The response of energy foundations under thermo-mechanical loading

La réponse des fondations thermo actifs sous chargement thermo mécanique

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ABSTRACT: The need to establish a sound basis for the understanding of the behaviour of geo-structures that are utilised for energy exchange within ground source heat pump systems has received increasing attention in recent years and a number of physical and numerical modelling studies of such systems have been undertaken. This paper details the results of a preliminary numerical study of the response of a foundation pile under steady-state heating, which when compared to the results of published observations, raises some interesting questions regarding the models of behaviour proposed in the literature and areas requiring further study in the future.

RÉSUMÉ : La nécessité d'établir une base solide pour la compréhension du comportement des géo-structures qui sont utilisés pour l'échange d'énergie dans les systèmes de pompe géothermique a reçu une attention croissante ces dernières années et un certain nombre d'études de modélisation physique et numérique de ces systèmes ayant été entrepris. Cet article détaille les résultats d'une étude numérique préliminaire de la réponse d'une fondation sur pieux sous chauffage stationnaire qui, lorsqu'il est comparé aux résultats de certaines observations publiées, soulève des questions intéressantes concernant les modèles de comportement proposés dans la littérature et les zones nécessitant une étude plus approfondie dans le futur.

KEYWORDS: pile, foundations, ground source energy, thermo-mechanical loading.

1 INTRODUCTION

The use of ground energy systems that employ heat-exchange loops within trenches and boreholes is well established and the technology is recognised as a key component for future sustainable energy use (Mackay, 2009).

While still a small component of the ground energy market, the use of civil engineering structures that are in contact with the ground (geo-structures) to replace the more convention heat-exchange methods is creating great interest. Bearing piles have been used for this purpose since the mid-1980s and more recently other elements have been used, e.g. retaining walls & tunnel linings.

Energy geo-structures and in particular, bearing piles are now often used in Austria, Germany and the UK, and there is increasing interest in their potential in many countries including the USA, Japan and China. However, the uptake of these alternative means for facilitating heat-exchange with the ground has been impeded by a lack of technical evidence regarding the impact of the thermal cycles on the serviceability and safety performance of the geo-structures.

This paper presents the results of a set of numerical analyses that were undertaken to evaluate the mechanisms of response of piles used for heat-exchange. First, to complete this introduction, observations of the thermo-mechanical (TM) response of piles and clay soil are reviewed. Then the basis for the analyses and the predictions that were obtained are presented, and the implications of the results are discussed. Finally, some ideas for future research in this field are suggested.

1.1 *Energy geo-structures*

Very few field or laboratory studies, where the TM response of energy geo-structures has been systematically observed, have been published. Energy geo-structures include load bearing piles, piled and diaphragm walls, and tunnels. To-date, published TM studies have involved only pile foundations (Brandl, 2006; Laloui et al. 2006; Bourne-Webb et al. 2009; McCartney & Rosenberg 2010).

The mechanisms of response seen in the pile tests appear to be broadly consistent and can be described in a simple schematic way (Amatya et al. 2012; Bourne-Webb, et al. 2013). Underlying this descriptive framework is the implicit assumption that the pile expands and contracts relative to the surrounding soil when heated and cooled, respectively. Thus, when heated the axial strain/forces in the pile become more compressive and when cooled less compressive (potentially even tensile pile axial response is seen), Fig. 1.

Associated with the pile axial response described above, the response at the pile-soil interface is also affected with the changes in mobilised pile shaft friction (shear stress) opposing the expansion and contraction of the pile, Fig. 1. These changes in pile axial response and mobilised pile-soil interface friction will occur on a daily and seasonal basis as the heating/cooling energy demand of the structure, that the ground energy system serves, varies.

1.2 *Thermo-mechanical characterization of clay*

The effect of temperature changes on the behaviour of soil is of interest in a number of fields including the sequestration of nuclear waste, buried high voltage electricity cables, buried pipelines, and increasingly energy geo-structures.

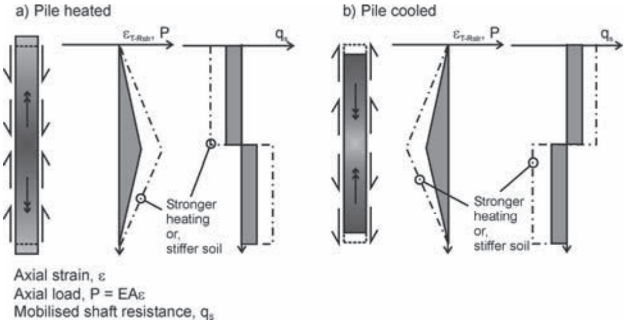

Figure 1. Schematic response of a pile subjected to heating and cooling, after Bourne-Webb et al. 2013.

In addition to the general impact on soil behaviour, the impact of temperature cycles at the pile-soil interface is also of interest in the case of energy geo-structures.

Experimentally, the effect of temperature on the mechanical behaviour of clayey soils has been found to be equivalent to that of strain rate, Marques et al., 2004. The effects are permanent and the soil behaviour can be described by a unique stress-strain-temperature law. In addition, it is found that while peak undrained strength increases with decreasing temperature, the critical state failure envelope is unique in stress space but temperature dependent in void ratio–mean effective stress space.

The thermal volumetric response of clay soil has been examined in a number of laboratory investigations (Campanella & Mitchell 1967; Baldi et al. 1988; Cekerevac & Laloui 2004) and it was found that the volume change of a clay sample in response to a change in temperature depends on the over-consolidation ratio (OCR). When heated, normally consolidated soil (OCR = 1) contracts (implying a negative coefficient of thermal expansion) and as the OCR increases, the soil becomes increasingly less contractive with moderately to highly over-consolidated (OC) clay being expansive, i.e. with positive values of the coefficient of thermal expansion, Fig. 2.

The testing also suggests that the thermal expansion of OC clay is reversible but there is a limit to the range of temperatures over which this occurs. At higher temperatures OC clay becomes contractive, e.g. at about 50°C in Fig. 2.

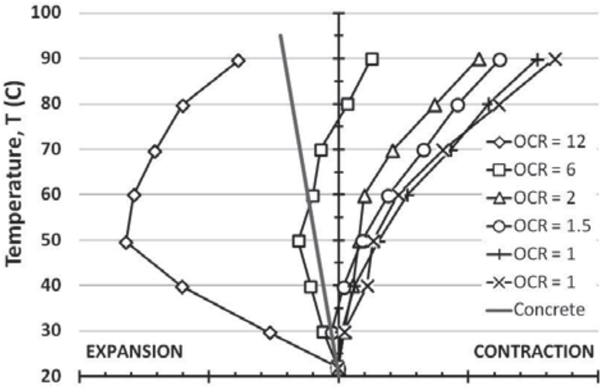

Figure 2. Effect of OCR on thermal volumetric response of Kaolin, after Cekerevac & Laloui, 2004.

Thus, a heavily OC clay such as the London Clay that supported the Lambeth College test pile, should expand more than concrete, perhaps by a factor of two or more.

The relative deformation of the pile with respect to the soil, in response to temperature change, is thought to be the source of the observed changes in pile response. Therefore, in this study, the effect of variations in the soil coefficient of thermal expansion relative to that of a concrete pile undergoing heating was evaluated. Table 1 summarises some typical values of this parameter for stiff over-consolidated clay found in the literature, and which formed the basis for selecting values for the numerical analyses, Table 2. Also, detailed in Table 1 are values of the coefficient of thermal expansion for water and concrete. The latter is primarily dependent on the type of aggregates that are used in the concrete mix.

Table 1. Typical values of volumetric coefficient of thermal expansion, β quoted for two clayey soils, concrete and water.

Material	*β (E-5, °K^{-1})*
Boom clay	4 to 6
Opalinus clay	
Concrete	2 to 4
Water (at 22°C)	27

2 BASIS FOR FINITE ELEMENT ANALYSES

2.1 *Geometry and boundary conditions*

A single pile with a diameter, D of 1.0 m and length, L of 30 m has been modelled in the program ADINA V8.5.0 assuming axisymmetry. After initial verification analyses, the side and bottom boundaries of the finite element mesh were set at a distance of 60 m (2L) and 90 m (3L) respectively, Cruz Silva, 2012.

No interface elements were introduced between the pile and soil solid elements, implying that the contact was perfectly rough. This also implies that the stiffness in the interface zone is the same as that for the soil, whereas the response on the pile-soil interface is known to be significantly stiffer.

Mechanical loading of the pile was modelled by applying a boundary pressure (6 MPa) that resulted in a pile settlement of about 1% of the pile diameter, i.e. about 10 mm. Displacement boundary conditions fix horizontal movement on the bottom and the two side boundaries while vertical movement is prevented only on the bottom boundary.

Thermal loading of the pile was modelled by the application of an increment of temperature ΔT=+30°C to all the elements making up the pile under steady state heat flow conditions. It is acknowledged that this is a simplification with respect to the actual temperature distribution in the pile cross-section and surrounding soil with time, but is considered to be reasonable with respect to the temperature along the pile which has been found to be almost constant, Bourne-Webb et al. 2009. Thermal boundary conditions ensured zero heat flow on the model centreline, and zero temperature change on the side and lower boundaries. Two scenarios were examined regarding the thermal boundary condition along the ground surface: zero heat flow and constant temperature. The resultant temperature fields are shown in Fig. 3. Again, these are acknowledged to be significant simplifications of the actual thermal conditions at the ground surface, although the latter is probably closest to reality.

2.2 *Material parameters*

In these analyses, both the pile and the soil were assumed to be elastic. This is considered to be a reasonable assumption for the structural element but is acknowledged to be a great simplification with respect to soil response which can be strongly nonlinear.

However, the aim of this study was to examine the pile response to temperature change on a simplified basis; additional layers of complexity may be added subsequently, including e.g. an interface with finite shear resistance, nonlinear TM/THM soil model(s), more realistic thermal loading and boundary conditions.

The adopted model parameters are shown in Table 2. In all the analyses undertaken, β for the concrete was held constant with a value of 3.0E-5°K^{-1} (note that the coefficient of linear thermal expansion, $\alpha = \beta/3$). The values of β assumed for the soil were zero, half and double that for the concrete; representing a moderately OC clay.

In addition, the Young's modulus of the soil was increased by a factor of two from the base value of 30 MPa, in order to assess the effect of this parameter on the predicted thermal response of the pile.

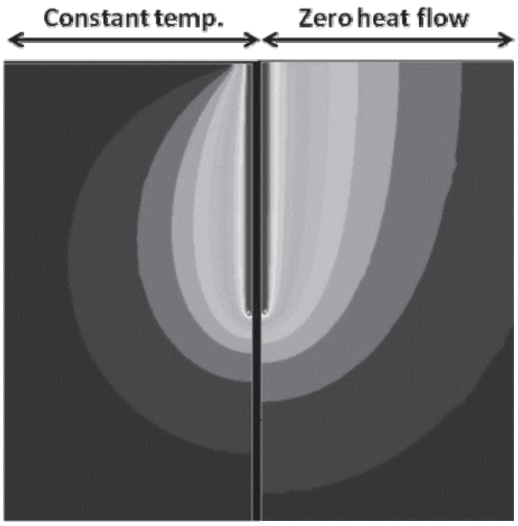

Figure 3. Steady-state temperature field as function of surface thermal boundary condition (contour interval: 2°C)

Table 2. Material parameters assumed for numerical analysis.

Parameter	*Concrete*	*Soil*
Young's modulus, E (MPa)	30000	30 or 60
Poisson's ratio, μ (-)	0.3	0.3
Coefficient of volumetric thermal expansion, β (E-5, °K^{-1})	3.0	0, 1.5 or 6.0
Thermal conductivity, k (kJ/hr.m.K)	8.4	4.0
Volumetric heat capacity, ρc_p (kJ/m^3.K)	1950	1500

3 PREDICTIONS

3.1 *Coefficient of thermal expansion*

The effect of changes in the value of the coefficient of volumetric thermal expansion, β of the soil, the stiffness of the soil and the thermal boundary condition on the ground surface of the model are illustrated, in terms of changes in pile axial stress, Fig. 4 and pile-soil interface shear, Fig. 5.

When comparing the plots, the dashed line for the β = zero case (the soil is thermally inert) provides a baseline for comparison, as the results are independent of the thermal boundary condition on the ground surface.

When the soil is less thermally expansive than the pile, i.e. β = 1.5E-5°K^{-1} and zero, heating the pile led to compressive axial stress with the maximum stress change for each β-value equating to about +12% and +15% of the stress that would be mobilised if the pile was fully restrained, P_{fix} (Table 3). The constant temperature boundary condition results in slightly greater (1 to 2%) restraint of the pile thermal expansion and thus, higher compressive axial stress are developed.

The effect of the thermal boundary condition on the ground surface becomes clearer when the soil is assumed to be more expansive than the pile (β = 6.0E-5°K^{-1}); when a zero heat flow condition was assumed, the pile went into tension (max. stress about -2% of P_{fix}) however, as identified above, the use of a constant temperature boundary condition resulted in greater restraint and the resulting stress changes were compressive (max. stress about +5% of P_{fix}) along the entire length of the pile.

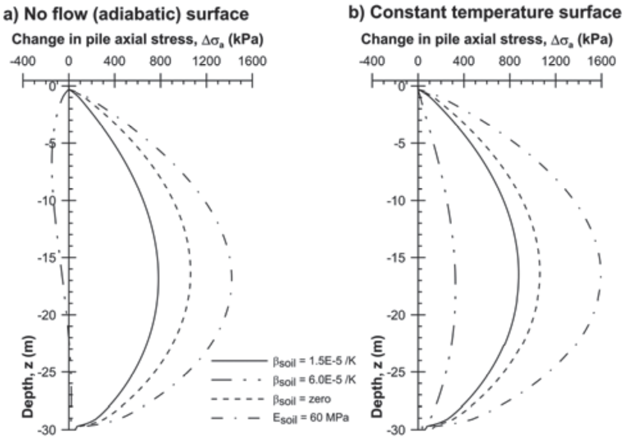

Figure 4. Change in pile axial stress due to temperature change of +30°C, Cruz Silva 2012.

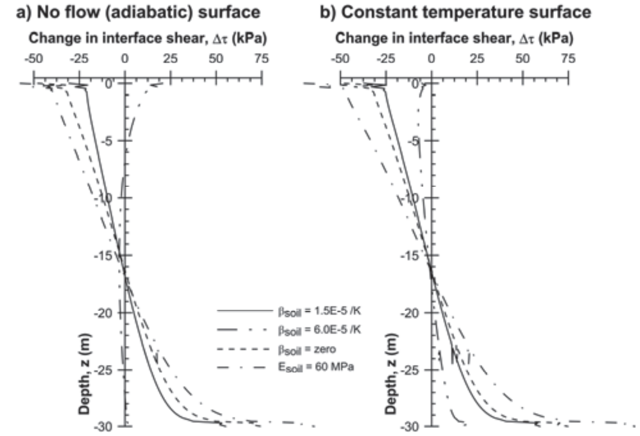

Figure 5. Change in pile-soil interface shear stress due to temperature change of +30°C, Cruz Silva 2012.

The shape of the profiles of predicted axial stress change (approx. parabolic) in Fig. 4 are directly related to the shape of the profile of mobilised friction at the pile-soil interface, Fig. 5 which is approximately linear (note that in Fig. 1 the mobilised friction was assumed constant and therefore the variation in axial stress was linear with depth).

Here again the effect of the coefficient of volumetric thermal expansion of the soil and the thermal boundary condition on the ground surface is seen. As the contrast in β-values of the pile and the soil increases, the magnitude of the predicted change in shear stress on the pile-soil interface, and the constant temperature condition leads to larger changes in shear stress compared to the zero heat flow condition.

As a consequence of the model being elastic and the interface not being modelled explicitly, i.e. with an appropriate stiffness and limiting strength, the shape of the interface friction (shear stress) profiles differs from that expected based on the simple model in Fig. 1 (which effectively assumes perfect plasticity) and the profiles inferred from observations in test piles, Amatya et al. 2012. The variation in shear stress along the pile-soil interface suggested here is only likely to be correct while the maximum stress values are below the yield strength on the interface.

3.2 *Soil stiffness*

In these analyses, the coefficient of thermal expansion in the soil was held at 1.5E-5°K^{-1}, and the soil Young's modulus was doubled from 30 MPa to 60 MPa. The predicted response in terms of change in axial stress and pile-soil interface shear for this case is also shown in Figs. 4 and 5 (dash-dot line) and can be compared to the analysis that used a soil Young's modulus of 30 MPa (solid line).

As the soil Young's modulus doubled from 30 MPa to 60 MPa, both the change in axial stress and interface shear stress increased, although the proportionality between the solutions was slightly less than two, due to relative pile-soil compressibility effects.

These results show that the operational stiffness in the soil mass will influence the response seen in the thermally loaded pile, and also illustrates how a stiffer shear response at the interface may lead to higher axial stresses in the pile.

4 DISCUSSION

Although a simple elastic model has been used to represent the pile and soil in the analyses presented here, the results presented highlight some interesting features.

The first relates to the compatibility of these results with observations and the simple descriptive models previously presented. The descriptive model was developed from and in order to explain the observed mechanisms of response in the few TM pile tests that have been reported in the literature and thus, implicitly assumes that the pile expands/contracts more that the soil.

In the analyses presented here when this assumption was met, the predicted response was inline with observations, with some differences due to the assumption of elastic soil response, i.e. linear variation of friction at pile-soil interface.

The predicted changes in axial stress were rather small when compared with the values measured in the field, and the theoretical value for a pile fully restrained against thermal deformation. Table 3 provides a comparison of the predicted (FEA) and observed restraining effect on two test piles, from Amatya et al. 2012.

This suggests that the pile as modelled in the FEA was almost completely free to expand and contract (the predicted deformation between the extremities of the pile confirms this), even when additional restraint in the form of either a larger differential in soil-concrete β-values or higher soil stiffness was considered.

Table 3. Thermal load and axial stress response of model and test piles.

Parameter	*FEA*	*Lambeth*	*EPFL*[2]
Temperature change, ΔT (°C)	+30	+29[1]	+21
Max. axial stress change as %-fully restrained value, P_{fix}[3]	10% - 20%	56%	36%

Notes: 1. First heating phase of Lambeth College heat sink pile;
2. First heating phase, Test T-1, EPFL
3. $P_{fix} = \alpha \Delta T A_{pile} E_{pile}$ (= 7069 kN for FEA results)

The second point of note relates to the importance and interdependence of the thermal boundary condition as demonstrated here by the assumption of either zero heat flow (perfect insulation) or constant temperature (no change relative to starting temperature) on the ground surface and the relative thermal expansion between the soil and the pile.

The results suggest that the thermal boundary conditions and thus the temperature field within the model impart their own form of restraint in the pile-soil interaction process, in addition to any mechanical restraint of the pile.

In particular, the cases examined here illustrate that the temperature field in the vicinity of the head of the pile was crucial in determining the form of response obtained from the analysis, i.e. while heating a pile in a soil with a higher coefficient of thermal expansion than the pile itself – as was the case in the Lambeth College test - compressive stresses where predicted only when a constant temperature boundary condition was specified at ground surface.

The constant temperature surface boundary condition meant that the soil near the surface and adjacent to the pile head was cooler, and despite the soil having a higher coefficient of thermal expansion, the pile was still able to expand relative to the soil mass and thus generate compressive axial stresses.

5 CONCLUSIONS

A linear elastic numerical model has been applied to the problem of the TM loading of piled foundations and the results have been found to generally reproduce observed mechanisms of behaviour.

The results presented here highlight that there is a complex interaction between the foundation and soil material's thermal characteristics, and the thermal boundary conditions. The sensitivity of the predicted response to these relationships needs to be investigated further.

Finally, the factors that determine the degree of fixity against thermal expansion that can be mobilised on the pile shaft also require deeper investigation, and future studies will focus on the pile-soil interface and the impact of thermal boundary conditions.

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