Thermal and Thermal-Mechanical Analysis of Thermo-Active Pile Foundations

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Abstract

Thermo-active foundations make use of shallow geothermal energy to heat or cool buildings. By making use of this green and renewable energy form, this technology can significantly reduce building energy and maintenance costs in the long term and reduce carbon dioxide emissions. However, a complete understanding of the thermal-mechanical behaviour of such foundations has not yet been achieved which has been a major obstacle to the uptake and the industrial development of this technology. A thermal and thermal-mechanical numerical study of a thermal active pile was performed in this thesis using the finite element software Abaqus. The thermal analysis focused on one modelling aspect of the problem, the simulation of the heating of the pile. The thermal-mechanical analysis studied the effect, in terms of thermally induced stresses in the pile, of the relationship between soil and concrete coefficients of thermal expansion, the ground surface temperature and the pile length/ to diameter ratio. The relationship between the soil and concrete coefficient of thermal expansion was found to have a key role in the observed behaviour of the pile affecting both the direction and the magnitude of the thermally induced stresses in the pile. The ground surface temperature showed an important effect when the soil was more thermally expansive than concrete, leading to considerable stress changes in the pile. An increase in the pile length to diameter ratio also led to an increase of the thermally induced stresses in the pile.

Keywords: *foundation pile; thermal-mechanical; geothermal energy; finite elements.*

I. INTRODUCTION

Following the world's current drive towards urban sustainability and green construction, the use of geothermal energy contained in the subsurface of the earth has risen in popularity as a directly usable and renewable energy form. Shallow geothermal energy can be extracted through the use of ground heat exchangers such as trench collectors and borehole heat exchangers, or through foundation elements, which when used for this purpose are also referred to as thermo-active foundations or energy foundations. Among these options, the use of foundation elements as ground heat exchangers has been rising in the past years. By using foundation elements which are already required for structural reasons as ground heat exchangers, a considerable initial cost saving is achieved when compared to the construction of a separate system for the sole purpose of ground heat exchange (Brandl, 2006).

Piles make the best ground heat exchangers as they maximize the surface area in contact with the soil and extend to greater depths than shallow foundations, where the soil temperature is less affected by the exterior air temperature, allowing better heat extraction.

Heat is generally extracted or injected into the ground by the circulation of a fluid through polyethylene pipes called absorber pipes which are installed inside these foundation elements or placed directly into boreholes. Ground heat exchangers are used in conjugation with a heat pump, which is referred to as a ground-coupled heat pump system. The heat pump is required to adjust the temperature levels extracted from the ground to more suitable levels depending on the building's heating or cooling needs. A more complete description of the working of a ground coupled heat pump system may be found in Brandl, 2006.

Data from existing applications report that the use of energy piles can save up to two thirds of a building's conventional heating and cooling costs (Brandl, 2006), and lead to a reduction in CO_2 emissions of up to 50% (Laloui et al., 2006).

While energy piles have increasingly been used in recent years, a full understanding of their thermal-mechanical behaviour has yet to be achieved due to the complexity of the problem and a lack of published quantitative evidence regarding their thermal-mechanical behaviour. Current thermal pile design often neglects the effect of the thermal load while published evidence from test piles points to the possibility of considerable additional stresses and strains in the pile due to the thermal load (Laloui et al., 2006, Bourne-Webb et al., 2009). It is believed that the behaviour of thermo-active piles is strongly influenced by the thermal and mechanical properties of its surrounding soil, especially its coefficient of thermal expansion (Freitas et al., 2013). Thermally induced stresses in the pile can potentially reduce the design safety margin when compared to a conventional pile design which does not take into consideration the thermal load. The lack of a complete understanding of the effect of the thermal load in the structural behaviour of the pile has been a major obstacle to the uptake and to the industrial development of this technology as it is difficult to demonstrate to clients that besides being an economically viable and green technology, it is also safe.

This work aims to fill some gaps regarding the understanding of the thermal-mechanical behaviour of energy piles and contribute, in conjugation with other ongoing and past investigations, to the ultimate goal of gaining a complete understanding of the effects of the thermal load on a foundation element. In order to achieve these goals, systematic thermal and thermal-mechanical numerical analyses of an energy pile were performed and the results are reported and discussed in this paper.

II. THE EFFECT OF HEATING AND COOLING A PILE

When a pile is subjected to a temperature change, it will attempt to expand if heated or contract if cooled proportionally to its coefficient of linear thermal expansion, α (m/m/K), according to (1), where ε_T represents thermal strain and ΔT temperature change (K).

$$\varepsilon_T = \alpha \Delta T \tag{1}$$

Equation (2) describes the resulting pile geometry change, due to the thermal load if it were completely unrestrained, where, ΔL represents the change in length and L_0 the initial length of the pile.

$$\Delta L = L_0 \, \varepsilon_T \tag{2}$$

If no restraint is applied to the pile (free body response), when subjected to a thermal load, the pile changes in volume without mobilizing any additional stresses. However, in reality, piles will always be subjected to some level of restraint imposed by the surrounding soil and the building structure above its head. This restraint will prevent part of the thermal expansion/contraction of the pile which results in additional stresses. Considering the pile as a perfectly elastic and homogeneous material, the additional axial load, P, due to a temperature change will be proportional to the cross-sectional area, A, Young´s Modulus, E, and the equivalent strain due to the restraint, ε_{T-Rstr} (3).

$$P = EA\varepsilon_{T-Rstr} \tag{3}$$

Figures 1 and 2, illustrate part of a descriptive mechanistic framework proposed by Bourne-Webb, et al., 2013 regarding the effects of a heating and cooling thermal load in a pile partially restrained laterally by surrounding soil, admitting a rigid-perfectly plastic shaft resistance, q_s, zero base resistance and a non-thermally expansive soil (α=0). The heating thermal load induces pile expansion, the restraint of this expansion results in additional compressive stresses in the pile. The opposite behaviour occurs when the pile is cooled. In these figures, it can also be seen that thermally induced axial load is higher at mid-depth, which is the section where the strain restraint, ε_{T-Rstr}, is higher and reduces towards the ends of the pile where no strain restraint is applied. Because the top and bottom halves of the pile expand equally but in opposite directions, the resulting shear stress profile is antisymmetric. However, if the pile is not symmetrically restrained, the maximum strain restrain will no longer occur at mid-depth and the axial and shear stress profiles will vary accordingly. Naturally, the stiffer and stronger the soil is, the more restraint will be applied on the pile and consequently, the higher the thermal induced axial and shear stresses will be. These figures also consider that the pile ends are free to move and consequently no axial stresses develop in these sections. However, in reality, piles will always be subjected to some level of restraint at its ends: foot restraint imposed by the soil and head restraint imposed by the overlying structure, therefore thermally induced stresses can also occur in these sections.

While the descriptive framework previously presented is very straight forward and easily understandable, in reality, the problem of a thermally loaded foundation pile is of great complexity. Soil is generally highly heterogeneous and therefore, unlike what is seen in Figures 1 and 2, the restraint it will induce in the pile will change in depth, which will affect the behaviour of the pile (Laloui et al., 2006). As the soil will also be heated/cooled together with the pile, it will also experience expansion/contraction, and the relationship between the concrete and soil thermal expansion values is also likely to play a role in the resulting behaviour.

A more complete overview of the effect of a thermal load in a foundation pile can be found in Amatya et al. 2012.

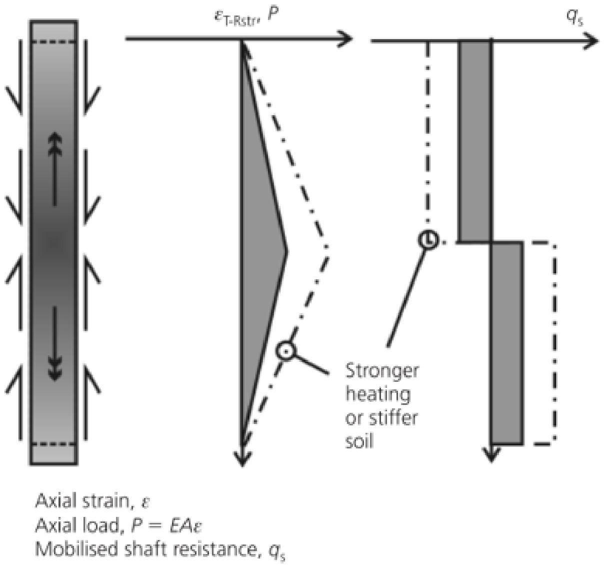


Figure 1. Thermal response of a pile laterally restrained: heating thermal load (Bourne-Webb, et al., 2013).

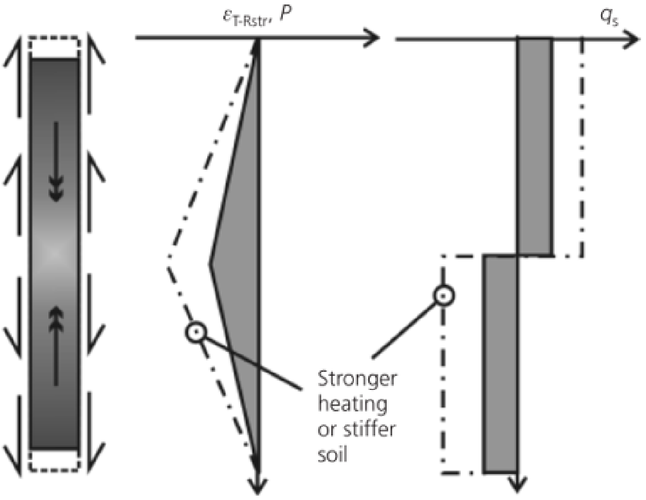


Figure 2. Thermal response of a pile laterally restrained: cooling thermal load (Bourne-Webb, et al., 2013).

III. THERMAL ANALYSIS

A. Axisymmetrical Model

A 2D axisymmetric numerical model of a thermo-active pile was developed using the finite element software Abaqus. The main objective of this model was to determine whether or not the way the heating of the pile is simulated significantly affects the temperature field close to it once a steady state is reached.

The pile has a diameter (D) of 1 m and a length (L) of 30 m, the bottom and side boundaries of the finite element model were set at a distance of 90 m (3L) and 60 m (2L) respectively. Brandl

(2006) reports that soil temperatures are steady at between 12ºC and 15ºC below a depth of about 10 m to 15 m in most European countries. Based on this, all the elements in the model were assigned an initial temperature of 12ºC. Likewise, the bottom and right hand side thermal boundaries were defined to remain constant at 12ºC. The top boundary was defined as having no heat flux (adiabatic) since in this study we don't want to take into consideration the effect of the outside temperature. The geometry, boundary conditions and mesh configuration of the model are indicated in Figure 3. A total of 864, 4 node heat transfer elements were used in the model.

Two different materials, concrete and soil, whose thermal and mechanical properties are indicated in Table 1 were created. The pile is modelled with solid elements assigned the properties for concrete while the surrounding ground is modelled with solid elements assigned the properties for soil. The pile- soil interface thermal conductance value was set to 25 W/m^2; this value was based on the value used for the evaluation of heat loss to the ground from a building by Thomas & Rees (1999). Thermal conduction was the only heat transfer mechanism taken into consideration as it is generally the dominant process of heat transfer in soils, while convection and radiation usually have negligible effects (Farouki, 1986).

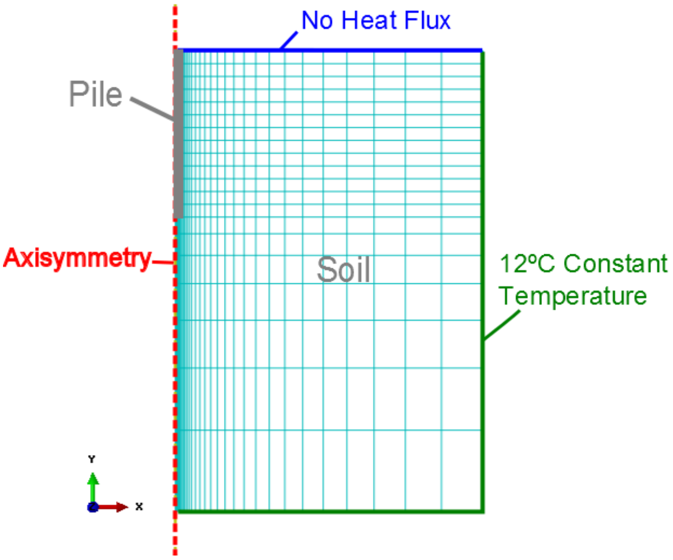


Figure 3. Axisymmetric model: finite element mesh and thermal boundary conditions.

	Soil	Concrete
Thermal conductivity, k (W/m.K)	1	2
Specific Heat, c (J/kg.K)	1220	940
Density, ρ (kg/m^3)	1600	2450
Young Modulus, E (MPa)	30	30 000
Poisson's Coefficient, ν	0.3	0.3
Maximum Shearing Resistance, τ_u (kPa)	75	-
Linear Coefficient of Thermal Expansion , α (m/m/K)	2E-5	1E-5

Table 1. Soil and concrete thermal and mechanical properties.

Thermal load on piles is often simulated in numerical models by applying a constant temperature increase or a heat flux in all elements or nodes constituting the pile. In reality, heat flows from absorber pipes which are either placed close to the centreline of the pile or close to the pile edge where the pipes are attached to the reinforcement cage. Three different modes of heating were simulated in the axisymmetric pile model: centreline heating, edge heating and full body heating whose characteristics are as follows:

- **Centreline Heating:** The pile is heated up to a constant temperature of 30°C ($\Delta T = +18^{0}C$) on the centreline over its full length (Figure 4(a)). This heating mode aims to simulate the case where the absorber pipes are placed in the centre of the pile.

- **Edge Heating:** The pile is heated up to 30°C ($\Delta T = +18^{0}C$) along a line which runs the depth of the pile and is located at a distance of 0.375 m (0.75R) from the pile centreline (Figure 4(b)).This heating mode aims to simulate the case where the absorber pipes are attached to the reinforcement cage, close to the edge of the pile.

- **Full Body Heating:** All elements making up the pile are heated to 30°C ($\Delta T = +18^{0}C$) (Figure 4(c)).This is the heating mode adopted in many published numerical studies of thermal active piles (Bodas Freitas et al., 2013, Suryatriyastuti et al., 2013)

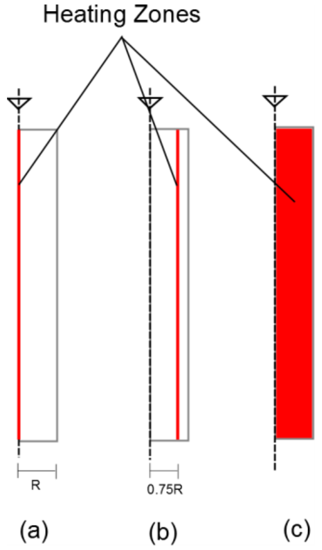


Figure 4. Modes of heating: (a) centreline heating; (b) edge heating; (c) full body heating.

The model runs in two steps: an initial step where the boundary conditions and the initial temperature of all elements are applied followed by a heat transfer step where the heating of the pile occurs. In order to assess if the three heating modes previously described produce similar temperature fields or not, steady state analyses were run for each of these and the results compared.

Figure 5 shows the temperature field predicted after a steady state was reached and for the case of full body heating, meaning all the elements forming the pile were heated up to 30^{o}C from the initial temperature of 12^{o}C. As expected, temperatures decreased radially from the pile to the edges of the model where the temperature was kept constant at 12^{o}C.

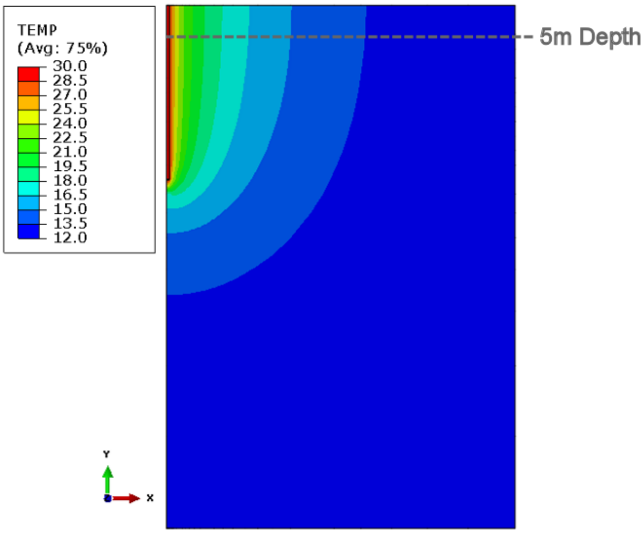


Figure 5. Model temperature field at steady state and for the full body heating case.

Figure 6 shows the first 4 m of the temperature profile obtained along a horizontal line at a depth of 5 m (dashed line in Figure 5) and for the three heating modes previously mentioned.

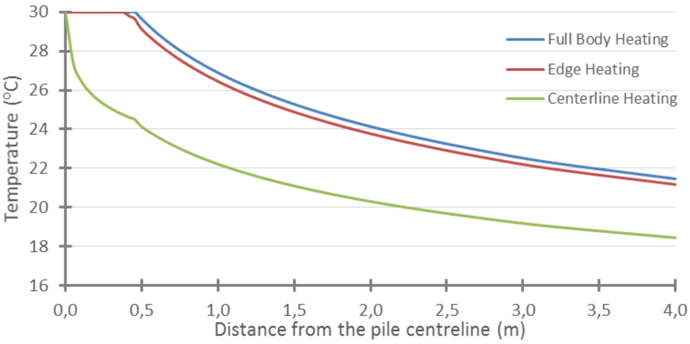


Figure 6. Radial temperature profiles at a 5 m depth.

While edge heating and full body heating led to similar temperature profiles, the difference between each being less than half a degree, centreline heating led to considerably lower temperatures; about 5^{0}C at the pile-soil interface (R=0.5 m) when compared to the other two heating cases.

With centreline heating, the heat flows from the centre of the pile and has to be thermally conducted through the concrete pile and into the soil while in case of edge heating, only the concrete cover to the reinforcement cage will affect the thermal flow and the pile body will be at a fairly constant temperature. Therefore, with full body heating and edge heating the pile will play a lesser role in the overall heat transfer process.

It can be concluded from these results that if the thermal pile being modelled has its absorber pipes placed close to edge of the pile, full body heating, which is often used in numerical simulations, will produce similar results to edge heating and is therefore a reasonable approximation. However, if the absorber pipes are placed along the centreline of the pile, pile heating should not be simulated as a full body heating and centreline heating should be adopted.

B. 2D Planar Model

A 2D planar model was also developed in order to see temperature profiles in plan since the previous analysed axisymmetric model will only allow us to see temperature profiles in depth. In the 2D planar model, we take advantage of the bi-directional symmetry of the problem and only one fourth of the pile and the surrounding soil is modelled.

As in the axisymmetric model, the pile diameter is 1 m and the side boundary of the model was set at a distance of 60 m. The geometry, boundary conditions and mesh configuration of the model are indicated in Figure 7.

The initial temperature of all elements is set to 12^{o}C. The same materials and their associated thermal and mechanical properties described in Table 1 were used.

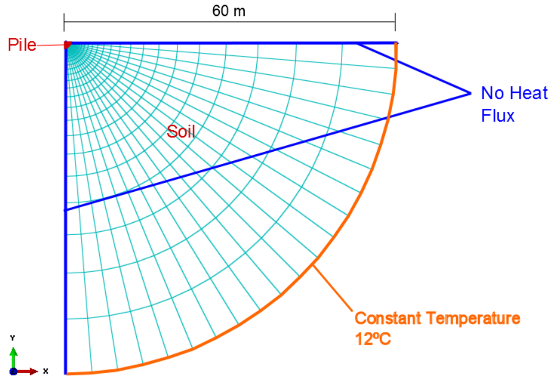


Figure 7. 2D Planar Model: finite element mesh, geometry and thermal boundary conditions.

Two different pile configurations were considered:

- **Ring Configuration:** In this configuration the pile is heated along a circular line located at a distance of 0.75R from the pile centre (Figure 8). This case corresponds to what we model in terms of a 2D plan view when “edge heating” is applied in an axisymmetric model.

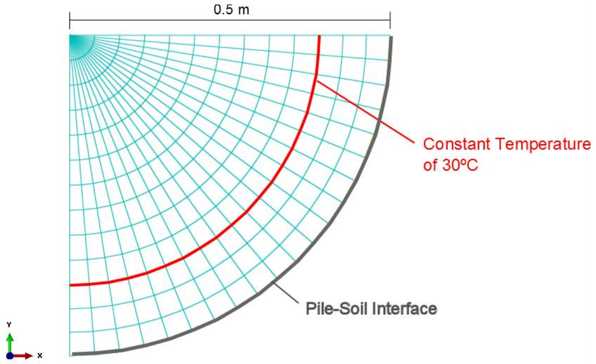


Figure 8. Pile ring configuration.

- **Pipe Configuration:** With this configuration, the aim is to model what really happens in a thermo-active pile. As the hot water circulates through the pipes of the pile, the pipe walls will heat and this heat will transfer by conduction to the pile and soil. A standard thermal pile configuration was modelled (Figure 9), where the 1 m diameter pile contains 4 pairs of pipes. The pipe diameter is 0.038 m and they are placed at a distance of 0.39 m from the pile centre (approximating the position of the tubes when attached to the inside of a reinforcement cage).

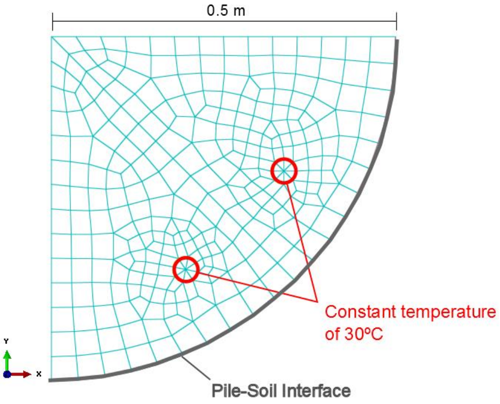


Figure 9. Pile pipe configuration.

The aim of these analyses was to determine whether or not the thermo-active pile problem can be simplified and studied with an axisymmetric model where heating in the ring configuration will take place or if the pipe layout should be modelled which would require the development of a 3D model. Both steady state and transient analyses were performed for the two configurations previously described, circular and pipe layout, and the resulting temperature fields compared. The initial temperatures of all elements is 12ºC while the temperature of the red zones indicated in Figures 8 and 9 were raised to a constant temperature of 30ºC in order to simulate the thermal load on the pile.

The evolution with time of the temperature field in the pile and the surrounding soil is shown in Figure 10. Figure 11 shows the evolution of temperature at the pile-soil interface until a steady state is reached. The temperature at the pile-soil interface is important as it is the relationship between the temperature of the pile and the surrounding soil together with their respective thermal expansion values that are expected to dictate the thermo-mechanical response of the pile-soil system.

The transient analysis highlights a considerable difference in terms of temperature levels in the pile and surrounding soil for the two configurations studied, especially during the first weeks of heating. The pipe configuration led to lower temperature levels in the pile than the ring configuration during the first weeks (Figure 101). However, the difference between the two cases diminishes as time passes and as we get closer to a steady state where similar temperature levels were displayed (Figure 11).

It can be concluded that for a steady state analysis of the thermal active pile problem, the definition of a pipe configuration is not necessary which means that the circular configuration, typically modelled in an axisymmetric study, is a good approximation of reality. However, if either a transient analysis is carried out, where the behaviour of the pile during the first weeks of functioning is the object of study or if the thermal load is changing with time, the pipe configuration should be adopted and a 3D model of the pile is therefore required.

It can also be observed from Figure 10 that the concrete heated faster than soil due to both its higher thermal conductivity and lower specific heat.

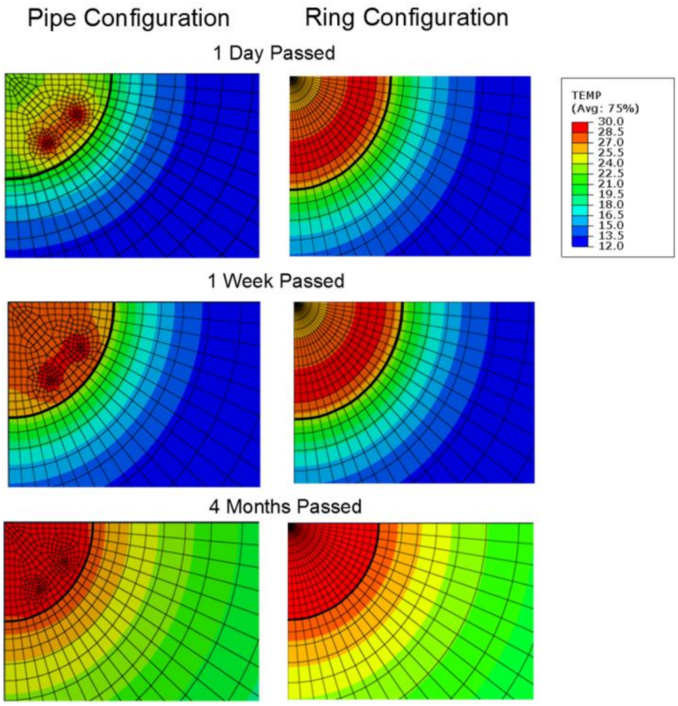


Figure 10. Temperature fields through time for the two pile configurations (the bold black lines represent the pile-soil interface).

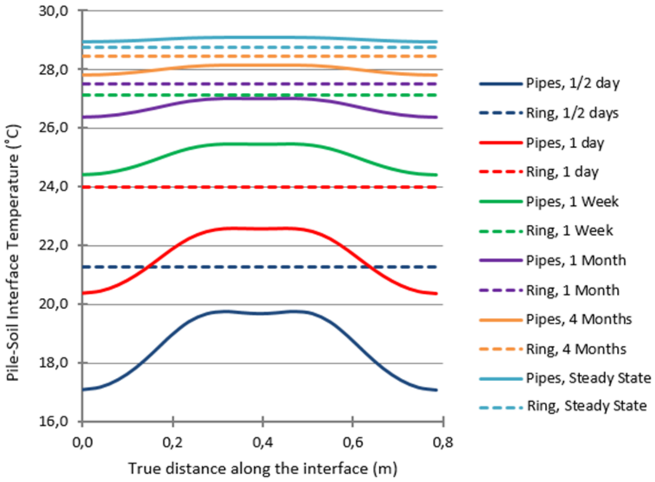


Figure 11. Pile-soil interface temperature profiles around pile circumference through time and at the steady state.

IV. THERMAL-MECHANICAL ANALYSIS

In the thermal-mechanical analysis, the mechanical aspect of the problem was also taken into consideration, in order to investigate how the thermal load affects the mechanical behaviour of the pile. The following aspects of the thermo-active pile problem were the objective of study:

- The influence of the ground surface temperature;
- The effect of differing relative values for the concrete and the soil coefficient of thermal expansion;
- The influence of the pile length and therefore the length to diameter ratio.

In order to investigate these aspects, a thermal-mechanical numerical model of the thermally-activated pile problem was developed using the finite element software Abaqus. This model was used to run a series of steady state thermal-mechanical analyses whose results are reported and discussed.

The axisymmetric thermal model previously developed for the thermal analysis (Figure 3) was adopted but was subject to some changes as the inclusion of the mechanical and thermal-mechanical effects added a lot of complexity to the problem.

The geometry and dimensions of the thermal-mechanical model remain identical to that of the thermal axisymmetric model previously described. The mesh was however reworked since the thermal-mechanical analysis demanded thinner elements than a purely thermal analysis, especially those elements close to the pile which are responsible for dictating the development of its base and shear resistance. The mesh was refined, especially at the pile-soil interface and close to the pile and a total of 3569 heat transfer four node elements were created for the baseline model (30 m long pile). The pile in the baseline analysis has a diameter of 1 m and length of 30 m. Piles of the same diameter but with lengths of 15 m and 45 m were also modelled as one of the parameter variations.

The same material properties indicated in Table 1 were adopted. The concrete linear coefficient of thermal expansion was assumed as 1.0E-5 m/m/K, according to data published in Tatro (2006) who reports values of concrete CTE between 0.76E-5 m/m/K and 1.36E-5 m/m/K, depending on the aggregate type used in its production.

A soil linear coefficient of thermal expansion of 2E-5 m/m/K was adopted for the baseline analysis, and values of 0.5E-5 m/m/K and 4E-5 m/m/K were also tested. These three values can be related to a lightly overconsolidated (OC), moderately OC and a heavily OC soil respectively. According to Cekerevac and Laloui (2004), soil thermal expansion will increase with an increase in its overconsolidation ratio (OCR), and highly OC soils can show a coefficient of thermal expansion several times higher than concrete.

Concrete was modelled as a purely elastic material while the soil was modelled as an elastic-perfectly plastic material with a Tresca failure criteria.

Pile-soil interface behaviour was modelled by the addition a layer of zero-thickness interface elements whose tangential behaviour is modelled with an elastic-perfectly plastic constitutive model. The interface elements mobilize shear resistance depending on the relative displacement (slip) between the solid elements representing the soil and those representing the concrete; in this case, reaching a maximum shearing resistance of 75 kPa for a total slip of 0.0015 m (0.15%D). The slip is measured as the vertical distance between nodes which initially, before any load is applied, are connected (slip = zero).

Initial vertical stresses corresponding to both the weight of soil and concrete were applied to all the elements of the model. The coefficient of lateral stress, K, was set to 1 meaning that the initial horizontal stresses were considered equal to the vertical ones.

The top surface of the model was set to a constant temperature of 18ºC for the baseline analysis. This was considered another key parameter for the study and values of 12ºC and 24ºC were also considered as one of the parameter variations. This range of temperatures aims to recreate the temperature levels we can expect below the ground slab of a modern building.

Rather than the 12°C used in the thermal analysis, to be consistent with the results of Bodas Freitas et al., 2013, the initial temperature field and bottom and right hand side thermal boundary conditions of the model were set to a constant temperature of 15ºC. Regarding the mechanical boundary conditions, the right boundary of the model is fixed in the horizontal direction while the bottom boundary is fixed in both directions. The left boundary of the model corresponds to the axis of symmetry.

Following the conclusions of the thermal analysis, where full body heating and edge heating were found to produce similar temperature fields at a steady state, and since the aim of the model was to recreate a thermal pile whose absorber pipes are placed close to its edges, the heating of the pile was simulated by applying an increase of 30ºC to all the elements making up the pile (full body heating). To avoid calculation problems a 0.5 m wide temperature transition was provided at the edge of the pile, at the ground surface, to allow the temperature to decrease from 45ºC to 18ºC. In the study presented here only pile heating ($\Delta T = +30$ºC) is considered; as the analyses are thermo-elastic cooling would result in qualitatively similar but reversed results.

The mesh, geometry and boundary conditions of the thermal and mechanical boundary conditions are illustrated in Figure 12.

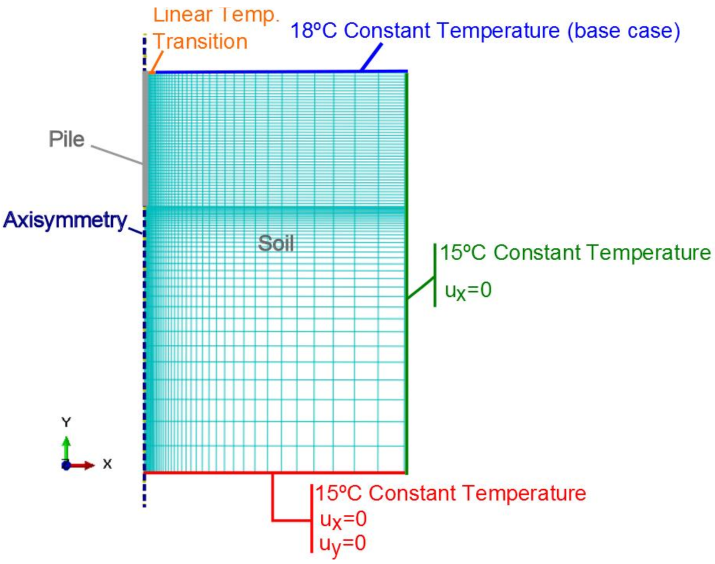


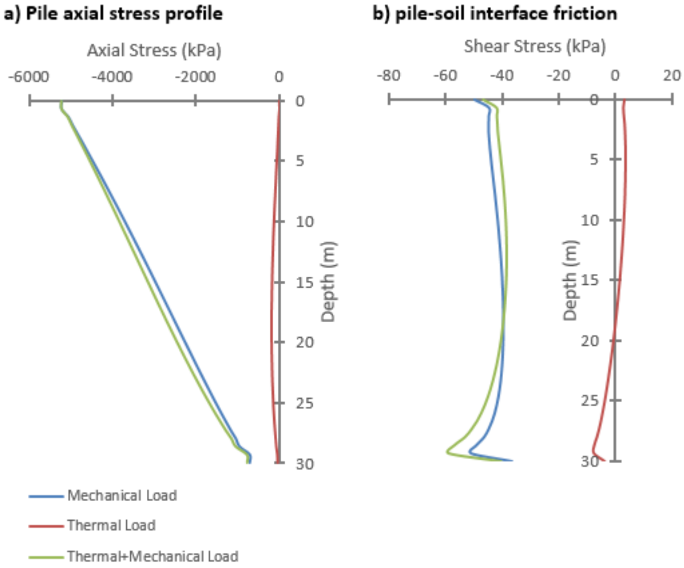
Figure 12. Finite element mesh, geometry and boundary conditions of the thermal-mechanical model.

The mechanical load on the pile is applied as a uniform pressure at its head. The applied mechanical load value was calculated as the design load of the pile according to the European regulation for geotechnical design (NP EN 1997-1). Regarding the base case (30 m pile), the calculated ultimate shaft resistance was 7069 kN and the ultimate base resistance was 651 kN. By applying the appropriate partial factors from NP EN 1997-1 to these values a pile design compression resistance of 4175 kN is obtained. Given the pile diameter of 1 m, this translates into a uniform pressure of about 5.3 MPa. The same methodology was applied in order to determine the mechanical load applied to both the 15 m and 45 m piles which resulted in uniform pressures of 2.8 MPa and 7.8 MPa respectively.

A. *Baseline Analysis*

The baseline analysis corresponds to a 30 m long pile, an 18ºC top thermal boundary condition and a soil with a coefficient of thermal expansion (2E-5 m/m/K) twice that of the concrete (1E-5 m/m/K). Axial normal stresses in the pile, Figure 13(a), and the pile-soil interface shear stresses, Figure 13 (b), show the effect of the mechanical load only, the thermal load only (temperature increase of 30°C) and the combined effect of both these loads. Note that positive axial stress values mean tensile stress while negative values mean compressive stress.

Similar behaviours to those described in Figure 1 were verified. The heating thermal load increased the axial compressive load in the pile. The maximum thermally induced axial stress was 182.2 kPa (about 2% of the stress change implied by perfect restraint, equation (3)) and occurred at a depth of 18.7 m, which corresponds to the point where the strain restraint was highest. If the pile was symmetrically restrained this point would be located at 15 m depth (middle of the pile) however, in this case, the lower half of the pile presents higher restraint than the upper half due to the presence of the soil at the pile base while the pile head is free to move. For this reason, it is expected that the point of maximum strain restraint will be located closer to the base which was indeed verified in the results.


a) Pile axial stress profile

b) pile-soil interface friction

Figure 13. Stresses in the pile and in the pile-soil interface.

The interface shear stress profile due to the thermal load (Figure 13 (b)) was also as expected. By inducing relative motion between pile and soil, the thermal load led to a reduction of shear stress above a depth of 18.7 m due to the pile expanding upwards and an increase of shear stress below this depth due to the pile expanding downwards. Naturally, the thermal load induced an equilibrated shear stress profile with a null value at the 18.7 m section which corresponds to the section of maximum strain restraint.

Figure 14 shows the effect of the mechanical load only, the thermal load only and the combined effect of both these loads in terms of pile vertical displacements. As expected, the mechanical and thermal load induced opposite effects. While the mechanical load induces a downwards movement in the pile leading to a settlement of -10.5 mm at the pile head, the thermal load makes the pile expand and induces an upwards movement returning the pile head almost to the initial position by inducing a vertical displacement of 9.1 mm, i.e. a resultant settlement of -1.4 mm. Notably, the displacement at the base of the pile is virtually unchanged however when other parameter combinations were evaluated (see the Parameter Study) this was found to be a consequence of the parameter set being considered in this particular case.

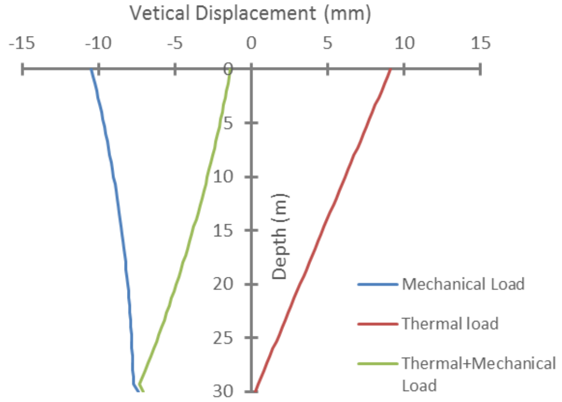


Figure 14. Pile vertical displacement.

According to equations (1) and (2), if no restraint is applied in the pile, the maximum length change it can experience due to a thermal load of +30ºC is 9 mm. In the baseline analysis case, the pile length change due to the thermal load was 8.7 mm, meaning that the restraint applied to the pile by the soil is very low which explains the low magnitude thermally induced stresses verified.

While a “standard” thermal pile behaviour was observed for the baseline case, in reality the thermally induced stresses are highly dependent on the relationship between pile and soil coefficients of thermal expansion as well as the temperature field in the ground, as will be verified and discussed in the Parameter Study.

B. Parameter Study: Coefficient of Thermal Expansion

Figure 15 (a) and (b) illustrate the axial stress and interface shear stress changes developed due to the heating thermal load ($\Delta T = +30$ºC) for the three combinations of soil and concrete thermal expansion values previously detailed. All the remaining model parameters remained the same as in the baseline analysis.

These figures clearly show the influence of the relative values of the concrete and soil thermal expansion coefficients with respect to the changes in axial stress and shear stress during thermal loading, confirming the results reported by Bodas Freitas et al, (2013). In fact, this relationship is responsible for dictating not only the magnitude of the thermally induced stresses but also their direction.

When soil is half as thermally expansive as concrete (blue lines in Figure 15) similar behaviour to what was previously described in the baseline analysis (red lines) was observed, however the magnitude of the developed stresses was considerably higher. This happens because the soil has a lower tendency to expand; the relative movement between the soil and the pile is greater and therefore the change in shear stress in the interface is larger. This results is greater restraint of the pile and consequently, the development of larger magnitude thermally induced axial stress.

When the soil is four times more expansive than concrete (green lines), the pile goes into tension. In this case, because the soil is considerably more thermally expansive than concrete, it will expand more than the pile, which leads to the development of tensile stresses.

When the soil is two times more expansive than concrete (the base case), we are in a situation in between the two previously described. As the soil is more expansive than the concrete, tensile stresses would be expected in response to heating, this doesn’t happen because the pile is at a higher temperature than the soil. For the combination of parameters used in this case, the resultant effect is for the pile to expand slightly more than the soil does and the two effects, soil and pile expansion, end up opposing each other and resulting in low magnitude thermally induced compressive stresses.

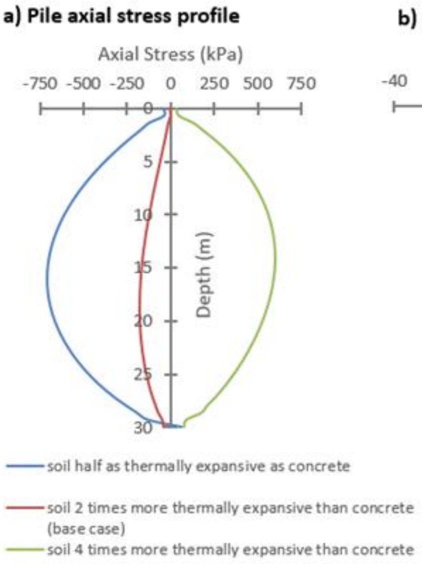


Figure 15. Thermally induced stresses for three cases of thermal expansion values.

The change in pile vertical displacements due to the thermal load is plotted in Figure 16. It can be seen that as we increase the coefficient of thermal expansion of the soil, the more the pile moves upwards due to the thermal load. This is due to the added increase in volume the soil experiences which “pushes” the pile upwards. Comparing the results from the cases when the soil is 2 times and 4 times more expansive than soil, it can also be seen that the pile is also slightly stretched due to the high tensile tresses the soil imposes over it. In fact, according to Equations (1) and (2), if the effect of soil expansion is ignored, the maximum length change the pile can experience due to a thermal load of +30ºC is 9 mm, while for the case when the soil was 4 times more thermally expansive than concrete, this length change was 9.4 mm, proving the stretching effect the soil has over the pile

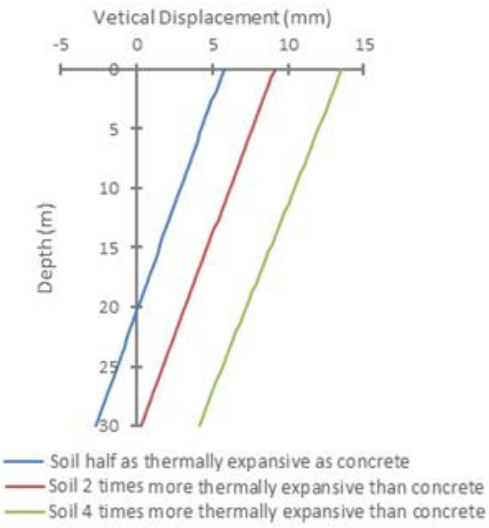


Figure 16. Thermally induced vertical displacements for three cases of thermal expansion values.

C. Parameter study: Surface Temperature

Figure 17 (a) and (b) illustrate the thermally induced stresses in the pile and interface for three different ground surface temperature boundary conditions: 12ºC; 18ºC (base case) and 24ºC. Naturally, these boundary conditions will have a great effect over the soil temperature field especially in the upper part of the model and therefore affect how much it will try to expand or contract, and how it will interact with the pile. Because all the elements forming the pile are heated to a constant temperature of 45ºC, a change in the ground surface thermal boundary condition will only affect the temperature of the soil and therefore how much it expands or contracts. Besides the ground surface temperature, all the other model parameters remained the same as in the baseline analysis.

In comparison to the base case (red line), an increase in ground surface temperature changed the thermally induced axial stresses from compressive to tensile and the direction of the interface shear stresses. To understand this behaviour it is important to remember that in this analysis, the soil is twice as thermally expansive as the pile; therefore, any increase in temperature will lead to a significant expansion of the soil. By increasing the ground surface temperature, we also increase the average temperature of the soil mass beneath it, which will lead to expansion and the development of tensile stresses in the pile, as the soil will expand more than the pile.

The opposite phenomenon happens when we decrease the ground surface temperature. Reducing the temperature of the soil below the initial state will lead to contraction and the development of larger compressive stresses in the pile. In this case, even though the pile is less expansive than the soil, because it is subjected to considerably higher temperatures it will still show a tendency to expand more than the soil which will lead to compressive thermally induced stresses.

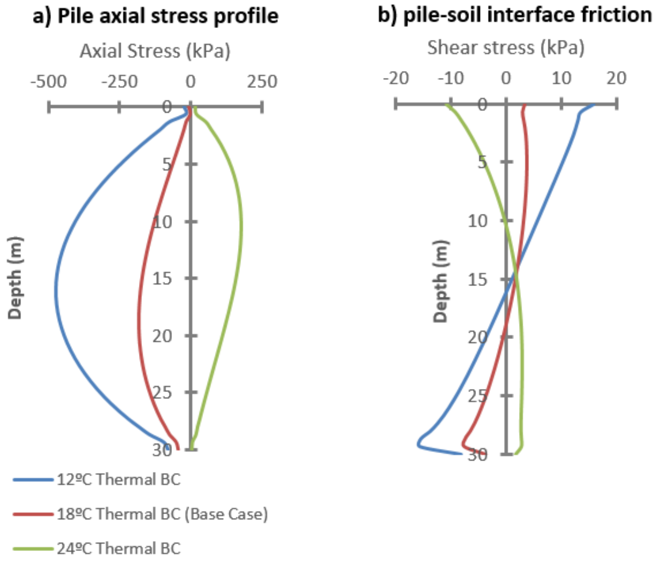


Figure 17. Thermally induced stresses for three different ground surface temperatures.

D. Parameter study: Pile length to diameter ratio

Figure 18 (a) and (b) illustrate the thermally induced stresses in the pile and interface for three different pile lengths: 15 m, 30 m (base case) and 45 m. The pile diameter is 1 m for the three cases, the soil is two times more expansive than concrete, and all the remaining model parameters are those of the baseline analysis.

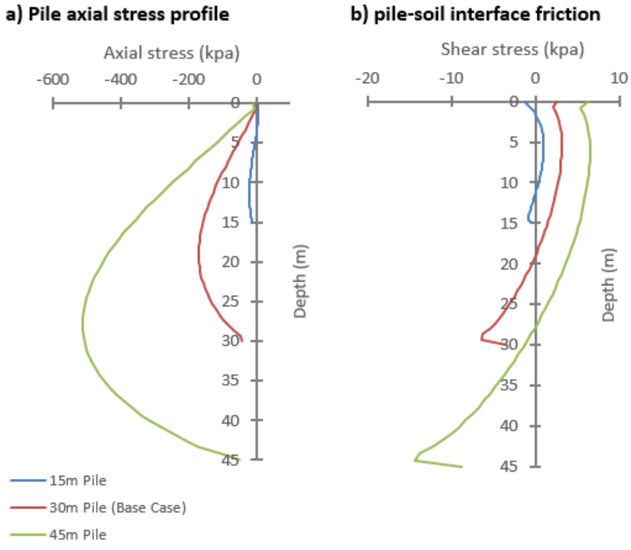


Figure 18. Thermally induced stresses for three different pile lengths.

While a change in the pile length did not induce any behaviour changes in the pile, i.e. the resultant effect was compressive thermally induced axial stresses in all three cases, the magnitude of the developed stresses was clearly affected by this change as the longer the pile (larger the ratio, L/D), the larger were the mobilized pile axial normal stresses and the pile-soil interface shear stresses. Two phenomena are believed to be the cause of this increase in thermally induced stresses:

1. The main cause derives from the fact that the longer the pile is, the more it will expand or contract when subjected to a temperature change and therefore the higher the shear stresses mobilized at the pile-soil interface will be. This mobilization of shear stress will induce strain restraint in the pile and thermally induced stresses are directly proportional to the amount of strain restraint (equation (3)). If the soil and the interface remain elastic, the increase in thermally induced stress due to the increase in strain restraint with pile length is believed to be a linear effect.
2. A second cause of this behaviour, while perhaps less important than that described above, is the variation of the soil temperature field with depth. In fact, in the baseline analysis, the top boundary of the model is kept at 18ºC while the bottom at 15ºC, This means that the initial temperature field around the 15 m pile will be generally warmer than that of say the 45 m pile and therefore, in the former case, the effect of the temperature change in the pile on the soil temperature will be less. If the temperature change is less, then the relative movement on the pile-soil interface will be smaller leading to lower changes in shear stress and pile restraint.

E. Summary and interaction between variables

Figure 19 illustrates the maximum thermally induced axial load in the pile as a function of the ground surface temperature for the three ratios of soil to concrete coefficient of thermal expansion previously considered and for a pile length of 30 m. This figure highlights the strong influence of the ground surface temperature over the thermally induced axial load on the pile, as previously discussed. A clear connection between this influence and the relationship between soil and concrete coefficients of thermal expansion can be seen. In fact, the effect of the ground surface temperature will greatly increase with an increase of the coefficient of thermal expansion of the soil and the thermally induced stresses will become increasingly tensile. This behaviour can be explained as the higher the soil coefficient of thermal expansion is, the more it will tend to expand relative to the pile for the same temperature change and therefore the more tensile the stresses it will induce.

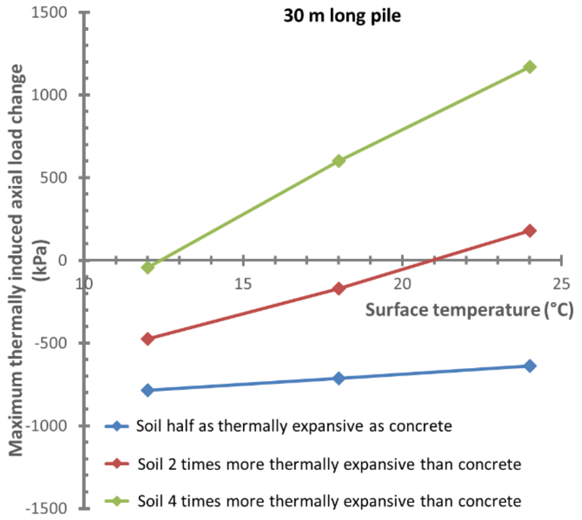


Figure 19. Maximum thermally induced axial stress on the pile as a function of the ground surface temperature (30 m pile).

Figure 20 shows the same data set redrawn with the maximum thermally induced axial stresses expressed as a function of the ratio between soil and concrete linear coefficient of thermal expansion (α_{soil} and α_{conc}) and for a pile length of 30 m. Once again, the significant influence of the ground surface temperature over the thermally developed stresses is clearly seen. However and as expected, these lines converge to the same value for the case of a soil with a coefficient of thermal expansion of zero, where a change of the ground surface temperature won't produce any effect because the soil becomes "immune" in terms of volumetric changes to any thermal load and the pile temperature is unaffected by the ground surface temperature as it was modelled to heat uniformly to 45ºC and to remain at this temperature.

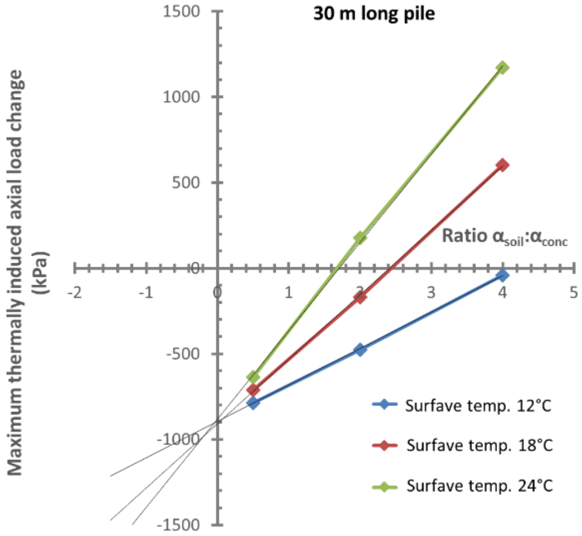


Figure 20. Maximum thermally induced axial stress on the pile as a function of the ratio between soil and concrete's thermal expansion coefficients. (30 m Pile).

When the ratio of soil to concrete coefficient of thermal expansion is equal to zero, the maximum thermally induced axial stress in the 30 m pile is about 900 kN; in the 15 m long pile it was about 300 kN and the 45 m pile, 1600 kN. In relation to the length of the pile, the thermally induced stress in the pile when the ratio of soil to concrete coefficient of thermal expansion is equal to zero is approximately linear.

V. CONCLUSIONS

Thermal and thermal-mechanical numerical analyses of a thermo-active pile were performed using the finite element software Abaqus. It is believed that these analyses produced important and interesting results which will contribute to improving our current knowledge regarding the thermal-mechanical behaviour of energy foundations.

The thermal analysis showed that at a steady state, full body and edge heating produced similar temperature fields; however those obtained from centreline heating showed considerably lower temperatures especially at the pile-soil interface. Consequently, if the energy pile being simulated has its heat exchange pipes placed close to the centreline, full body heating is not appropriate and centreline heating should be adopted. The pipe layout and ring heating produced similar temperature fields at a steady state; however the transient analysis showed that the temperature fields differed considerably during the first weeks of heating. If a transient analysis of an energy pile is required, it is recommended that the pipe layout is modelled

Results from the thermal-mechanical analysis indicated that the relative values of the coefficient of thermal expansion for the soil and the concrete play a key role in dictating the behaviour and the magnitudes of the developed stresses on a pile subjected to thermal load. It was observed that even for the same thermal load, this ratio can dictate if the thermally induced stresses on the pile will be compressive or tensile.

It was also assessed that the ground surface temperature has a very important influence over the thermally induced stresses developed in the pile if the soil is more thermally expansive than concrete. This effect was however considerably less significant if the concrete is more expansive than soil. It is therefore recommended that numerical simulations of energy piles pay close attention to the correct definition of the ground surface temperature.

The ratio between pile length and diameter showed a clear influence over thermally induced stresses. For the same pile diameter, the longer the pile, the larger the thermally induced stresses will be. This phenomenon is believed to be caused mainly by the increased shear stress mobilized at the pile-soil interface which increases restraint on the pile. To a lesser extent, the variation of the ground temperature with depth may also affect the development of thermally induced stresses for piles with different lengths, especially when soil presents a higher thermal expansion coefficient than concrete.

REFERENCES

Amatya B.L. Soga K. Bourne-Webb P.J. Amis T. and Laloui L. 2012. Thermo-mechanical behaviour of energy piles, Géotechnique, 62(6), 503-519.

Bodas Freitas, T. M., Cruz Silva, F. and Bourne-Webb, P.J. (2013). The response of energy foundations under thermo-mechanical loading, Accepted for publication in the Proc. 18th ICSMFE, Paris, 4 pages.

Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, T. & Payne, P. (2009) Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles, Geotechnique, 59 (3), 237-248.

Bourne-Webb, P., Amatya, B. & Soga, K. (2013) A framework for understanding energy pile behaviour,. Proceedings of the Institution of Civil Engineers Geotechnical Engineering.

Brandl, H. (2006) Energy foundations and other thermo active ground structures, Geotechnique, 56 (2), 81 – 122.

Cekerevac C and Laloui L (2004) Experimental study of thermal effects on the mechanical behaviour of a clay. International Journal for Numerical and Analytical Methods in Geomechanics 28(3): 209–228.

Farouki, O. T. (1986) Thermal Properties of Soils, Series on Rock and Soil Mechanics Volume 11, Trans Tech Publications, Germany.

Laloui, L., Nuth, M. & Vulliet, L. (2006) Experimental and numerical investigations of the behaviour of heat exchanger pile, International Journal for Numerical and Analytical Methods in Geomechanics, 30, 763-781.

Tatro S.B., (2006). Thermal properties, in – STP169D Significance of tests and properties of concrete and concrete-making materials, Lamond and Pielert eds., ASTM International, USA, p. 226-237

Thomas H. R., Rees S. W. (1999). The thermal performance of ground floor slabs – a full scale in-situ experiment. Building and Environment 34 (1999). Pp 139 – 164.

Surayatriyastuti, M., Mroueh, H, and Burlon, S. (2013). Numerical analysis of a thermo-active pile under cyclic thermal loads, Proc. European Geothermal Conference, EGC 2013, Pisa, Italy, 1-8.