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Computational study on the effects of boundary conditions on the modelled thermally induced axial stresses in thermo-active piles

Analyse numérique de l'influence des effets de bords sur la contrainte axiale thermiquement induite dans les pieux énergétiques

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ABSTRACT: Axial stresses are thermally-induced when a thermo-active pile is heated or cooled, as the soil surrounding the pile restricts the expansion or contraction of the pile. In order to investigate the thermally-induced axial stresses a thermo-active pile is subjected to when it is heated, a fully coupled 3D thermal-hydro-mechanical (THM) finite element analysis is conducted, which includes the simulation of a hot fluid flowing through the heat exchanger pipes. As these 3D analyses are computationally expensive and time-consuming, this paper compares the thermally induced axial stresses obtained from the 3D analysis with those modelled in axi-symmetric analyses when other thermal boundary conditions are applied as alternatives to simulating the flow of a fluid through the pipes within the thermo-active pile. It is shown that similar magnitude and distribution of thermally induced axial stresses can be simulated by modelling the thermo-active pile as a uniform volume heat flux, where the magnitude is equal to that required to heat up the edge of the pile at mid-depth to the temperature of the hot fluid that is circulated into the thermo-active pile at steady-state in the long-term.

RÉSUMÉ: Tant qu'un pieu énergétiques est chauffé ou refroidi, des contraintes axiales sont induites parce que le sol tout autour du pieu limite sa expansion ou contraction. Afin d'étudier les contraintes axiales thermiquement induites dans un pieu énergétiques, on conduit une analyse thermo-hydro-mécanique tridimensionnelle aux éléments finis. En particulier, on simule l'écoulement d'un fluide chaud à travers les tuyaux de l'échangeur de chaleur. Puisque les analyses tridimensionnelles sont coûteuses en temps de calcul, on compare les contraintes axiales obtenues par l'analyse tridimensionnelle avec celles obtenues par des analyses axi-symétriques où on utilise plusieurs effets de bord afin de simuler l'écoulement du fluide dans les tuyaux. On montre qu'on peut obtenir les contraintes axiales en simulant le pieu comme un volume uniforme de flux de chaleur dont la magnitude peut être calculée selon une méthode particulier.

Keywords: Thermo-active piles; thermal effects; finite element analyses; thermal boundary conditions; axial stresses

1 INTRODUCTION

Thermo-active piles are a popular foundation strategy due to their ability to provide low carbon heating and cooling as ground source heat exchangers while guaranteeing structural stability. Thermo-active piles differ from conventional piles by being equipped with heat exchanger pipes, forming a closed loop, which are often attached to the reinforcement cage. By circulating a hot or cold fluid through the pipes, heat can be exchanged with the ground and the cooled or heated fluid can then be used for cooling or heating purposes in the building.

When a thermo-active pile changes temperature, its expansion or contraction is restricted by the surrounding soil and this gives rise to thermally-induced axial stresses, which is an important factor to consider during design. Recent numerical studies (Gawecka et al., 2016; Gawecka et al., 2017; Liu, 2017) are based on axi-symmetric finite element analyses, simulating the heating/cooling of the thermo-active pile by applying either a heat flux or change in temperature as a boundary condition. This is, naturally, a simplification, with a 3D analysis in which the simulation of a hot fluid flowing through the heat exchanger pipes is included being the most accurate approach to estimating the distribution of thermally-induced axial stresses within the pile. However, while these analyses reproduce in greater detail the heat transfer mechanisms taking place within the pile and between the pile and the soil, they are computationally expensive and time-consuming. Therefore, in this paper, the Imperial College Finite Element Program (ICFEP, Potts & Zdravkovic, 1999), which is capable of simulating coupled thermo-hydro-mechanical (THM) problems (Cui et al., 2018b), is used to assess the accuracy of simpler axi-symmetric analyses by comparing the modelled response with that obtained using a 3D approach where the existence of heat exchanger pipes is explicitly considered. Two possible strategies were followed to simulate the heating of the thermo-active pile in the axi-symmetric analyses:

- change in temperature over the entire volume of the thermo-active pile
- constant heat flux over the entire volume of the thermo-active pile.

Throughout this paper, the adopted sign convention is that tension is taken as positive.

2 FULLY COUPLED 3D THM FINITE ELEMENT ANALYSIS

A fully coupled 3D THM finite element analysis, which includes the simulation of a hot fluid flowing through the pipes, is conducted to establish the reference response to thermal loading of a thermo-active pile. The considered pile has a diameter of $900\ mm$ and a length of $25\ m$, with a single U-loop pipe arrangement, which is illustrated in Figure 1. The thermal loading is applied by circulating a hot fluid that is 20^oC above the ambient temperature.

The heat exchanger pipes have an internal diameter of $26\ mm$ and the fluid is assumed to be circulated at a velocity of $0.2\ m/s$, while the concrete cover between the pipe and the pile edge is taken as $0.07\ m$. These characteristics are adopted from the thermal response test reported by Loveridge et al. (2014).

Before the thermo-active pile is heated, it is loaded to a vertical load of $2900\ kN$, which corresponds to a factor of safety of 2.6 applied to its ultimate capacity, estimated using the α-method with $\alpha = 0.5$.

2.1 Mesh, stratigraphy and types of elements

The stratigraphy adopted in this 3D finite element analysis is similar to that described by Gawecka et al. (2016), which is a simplified profile consisting of a single layer of London Clay. The discretised soil domain is $64\ m$ deep and $80\ m$ in diameter, as shown in Figures 1 and 2. Note that, due to symmetry, only half of the problem is simulated.

The thermo-active pile and London Clay are discretised using 20-noded isoparametric elements, with three displacement and one temperature degrees of freedom at each node. A pore water pressure degree of freedom also exists at corner nodes for the elements modelling the soil. The pipes are modelled with one-dimensional 3-noded bar elements (Gawecka et al., 2018), with three displacement and one temperature degrees of freedom at each node and pore water pressure degrees of freedom at each of the end nodes.

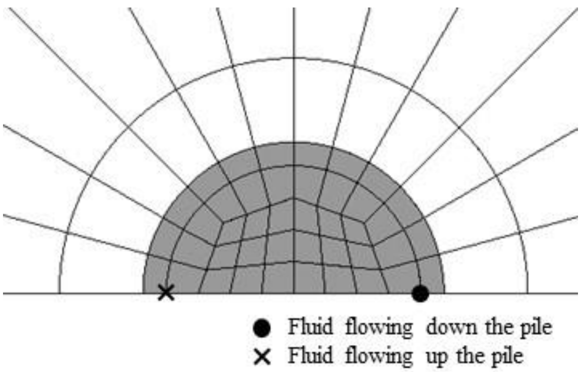

Figure 1. Plan view of the zoomed-in finite element mesh used in the 3D analysis detailing the pile (shaded in grey) and an illustration of the pipe arrangement

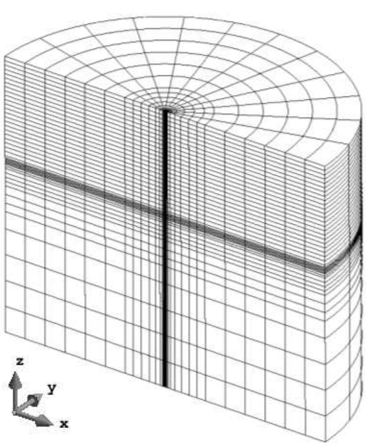

Figure 2. Finite element mesh used in the 3D analysis

2.2 Initial and boundary conditions

The initial conditions in terms of temperature, pore water pressure and at-rest coefficient of earth pressure (K_0) are identical to those described in Gawecka et al. (2017): the initial temperature of the ground is assumed to be 19.5^oC; the ground water table is located at the ground surface and an initial underdrained pore water pressure profile is used (Figure 3a); and a typical K_0 profile, represented in Figure 3b is adopted.

In terms of displacement boundary conditions, the bottom of the mesh is restricted from moving in all directions, while the nodes on the far cylindrical boundary are restricted in the radial direction. Additionally, the nodes on the vertical plane of symmetry are restricted from moving along the y-axis (i.e. the direction normal to the plane). Hydraulic boundary conditions specifying a no change in pore water pressure at the top and bottom boundaries of the mesh were adopted, and no water flow was allowed across all other boundaries. Lastly, a no change in temperature boundary condition was specified at all boundaries of the mesh, except on the plane of symmetry where no heat flow was allowed.

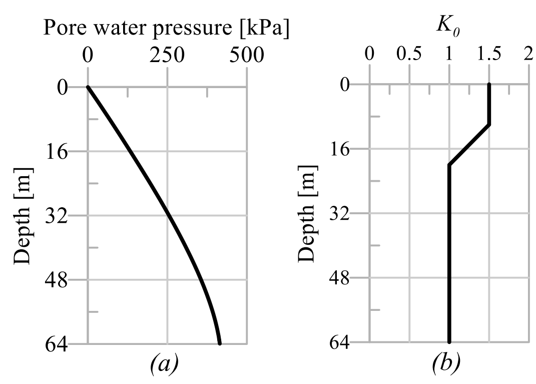

Figure 3. (a) Initial pore water pressure profile and (b) K_0 profile

2.3 Material models and properties

2.3.1 London Clay

The London Clay is modelled as a non-linear elasto-plastic material, coupling a Mohr-Coulomb failure surface with the Imperial College Generalised Small-Strain Stiffness (IC.G3S) model (Taborda et al., 2016). The permeability, k, of London Clay is determined by the non-linear permeability model $k = k_0 e^{-Bp'}$, where k_0 and B are parameters and p' is the mean effective stress. Table 1 shows all the material properties adopted for London Clay, which are identical to those adopted in Gawecka et al. (2017).

Table 1. Material properties for London Clay

Mohr-Coulomb strength properties	
c'	$5.0\ kPa$
ϕ'	25.0^o
ν	12.5^o
Small-strain stiffness properties	
G_0	$51743.55\ kPa$
p'_{ref}	$100\ kPa$
m_G	1.0
m_K	1.0
a	0.000056
b	0.9
$R_{G,min}$	0.06450
G_{min}	$2667\ kPa$
K_0	$26692.73\ kPa$
r	0.000127
s	1.8
$R_{K,min}$	0.13275
K_{min}	$5000\ kPa$
Thermal and thermo-mechanical properties	
γ_s	$20.0\ kN/m^3$
α_s	$1.7 \times 10^{-5}\ m/mK$
α_f	$6.9 \times 10^{-5}\ m/mK$
K_f	$2.2\ GPa$
ρC_p	$1820\ kJ/m^3K$
λ	$1.79 \times 10^{-3}\ kW/mK$
Seepage properties	
k_0	$1.0 \times 10^{-10}\ m/s$
B	0.0023

In Table 1, c' is the cohesion, ϕ' is the angle of shearing resistance, ν is the angle of dilation, G_0 is the maximum shear modulus at the reference mean effective stress, p'_{ref} is the reference mean effective stress, m_G and m_K are parameters defining the dependence of the elastic stiffness on mean effective stress, a, b, r and s are stiffness degradation parameters, $R_{G,min}$ is the minimum normalised value of the tangent shear modulus, G_{min} is the minimum shear modulus, K_0 is the maximum bulk modulus at the reference mean effective stress, $R_{K,min}$ is the minimum normalised value of the tangent bulk modulus, K_{min} is the minimum bulk modulus, γ_s is the unit weight, α_s and α_f are the linear coefficients of thermal expansion for the soil skeleton and pore fluid respectively, K_f is the bulk modulus of pore fluid, ρC_p is the volumetric heat capacity and λ is the thermal conductivity.

2.3.2 Concrete pile

The concrete thermo-active pile is modelled as a linear-elastic material and its properties are given in Table 2 (Gawecka et al., 2017).

Table 2. Material properties for concrete pile

Linear material properties	
E	$40 \times 10^6\ kPa$
μ	0.3
Thermal and thermo-mechanical properties	
γ_s	$24.0\ kN/m^3$
α_s	$8.5 \times 10^{-6}\ m/mK$
ρC_p	$1920\ kJ/m^3K$
λ	$2.33 \times 10^{-3}\ kW/mK$

2.4 Modelling procedure

In the finite element analysis, the thermo-active pile is first loaded by linearly increasing the vertical load applied at the top of the pile to $2900\ kN$ in 50 hours, allowing full dissipation of excess pore water pressures once loading is complete. Subsequently, water is circulated through the pipes at the required flow rate by applying a pore water pressure differential between the pipe inlet and outlet. Since the Galerkin finite-element method leads to numerical oscillations when modelling an advection-dominated heat flux, the Petrov-Galerkin finite-element method (Cui et al., 2018a) is adopted for the pipes. Hot water at $39.5^{o}C$ is circulated for 5 months during which the thermally induced axial stresses are monitored by applying a thermal boundary condition of $T = 39.5^{o}C$ at the pipe inlet. A coupled thermo-hydraulic boundary condition (Cui et al., 2016) is specified at the pipe outlet to enable the removal of the energy corresponding to the water flowing out of the mesh.

2.5 Results and discussion

As the thermo-active pile heats up and expands, the soil surrounding it restricts its expansion, giving rise to thermally-induced compressive axial stresses. Since the temperature field within the thermo-active pile is non-uniform, the thermally-induced axial stresses are not only a function of time, but also a function of depth within the pile and the position within the cross-section. In this paper, thermally-induced axial stresses are cross-sectionally averaged (denoted by $\overline{\sigma_T}$, which is a function of time and depth), and only its maximum value over the pile length (denoted by $\overline{\sigma_T}_{max}$, which is a function of time only) is presented.

Figure 4 shows the evolution of $\overline{\sigma_T}_{max}$ with time. It can be seen that $\overline{\sigma_T}_{max}$ increases as the pile is heated up, reaching a peak. $\overline{\sigma_T}_{max}$ then reduces gradually with time as the soil surrounding the pile expands due to an increase in temperature, reducing the restraint that it imposes on the pile. This response is clearly transient in nature and can only be captured if heat flux across the soil, which is a time-dependent phenomenon, is considered. Figure 5 plots this behaviour onto the current design chart proposed by GSHPA (2012) for piles 900 mm in diameter installed in London Clay.

As seen in Figure 5, the peak $\overline{\sigma_T}_{max}$ obtained from the 3D analysis is 529.31 kPa, which is 142% larger than that suggested by the current design chart. With time, the reduction in the restraint imposed by the soil leads to a decrease in thermally-induced axial stresses to values closer to those suggested by the GSHPA (2012). The large difference observed in the short- to medium-term is likely to reflect the different modelling approaches used. In effect, according to GSHPA (2012), the design charts were developed using a thermal pile software based on the load transfer method (t-z method), which is unable to incorporate the non-isothermal response of soil.

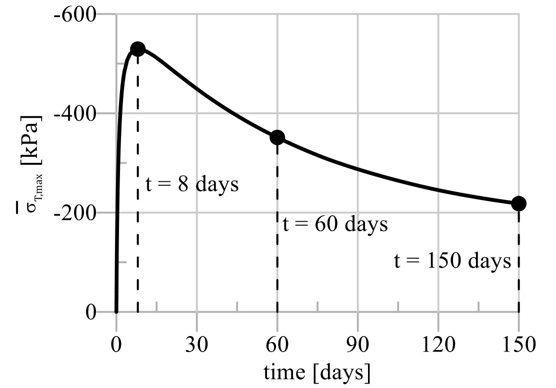

Figure 4. Evolution of $\overline{\sigma_T}_{max}$ with time from the 3D finite element analysis

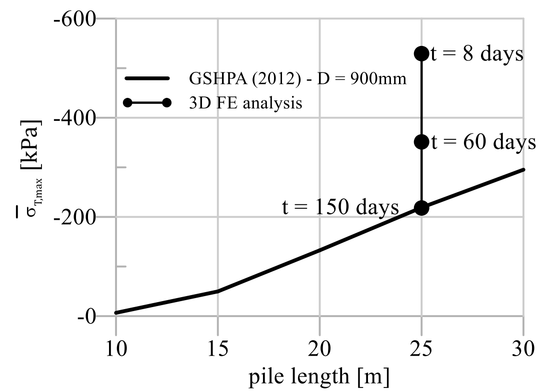

Figure 5. Peak $\overline{\sigma_T}_{max}$ and transient behaviour plotted on the design chart given by GSHPA (2012)

3 FULLY COUPLED AXI-SYMMETRIC THM FINITE ELEMENT ANALYSES

Although 3D analyses can simulate thermally induced axial stresses accurately, they are computationally expensive and time-consuming. As a result, a number of fully coupled axi-symmetric THM analyses are conducted where different thermal boundary conditions are prescribed to simulate the heating of the thermo-active pile, and the resulting stresses are then compared with those from the 3D analysis. In this paper, two different approaches have been considered:

- Approach I: change in temperature over the entire volume of the thermo-active pile (Section 3.1)
- Approach II: constant heat flux over the entire volume of the thermo-active pile (Section 3.2).

The mesh that is used for all the axi-symmetric analyses has the same dimensions and follows the same discretisation as that in the 3D analysis. The adopted stratigraphy, initial and boundary conditions and material models and properties are also identical to those used in the 3D analysis, with the exception of the one-dimensional elements used for simulating heat exchanger pipes, which are naturally not present in the axi-symmetric analyses. The same modelling sequence as that adopted in the 3D analysis is used in the axi-symmetric analyses (loading of thermo-active pile and dissipation of pore water pressure prior to the application of the thermal boundary condition).

3.1 Approach I: change in temperature over the entire volume of the thermo-active pile

In this approach, the heating of the thermo-active pile is modelled by prescribing a change in temperature over the entire volume of the thermo-active pile. The pattern of change in temperature follows that adopted by Gawecka et al. (2017), according to which the pile temperature increases linearly from $19.5^{o}C$ to $39.5^{o}C$ in one month and is held constant at $39.5^{o}C$ for four months. Thermally-induced axial stresses are then monitored over the five months of heating.

Figure 6 shows the evolution of $\overline{\sigma_T}_{max}$ with time obtained when Approach I is adopted and when compared to that obtained from the 3D analysis. It can be seen that the peak $\overline{\sigma_T}_{max}$ obtained from Approach I, which is $793.49\ kPa$, overestimates that from the 3D analysis by 50%. This suggests that, although the applied temperature change is the same ($20°C$), the uniform heating of the pile in the axi-symmetric analysis represents a higher energy input into the problem. As a result, the thermal expansion of the pile is larger, leading to greater axial forces. Similarly, as more energy is being transferred to the soil, the restraint applied to the pile is released at a faster rate, as indicated by the larger slope of the dashed line in Figure 6. Overall, Approach I appears to be a considerably conservative form of simulating the heating of a thermo-active pile.

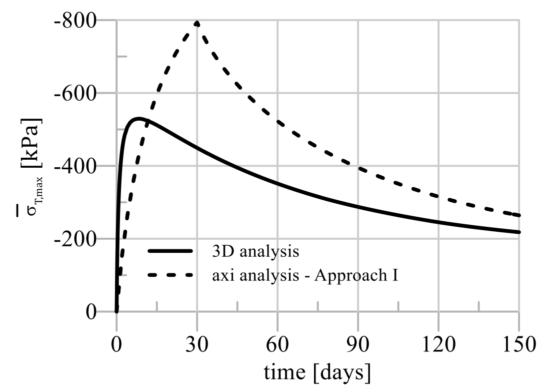

Figure 6. Evolution of $\overline{\sigma_T}_{max}$ with time for the axi-symmetric analysis adopting Approach I compared with that from the 3D analysis

3.2 Approach II: constant heat flux over the entire volume of the thermo-active pile

In this approach, the heating of the thermo-active pile is modelled by applying a constant heat flux over the entire volume of the thermo-active pile. In this paper, the magnitudes of the heat flux that correspond to the edge of the thermo-active pile at mid-depth reaching $39.5^{o}C$ after 3, 6, 12 and 120 months of heating are considered. Table 3 summarises the analyses conducted which adopt Approach II to simulate the heating of the thermo-active pile and Figure 7 shows the evolution of $\overline{\sigma_T}_{max}$ with time obtained from each analysis, together with that from the 3D analysis.

Table 3. Analyses conducted adopting Approach II to simulate the heating of thermo-active pile

Analysis	Heat flux applied	Time required for the pile edge at mid-depth to reach $39.5^{o}C$
II.1	$160\ W/m^3$	3 months
II.2	$139\ W/m^3$	6 months
II.3	$124\ W/m^3$	12 months
II.4	$104\ W/m^3$	120 months

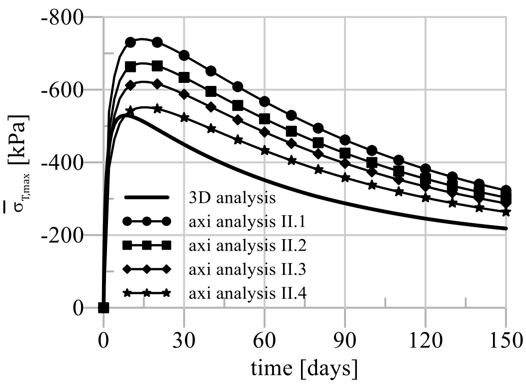

Figure 7. Evolution of $\overline{\sigma_T}_{max}$ with time obtained from each analysis adopting Approach II compared with that from the 3D analysis

As expected, the obtained results (Figure 7) indicate that higher volume fluxes (i.e. shorter time for the pile edge at mid-depth to reach the temperature of the injected fluid in the 3D analysis) lead to higher values of thermally-induced axial stresses. Moreover, it is interesting to note that higher peak values are also followed by sharper reductions in axial stresses, which confirms the observation made previously that higher energy inputs result in higher soil temperatures and, thus, in a faster release of the restraint applied by the soil to the pile. Furthermore, Figure 7 shows that when the heat flux that corresponds to the edge of the pile at mid-depth being heated to $20^{o}C$ above the initial temperature at 120 months (which essentially corresponds to a steady-state condition in the long-term) is applied, the peak $\overline{\sigma_T}_{max}$ obtained ($551.53\ kPa$) is similar to that determined in the 3D analysis (overestimation of 4%). This suggests that the peak $\overline{\sigma_T}_{max}$ may be roughly estimated by conducting a fully coupled axi-symmetric THM analysis in which the heating of the thermo-active pile is simulated by applying a heat flux that results in the pile edge at mid-depth being heated to the temperature of the injected fluid at steady-state in the long-term. Naturally, it is expected that such a procedure may change for different arrangements and number of pipes, as these are factors controlling the energy being transferred into the system.

4 CONCLUSIONS

A fully coupled 3D THM finite element analysis which includes the simulation of a hot fluid circulating through heat exchanger pipes embedded in a pile is conducted. This procedure is believed to be the most accurate approach to estimating the thermo-mechanical response of the pile when subjected to temperature changes.

The peak cross-sectionally averaged thermally-induced axial stress obtained from the 3D analysis is found to be significantly larger than that suggested by available design charts for piles with the same dimensions installed in similar soils, suggesting that thermally-induced axial stresses and, in particular, time-dependent effects, deserve careful consideration.

Given that 3D analyses are computationally expensive and time-consuming, attempts have been made to estimate thermally induced axial stresses using axi-symmetric analyses where the heating of the thermo-active pile is simulated by applying simpler boundary conditions, i.e. prescribing a change in temperature or applying a constant heat flux over the entire volume of the thermo-active pile.

Based on the results from the axi-symmetric analyses, it is clear that any alternative modelling approach needs to mimic the energy being transferred into the soil, as temperature changes in the pile-soil system control the development of peak stresses and their reduction with time. In effect, when the pile temperature is changed uniformly, the results presented in this paper suggest that excessive energy is being transferred, leading to considerably larger peak stresses than those obtained when the presence of heat exchanger pipes is simulated. Similar conclusions are drawn in the case where a volume heat flux is prescribed. However, in this case, the results suggest that peak $\overline{\sigma_T}_{max}$ can be roughly estimated by applying a heat flux that corresponds to the pile edge at mid-depth being heated in the long-term (120 months) to the temperature of the injected fluid. However, this procedure is likely to be affected by changes in the pipe arrangement, meaning that a more general method for estimating accurately thermally-induced axial stresses from axi-symmetric analyses needs to be developed.

5 ACKNOWLEDGEMENTS

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