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# Thermal performance of seasonally, thermally-activated floating pile foundations in a cohesive medium


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**ABSTRACT**

The thermal-activation of pile foundations for use within shallow geothermal energy systems has received much attention with a number of studies having reported full- and small-scale testing and/or numerical analysis. Various conditions in terms of pile type, ground profiles and thermal loading, have been considered in these studies, leading to a broad understanding of the thermo-mechanical behaviour of thermally-activated pile foundations. One area that requires further attention is the clarification of the foundation response under seasonal cyclic thermal loading. This study systematically assesses the impact of cyclic thermal loading in relation to the initial mechanical loading, for isolated floating piles and pile groups in a cohesive soil medium. For piles where the shaft resistance dominates the pile total resistance, it was found that irrecoverable movement will be small and thermal stress and pile head movements change in a cyclic and regular manner. It is shown that the effect of the coefficient of thermal expansion of the soil, is much reduced from that suggested in studies using constant thermal loads applied over long periods. The effect of the overlying building was explored and it is shown that thermal-activation of the pile foundation mitigates the effect of the imposition of a higher average temperature at the surface.



**KEY WORDS**: shallow geothermal energy, pile foundations, soil-structure interaction, thermal analysis


Main text: 8350 words

Figures: 12 Tables: 2

## 1. INTRODUCTION

### 1.2 Overview

Air-conditioning systems for buildings utilise a considerable proportion of existing energy resources, which are often polluting and non-renewable. In the EU-28, around 80% of all residential energy use is for the provision of space heating and cooling and hot water, and around half this energy is derived from fossil fuels. In addition to the dichotomy of reducing Green House Gases (GHG) while meeting existing needs; global demand for energy services is expected to increase by as much as an order of magnitude by 2050 (Dincer, 2000) [1]. This has led to the search for alternative technologies that satisfy building heating and cooling needs while reducing energy consumption and GHG emissions.

One way forward is the widespread implementation of shallow geothermal energy (SGE) systems. Conventionally, ground–coupling in SGE systems is provided via pipe systems laid either horizontally, in shallow trenches, or vertically, in boreholes, however the cost of these groundworks can represent a large proportion of the installation cost of the system. Increasingly, building elements in contact with the ground, referred to as energy geo-structures, are being utilised as heat exchangers (Brandl, 2006) [2]. Taking this approach leads to a substantial reduction in the cost of inserting the heat exchangers, improving the economic viability of the SGE system. It also makes the use of SGE more feasible for sites with limited space which precludes large borehole fields, especially urban developments.

Thermally-activated (TA) piles are the most common form of energy geostructure and act as load-bearing foundations while also providing for heat exchange with the ground as part of a SGE system. TA piles were first used in Austria in the 1980s (Brandl, 2006) [2] but their application has accelerated in the last two decades, as the search for renewable heating and cooling sources intensified. In the same period, much research has been undertaken to develop a better understanding of the mechanisms of behaviour of TA piles, so as to provide assurance regarding the efficacy and safety of the application in SGE systems.

In the following, research relevant to this study has been synthesised, with a focus on the effect of thermal loading time history, and then aspects of this response are examined via numerical analysis of a pile in a cohesive medium, from which the implications for the use of isolated TA piles and pile groups are discussed.

### 1.2 Full and Small Scale Tests on Isolated Piles and Pile Groups subject to Cyclic Thermal Load

The focus of this study was on the response of floating piles in cohesive media where the load resistance of the pile derives primarily from the shaft resistance, $R_{s,u}$ with the base resistance, $R_{b,u}$

providing only a small proportional of the total compression resistance, $R_{c,u}$. In developing the subsequent discussion, it is hypothesised that not only the mechanical but the subsequent thermo-mechanical response of single piles and pile groups is controlled by the factor of safety with respect to the ultimate shaft resistance, FS-shaft = $R_{s,u}/F$ (F is the applied mechanical load). In this article, the global factor of safety will be identified as FS-global = $R_{c,u}/F$, and when the base resistance is a small proportion of the total, in effect FS-global $\approx$ FS-shaft.

### 1.2.1 Full-scale testing

Despite the increasing number of full-scale tests involving isolated TA piles, few involve cyclic thermal loading; instead a variety of differing thermal loads have been used: heating pulses (Akrouch et al., 2014; Laloui et al., 2003; Santayana et al. 2018) [3 - 5], alternation between extended periods of heating and cooling (Bourne-Webb et al., 2009; Sung et al., 2018) [6, 7], high frequency (daily-weekly) cycling of heating or cooling (Szymkiewicz et al., 2015; Faizal et al., 2016 & 2018; Sutman et al., 2017) [8 - 11] and the functioning of operational systems (McCartney & Murphy 2017) [12]. One full-scale pile group test has been reported to-date (Mimouni & Laloui, 2015; Rotta Loria & Laloui, 2017) [13, 14] in which the thermal loading involved heating of differing configurations of four thermally-activated piles, located within a larger piled foundation.

Because of the very different conditions used in each test, it is quite difficult to draw any significant conclusions regarding the impact of realistic cyclic thermal loading on isolated piles, at this scale. However, these studies have informed our basic understanding of the mechanisms of behaviour of TA piles. While none of the studies has reported unstable pile response, (Faizal et al., 2016 & 2018) [9, 10] report a progressive accumulation of thermal effects for a pile in dense sand, which is attributed to unbalanced heating/cooling loads; similarly (McCartney & Murphy, 2017) [12] and (Mimouni & Laloui, 2015) [13] observed thermal effects in addition to the simple thermo-mechanical response of the test piles, which were attributed to the progressive thermal-activation of the surrounding ground. In terms of group effect, (Mimouni & Laloui, 2015; Rotta Loria & Laloui, 2017) [13, 14] demonstrate how thermal-activation of differing configurations of piles, individually or as a group, alters the observed pile response and that this alters with time as heat from one pile reaches others, with pile thermal movements increasing and thermal stress reducing.

In Figure 1, Bourne-Webb at al. (2019) [15] and Bourne-Webb and Bodas Freitas (2020) [16] have collated the results from these tests and presented them in terms of the key design parameters, normalised as follows:

- Vertical displacement at the head of the pile(s), $y_{th,0}/y_{th,free}$ (where $y_{th,0}$ is the pile head thermal displacement, positive downwards, and $y_{th,free}$ is the thermal movement of an unrestrained column the same length as the pile being considered, equation (1));
- Maximum thermal axial stress $\sigma_{th,max}/\sigma_{th,fixed}$ (where $\sigma_{th,max}$ is the maximum axial thermal stress, tension positive, $\sigma_{th,fixed}$ is the theoretical maximum stress that can be generated in a fully restrained column, equation (2)).

$$y_{th,free} = (-\alpha.\Delta T)L \tag{1}$$

$$\sigma_{th,fixed} = (-\alpha.\Delta T)E \tag{2}$$

Where the minus sign ensures the normalised values are positive when thermal stresses are compressive during heating and tensile during cooling, and the pile head displacement is upwards during heating and downwards during cooling, $\alpha$ is the linear coefficient of thermal expansion (CTE) of the pile material, $\Delta T$ is the average uniform temperature change imposed on the pile, L is the pile length and E the modulus for the pile material.



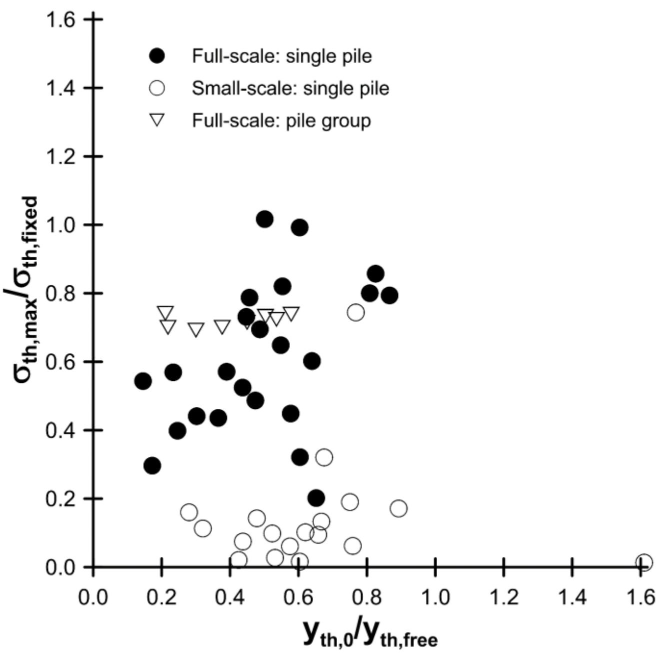


**Figure 1. Normalised thermal responses of full-scale single pile and pile group tests, and small-scale tests on single piles, after [15, 16]**

These data illustrate how the displacement response of the TA pile is associated with the internal stress response with larger thermal movements, resulting in reduced maximum thermal stress. Bourne-Webb and Bodas Freitas (2020) [16] also highlight that in the group test reported by (Mimouni & Laloui, 2015) [13] and (Rotta Loria & Laloui, 2017) [14], the TA pile group is in the corner of a conventionally piled raft foundation which restrains the test pile heads, leading to a thermal response (larger $\sigma_{th,max}/\sigma_{th,fixed}$ and reduced $y_{th,0}/y_{th,free}$ compared to isolated piles, open-triangles Figure 1) which is particular to the test conditions, and may not be generalised to other TA pile groups.

### 1.2.2 Small-scale testing

Small-scale testing, at 1-gravity or in the centrifuge at accelerations of multiple-gravities, is often promoted as a cost effective alternative to full-scale testing, and a number of studies of TA isolated piles and small groups have been published. In reviewing a number of these studies, Bourne-Webb and Bodas Freitas (2020) [16] note that there is a strong trend for these tests, which were mostly in sand, to impose significantly less restraint on the pile than that observed in full-scale tests, leading to much smaller thermal stress changes and larger pile head movement, Figure 1. Few studies have involved small-scale testing in cohesive materials.

Using centrifuge testing to analyse TA piles in lightly over-consolidated (OC) and moderately OC clay, (Ng et al., 2014) [17] report that after five cycles of heating and cooling, in both cases a gradual accumulation of pile head settlement occurred, with that for the lightly OC clay being nearly double that of the moderately OC clay. It was also apparent in the former that settlements were continuing to accumulate throughout the test, while in the latter the rate of settlement had reduced substantially at the end of the five cycles. The response of the moderately OC clay was somewhat unexpected as the thermal response of the clay was expected to be thermally-elastic and the thermal effects recoverable. It is reported that in both cases that the majority of the non-recoverable settlement occurs during the cooling phases and the response is quasi-linear in the heating phases (with the pile head movement approximately equal to the thermal expansion of the pile).

(Nguyen et al., 2019) [18], present similar effects for a TA pile in a compacted clay with the thermally induced settlements seeming to largely stabilise after 4 to 5 cycles of heating and cooling. (Wu et al., 2018 & 2019) [19, 20] also report ratcheting and an increase in pile head settlement. (Wu et al., 2019) [20] examined the effect of cyclic thermal loading on floating and end-bearing piles, and in the case of the floating piles reported a progressive increase in the mobilised base reaction (provided by a specially devised spring support) during each heating cycle. This latter effect is significant to this discussion as it implies that the pile base must be settling during each heating cycle. If the first cycle of each of each the above model tests is examined, it is apparent that when the pile is first heated the expected pile head heave (upwards movement) is small, less than 10% of $y_{th,free}$ or even a settlement. This means that the rest of the thermal expansion must be pushing the pile base down, hence the increased mobilisation reported by (Wu et al., 2019) [20]. In the subsequent cooling cycle, the pile contraction then appears very large but is exaggerated by the initial unseen pile base settlement and associated mobilisation of base reaction which must be needed to ensure load equilibrium in the thermal cycles. Bourne-Webb and Bodas Freitas (2020) [16] suggested that this effect may be indicative of low shaft restraint and transfer of load to the pile base during cyclic thermal loading, to ensure equilibrium is maintained.

### 1.3 Numerical Analysis of Isolated Piles and Pile Groups subject to Cyclic Thermal Load

A number of investigations using numerical analysis to study TA piles have been reported. These studies consider a range of potential pile and soil thermal and mechanical behaviours, geometries (Zito et al., 2020) [21], thermal loads and boundary conditions (Bourne-Webb et al. 2020) [22].

#### 1.3.1 Thermally-activated isolated piles

Some relevant studies on the response of a TA isolated pile are discussed below. In this discussion, the mechanical load is compared to the ultimate shaft resistance, $R_{s,u}$ calculated based on the parameters quoted in each article. This has been done in order to obtain an indication as to how the load-displacement response of the pile might develop as a function of FS-shaft = $R_{s,u}$ /F > 1.0 (where F is the applied load).

(Olgun et al., 2014) [24] and (Adinolfi et al., 2018) [25] consider a pile in a cohesive medium in which the applied load is estimated to have a factor of safety of at least 2.0 both globally and with respect to the shaft resistance, i.e. FS-global = 2.0 ≈ FS-shaft. Though using different models for the pile-soil resistance, (Gawecka et al., 2017) [26] and (Di Donna & Laloui, 2015) [27] consider piles in over-consolidated and normally-consolidated clay soils respectively which also have FS-shaft around 2.0. Although the thermal loading applied in each study differs, the cyclic thermal response was thermo-elastic. However, other effects are superimposed on the cyclic response. In (Olgun et al., 2014) [24], there are unbalanced heating/cooling loads which lead to a progressive change in the pile head movements and axial stresses as the surrounding ground is thermally-activated over time, (Adinolfi et al., 2018) [25] and (Gawecka et al., 2017) [26] demonstrate a similar effect. (Di Donna & Laloui, 2015) [27] used an advanced soil model to capture thermally-induced soil consolidation in which the associated foundation settlements are superimposed on the cyclic pile-soil thermal interaction, which is essentially thermo-elastic.

Tsetoulidis et al. (2016) [28] present a numerical study based on the Lambeth College test pile [6] modelling the main soil stratum as an undrained cohesive material. The effect of increasing the initial mechanical load on the subsequent response during sustained cooling and heating was examined. The results illustrate that as the initial pile mechanical loading increases (FS-global falls from about 4 to 1.3), the mobilised shaft and base resistances have to increase and that leads to a progressive alteration in the way the pile reacts to cooling and heating. At lower mechanical loads (FS-global > 2), cooling leads to reduced compressive stress and heating to higher. However, at higher mechanical loads (reducing FS-global), during cooling and heating, the axial loads become more compressive compared to the axial loads under mechanical loading alone.

Though based on frictional models for the soil resistance, (Pasten & Santamarina, 2014) [29] used the load-transfer method and demonstrated that while the external mechanical load was less than the shaft resistance, pile thermal settlements were fully recoverable even after 50 cycles of heating and cooling. Conversely, when the mechanical load exceeded the shaft resistance, then irreversible settlements would accumulate as the number of cycles increased though at a gradually slower rate. Similar effects have been reported in studies using other numerical methods, (Saggu & Chakraborty, 2014) [30], (Rammal et al., 2018) [31], and (Wang et al., 2019) [32].

### 1.3.2 Thermally-activated pile groups

When examining pile group behaviour under thermal load, one must first consider the impact of mechanical loading and in particular, the effect this has on the mobilised shaft resistance. It is accepted wisdom that piles within a group will interact mechanically with each other and that this interaction is amongst other things a function of soil homogeneity, pile group size, pile-soil relative stiffness, pile length to diameter ratio, L/D and the pile spacing to diameter ratio (s/D) – the closer the piles are to each other, the more they interact with each other, and the greater the pile settlement compared with that of an isolated pile with the same average load applied, (Poulos, 1968 & 1979) [33, 34]. This behaviour can be described in a simplified manner by interaction factors that act as a multiplier to the single pile behaviour to reflect the relative influence of other piles within the same group and (Rotta Loria and Laloui, 2016) [36] have proposed using a similar approach for assessing the movement of TA pile groups.

The impact of the initial mechanical load can be seen by comparing the analysis of an isolated pile and a pile group presented by (Di Donna and Laloui, 2015) [27]. Figure 2(a) illustrates the alterations in pile load-transfer within the group, compared to the single pile: (i) about a third of the applied load transfers to the pile bases within the group compared to less than 10% on the single pile; (ii) the axial load profile is close to vertical in the upper half of the group piles (especially on the centre pile), implying a reduction of mobilized shear stress compared to the single pile; and it is slightly more inclined in the lower part, implying increased mobilized shear stress. Though not shown here, under mechanical loading, (Di Donna and Laloui, 2015) [27] report that the group average pile settlement was approximately double that for the isolated pile, this is a result of the compression of the soil between the piles and transfer of load to the pile bases within the group. In Figure 2(b) from (Jeong et al., 2014) [37], the axial load profile indicated for the pile group shows a similar effect. This is a general effect that is to be expected, despite FS-shaft being around 2 for the average load applied to each pile in the group.

When thermally-activating the pile group, Di Donna and Laloui (2015) [27] report that, after 10 years of cyclic heating and cooling, the response is similar to that of the isolated pile, with a small increment in average settlement due to thermally-induced consolidation effects that occurred in the first year, followed by an essentially thermo-elastic cyclic displacement and stress change, during the remaining thermal load cycles.

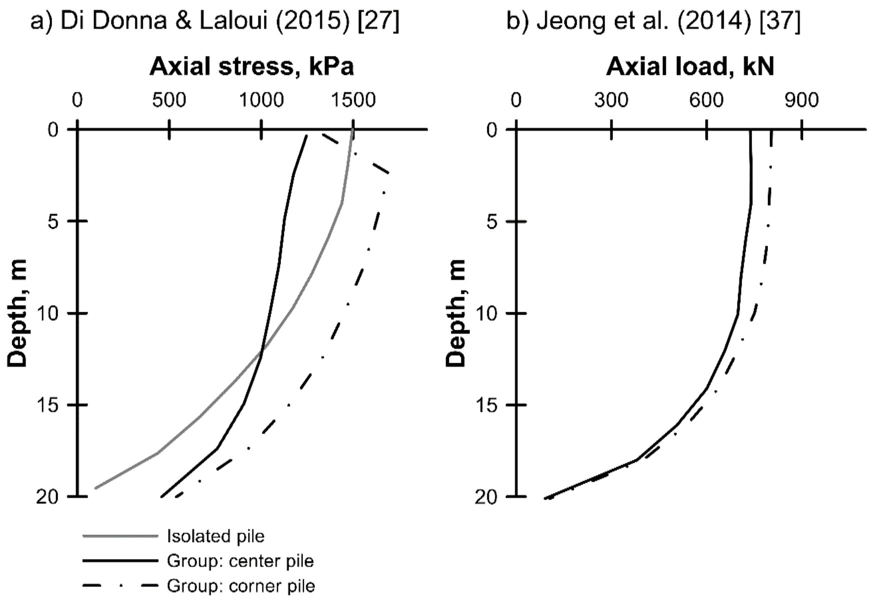


**Figure 2. Mobilization of pile resistance on isolated and grouped piles**

Other studies either assume or report a thermo-elastic response. Analysing a small piled raft, (Salciarini et al., 2015) [38] report that under sustained thermal load, thermal axial loads reduce with time as the heat diffuses from the pile into the soil which is assumed to have a CTE that is three-times that of the pile. Modelling a cyclically TA pile group, (Suryatriyastuti et al., 2016) [40] applied a pile-soil interface model that allows for cyclic degradation of the shearing resistance, inevitably leading to predictions of ratcheting vertical displacement behaviour with load transferring progressively from the shaft to the base, and the axial stress in the pile becoming more compressive. (Salciarini et al., 2017) [41] modelled a unit cell of an infinite raft in a poro-elastic soil medium, subjected to two years of thermal cycling modelled using a periodic temperature function, and reported that vertical movements were thermo-elastic, reflecting the ability of the stiff raft to redistribute the thermal effects across the group, but there was some drift in the thermal axial stress mobilised from cycle to cycle. The authors also noted that the pile response was affected by the time duration of the thermal load and how this related with the time scale for thermal and hydraulic conduction in the soil.

### 1.4 Synthesis

While the results from full- and small-scale testing of TA piles and pile groups have promoted the development of our understanding with respect to the underlying mechanisms of behaviour, they have been less useful in terms of understanding the long-term impact of cyclic thermal loading and the details of pile group interaction effects, except in a very general sense. Numerical modelling on the other hand seems able to reproduce the response seen in full- and small-scale TA pile tests, and this allows us to use these tools to investigate other scenarios.

Based on the above it is hypothesised that for isolated thermally-activated piles loaded in compression, while the FS-shaft is in excess of 1.0, essentially thermo-elastic behaviour can be expected but other thermal effects (e.g. unbalanced thermal loads, thermally-induced consolidation, prescribed strength degradation on the pile-soil interface) may impose an additional component of thermal movement/load. On the other hand, when FS-shaft falls below 1.0 (and noting there may be a transitional behaviour around FS-shaft = 1.0), then a thermal ratcheting effect will be mobilised, as no further shaft resistance can be mobilised when the thermal expansion/contraction of the pile is in the same direction as shearing imposed by the mechanical load. To balance this, an additional pile base reaction needs to be mobilised which requires an increment of pile base settlement. In the case of balanced cyclic thermal loads (i.e. no net cooling or heating), the thermal ratcheting appears to diminish after less than 10 cycles.

In pile groups, depending on the pile configuration, the mobilization of pile resistance in response to mechanical loading will differ from that for an isolated pile with the same average pile load. Because of pile-soil-pile (and when present, the pile cap/raft) interaction, pile settlements increase, mobilisation of shear stress on the upper part of the pile-soil interface is suppressed while it increases in the bottom part and if needed, an additional base reaction will be mobilised. This alteration in mobilisation of shaft resistance under mechanical load, will impact on the response of the pile group when it is then thermally-activated. Current approaches e.g. (Rotta Loria and Laloui, 2016) [36] consider the mechanical and thermal interaction response to be equivalent effects.

To lend clarity to the above, this study extends the work of (Bodas Freitas et al., 2013) [39] and (Bourne-Webb et al., 2016) [43] to examine the response of thermally-activated piles in cohesive soils under cyclic thermal loading. Whereas these previous studies modelled the pile thermal response under steady state thermal conditions, in this study the thermal loading has been represented by a periodic function which mimics balanced seasonal cyclic heating and cooling thermal loads. The work also considers the surface temperature boundary via an "outside" condition, as if the pile head were exposed to the atmosphere (say, in a pile test), and an "inside" condition, as if at the pile head there was a temperature controlled structure (as will be the case operationally), for details see Section 2.3. Further, to examine pile-soil-pile interaction effects, the domain size was varied so as to provide a simple representation of group effects, based on a unit cell in a piled foundation of infinite extent.

# 2. BASIS FOR NUMERICAL ANALYSES

## 2.1 Model Geometry

A two-dimensional axisymmetric geometry was selected which models a single 1 m diam., 30 m long pile embedded in a domain that is 90 m deep and extends radially from the pile centreline either 30 m or 4 m, Figure 3. When R = 30 m, the pile is effectively isolated and when R = 4, an infinite foundation with piles in a honeycomb grid spaced at approximately 8 m centres is modelled. A 1.6 m diam., 1 m deep pile cap was placed at the head of the pile, this has only a minor effect on the pile behaviour and provides a buffer between the thermal boundary conditions applied in the pile and along the surface. When considering "inside" cases, a 0.5 m thick ground bearing slab is introduced into the model (Figure 3(c)), this also serves to provide a buffer between the applied surface temperature boundary condition and the rest of the model. While integral with the cap, the slab is very flexible and does not provide any significant restraint to the pile. It should also be noted that this model does not consider the impact of building stiffness on the response of the TA piles however, given that the pile foundation is in effect infinite in extent and all the piles are TA simultaneously, it is considered that any effect would be negligible. The bottom boundary was fixed in the vertical and horizontal directions while the side boundaries are only fixed in the horizontal direction. The analyses were undertaken using the finite element program ABAQUS 2016 [44].

## 2.2 Material Thermal and Mechanical Properties

The pile, the ground in which the pile is embedded and the pile-soil interface were modelled in the same manner as (Bodas Freitas et al., 2013) [38] and (Bourne-Webb et al., 2016) [43], i.e. the pile is assumed to behave elastically while the soil is modelled as linear elastic-perfectly plastic with a Tresca type failure criterion, i.e. purely cohesive. In [38] & [43] the Young's modulus for the soil was assumed constant however for this study it was assumed to increase linearly from 18 MPa at the surface, to 182 MPa at the bottom boundary, which was modelled as a stepped profile as indicated Figure 3(a). The pile-soil interface was modelled by attributing to the contact between the two materials, a shearing resistance that is proportional to the normal stress ($\tau = \mu.\sigma_n$), with the proportionality constant $\mu$ set artificially high ($\mu$ = 1000) to ensure the available shearing resistance is in effect independent of the confining stress and is equal to the specified maximum shear stress, $\tau_{max}$ of 75 kPa (equal to the soil cohesion). Further, the shear strength was specified to be fully mobilised at a relative displacement on the contact of 0.0015 m. This value is not an intrinsic property and was arrived at by simulating pile static load tests numerically and selecting the value which yielded what was considered a reasonable load-displacement response for a shaft resistance dominated pile. Transient thermal conditions were modelled, as detailed below. Further, it was assumed that no excess pore water pressures were generated by the thermal loading and the only thermo-mechanical coupling considered was that between temperature and volumetric change, via the CTE.

Thermal and mechanical properties assumed for the soil and pile are detailed in Table 1. The pile was assumed to behave elastically while the soil is modelled as linear elastic-perfectly plastic with a Tresca failure criterion, i.e. purely cohesive. The pile and soil materials were assumed to expand linearly when heated or cooled.

The pile-soil interface was modelled as elastic-perfectly plastic with a constant cohesive shear strength equal to that of the soil (75 kPa), that is attained at a relative displacement (elastic slip) of 0.0015 m.



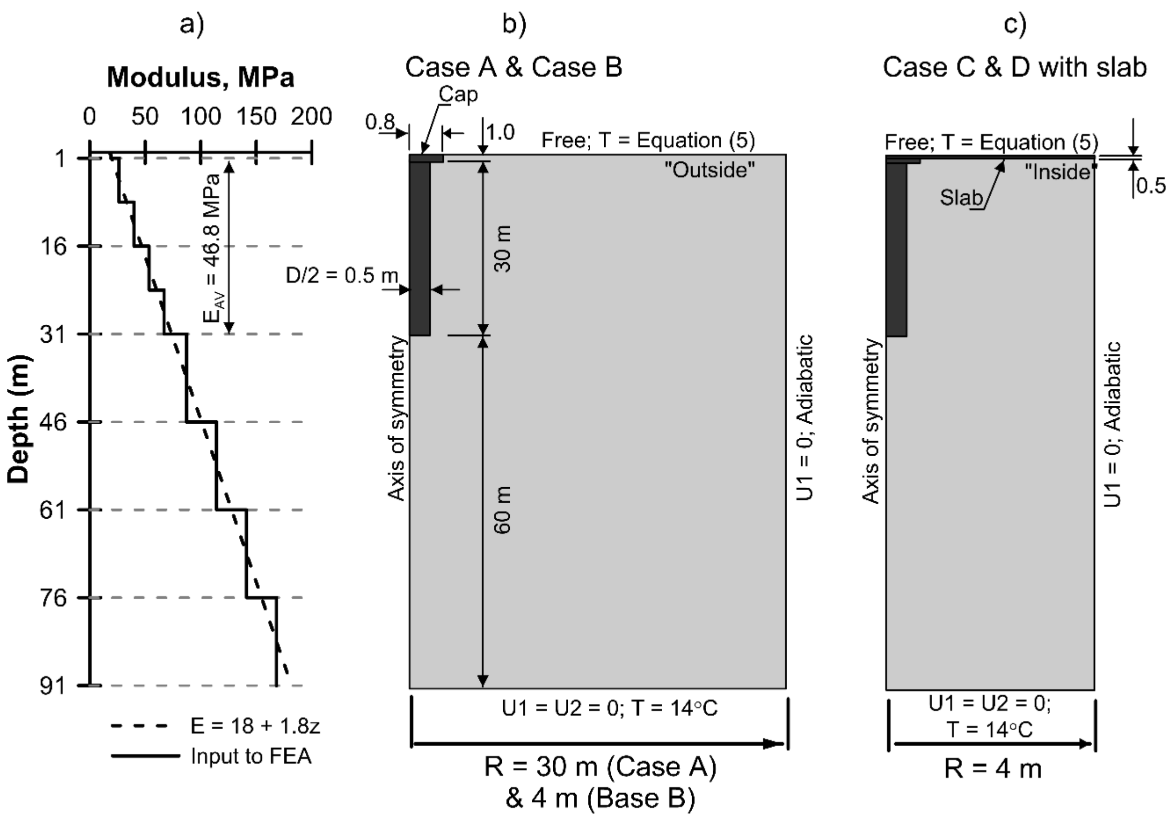


**Figure 3. Soil stiffness profile, and schematics of the model (not to scale)**
(U1: horizontal fixity, U2: vertical fixity, T: Temperature)

**Table 1. Material properties adopted in analyses**

| Parameter | Unit | Pile | Soil |
|---|---|---|---|
| Density, $\gamma$ | $kg/m^3$ | 2450 | 1600 |
| Young's modulus, E | MPa | 30000 | 25 + 1.67z |
| Poisson's ratio, $\nu$ | - | 0.3 | 0.3 |
| Soil shear strength, c | kPa | n/a | 75 |
| Pile-soil adhesion, a | kPa | n/a | 75 |
| Thermal conductivity, k | W/m.K | 2 | 1 |
| Specific heat, c | J/kg.K | 940 | 1220 |
| Linear coefficient of thermal expansion, $\alpha$ | $\mu\varepsilon$/K | 10 | 20 |

### 2.3 Initial and Boundary Conditions and Modelling Sequence

The modelling sequence and temperature boundary conditions were applied as follows:

1) The initial stress field assumed that the vertical total stress equals the horizontal stress and an initial temperature, $T_0$ = 14°C was applied uniformly across the problem domain. This value approximates the annual average air temperature of Milan, Italy. (https://www.timeanddate.com/weather/italy/milan/climate);

2) Subsequently, a periodic temperature function, Equation (5) and Figure 4(a), was applied at the ground surface over a period of 10 years, mimicking the monthly average temperature variation in Milan. This was done to mimic a more realistic temperature profile in the near-surface region. It was found that 10 years was sufficient to establish a temperature field that was in a dynamic thermal equilibrium with the boundary condition, Figure 4(b).

$$T = T_{avg} + \Delta T.\sin[(2\pi/P)t - \pi/2] \quad (5)$$

$T_{avg} = T_0$ = 14°C is the average annual air temperature, $\Delta T$ = 11°C is the temperature amplitude, and P = 1 year is the period of the function.

In this phase of the calculation, adiabatic conditions were assumed along the side boundaries and a constant temperature ($T_0$ = 14°C) was specified on the bottom boundary.

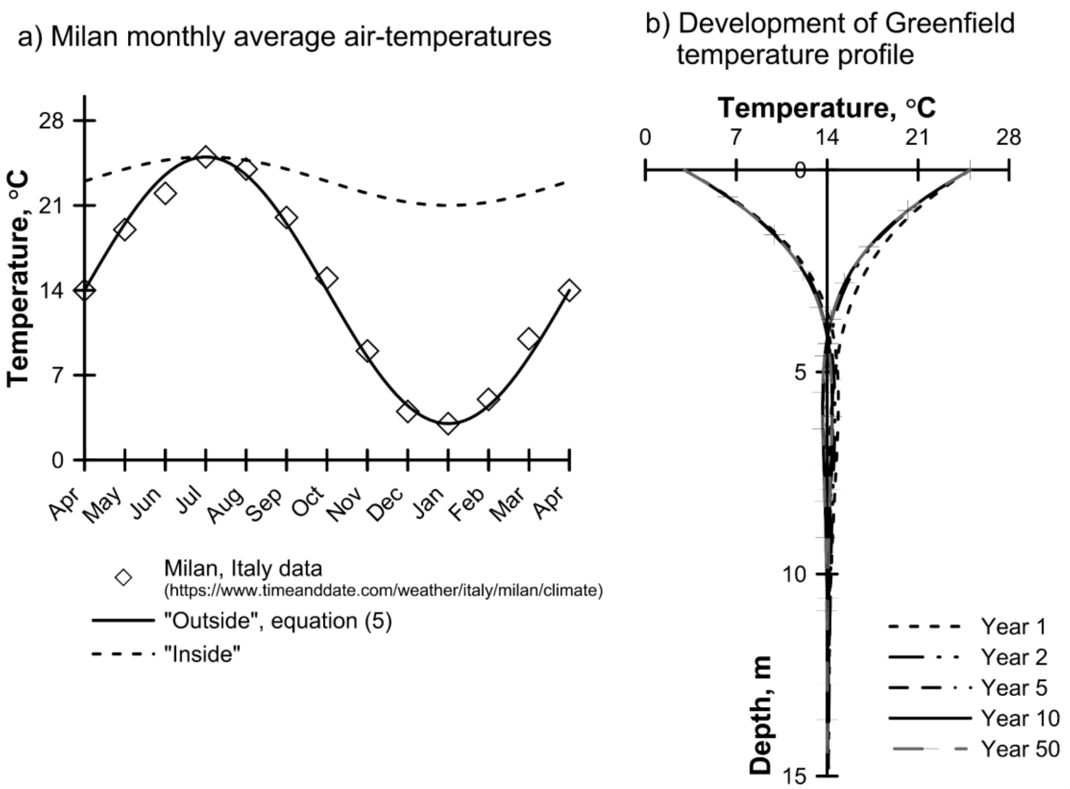


**Figure 4. Seasonal surface temperature boundary conditions applied and development of initial temperature profile**

3) The pile and pile cap, and in Case C & D a ground bearing slab, Figure 3(c), were wished-in-place and a load of either 3500 kN or 7000 kN, corresponding to a FS-global $\approx$ FS-shaft of 2 and 1 respectively, was applied as a uniform pressure acting on the top of the pile cap, over a radius of 0.4 m.

4) Ten years of thermally-activated pile operation were then initiated where a temperature following Equation (5) was applied on a line over the length of the pile shaft, at a radius of 0.4 m (implying 0.1 m concrete cover). In this case, $T_{avg}$ = 14°C; $\Delta T$ = 12°C; P = 1 and $\varphi_t = \pi/2$. Zito (2019) [45] showed that for periods greater than about four weeks, the temperatures applied in this way were on average, equivalent to those for temperature changes applied at discrete pipe locations on the same circumference, 0.4 m from the pile axis.

In addition to thermally-activating the pile, this stage considered one of two surface boundary temperature conditions, i.e.

(i) “Outside” where the condition described in 2) above was continued;

(ii) “Inside” where the condition was altered to reflect the presence of a climate-controlled overlying building with $T_{avg}$ = 23°C, $\Delta T$ = 2°C, P = 1 year, Figure 4(a).

Based on the conditions described above, four separate cases were studied as summarised in Table 2.

**Table 2. Cases considered in numerical study, Figure 3(b) & (c)**

| Case | R (m) | Surface BC | T-A Pile | Slab |
|---|---|---|---|---|
| A | 30 | Outside | Yes | No |
| B | 4 | Outside | Yes | No |
| C | 4 | Inside | Yes | Yes |
| D | 4 | Inside | No | Yes |

These combinations were chosen so that the influence of pile-soil-pile interactions could be examined further (A – B), along with the impact of the surface (B – C) and the pile (C – D) thermal boundary conditions.

The sign conventions adopted in this work have been mentioned before in relation to equations (1) and (2) but are restated here, i.e. tensile stress/load is positive, downward displacement (settlement) is positive and shaft friction that resists downwards pile movement in relation to the soil is positive.

# 3. RESULTS & DISCUSSION

## 3.1 Mechanical pile-soil-pile interactions

The pile response following the application of loads of 3500 kN (FS-shaft ≈ 2) and 7000 kN (FS-shaft ≈ 1) is shown in Figure 5. The pile response in Case A at 3500 kN, is typical of an isolated pile, the mobilised unit shaft resistance is relatively uniform (and about half the ultimate shear strength of 75 kPa), the pile axial load reduces more-or-less linearly with depth, and the settlement (6.4 mm) is less than 1% of the pile diameter. The fluctuations seen in the mobilised shaft friction are due to the step-changes in stiffness through the soil profile, and illustrates the sensitivity of the shaft friction mobilisation to the soil stiffness. The response in Case B at the same load is quite different and typical of a pile group (see Figure 2) compared to Case A the mobilized shaft friction is suppressed in the upper part of the pile (load profile near-vertical) but increases in the lower (load profile with higher gradient), relative to the isolated pile. The axial load transfer alters as a consequence and the pile head settlement increases to 38 mm (5.9x the isolated pile). The zone of (stress) influence of the pile group is much greater than that of an isolated pile and the additional settlement largely derives from the compression of the soil profile in this zone of influence. It is apparent that the shaft resistance is fully mobilised close to the pile base, and that the pile base resistance is almost fully mobilised as well.

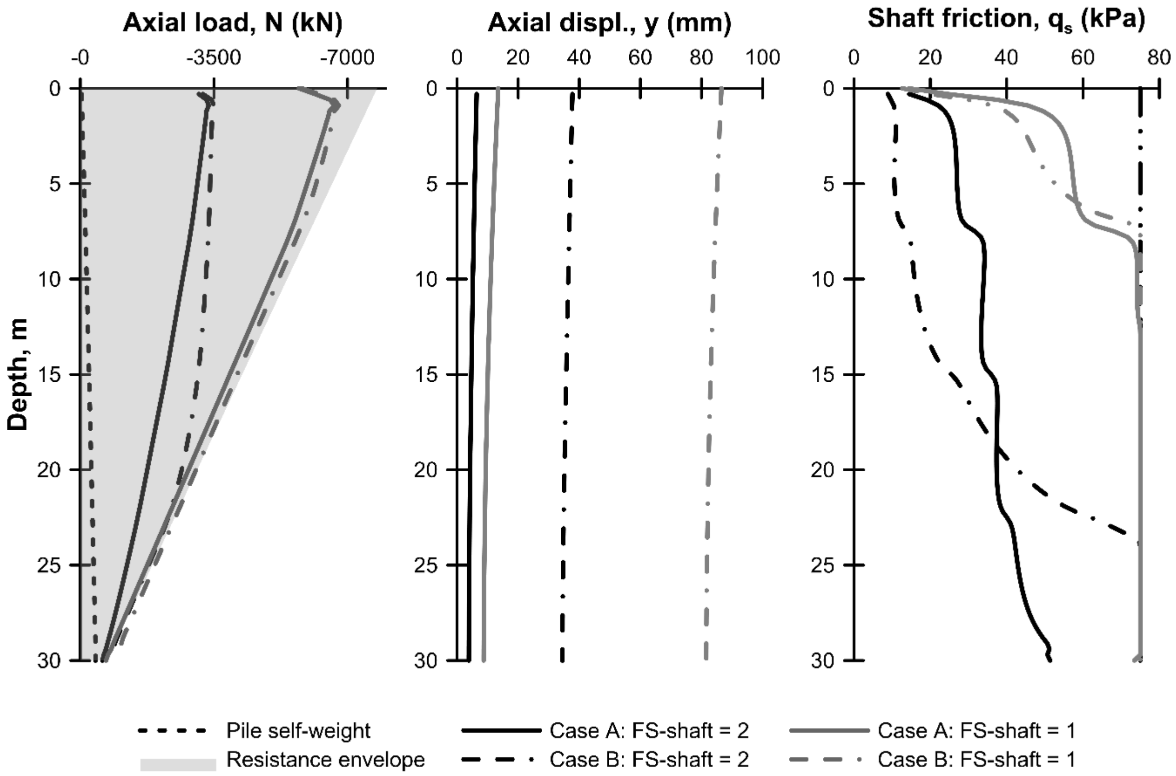


**Figure 5. Effect of pile proximity on mechanical axial load-transfer response**

As the applied mechanical load is increased to 7500 kN (FS-shaft = 1), the differences between Case A and Case B diminish. In both cases, the base resistance is almost fully mobilised and the shaft friction is fully mobilised below about 8 m depth. For both cases (A and B), pile head settlements when FS-shaft = 1 are approximately double those obtained for FS-shaft = 2.

### 3.2 Thermo-mechanical pile-soil-pile interactions

#### 3.2.1 Floating pile with FS-shaft = 2.0

The impact of the differing mechanical pile-soil-pile interactions, discussed in the previous section, on the subsequent response to cyclic thermal loading is illustrated in Figures 6 and 7 for piles with FS-shaft = 2. In Figure 6(a), the response for Case A (R = 30 m) after 1, 3 and 10 years of thermal-activation starting with pile heating (summer) are shown, along with that after 10 years with the pile thermal-activation starting with cooling (winter). It is apparent that there are only minor changes from year-to-year and after 3 years the cyclic behaviour from year-to-year is indistinguishable, see also Figure 7(a) and (b). When instead the thermal-activation starts with cooling, there are only minor differences in the response. As expected from e.g. Bourne-Webb et al. (2013) [46], heating leads to an increase in compression (negative thermal axial loads, $N_{th}$), upwards (negative) movement of the pile head, $y_{th,0}$ and a reduction (negative) in mobilised shaft resistance, $q_{s,th}$ in the upper part of the pile and an increase in the lower part. The response reverses when the pile is cooled. The depth to the neutral point, where the shaft friction reverses and axial thermal load is a maximum, is at around 18 to 19 m depth (about 0.6L) during both heating and cooling.

The thermal effects in Case B (R = 4 m) are shown in Figure 6(b) and are clearly different. During heating, in the lower part of the pile, downwards expansion leads to pile-soil interface shearing in the same direction as that imposed by the mechanical loading, which was already fully mobilised below about 23 m depth (see Figure 5) and thus, the only possibility for mobilising additional shaft resistance lies above this level. This means that the maximum axial thermal stress occurs higher in the pile in Case B than in Case A, and the stress change and the associated changes in shaft friction are smaller. When the pile is cooled, the upwards contraction in the lower part of the pile leads to pile-soil interface shearing reducing the shaft friction mobilised by mechanical loading, and because the shaft friction in the upper part was suppressed by pile-soil-pile interaction, a stronger axial load response is mobilised than for heating, though still less than that for Case A.

As discussed above, in Case B the pile thermal response is constrained by the mobilization of the pile shaft resistance imposed by the mechanical loading, and during both heating and cooling slightly larger pile movements are required to equilibrate the pile thermal response, in comparison with Case A. Further, in Case B, there is some ratcheting movement of the pile head, towards larger thermal settlement (downwards head displacement) during cooling and reduced heave (upwards head displacement) during heating. Figure 7(a) and (b) illustrate that in Case B, it takes some time for the year-to-year response to fully stabilise and there is a small gradual increase in pile head settlement and thermal axial load until around Year 4. Commencing thermal-activation with cooling results in slightly larger settlement and thermal loads.

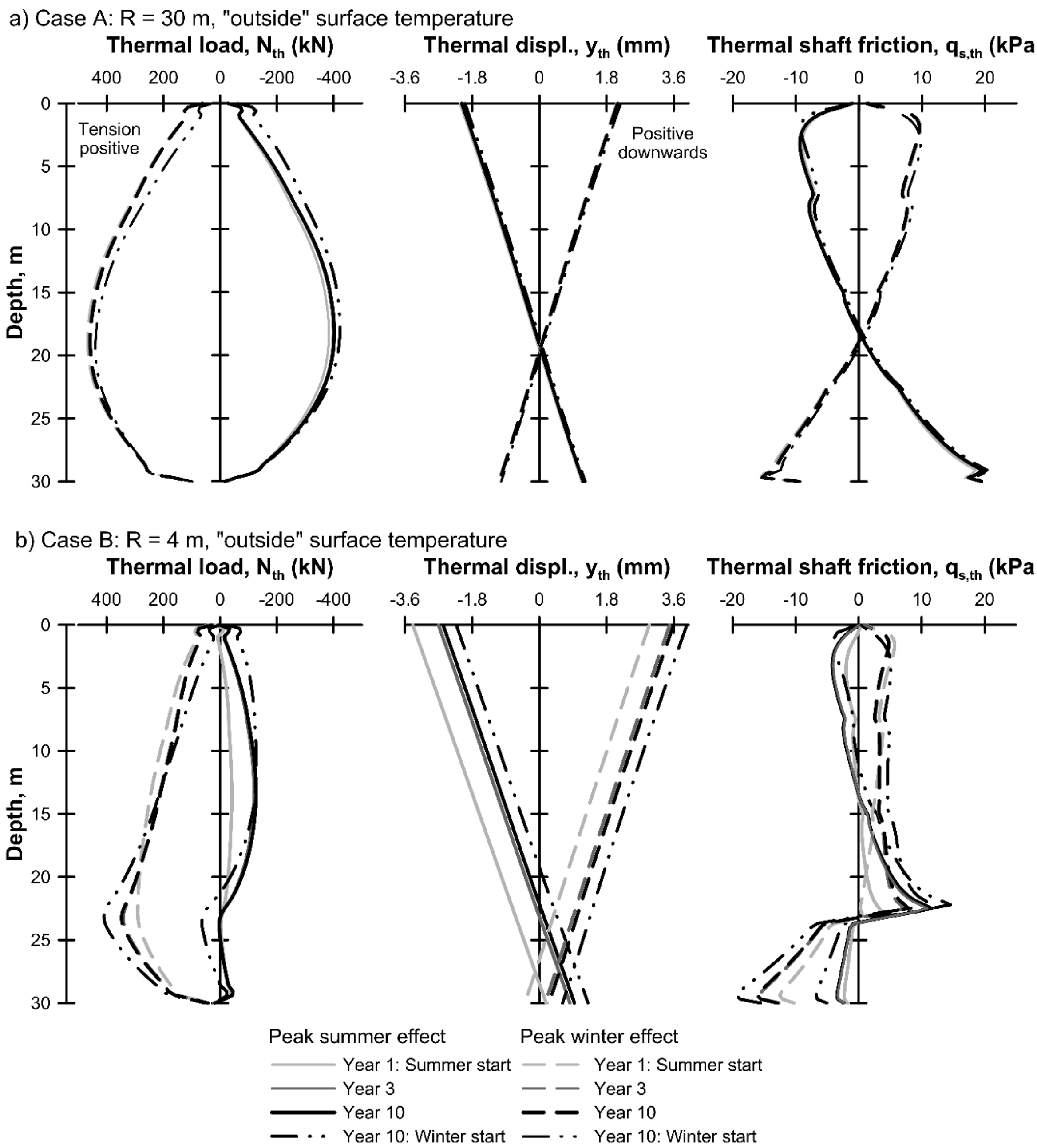


**Figure 6. Effect of pile proximity on thermo-mechanical response of floating pile: FS-shaft = 2**

Figure 7(c) examines the thermal response of Cases A and B using the scheme described by Bourne-Webb et al. (2019) [15] where the normalized maximum axial thermal load response ($\sigma_{th,max}/\sigma_{th,fixed}$) is plotted against the normalized pile head thermal displacement ($y_{th,0}/y_{th,free}$). The figure also highlights the differences in response depending on whether the seasonal thermal activation starts with heating (summer) or cooling (winter). In Case A, the difference is small but in Case B, pile head movements and stress responses are visibly larger for the winter start compared to a summer start.

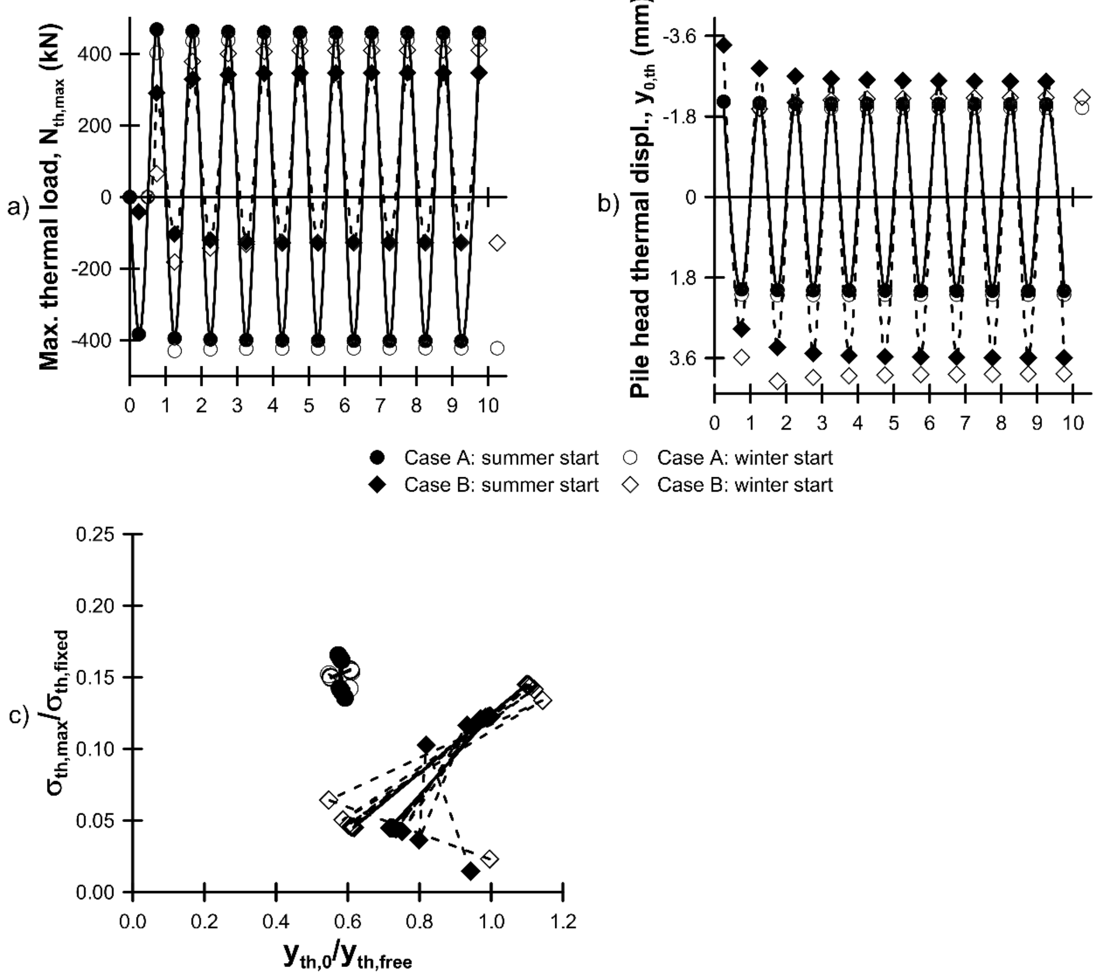


**Figure 7. Effect of pile proximity on thermo-mechanical response over time: FS-shaft = 2**

### 3.2.2 Floating pile with FS-shaft = 1.0

When floating piles are designed with conventional factors of safety, FS-shaft is likely to be large, however when piles are used as e.g. settlement reducing elements in raft foundations, the pile is deliberately designed with low factors of safety, i.e. FS-global and thus, FS-shaft approaching a value of 1.0 (Burland, 1995) [47]. In the following, a load of 7000 kN is applied to the pile, reducing FS-shaft to approximately 1.0. Figure 8 shows the maximum values of thermal axial load and pile head displacement at the peak of heating and cooling cycles for the scenario with FS-shaft = 1. Rather than the quasi thermo-elastic response described for FS-shaft = 2, when FS-shaft = 1, and irrespective of whether the pile is isolated (Case A: R = 30 m) or within a large group (Case B: R = 4 m), not only do pile head settlements accumulate, there is also a drift in the pile axial load response to less compression (tensile thermal axial load) as the number of thermal load cycles increase.

Figure 8(a) examines the maximum thermal load that is generated by the cyclic thermal loading. In Case A with FS-shaft = 1, this cycles between a small compression during heating and a rather more sizeable tension during cooling. Also shown is the maximum thermal tension that occurred in Case A during heating (open circles), which are almost equal to the thermal compression, i.e. less than 1% difference at the end of the period considered. In Case B, the initial heating cycle generates a small compression but thereafter the maximum thermal axial loads are tensile during both heating and cooling. The responses in both cases can be attributed to the high levels of shaft and base mobilisation generated by the imposed mechanical load with FS-shaft = 1, as illustrated in Figure 5. That there are thermal tension loads rather than compression during heating is considered to be due to the limited restraint on the pile shaft during heating which means that the tension loads generated during cooling are not able to be reversed during heating (remembering that the thermal changes are with respect to the initial mechanical load). During cooling, in the upper part of the pile, the thermal contraction is in the same direction as the imposed mechanical load and in Case A, it appears that there is slightly more margin with respect to the ultimate shaft resistance and so a larger thermal tension is able to be generated than in Case B, i.e. about 680 kN versus 470 kN. In both cases, the change in thermal axial load stabilises within the period considered, Figure 8(a).

In Case B, the accumulation of pile settlement stabilises within the 10 year operational period considered in the analyses, Figure 8(b). However, in Case A, as a consequence of the cyclical mobilisation of the pile base, the pile head thermal settlement continues to accumulate beyond the 10 years, with irrecoverable settlements developing in the heating phases, which reduce from about 1 mm in the first cycle to about 0.3 mm/cycle at the end of the period considered.

Figure 8(c) compares the normalized maximum axial thermal load response ($\sigma_{th,max}/\sigma_{th,fixed}$) versus against the normalized pile head thermal displacement ($y_{th,0}/y_{th,free}$) for the FS-shaft = 1 scenario. Compared to the FS-shaft = 2 scenario, the response shows much larger pile head thermal movements, that accumulate and are approaching two-times the unrestrained pile thermal movement. The thermal stress ratio falls in a similar range of values in both FS-shaft scenarios.

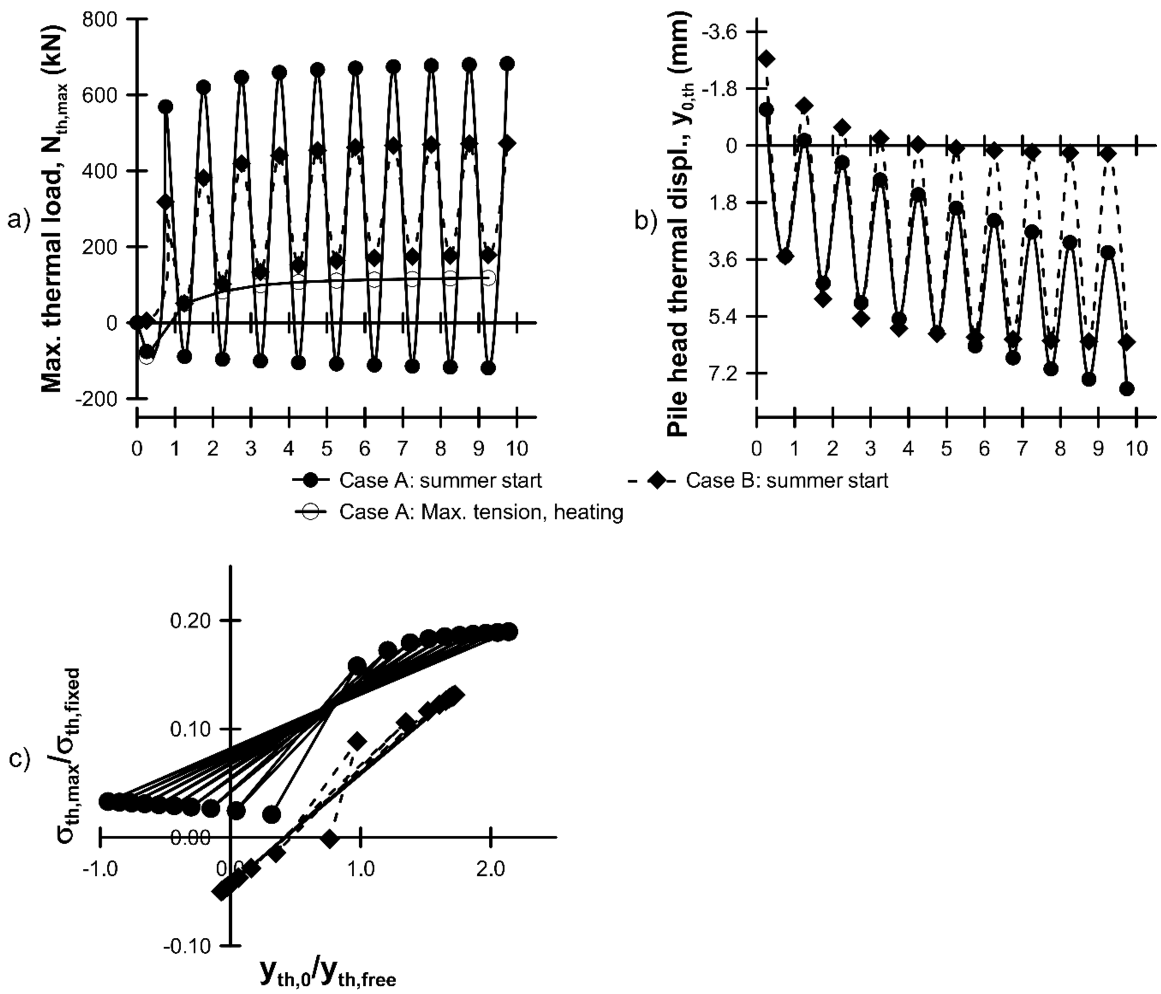


**Figure 8. Effect of reduced FS-shaft = 1 on thermally-activated pile response**

Case B with FS-shaft = 1, is closest to the situation in a combined piled-raft foundation, with piles located under each column (in this case on a building grid spacing of 8 m) and these analyses suggest that despite the low initial FS-shaft (and FS-total), the additional average settlement induced by thermal-activation of the piles would be around 3 mm with a recoverable cyclic component of ±3 mm superimposed. Given that piled rafts typically undergo several, to tens of centimetres of settlement (in this case about 8 cm, see Figure 5) an additional thermally-induced settlement of less than one centimetre is unlikely to be of great concern.

### 3.3 Effect of surface boundary condition and pile thermal activation

Many numerical studies undertaken to-date, consider the surface boundary as either having a constant temperature or as adiabatic. However, Bourne-Webb et al. (2016) [43] using steady state analysis, illustrated how the response of thermally-activated piles is altered by the choice of surface boundary temperature. The change in surface temperature relative to the initial condition leads to an alteration in the temperature field of the underlying soil mass which e.g. when the surface temperature increased, imposed additional tensile axial stress in the pile and reduced the pile head settlement. Here, the impact on the response of a thermally-activated pile with FS-shaft = 2 is examined by a) comparing the Case B and Case C analyses (where the surface temperature condition is changed to an “inside” scenario in the latter, while the pile remains thermally-activated), and b) comparing Case C to the Case D analysis (where the “inside” surface condition is maintained but the pile was not thermally-activated).

Comparing Case B in Figure 6(b), with Case C in Figure 9(a) shows that a significant tensile thermal load develops at the pile head during cooling and remains, with a smaller magnitude, even when the pile is heated. The thermal displacement response does not appear to differ significantly and the changes in shaft friction mirror the effect seen in the axial load profile. In Case C, there is a second maximum which has almost the same magnitude and location as that seen in Case B which is generated by the pile response to thermal loading.

Further, the effect of changing to an “inside” temperature condition on the upper surface seems to develop mostly in the upper half of the pile, while the response in the lower half is remarkably similar between Case B and Case C. This might be attributed to the presence of the slab at the surface however the results from Case D, Figure 9(b), show that this reaction is mostly due to the change in surface temperature to an “indoor” condition (note that the results from Year 5 have been added to the Case D profiles). During pile heating, the compression thermal loads are mitigated, as the pile expands upwards with the warming soil mass. In Figure 9(b), the progression of the heating front from the surface can be seen as the pile thermal expansion progresses to greater depth as time proceeds; after Year 5, the whole pile is within the zone influenced by the presence of the thermally controlled building, and this coincides with the thermal response of the pile stabilising.

Zito (2019) [45] extended the analysis of Case D to 100 years, when the thermally-induced pile tension is predicted to increase by about an extra 90 to 100 kN and the heave at the pile head, a further 6 to 7 mm. The results of Case C which stabilise after a few years, imply that the thermal-activation of the pile is mitigating these effects, Figure 10(a) and (b). Further, in this case, at least, it would seem that the effect of introducing an “indoor” condition at the surface, marginally alters the thermo-mechanical response relative to an “outdoor” condition.

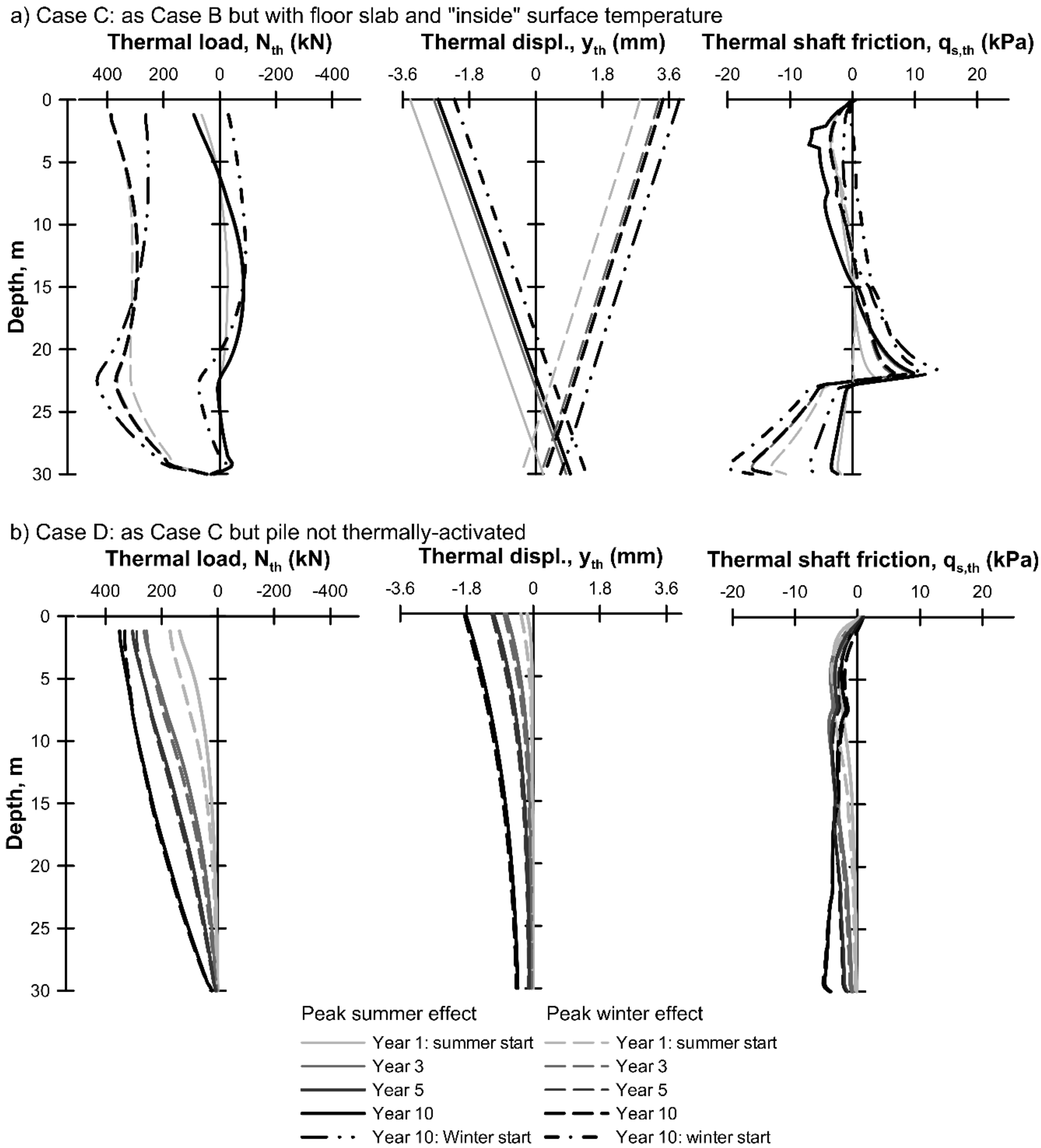


**Figure 9. Effect of surface temperature on thermo-mechanical response of pile**

Comparing Figure 10(a) with Figure 7(a) it is apparent that while compressive thermal stress during heating is reduced, the maximum tension generated is approximately the same whether an "outside" or "inside" condition is modelled. Likewise thermally-induced pile had movements are broadly similar over the period considered.

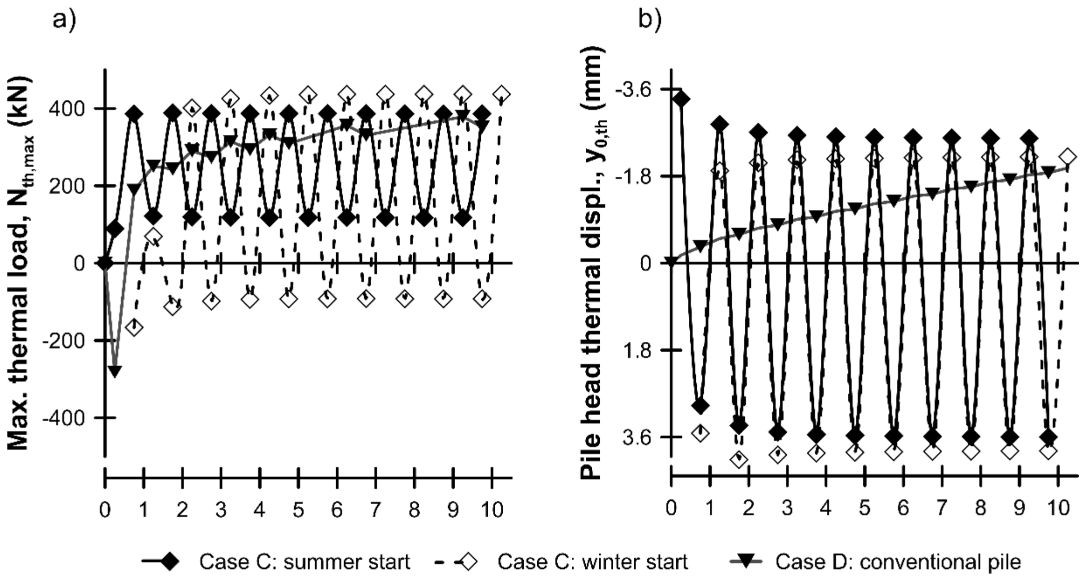


**Figure 10. Effect of surface temperature on thermo-mechanical response over time**

### 3.4 Seasonal thermal-activation versus steady state conditions

Bourne-Webb et al. (2016) [43] used steady state thermal analysis to investigate the effect of various parameters on the response of thermally-activated piles, and identified that differing thermo-mechanical response can develop, depending on the ratio of the soil CTE to the pile CTE, $\alpha_s/\alpha_c$. Figure 11(a) illustrates how in steady state conditions, as the ratio $\alpha_s/\alpha_c$ increases, the normalised thermal stress behaviour reverses as the pile head deformations increase, e.g. during heating, low CTE ratios yield compression but high CTE ratios yield tensile thermal stress.

Figure 11(b) zooms in on the top left of Figure 11(a) and compares the response of the Case A analysis in which the $\alpha_s/\alpha_c$ ratio has been varied between 0 and 4 (as indicated), for the 9$^{th}$ heating cycle with that of the steady state analysis with the pile temperature increasing 12°C from [43]. It is apparent that while the steady state response leads to positive or negative normalised stress ratios, depending on the CTE ratio, this does not occur for the seasonally thermally-activated pile in which the normalised stress ratio is always positive. It is evident that seasonal thermal-activation of the pile leads to thermo-mechanical effects that are more akin to that of a thermally-activated pile embedded in a thermally inert material (soil CTE $\rightarrow$ 0), under steady state conditions. This is primarily due to the much smaller volume of soil that is thermally-activated during each seasonal cycle compared to the steady state condition where the entire soil mass is affected (Bourne-Webb et al., 2020) [22]. It should be noted however that, although the difference is much smaller than for the steady state case, from the results presented here, assuming the soil CTE is zero in an analysis of the seasonal thermally-activated pile could lead to the thermal stresses being over-estimated by up to about 20%, and thermal movements under-estimated by up to about 15%.

Comparing these results from the transient analysis with the full-scale test results shown in Figure 1, which involve thermal loading of a few days to weeks or transient cyclic loading over several years, it is found that there is a good match in terms of average $y_{th,0}/y_{th,free}$ ratio. However, the stress ratio, $\sigma_{th,max}/\sigma_{th,fixed}$ remains low in these analyses compared to the full-scale results, which is an effect commented on by Bourne-Webb et al. (2019) [15] and seems to be due to the particular set of soil parameters assumed for the analyses, and is seen in many numerical studies published to-date.

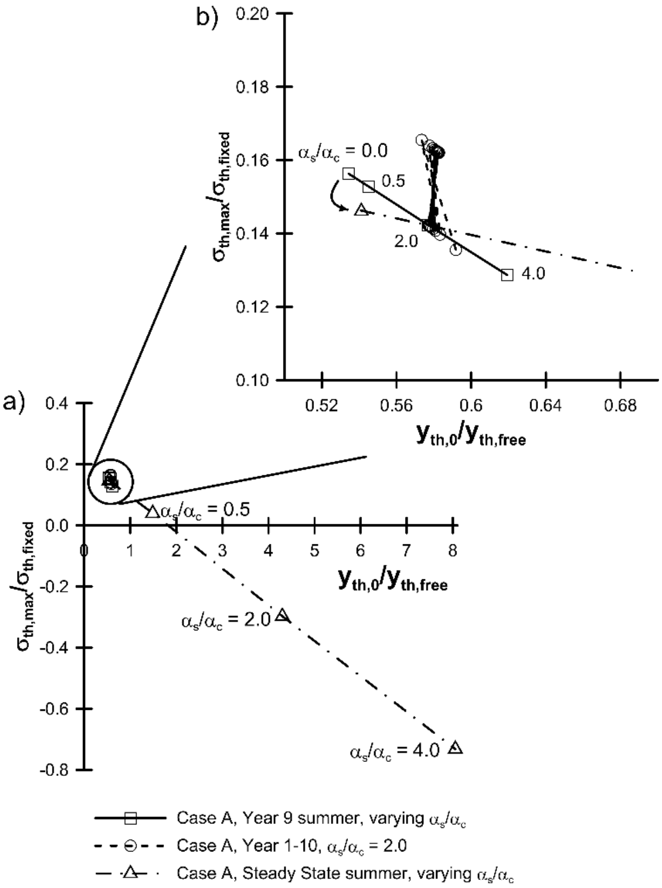


**Figure 11. Effect of transition to steady state thermal conditions**

An important consequence of the above is with regard to the use of interaction type methods for the evaluation of the movements of TA pile groups as proposed by (Rotta Loria and Laloui, 2016) [36]. This approach derives interaction factors based on steady state analysis which are then applied to problems involving seasonally thermal-activated pile problems – it is clear from the above that thermally-induced movements (and hence interaction factors) will be over-predicted, with the effect increasing with CTE ratio. Further, these interaction factors do not account for the effect of the initial mobilization of the pile resistance on the subsequent thermal response. Based on the work presented herein it is apparent that the thermal interaction effect will depend on the absolute pile spacing and the time over which the thermal load is applied, not just the relative pile spacing as used in e.g. (Rotta

Loria & Laloui, 2016) [36], as these in conjunction with the thermal properties of the soil, will define the volume of soil that is thermally-activated during the transient loading. Once again, steady state analysis will overstate this effect. This is why in (Rotta Loria & Laloui, 2016) [36], when comparing the method against 3D analysis of various pile group configurations, the method only seemed to be reliable for large pile spacing (more than about 10 pile diameters) where thermal (and mechanical) interactions, even at steady state, are very small.

### 3.5 Seasonal heat exchange

Figure 12 illustrates the radial heat flow from the pile to the ground after 10 years of thermal activation. In Case A and B, there was no difference from season to season, or whether the pile thermal loading started in summer or winter, because the thermal load was balanced and the zone of thermal influence was within the limits of the boundaries used in the analyses. If a smaller domain radius was considered then thermal pile-pile interaction may begin to compromise the heat exchanged with the ground. In Case C, because of the "indoor" temperature conditions modelled at the surface, heat injection in summer reduced and heat extraction in winter increased, in relation to the "outdoor" scenario.

Average heat flows are indicated in the legend of Figure 12, relative to Case A. These differed only a few percent, except for Case C: winter where heat flow was 15% higher. These equate to heat exchange rates of about 80 to 90 W/m length of pile which lie at the upper bound of typical values quoted for heat exchange through piles, e.g. Brandl (2006) [2]. It is interesting that for Case A and B, the effect of the surface temperature boundary condition is only seen to a depth of about 5 m; however, it increases to about 13 m for Case C. It was thought that perhaps the heat transfer might be altered further in this latter case, if heat exchange via the pile continued for longer, but the results show that the average heat exchange and depth of seasonal variation had largely stabilised by around Year 6, Zito (2019) [45].

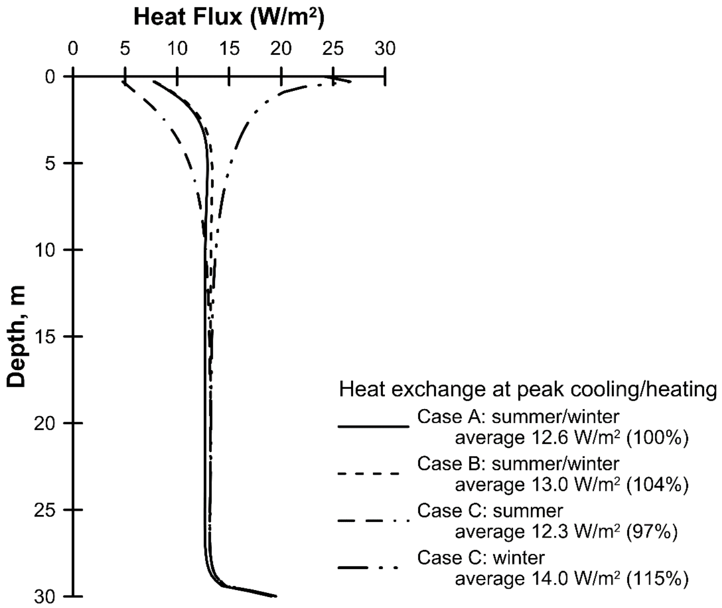


**Figure 12. Effect of pile spacing and surface temperature on seasonal heat exchange after 10 years operation**

## 4. CONCLUSIONS

The purpose of this study was to examine the behaviour of a floating pile in a cohesive medium which is subject to both mechanical vertical load and balanced seasonally cyclic thermal loading, to put this in the context of previous studies and provide some clear guidance as to what the key factors to be considered in design might be. Whilst analysing a single pile, the effect of pile-soil-pile interaction such as would occur in large pile groups was also assessed in a simple manner by reducing the radius of the analysis domain. Based on the work presented above the following observations and conclusions are made:

- Amongst other things, the response of a TA pile depends on (i) the level of applied mechanical load and in particular, the degree of mobilisation of the pile shaft resistance and (ii) how the shaft and base resistance is mobilised under this initial mechanical load, which depends on whether the pile is isolated or influenced by similarly loaded adjacent piles, i.e. it is a function of pile spacing.
- For floating piles in a uniform cohesive medium (where $R_{s,u} >> R_{b,u}$), design to conventional safety margins will inevitably result in the factor of safety with respect to the ultimate shaft resistance being significantly larger than 1.0. When the pile is isolated, the response when cyclically thermally-activated will then be thermo-elastic. The behaviour is recoverable and thermally-induced stresses and pile head displacements cycle within a small range.
- For piles within a group (in this case an infinite group) with the same average load as the isolated pile with a conventional safety margin, the mobilization of the pile resistance under mechanical loading is different to that of an isolated pile, due to pile-soil-pile interactions, which in turn alter

the response when the pile is cyclically thermally-activated. The response is initially inelastic, thermally-induced stresses decrease and pile head displacements increase compared to the isolated pile, implying less pile restraint. However, because of the low initial mobilisation of the shaft resistance (FS-shaft >> 1.0), the changes in response due to pile-soil-pile interactions remained small, and are unlikely to be of concern.

- The situation where FS-shaft reduces towards a value of 1.0 (which occurs e.g. in rafts utilising settlement reducing piles) was also examined and important differences were identified – irrecoverable thermal pile head ratcheting and increased tensile thermal loads relative to FS-shaft = 2 developed. In this case, the magnitude of the thermal effects are also unlikely to be of concern for design.
- In addition to the thermal-activation of piles, commissioning of a SGE system also implies the presence of a climate controlled building (which the piles support) and a change in the surface thermal boundary condition from an “outside” to an “inside” condition. The effect of this boundary temperature change is superimposed on the response of the TA pile. In this case, the impact is not a concern as the induced thermal effects after 10 years were similar whether the pile was thermally-activated or not, and thermal-activation of the pile actually mitigated the long-term effect of the surface heating. Clearly, this finding needs to be explored over a wider range of conditions to understand how generally applicable it is.
- Previous work assumed that steady-state analysis would provide a bound on the likely response of TA piles. This is true up to a point, however the behaviour under seasonal cyclic thermal loading appears to remain within a smaller range of response with larger thermally-induced axial load and smaller pile head displacement. This is due to the reduced impact of the thermal loads on the soil mass surrounding the pile foundation. The effect of the ratio of soil to pile CTE was re-examined and shown to be greatly reduced when considering balanced cyclic thermal loading, compared to steady state analysis.
- As a consequence, steady state analysis may not be appropriate for deriving so-called thermal interaction factors for use in the analysis of TA pile groups, as for large soil to pile CTE ratios the thermal displacements are likely to be significantly overstated. Further, such thermal interaction factors will vary not only with the relative pile spacing s/D, but also with the absolute pile spacing, the time over which the thermal loading is applied and the thermal properties of the intervening materials, i.e. the rate at which heat diffuses through the ground around the pile, i.e. interaction factors determined from one point in time will not be applicable at other times.
- Based on the cases considered in this study, assessment of the heat exchange potential of a pile through the analysis of an isolated pile seems to be a reasonable approach, and while the surface

boundary condition has an effect on heat exchange this was found to be less than 5% on average. Once again, this needs to be explored for a wider range of conditions.

## ACKNOWLEDGEMENTS

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