Effect of domain size in the modelled response of thermally-activated piles

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Abstract The application of thermally-activated pile foundations has received significant attention in the last decade with a number of large- and small-scale tests having been undertaken. Alongside these physical studies, a number of investigations utilising numerical analysis have been undertaken to examine the behaviour of single piles and pile groups. Focussing on studies examining single piles, it is apparent that a variety of differing domain dimensions have been used. The work presented in this paper had the objective of systematically examining the influence of the domain size and how it affects the predicted thermo-mechanical response of the pile. It shows that the domain size has an important impact on the initial distribution of mobilised shaft friction due to applied mechanical load which then impacts on the subsequent thermo-mechanical response.

Keywords: Energy geostructures, pile foundations, soil-structure interaction, numerical analysis

1 Introduction

The application of thermally-activated pile foundations has received significant attention in the last decade with a number of large- and small-scale tests having been undertaken. Alongside these physical studies, a number of investigations utilising numerical analysis have been undertaken, some of those relating to single pile analyses are tabulated in Table 1. The cases in Table 1 have been summarised by the half-width (or radius, R) of the model, the pile diameter (D), and the ratio, 2R/D where 2R is in effect, the spacing between adjacent piles (when the lateral boundary condition is set as adiabatic for heat flow, and horizontal movements but not vertical are fixed). Bourne-Webb et al. (2020) have shown that for an isolated pile, assuming a constant temperature on the lateral boundary results in larger thermal stress than when assuming an adiabatic condition, while pile head thermal movement is largely unaffected.

It is apparent that a range of choices have been made regarding the domain radius, ranging from a few metres up to several tens of metres, and the values of 2R/D (>8) are such that mechanical interactions between piles would be expected to be finite but small, Poulos (1968). In the studies referenced, the model domain height was in the range of 1.4 to 6 pile lengths, with most in the range of 2 to 3. Neither the effect of the domain vertical dimension nor the thermal boundary condition at the bottom are considered here.

Given the range of model sizes used, even if the mechanical pile-to-pile interactions might be expected to be small, it is important to assess if this affects the predicted response significantly. Likewise, in both transient and steady state solutions, the effect of thermal interactions between piles will depend on their absolute spacing and the thermal properties of the soil and pile materials. The study presented here was undertaken with the objective of determining whether the choice of model dimension leads to differing interpretations of the impact of cyclic thermal activation on an isolated pile foundation.

Table 1 Summary of domain half-widths used in published numerical studies

Source	Half-width, R (m)	Pile diameter, D (m)	2R/D	Far-field thermal BC
Zito (2019)	4 / 30	1.0	8 / 60	Adiabatic
Rotta Loria et al. (2015)	4.4	0.88	10	Const. $T = T_0$
Saggu & Chakraborty (2014)	7.0	0.5, 1.0	14 / 28	Adiabatic
Rammal et al. (2018)	8.0	0.52	30.8	Adiabatic
Khosravi et al. (2016)	10	0.61	32.8	Not stated
Alberdi-Pagola et al. (2017)	7.5	0.30	50	Adiabatic
Bourne-Webb et al. (2016)	30	1.0	60	Const. $T = T_0$
Di Donna & Laloui (2015)	25	0.8	62.6	Const. $T \neq T_0$
Sani & Singh (2018)	20	0.60	66.6	Adiabatic
Tsetoulidis et al. (2016)	24	0.60	80	Const. $T = T_0$
Georgiadis et al (2018)	60 - 80	0.75 - 1.5	90 - 160	Const. $T = T_0$
Gawecka et al. (2017)	50	0.6	166	Const. $T = T_0$
Adinolfi et al. (2018)	40 / 50	0.80 / 0.60	100 - 166	Adiabatic
Vieira & Maranha (2017)	60	0.60	200	Adiabatic

2 Basis for analyses

The 2D axisymmetric geometry selected for this assessment consists of an isolated 1 m diameter, 30 m long pile embedded in a domain that extends either 30 m or 4 m radially from the pile centreline and is 90 m deep. A 1.6 m diam. by 1 m deep pile cap was placed at the head of the pile; this provides a buffer between the surface and pile thermal boundary conditions. The bottom boundary is fixed in the vertical and horizontal directions while the side boundary is only fixed in the horizontal direction. The analyses were undertaken using the finite element program ABAQUS.

The pile, the ground in which the pile is embedded and the cap and pile-soil interfaces were modelled in the same manner as Bodas Freitas et al. (2013) and Bourne-Webb et al. (2016), with the exception that the Young's modulus for the soil was assumed to increase from 25 MPa at the surface, to 175 MPa at the bottom boundary, rather than being constant. The soil and pile thermal and mechanical properties are presented in Table 2.

Adiabatic conditions were assumed along the side boundaries and a constant temperature (T_0 = 14°C) was used on the bottom boundary. An initial "Greenfield" ground temperature condition was arrived at by applying a harmonic temperature function, Equation (1), at the ground surface over a period of 10 years.

$$T = T_{avg} + \Delta T.\sin[(2\pi/P)t - \varphi_t] \quad (1)$$

where $T_{avg} = T_0$ = 14°C is the average annual air temperature; ΔT = 11°C is the temperature amplitude; P = 1 year is the period of the function and $\varphi_t = \pi/2$ is the phase of the function. Zito (2019) showed that after 10 years, the temperature field had stabilised in a dynamic thermal equilibrium with the boundary conditions, Fig. 1.

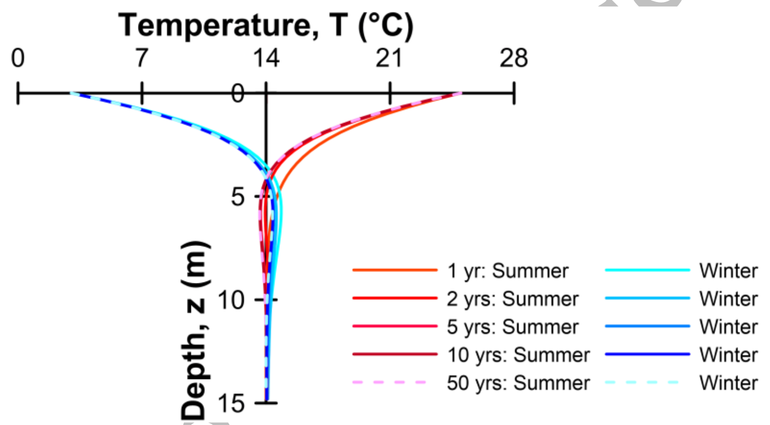

Fig. 1. Greenfield temperature field (below c. 13 m, $T \approx T_{avg}$), Zito (2019).

Table 2 Material properties adopted in analyses

Parameter	Unit	Pile	Soil
Density, ρ	kg/m³	2450	1600
Young's modulus, E	MPa	30000	Varies
Poisson's ratio, ν	-	0.3	0.3
Soil cohesion, 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, α	με/K	10	20

Having established the Greenfield temperature field, the pile was loaded mechanically to 3500 kN and subsequently, 10 years of thermally-activated pile operation was simulated. The mechanical load implies a global factor of safety (FoS) and a FoS on ultimate shaft resistance of about 2.0. The pile thermal loading involved a harmonic function the same as Equation (1) but with T_{avg} = 14°C; ΔT = 12°C; P = 1 year and $\varphi_t = \pi/2$.

3 Results and discussion

3.1 Mechanical loading

Fig. 2 illustrates the mobilised pile response following the application of a working load of 3500 kN. Pile head settlement is about 6.5 mm and 38 mm (settlement ratio, R_S of 5.9) for half-widths of 30 m and 4 m, respectively. There are also significant differences in the pile axial load and mobilised shaft friction profiles. This can be explained by the pile-pile interaction implied by the side boundary being 4 m from the pile rather than 30 m. The response in the 4 m radius domain is similar to that for pile within a large piled raft.

In the 4 m domain, the load transfer from the piles is causing the ground surrounding the piles to settle, leading to less relative movement on the pile-soil interface and hence lower mobilised shaft friction in the upper part of the pile, while in the lower part of the pile, the shaft resistance is fully mobilised, Fig. 2. By contrast, the pile response in a 30 m half-width domain, is more typical of an isolated pile, the mobilised shaft friction is relatively uniform (and about half the ultimate shear strength of 75 kPa), and the pile axial load reduces more-or-less linearly with depth. The steps seen in the mobilised shaft friction are due to the changes in stiffness through the soil profile.

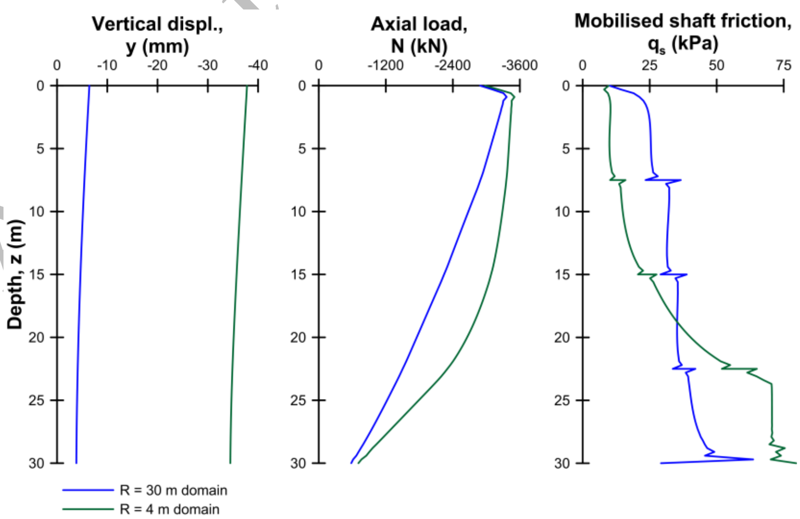

Fig. 2. Pile axial response and mobilized shaft friction under working load.

3.2 Thermal-Mechanical loading

Following the application of the pile head load, seasonal temperature cycles of 14±12°C were applied to the pile to simulate thermal activation of the foundation, as discussed in Section 2. Fig. 3(a) illustrates the variation in axial load and mobilised shaft friction for the analysis with a 30 m radius domain, during this period. It is apparent that during both heating and cooling the response is almost symmetric in terms of the axial thermal load and changes in mobilised shaft friction that were generated.

Also shown is the envelope of ultimate base ($R_{b,ult} = 11.c.(\pi D^2/4) = 650$ kN) and shaft resistance, ($R_{s,ult} = a.\pi DL = 7070$ kN) from which it is apparent that while on average, only half the shaft resistance is mobilised, nearly all the base resistance is mobilised at working load. Only during heating and close to the base of the pile, does the mobilized shaft resistance approach the ultimate unit shaft resistance of 75 kPa. The maximum thermal axial load change occurs at about 19 m depth where the change in shaft friction relative to that mobilised by the mechanical loading is zero (the so-called neutral point).

Fig. 3(b) illustrates the response from the analysis based on a 4 m radius domain, where it is apparent that the response is rather different. Under mechanical load, along with the base resistance, the shaft resistance is fully mobilised over the lower part of the pile, which means that during pile heating, no additional base reaction or shaft friction can be mobilised in this region, and only during cooling can it change, as indicated by the reduction in q_s during the Winter periods in Fig. 3.

Fig. 4(a) examines the thermally-induced pile head displacement response throughout the thermal loading period. The pile in the 30 m radius domain exhibits a regular oscillation of about ±2.1 mm throughout this period while in the 4 m radius domain, thermal ratcheting is evident in the first few cycles with the pile settling about 1 mm before stabilising to a variation between +2.6 mm (up) and -3.6 mm (down).

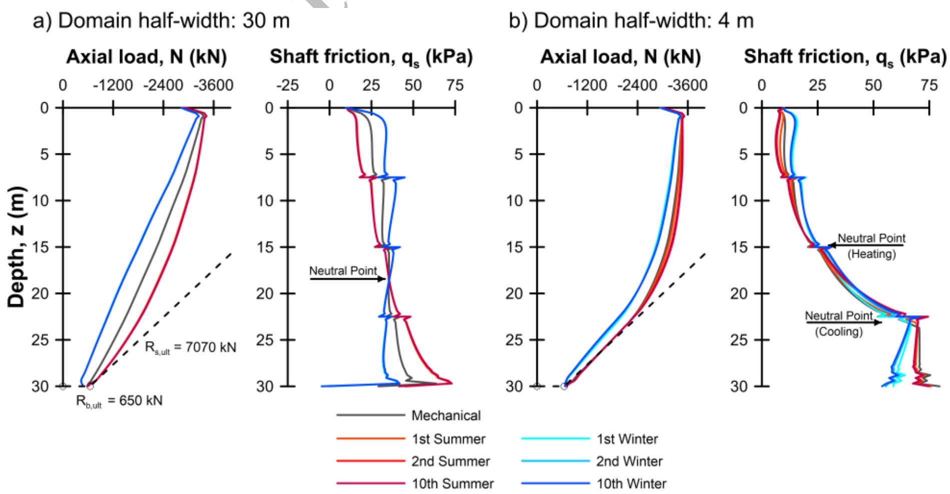

Fig. 3. Comparison of pile axial load and mobilised shaft friction for a) 30 m domain and b) 4 m.

In Fig. 4(b), the maximum axial thermal stress mobilised in each operational cycle is shown. As with the pile head displacements, the analysis with a 30 radius domain is rather regular with slightly higher tension (460 kN) versus compression (400 kN), while in the 4 m radius domain, the results show significant asymmetry with about 130 kN compression and 350 kN of tension. It is apparent that the reduction is domain radius and changes in the pile-soil-pile interaction, in effect reduces the restraint on the pile shaft resulting in larger pile head movement and reduced thermal stress.

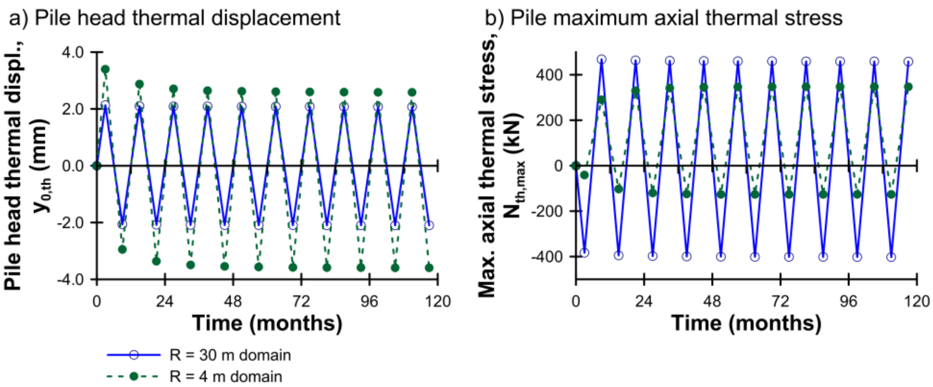

Fig. 4. Evolution of pile thermal responses during 10 year cyclic thermal operation.

The pile base load-displacement response is illustrated in Fig. 5. The pile in the 30 m radius domain shows reversible behaviour with a vertical oscillation of about ±1.2 mm at the pile base, while in the 4 m radius domain, additional settlement is mobilised in the first few cycles before stabilising to essentially reversible behaviour, commensurate with the pile head ratcheting seen in Fig. 4(a). This highlights how even with an apparently high margin of safety on the available shaft resistance, piles within groups where significant mechanical interaction occurs, may exhibit thermal ratcheting during operational heating and cooling. In this case, the effect is rather small but this may not be true in all cases.

The pile head and base movements in the 30 m radius domain are consistent with the location of the neutral point at about 19 m depth, Fig. 3(a). In the 4 m domain, movements at the pile head are broadly consistent with the movement of the neutral point to about 15 m and 25 m depth during heating and cooling respectively, Fig. 3(b), i.e. the deeper the neutral point, the larger the pile head thermal displacement is. During cooling, as the pile contracts, the mobilised shaft resistance on the pile-soil interface below 23 m depth reduces while that above increases in response, in order to maintain vertical equilibrium. During heating, the effect is more complicated, as no additional restraint can be mobilised on the shaft, in the lower part of the pile. This means that the heating can only mobilise changes in shaft resistance above this and thus the neutral point must move higher – this leads to a reduction in the thermally-induced stress and smaller pile head movement than during cooling, Fig. 4.

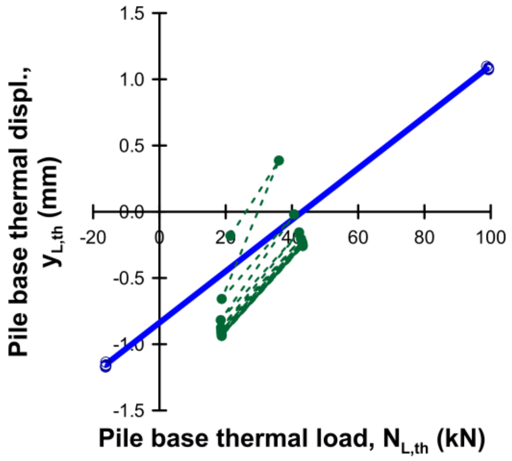

Fig. 5. Evolution of maximum axial thermal stress during thermal operation.

4 Conclusions

This study sought to clarify how the choice of domain size may have influenced the results reported in other numerical studies. It is apparent that when modelling an isolated pile the domain must be large enough to ensure that there are neither mechanical nor thermal interactions. If the lateral boundary is located too close to the pile then the predicted thermal solicitations will not be representative of an isolated pile.

The results also highlight how pile interactions will change due to the presence of other piles. Under mechanical load, the pile-soil-pile interactions alter the mobilisation of the pile shaft and base resistance, and this then impacts on subsequent pile-soil thermal interactions. In this case, the effects are small, due to the large FoS in terms of the mobilised shaft resistance at working load (FoS of 2) and ongoing work is examining the effect when a larger proportion of the shaft resistance is mobilised prior to thermal loading.

Despite the apparently large FoS on mobilised shaft resistance referenced to an isolated test pile, as the domain size reduces (piles get closer together), pile-soil-pile interaction under mechanical loading will lead to thermal ratcheting as load redistributes between shaft and base, and will alter the magnitude of the thermally-induced axial stress and pile head displacement: in this example, a mitigation of thermal axial stress and an increase in pile head movement.

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5 References

Alberdi-Pagola, M., Madsen, S., Lund Jensen, R., Erbs Poulsen, S. (2017). Numerical investigation on the thermo-mechanical behavior of a quadratic cross section pile heat exchanger, *Proc. of the IGSHPA Technical/Research Conference and Expo 2017*, Denver, USA, 134-143

Adinolfi M, Maiorano RMS, Mauro A, Massarotti N, Aversa S (2018) On the influence of thermal cycles on the yearly performance of an energy pile, *Geomechanics for Energy and the Environment*, 16(Dec.): 32-44

Bodas Freitas, T.M., Cruz Silva, F., Bourne-Webb, P.J. (2013). The response of energy foundations under thermo-mechanical loading, *Proc. of the 18th Intl. Conf. on Soil Mech. and Geot. Eng'g*, Paris, 3347-3350

Bourne-Webb P.J., Amatya, B., Soga K., Amis, A., Davidson, C., Payne P. (2009). Energy pile test at Lambeth College, London: geotechnical and thermo-dynamic aspects of pile response to heat cycles, *Géotechnique* 59(3): 237-248

Bourne-Webb, P.J., Bodas Freitas, T.M., Assução, R.M. (2016). Soil-pile thermal interactions in energy foundations, *Géotechnique*, 66(2): 167-171

Bourne-Webb P., Zito M., Bodas Freitas T.M. and Sterpi D. (2020) Effect of thermal boundary conditions on the response of thermally-activated floating piles in a cohesive material*, submitted to E-UNSAT 2020, 4th European Conference on Unsaturated Soils*, Lisbon, Portugal

Di Donna, A. and Laloui, L. (2015). Numerical analysis of the geotechnical behaviour of energy piles, *Int. J. Numer. Anal. Meth. Geomech.*; 39: 861–888

Gawecka, K.A., Taborda, D.M.G., Potts, D.M., Cui, W., Zdravkovic, L., Haji Kasri, M.S. (2017). Numerical modelling of thermo-active piles in London Clay, *Proc. of the Institution of Civil Engineers, Geotechnical Engineering* 170(GE3): 201-219

Georgiadis K., Skordas D., Kamas I., Comodromos E. (2018) Heating and cooling induced stresses and displacements in heat exchanger piles in sand, *Renewable Energy*, 147(Part 2): 2599-2617.

Khosravi, A., Moradshahi, A., McCartney, J.S., Kabiri, M. (2016). Numerical analysis of energy piles under different boundary conditions and thermal loading cycles, *Proc. 3rd European Conference on Unsaturated Soils, E-UNSAT 2016*, 6 pages,

Poulos HG, (1968) Analysis of the settlement of pile groups, *Géotechnique*, 18(4):449-471

Rammal D., Mroueh H., Burlon S. (2018) Impact of thermal solicitations on the design of energy piles, *Renewable and Sustainable Energy Reviews*, 92(Sept.):111-120

Rotta Loria, A.F., Gunawan, A., Shi, C., Laloui, L., Ng, C.W.W. (2015). Numerical modelling of energy piles in saturated sand subjected to thermo-mechanical loads, *Geomechanics for Energy and the Environment* 1(April): 1–15

Saggu, R. and Chakraborty, T. (2014). Thermal analysis of energy piles in sand, *Geomechanics and Geoengineering*, 10(1): 10-29

Sani A.K., Singh R.M. (2018) Response of unsaturated soils to heating of geothermal energy pile, *Renewable Energy*, 147(Part 2): 2618-2632

Tsetoulidis, C., Naskos, A., Georgiadis, K. (2016). Numerical investigation of the mechanical behaviour of single energy piles and energy pile groups, *Energy Geotechnics* (Wuttke, F., Bauer, S., Sánchez, M. eds), CRC Press, 569-575

Vieira, A., Maranha, J.R. (2017) Thermoplastic analysis of a thermoactive pile in a normally consolidated clay, *Int. J. Geomech*., 17(1): 04016030

Zito, M. (2019) Transient analysis of building-pile-soil interactions in thermally-activated foundations, Master Thesis, Politecnico di Milano