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Revisiting the effect of coefficient of thermal expansion in energy pile–soil interactions

L'effet du coefficient de dilatation thermique dans les interactions pieu énergétique-sol: une revue

T.M. Bodas Freitas*, P.J. Bourne-Webb
CERIS, Instituto Superior Técnico, Lisbon, Portugal

M. Fernandes
Ródio, Alenquer, Portugal (formerly Instituto Superior Técnico)

D. Sterpi
Politecnico di Milano, Milan, Italy

**teresabodas@tecnico.ulisboa.pt*

ABSTRACT: When pile foundations and the ground around them are thermally-activated as part of a shallow geothermal energy system, new and somewhat complex changes in pile-soil interaction occur. In this paper, the influence of the relative expansion and contraction between the pile and surrounding soil, as expressed via the ratio of the coefficient of thermal expansion (CTE) of the soil to that of the pile, is revisited. Previous steady-state thermo-mechanical analysis by the authors suggested that this may be a very significant parameter especially when the CTE ratio was somewhat greater than 1 but more recent work has shown there are a number of other factors which may work to either mitigate or exacerbate this effect. This paper brings together recent work relating to this effect, to provide guidance on the impact of the form of the thermal loading in time and the initial mobilisation of the pile shaft resistance on when the CTE ratio may be significant in the functioning of thermally-activated pile foundations.

RÉSUMÉ: Lorsque les fondations sur pieux et le sol qui les entoure sont thermiquement activés dans le cadre d'un système d'énergie géothermique peu profond, des changements nouveaux et quelque peu complexes dans l'interaction pieu-sol se produisent. Dans cet article, l'influence de la dilatation et de la contraction relatives entre le pieu et le sol environnant, exprimée par le rapport du coefficient de dilatation thermique (CTE) du sol à celui du pieu, est revisitée. Une précédente analyse thermomécanique en régime permanent par les auteurs a suggéré que cela pouvait être un paramètre très important, mais des travaux plus récents ont montré qu'il existe un certain nombre de d'autres facteurs susceptibles d'atténuer ou d'exacerber cet effet. Cet article rassemble des travaux récents relatifs à cet effet, pour fournir des indications sur l'impact de la forme du chargement thermique dans le temps et la mobilisation initiale de la résistance du fût du pieu lorsque le rapport CTR peut être significatif dans le fonctionnement des fondations sur pieux.

Keywords: Piles; thermal; interactions; safety

1 INTRODUCTION

In order to reduce humanity's reliance on carbon intensive energy and to reduce overall energy demand, many countries are looking to source energy via sustainable technologies. An example of this type of technology are shallow geothermal energy (SGE) systems, which can be used to heat and cool buildings. SGE systems have been widely used since the oil-shocks of the 1970s, especially in North America and Northern Europe and have been demonstrated to reduce environmental impact, have low operational costs and save on primary energy expenditure.

For the implementation of SGE, especially in urban areas, the utilization of the pile foundations as a substitute for borehole heat exchangers, has received increasing attention over the past 20 years, amidst efforts to establish renewable and sustainable, heating and cooling systems within the construction industry. A significant number of experimental studies both in the field and laboratory, supplemented by numerical studies, have been undertaken to examine the technical issues associated with the use of thermally-activated pile foundations (TAPS). When pile foundations and the ground around them are thermally-activated as part of an SGE system, new and somewhat complex changes in pile-soil interaction occur. These effects are a function of a number of factors, especially the restraint of the pile along its shaft and at the ends, in addition to the thermal characteristics of the soil and pile. In this paper, the influence of the relative expansion and contraction between the pile and surrounding soil, as expressed via the ratio of the linear coefficient of thermal expansion (CTE) of the soil to that of the pile, is examined.

While the CTE of construction materials like steel (11-13 με/K) are well defined, the CTE of concrete is somewhat more variable depending primarily on the mineralogy of the aggregates; e.g. Bonnell & Harper (1951) report values of 6.1-8.5, 8.6-10.4 and 12.2-13.7 με/K for limestone-, granite- and quartzite-based concretes. The CTE of granular soils will also depend largely on the mineralogy of the soil particles with e.g. Bonnell & Harper (1951) reporting values of 4.0- 6.5, 5.4 – 9.0 and 11 – 12.6 με/K for limestone, granite and quartzite aggregates. For concrete piles, in granular soils, the range of values for the CTE ratio is likely to be in the range of 0.5 to 2. In fine-grained soils, the volumetric response to drained thermal loading not only depends on mineralogy but also the over-consolidation ratio. Broadly speaking, in normally and lightly over-consolidated clay, the soil will contract irrecoverably during heating (thermally-induced consolidation) but as the soil becomes over-consolidated, recoverable thermal expansion is observed. In this latter case, indications from experimental data (e.g. Cekerevac & Laloui, 2004) suggest the CTE ratio could be in excess of two.

The potential influence of the CTE ratio in the response of thermally-activated (TA) piles was previously explored by Bodas Freitas et al. (2013), Bourne-Webb et al. (2016) and Bourne-Webb et al. (2019) for a TA pile in a cohesive medium and based on steady state thermal conditions. This suggested a strong effect with the thermal axial stress change becoming increasingly tensile as the CTE ratio increased, as illustrated in Figure 1 where the max. thermal stress in the pile, normalised by the thermal stress in a perfectly restrained pile, is plotted against the pile head thermal movement, normalised by the expansion of a perfectly unrestrained pile.

Rotta Loria & Laloui (2016), illustrated a similar effect when examining the influence of CTE ratio on the interactions between pairs of piles, and Gawecka et al. (2017) found that in back-analysing a TA pile test in over-consolidated London Clay, a CTE ratio of 1.8 was needed to achieve good agreement.

Recognising that steady state thermal conditions or long-periods of sustained thermal loading were not necessarily representative of realistic seasonal thermal loadings, and following the review of cyclic thermal loading of TA piles in Bourne-Webb & Bodas Freitas (2020), further work was undertaken using numerical analysis to explore how balanced periodic thermal loads impact on the behaviour of TA piles and the influence of CTE ratio within this.

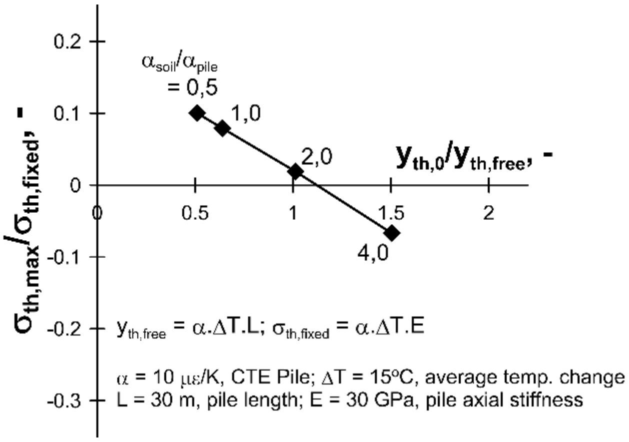

Figure 1. Influence of CTE for a pile in a cohesive medium under thermal steady state conditions (Bourne-Webb et al., 2019)

Bourne-Webb et al. (2022a, 2022b) highlighted how the response of TA piles to cyclic thermal loading was linked to the proportion of the available shaft resistance that was initially mobilised under mechanical loading (quantified by the factor M, the ratio between the shaft resistance mobilised at working load and the ultimate shaft resistance) which was a function of the load itself and pile spacing in groups. Bodas Freitas et al. (2021) modelled the response of a cyclically TA pile in a cohesive medium with the initial shaft mobilisation, M ≅ 50% and 90%, and with varying CTE ratio. In comparison to the steady state case previously examined, it was shown that the effect was much reduced, Figure 2.

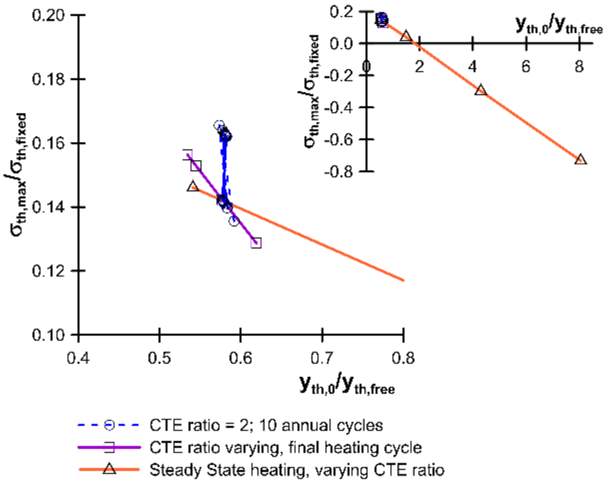

Figure 2. Influence of CTE for a pile in a cohesive medium under transient thermal loading, (Bodas Freitas et al., 2021)

To further explore these results, the work presented herein expands on that in Bourne-Webb et al. (2022a) by examining the role of the CTE ratio in the response of TA piles in granular media at differing levels of initial shaft resistance mobilisation.

2 BASIS FOR ANALYSES

In the axisymmetric finite element analyses presented here, a single reinforced concrete pile with a diameter of 1 m and a length of 30 m was considered, and Figure 3 illustrates the geometry used for the analysis domain. The radius of the model domain was varied between 30 m and 2 m. The reduced radial dimensions permit the behaviour of an infinite pile group to be examined based on a unit cell approach with the pile spacing being equivalent to 2x the radius.

The pile was modelled as a linear elastic material and the soil was modelled as linear elastic-perfectly plastic with a Mohr-Coulomb failure criterion, using the program ABAQUS 2016 (Dassault Systèmes, 2021), with the mechanical and thermal properties outlined in Table 1. The soil stiffness is shown graphically in Figure 3 and averages 129 MPa over the length of the pile.

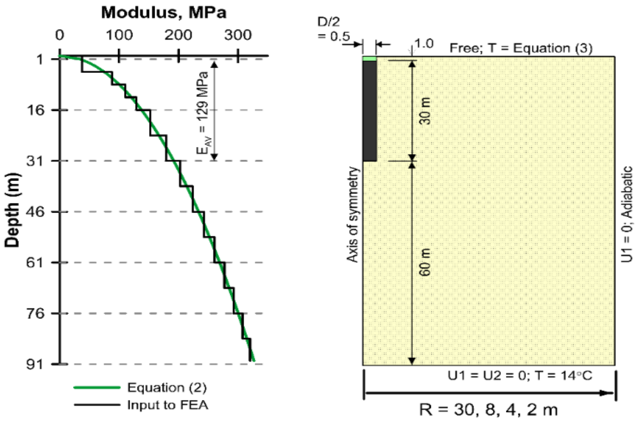

Figure 3. FE Model geometry and soil stiffness variation.

The modelling sequence and temperature boundary conditions were applied as follows: i) the initial stress and temperature fields were established based on the K_0 and T_0 values in Table 1; ii) a periodic temperature function, Eqn. (1) was applied at the ground surface over a period of 10 years, to mimic the initial temperature profile in the near-surface region (T_0 = 14°C, ΔT = 11°C; t is the time in years); iii) The pile was wished-in-place and then mechanically loaded; iv) 10 years of TA pile operation was modelled by applying a temperature change based on Eq. (1) along a line extending over the length of the pile shaft, at a radius of 0.4 m (T_0 = 14°C, ΔT = 12°C). During this period the surface temperature was switched to 23±2°C, to represent the climate-controlled building atop the foundation.

$$T = T_0 + \Delta T.sin[2\pi(t)] \qquad (1)$$

Mechanical loads were imposed on in order to generate different levels of initial shaft resistance mobilisation, M which are quoted alongside the respective results in Figures 4 to 6.

3 RESULTS & DISCUSSION

In the following, the results of a parametric analysis utilising the model described in the previous section are presented.

Figure 4 presents the baseline case for an isolated, cyclically TA pile (domain radius, R = 30 m) with a shaft mobilization M = 100% and shows the evolution of thermally-induced pile head settlement, $y_{0,th}$ and axial load, N_{th} for soil:pile CTE ratios of 1:1, 1:2 and 2:1, over 10 years. All start with pile heating, except CTE 1:1c which started with pile cooling. It is apparent that whether the TA starts with heating or cooling only affects the first couple of years, after which the response converges.

In all cases, during the first pile cooling phase, significant additional settlement developed: around 10 mm with CTE ratios of 1:1 and 2:1, after which it is almost stable, and about 20 mm when the CTE ratio was 1:2 (pile expands more than the soil) which continues to exhibit increasing settlement across the 10 years simulated. Thermally-induced axial load changes follow a similar pattern with an initial increase in compression followed by quasi-stable load variations with CTE ratios of 1:1 and 2:1 but a steady increase in load when the CTE ratio was 1:2.

Figure 5 illustrates the effect of cyclic TA for cases where the domain radius is reduced to R = 4 and 2 m, to capture TA pile group effects in an approximate manner. Again, CTE raios of 1:1 (C03, C10), 1:2 (C04, C13) and 2:1 (C07, C37) were considered. With R = 4 m, M remains close to 100% but when R = 2 m, M reduced to about 90%.

Compared to the isolated pile case, a clear reduction in induced thermal movement is seen and the effect of the CTE ratio variation is also progressively eliminated. Broadly speaking, the response is similar to those reported by (Bourne-Webb et al., 2022a). In terms of the thermal load changes, the case where the CTE of the pile is twice that of the soil continues to lead to significant increases (R = 4 m) or much larger amplitude (R = 2 m).

Although not shown here, when the value of M is reduced (moving from a factor of safety on shaft resistance of 1 to 2 with respect to the mechanical load), the increase in initial stability (reduced M) of the TA pile leads to the thermal ratcheting in R = 4 m cases being eliminated. Again, the main effect of the variation in CTE ratio is in the thermally-induced axial load changes which are smaller than the cases with high initial shaft mobilisation.

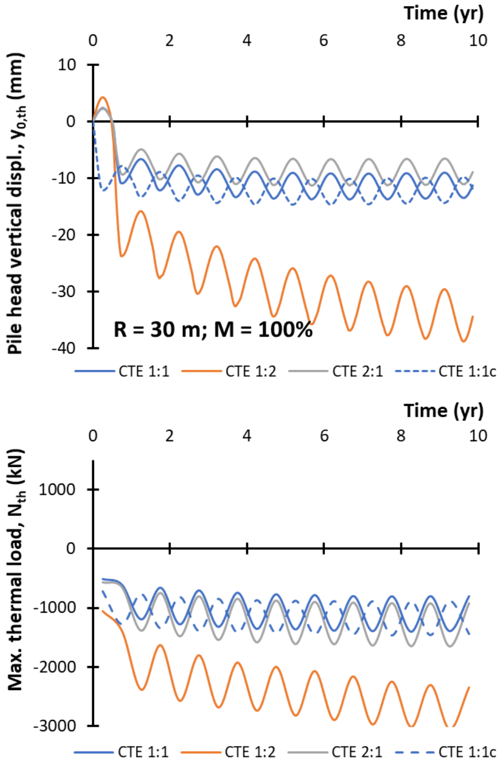

Figure 4. Isolated TA pile (R = 30) with high M.

4 CONCLUSIONS

The work presented in this paper continues to build on the understanding of the response of TA piles: the influence of the geometric layout of the pile(s), mechanical loading and key thermal parameters, i.e. CTE.

While under steady state thermal conditions the CTE has been shown to have a profound effect on pile-soil interactions, when balanced cyclic thermal loading is considered, the resulting effect depends on other factors as discussed above – namely, pile spacing and the initial shaft mobilisation under mechanical loading.

If piles are largely isolated, then care needs to be exercised when cyclic thermal loading is applied on piles with high initial mobilisation of the shaft. More so, if the CTE of the pile is larger than that of the soil.

Depending on the degree of mechanical interaction between piles within a group, which affects the initial shaft mobilisation, the effect of CTE variations in the cyclic thermal response can be reduced or even eliminated.

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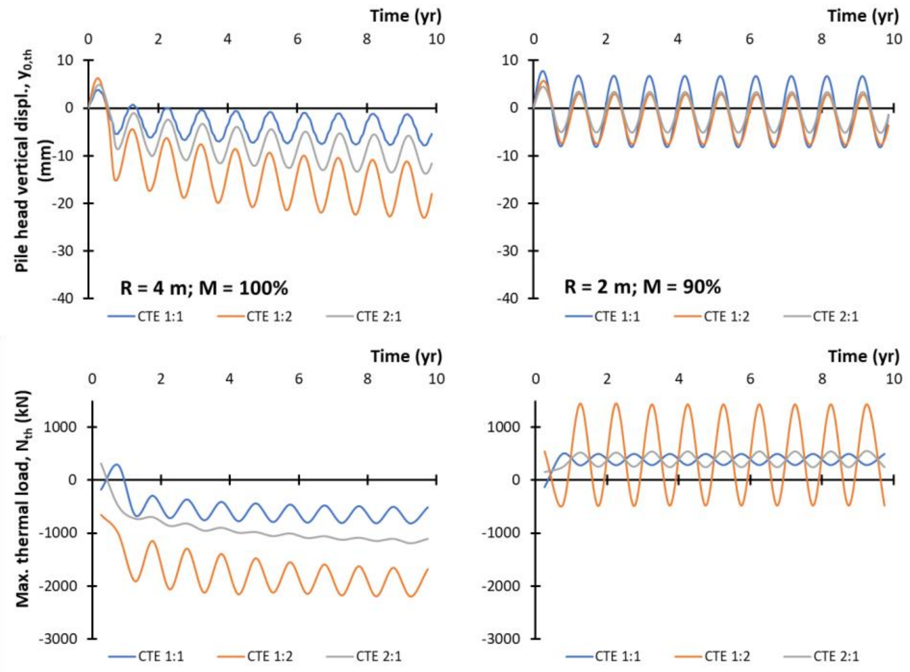

Figure 5. Pile group (unit cell: R = 4 & 2 m) with high M.

Table 1. Material parameters used in analysis

Parameter	Pile	Frictional soil
Density, ρ (kg/m^3)	2500	1900
Young's modulus, E (MPa)	30000	Figure 6
Poisson's ration, ν (-)	0.2	0.3
Angle of shearing resistance, φ' (deg.)	-	38
Angle of dilation, ψ (deg.)	-	0.1
Cohesion, c' (kPa)	-	0.1
Pile-soil interface friction, δ (deg.)	-	32
Pile-soil adhesion, a (kPa)	-	0
Pile-soil friction coeff., μ (-)	-	0.624
Relative displacement, y_{rel} (m)	-	0.0020
At-rest earth pressure coeff., K_0 (-)	-	0.429
Thermal conductivity, k (W/m.K)	2	2
Specific heat, c_s (J/kg.K)	940	800
Initial temperature, T_0 (°C)	14	14
Linear coeff. thermal expansion, α (με/K)	10 or 20	10 or 20