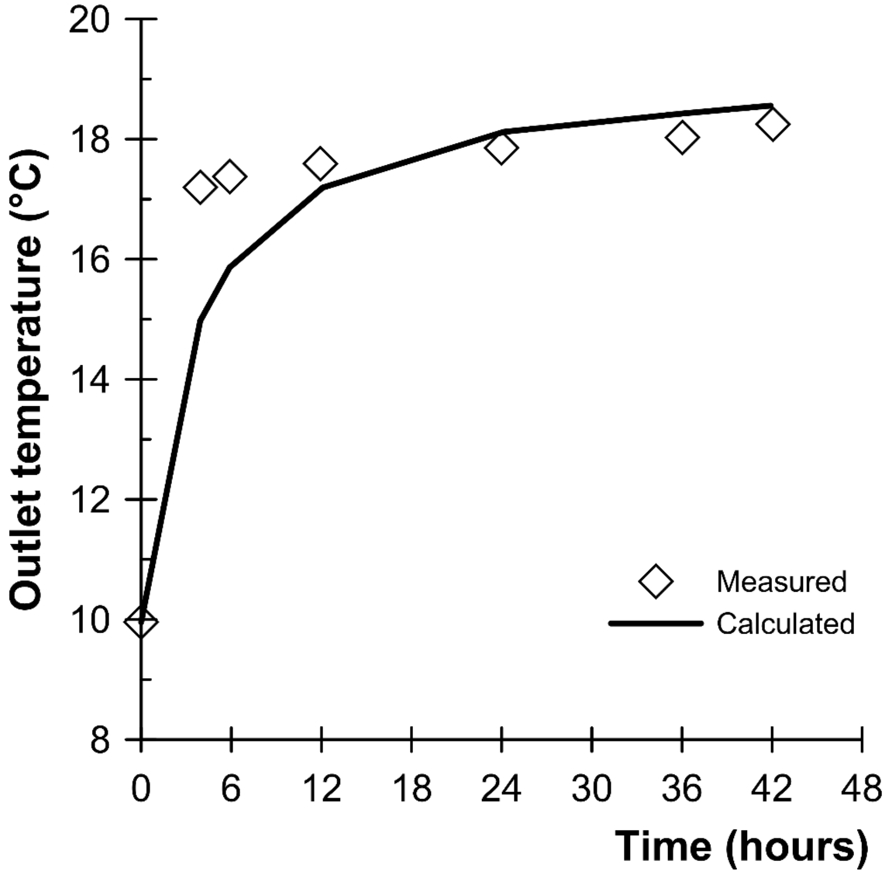

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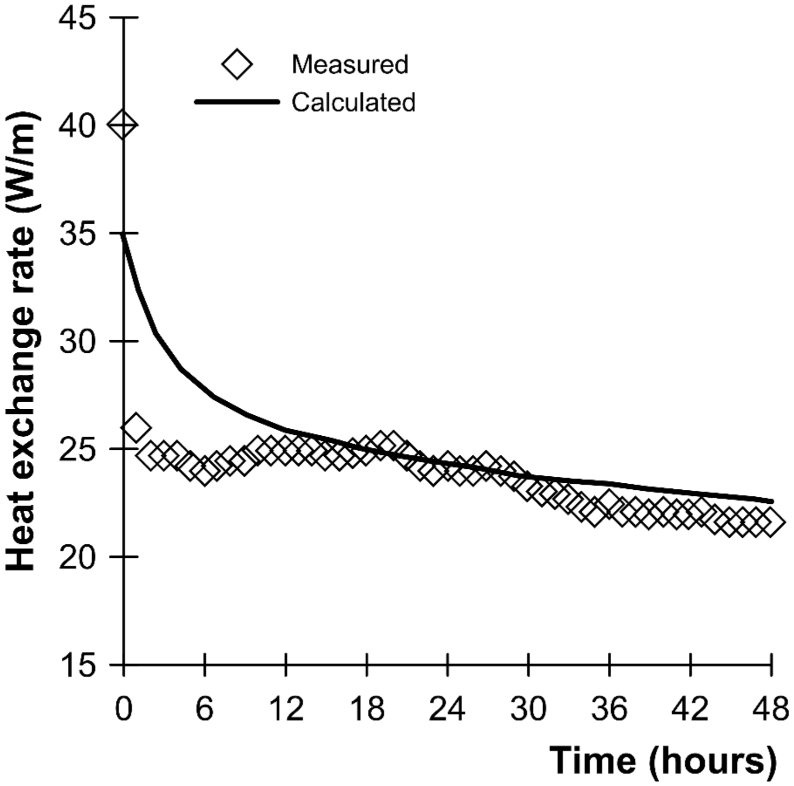


Figure 8

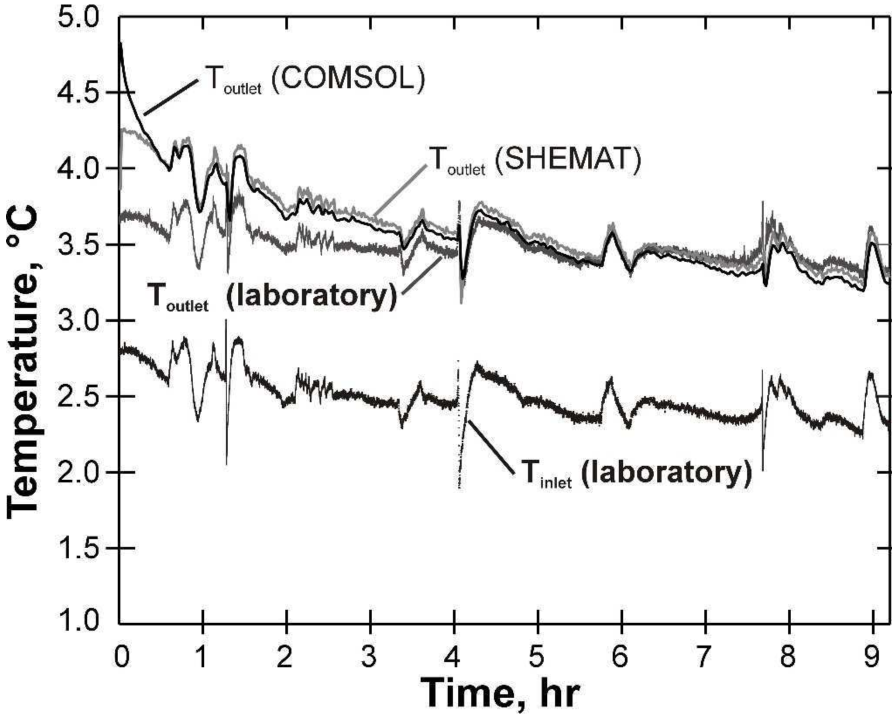


Figure 9

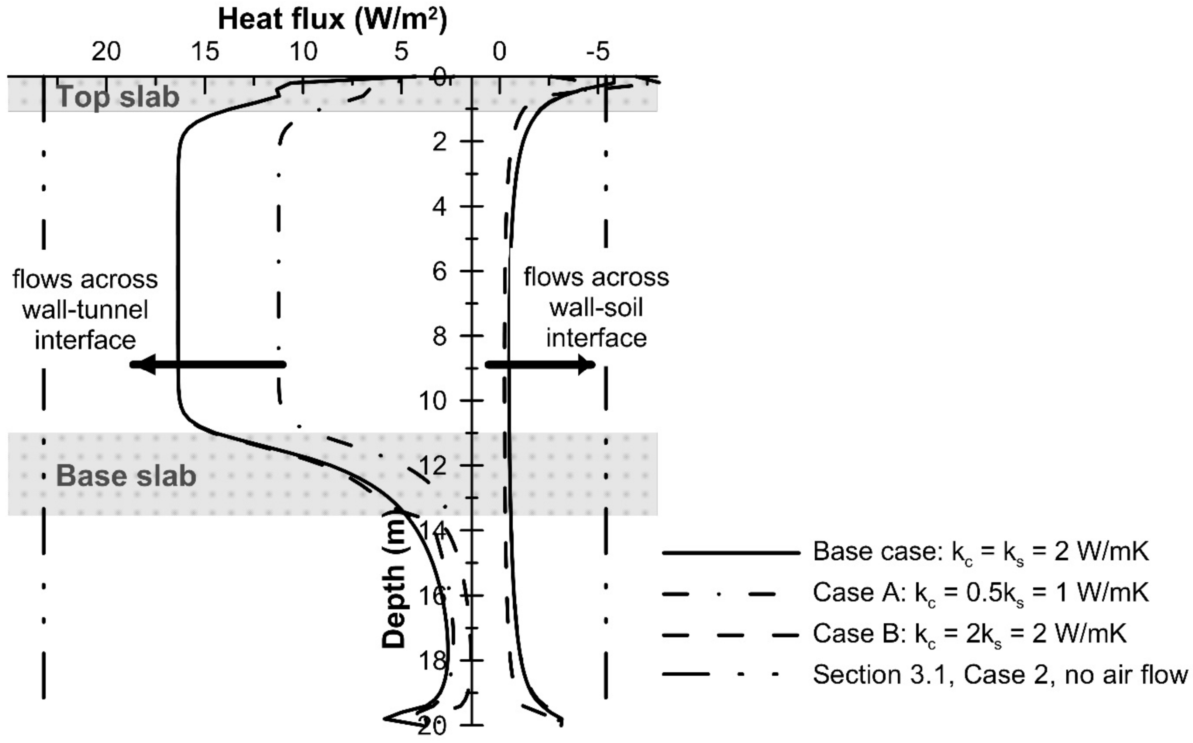


Figure 10

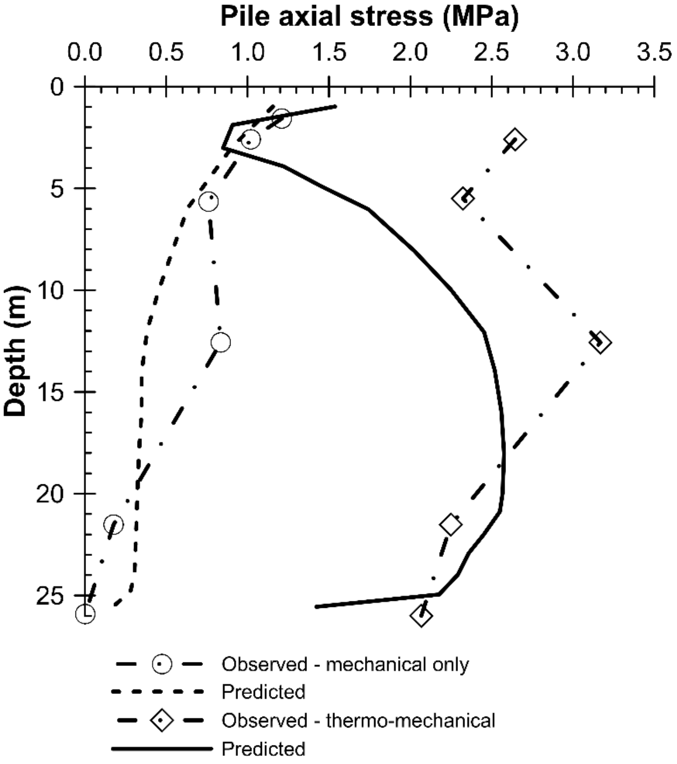


Figure 11

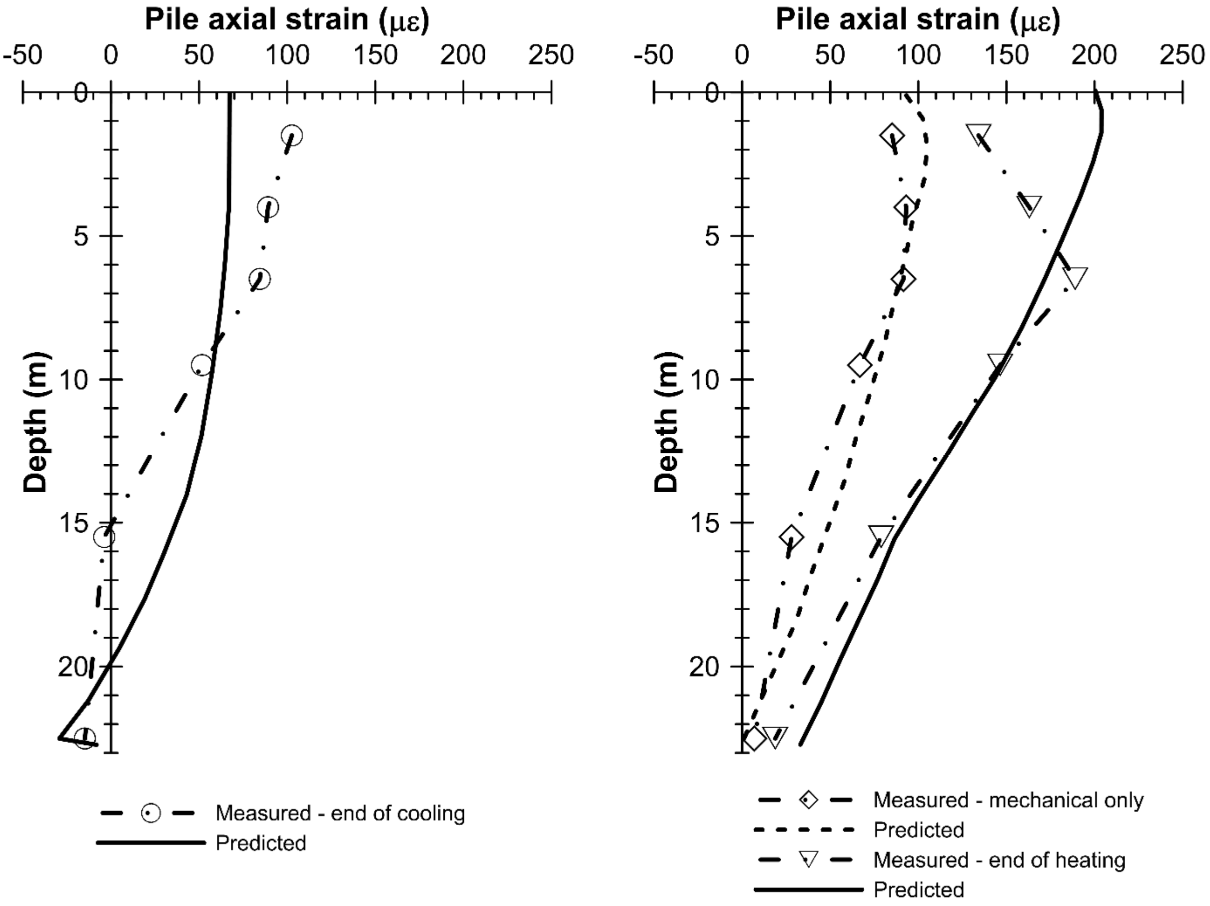
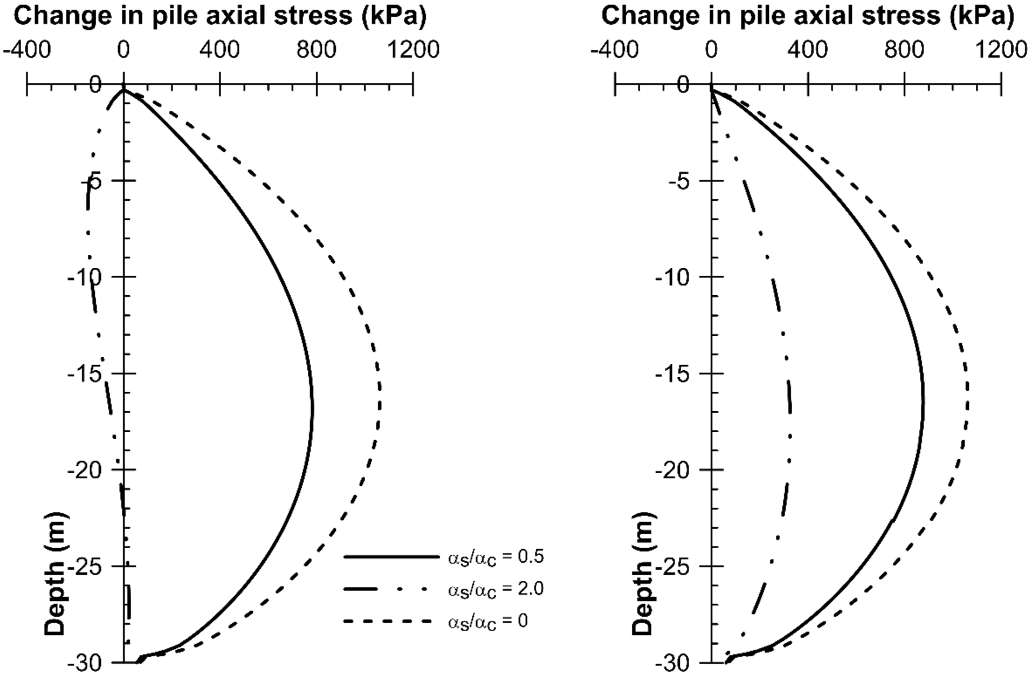
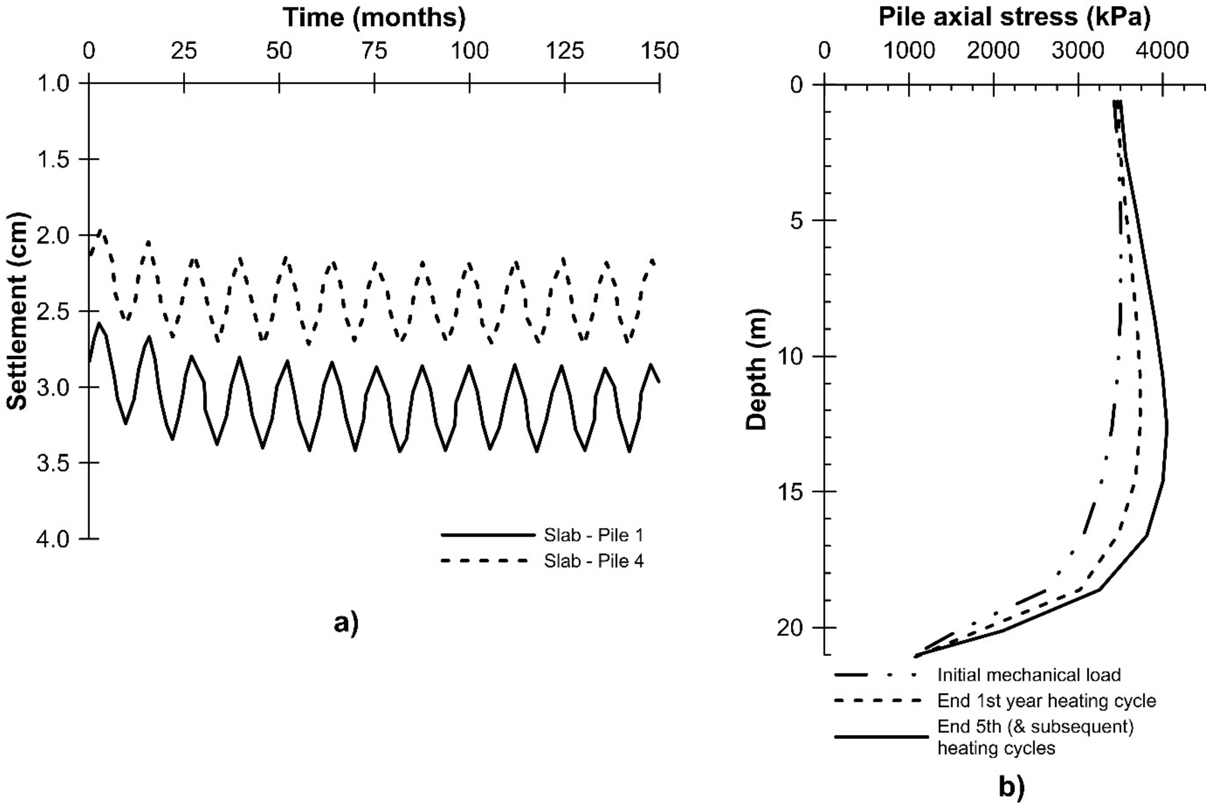


Figure 12



a) b)

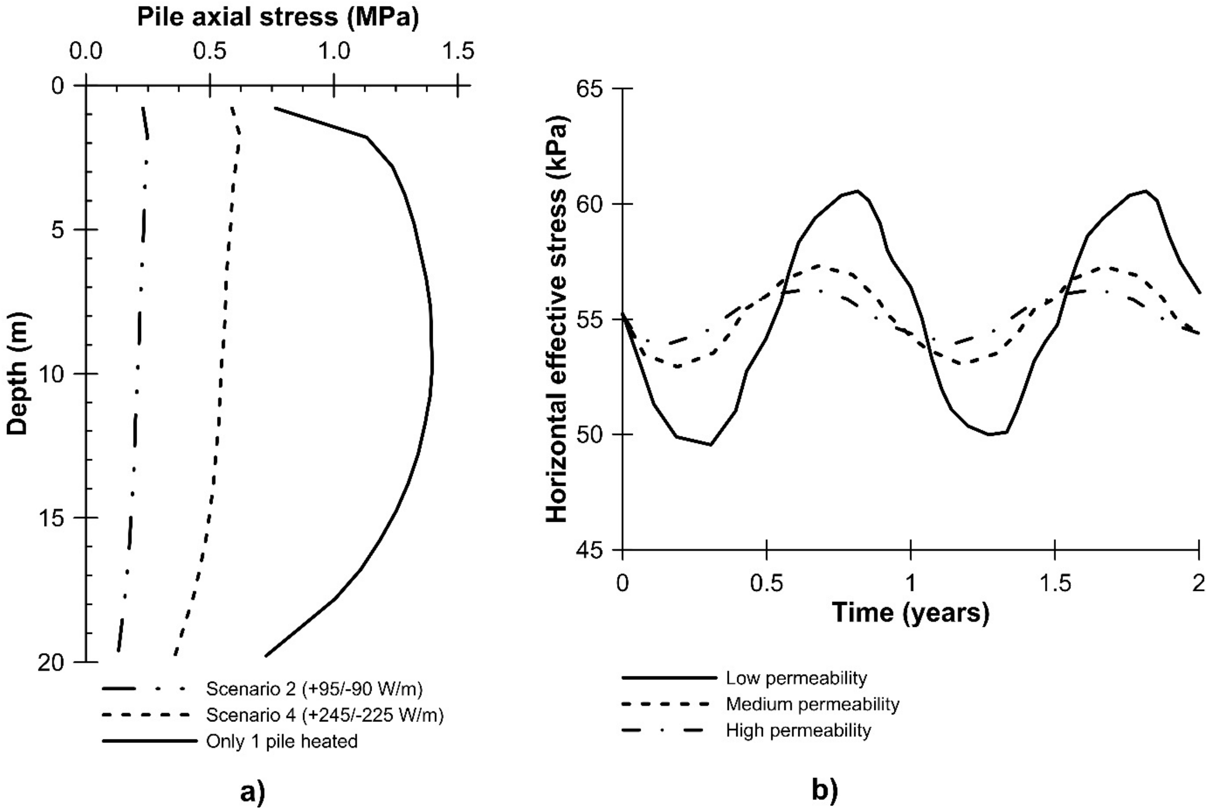
Figure 13



a)

b)

Figure 14



a)

b)

Figure 15

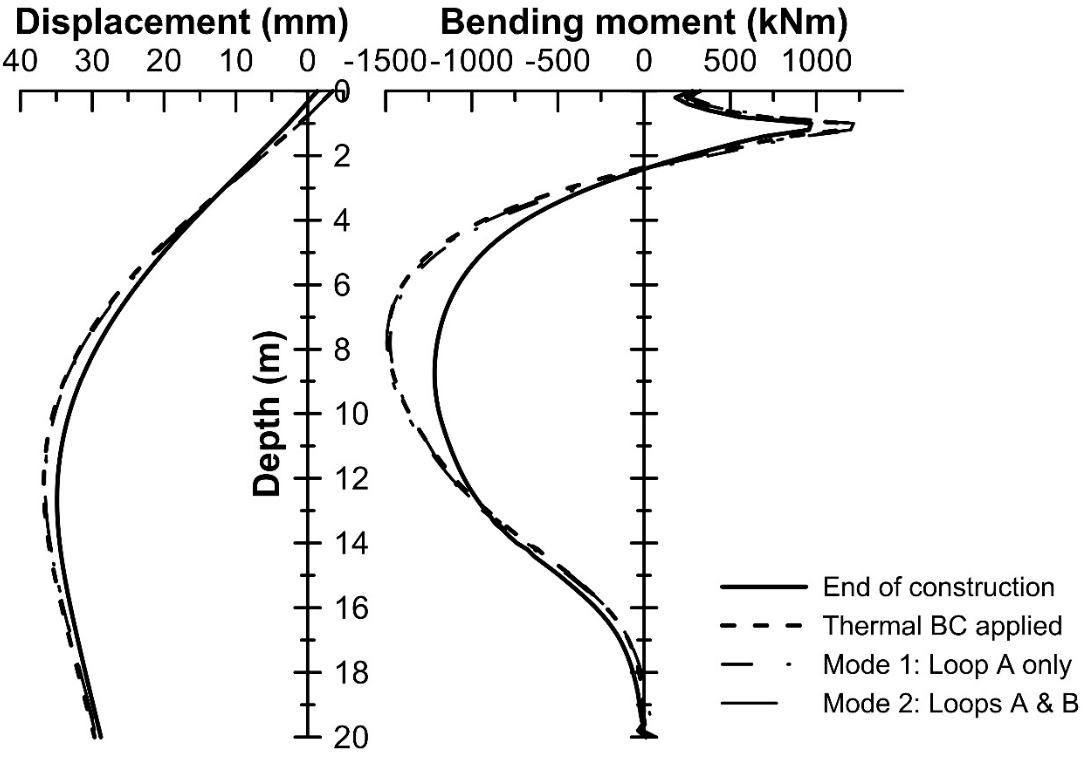


Figure 16