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Transient thermo-mechanical axisymmetric finite element analysis of energy piles

Analyse thermo-mécanique axisymétrique transitoire par éléments finis de pieux énergétiques

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ABSTRACT: Foundation piles that include geothermal liquid pipes are called "energy piles" and experience significant temperature changes during ground-source heat-pump operations. These temperature changes may affect the bearing capacity of the piles and lead to excessive displacements. Quantifying these effects is still a challenge for ensuring their long-term safety and stability.

Several computational methods have been developed to model and predict the thermo-mechanical (TM) response of energy piles. Amongst them, the TM load-transfer (LT) approach assumes a steady-state thermal response and it has been proved to reproduce the observed field behaviour of energy pile tests to a certain extent. A more elaborate approach is the transient coupled TM solid finite element (SFE) analysis which is able to consider more features of the complicated soil-structure interaction problem, such as transient heat propagation, thermal expansion etc.

This study presents the effects due to a transient temperature application with different time durations, by adopting the SFE approach. The transient heat propagation consequent to diverse thermal loading scenarios brings to more realistic results with respect to the LT steady-state thermal analysis. Therefore, the outcomes of this study are directly relevant to industry and practising engineers that need practical analysis tools for energy pile design.

RÉSUMÉ: Les pieux de fondation comprenant des conduites de liquide géothermique sont appelés «pieux énergétiques» et subissent des changements de température importants pendant le fonctionnement de pompes échanger de chaleur. Ces changements de température peuvent affecter la capacité portante des pieux et entraîner des déplacements excessifs. Quantifier ces effets reste un défi pour assurer leur stabilité à long terme.

Plusieurs méthodes informatiques ont été développées pour modéliser et prédire la réponse thermo-mécanique des pieux énergétiques. Parmi ceux-ci, l'approche par transfert de charge thermo-méchanique suppose une réponse thermique en régime permanent et il a été prouvé qu'elle reproduisait dans une certaine mesure le comportement observé sur essais des pieux énergétiques sur le terrain. Une approche plus élaborée est l'analyse par éléments finis solides thermo-méchanique accouplé transitoire, qui est capable de considérer les caractéristiques du problème complexe de l'interaction sol-structure, comme la propagation transitoire de la chaleur, la dilatation thermique, etc.

Cette étude présente les effets dus à une application de température transitoire avec différentes durées, en adoptant l'approche l'éléments finis solides. La propagation transitoire de la chaleur résultant de divers scénarios de charge thermique donne des résultats plus réalistes en ce qui concerne l'analyse thermique de transfert de charge en régime permanent. Par conséquent, les résultats de cette étude sont directement pertinents pour l'industrie et les ingénieurs praticiens qui ont besoin d'outils d'analyses pratiques pour la conception de pieux énergétiques.

Keywords: energy piles; transient thermo-mechanical analysis; energy; finite elements; soil-structure interaction

1 INTRODUCTION

Thermo-active deep foundations constitute a type of ground heat-exchanger pump closed-loop systems able to fulfil a double-function: structural support to the buildings and interiors' heating and/or cooling. In fact, they are special reinforced concrete piles inasmuch they contain U-shaped pipe loops, fixed to the reinforced cage, which are filled with a heat carrier fluid (Brandl 2006).

Although this promising technology has a lot of advantages, in terms of sustainability and cost savings, such that it has been already broadly employed in some countries (Austria, Switzerland, etc..), there is still reluctance in its total adoption by industry. This hesitancy is related to a lack in knowledge regarding the effects of heating and/or cooling on the stability and serviceability of the energy piles.

In order to contribute to the understanding of the energy piles' behaviour, a series of computational analyses have been performed by different authors: Thermo-Hydro-Mechanical coupled finite element models (Laloui et al. 2006, Di Donna and Laloui 2015, Gawecka et al. 2016), non-linear load-transfer (t-z) finite element analysis (Knellwolf et al. 2011, Ouyang et al. 2011, Pelecanos and Soga 2017), and TM finite element software (Yavari et al. 2014 and Saggu and Chakraborty 2015).

This paper presents the soil-structure interaction numerical study, concerning the radial heat propagation into the soil surrounding the energy pile. The multi-physics finite element software ANSYS 19.0 has been adopted in order to model the behaviour of an energy pile subjected to transient thermal loadings. The results obtained from the simulations show the capabilities of the transient thermal investigation with respect to the load-transfer finite element analysis whereby the steady-state thermal loadings' application is considered.

2 PROBLEM STATEMENT

The problem examined in this paper refers to the study of a pile casted into a homogeneous soil layer and thermally loaded with a heating-cooling cycle. The spread of heat propagation across the soil surrounding the pile induces settlements, whose entity is striclty related to the amount of time the thermal cycle is applied. One of the most suitable ways for modelling this kind of problem is by means of a transient thermo-mechanical finitle element analisys, rather than a steady-state numerical fomulation. The latter can be potentially considered as the last step of a transient thermal analysis, when the transient effects have become almost null, or even before the performance of a transient thermal analysis in order to establish initial conditions.

3 NUMERICAL FORMULATION

The study of a single pile that is axially thermo-mechanically loaded and casted into a uniform soil with a horizontal ground level can be pursued by adopting different numerical models. Two different numerical formulations are described below.

3.1 *Load-transfer model*

The non-linear t-z model is a numerical formulation used for simulating the load-transfer mechanism of an axially loaded pile (Fig. 1). The bearing capacity of a pile, subjected to a vertical load applied at its head, relies on the combination of the base resistance, Q_b, and the shaft resistance, Q_s, mobilised at the pile-soil interface.

Within a one-dimensional numerical modelling, the deep foundation can be discretised into a series of two-noded linear-elastic beam elements representing the pile's rigidity. In addition, non-linear springs are attached at each node in order to take also into account the soil's non-linear behaviour, which is governed by the Degradation and Hardening Hyperbolic constitutive Model (DHHM) as described in Pelecanos and Soga (2017) by the following relation:

$$t = \frac{k_m z}{\sqrt[d]{1+\left(\frac{k_m}{t_m}z\right)^{hd}}} \qquad (1)$$

where k_m is the maximum stiffness value when the displacement, z, is null [force/length^3]; t_m is the maximum shear stress when no hardening/softening is considered [force/length^2]; d is the unitless degradation parameter that affects the degradation of subgrade modulus, k, with displacement; h is the unitless hardening parameter governing the model trend at large displacements (h=1 is related to no hardening/softening)

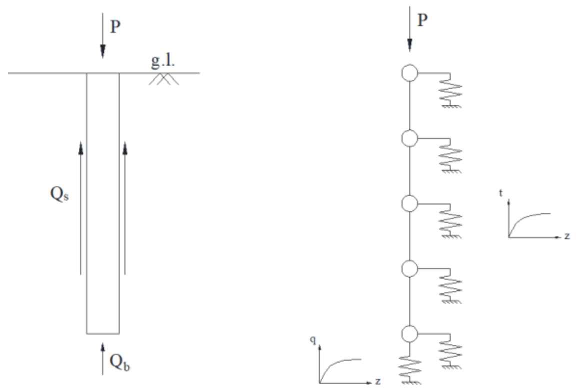

Figure 1. Discretisation of the axially-loaded pile into two-noded beam elements

In order to perform a thermo-mechanical load-transfer analysis, a steady-state temperature change is implemented in the model. Therefore, the mechanical load at the pile head is incrementally applied according to the following equilibrium equation:

$$\{P\} - \alpha_c EA \cdot \{\Delta T\} = \left([K_p] + [K_s]\right) \cdot \{z\} \qquad (2)$$

where P is the vector containing the external axial load values; α_c is the concrete thermal expansion coefficient; EA is the pile's axial rigidity; ΔT is the vector containing temperature change values; K_p is the pile's stiffness matrix; K_s is the soil stiffness matrix; z is the vector containing the vertical displacements' values.

3.2 *2D axisymmetric FE model*

Another way for numerically modelling this kind of problem is through a 2D axisymmetric FE analysis, thanks to which it is possible to avoid the 3D demanding computational time. This is considered licit when the loading, material and geometrical configurations are symmetrical. Therefore, a 2D axisymmetric geometry can be derived from a 3D case by means of the interception of a plane with the 3D drawing, i.e. xy plane in Fig. 2. The results obtained for one plane can be then extended for all the other vertical planes belonging to the same proper sheaf having the pile's axial axis in common.

This kind of configuration can be found implemented into different off-the-shelf software available nowadays, such as ANSYS. The static thermo-mechanical coupling is described by the following formulation:

$$\begin{bmatrix} 0 & 0 \\ C^T & 0 \end{bmatrix} \begin{Bmatrix} \dot{u} \\ \dot{T} \end{Bmatrix} + \begin{bmatrix} K & C \\ 0 & K_T \end{bmatrix} \begin{Bmatrix} u \\ T \end{Bmatrix} = \begin{Bmatrix} P \\ Q \end{Bmatrix} \quad (3)$$

where C is the coupling matrix; $\dot{u}$ is the velocity vector; $\dot{T}$ is the temperature rate vector; K is the global stiffness matrix; T is the temperature vector; u is the nodal displacement vector; P is the mechanical axial load vector; Q is the thermal load vector.

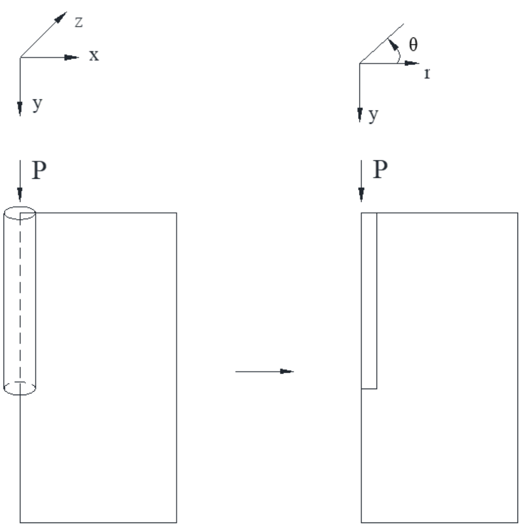

Figure 2. Simplification of the 3D problem into the 2D ax-isymmetric configuration

4 NUMERICAL MODELLING

Radial heat transfer between the deep foundation and the surrounding soil has been studied through a transient TM analysis by using ANSYS's Workbench.

4.1 Problem

A 2D-axisymmetric geometry is considered, where a pile of radius, r=0.5 m, and length, L=10 m, has been drawn into a soil stratum of 11r × 2L dimension (Fig. 3). The mesh is constituted of a series of 4-noded-Quad thermo-mechanical coupled elements (PLANE13), characterised by displacement and temperature degrees of freedom. Horizontal displacements are prevented by rollers, disposed at the soil layer lateral borders, whereas fixed constraints are applied at the bottom of the soil stratum, preventing any kind of displacement and rotation.

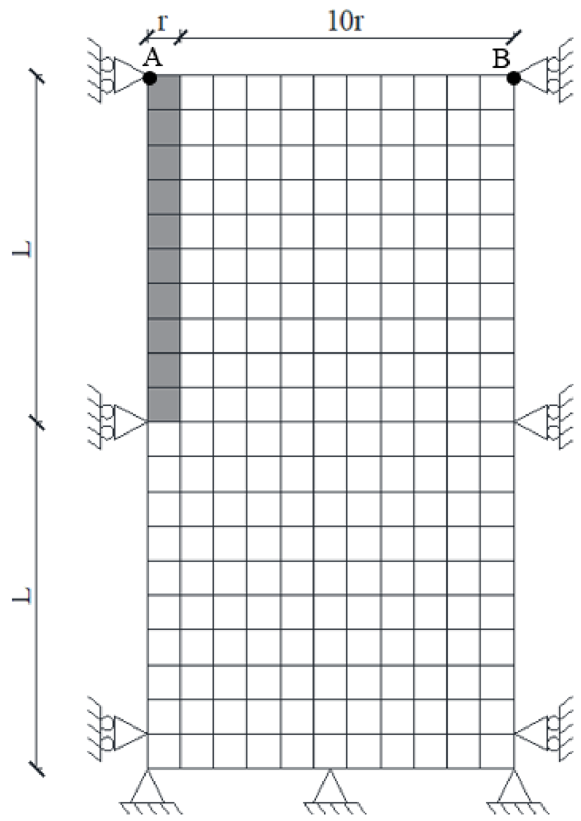

Figure 3. Sketch of the problem geometry and boundary con-ditions

The pile is assumed as a linear elastic material, characterised by a Young's modulus of 30 GPa and a concrete thermal expansion coefficient, α_c, of 9.5 x 10^{-6} m/m/°C. The soil stratum is considered homogeneous and characterised by a non-linear behaviour following the Mohr-Coulomb criterion. Pile and soil parameters are listed in Tab. 1.

Table 1. Parameters adopted for the soil and the pile: ρ, mass density; E, Young's modulus; υ, Poisson's ratio; c', effective cohesion; ϕ', friction angle; k, thermal conductivity; C_s, specific heat capacity; α, thermal expansion coefficient

	ρ	E	υ	c'	ϕ'	k	C_s	α
	[*kg/m³*]	[*MPa*]	[-]	[*kPa*]	[°]	[*W/m°C*]	[*J/kg°C*]	[*με/°C*]
PILE	2400	30000	0.2	-	-	2.3	960	9.5
SOIL	1700	50	0.3	5	30	1.8	880	17

The transient thermal analysis is performed by applying a time-dependent temperature cycle as boundary condition at all pile nodes. Initial thermal conditions assume a uniform temperature of 12 °C everywhere in the model, whereas boundary conditions assume no heat flow at all FE mesh boundaries which are placed far enough for no boundary interaction. The thermal cycle consists in a heating phase, reaching a maximum value of 24 °C, and a cooling phase with 0 °C lowest value (Fig. 4). The effects of the temperature propagation have been investigated for seven periods: 1 sec; 1 min; 1 h; 1 day; 1 week; 1 month and 1 year.

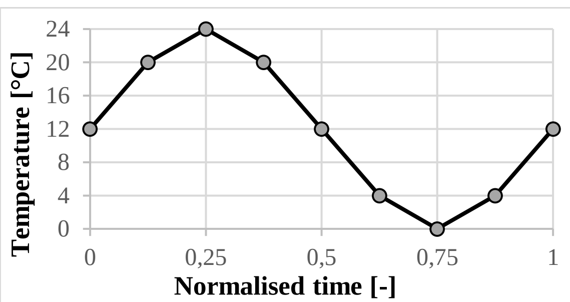

Figure 4. Temperature transition

4.2 Results

The application of a transient thermal loading has clearly effects in terms of displacements and temperature propagation in the soil, depending on the application period. The static structural analysis shows that the pile and the soil are subjected to thermal expansion during heating (Fig. 5-b) and thermal contraction during cooling (Fig. 6-b). The major effects are perceived all around the pile where the absolute displacement gradient values are higher. At a radial distance of roughly 7r and at a depth of 1.5L the displacement gradient is almost null, where the elements' square shape is preserved. This results from the temperature propagation within the soil. In fact, the maximum absolute temperature values and the absolute thermal gradient values are greater in the first 3 or 4 elements closer to the pile, during the heating phase (Fig. 5-a) and during the cooling phase (Fig.6-a).

The quantification of vertical displacements at the pile head (point A in Fig. 3) is showed for different time durations in the Fig. 7. It is evident that the vertical displacements develop further and further with the duration increase of the transient thermal loading application. Specifically, there is no significant difference between the 1 sec and 1 min curves, thereafter the displacement magnitude becomes more important from 1 h up to 1 year duration. Moreover, as the period varies from 1 sec up to 1 year, the null point, where the displacements' sign reverses, translates further towards right, therefore from 0.5 (1 sec) until 0.625 (1 year). The amount of delay is strictly related to the quantity of displacements previously cumulated during the deformation process and to the displacement gradient value at that point. Therefore, the amount of displacement to recover in 1day is less than the one in 1 year.

Fig. 8 shows the temperature propagation effect measured at a point "far away" from the pile (point B in Fig. 3) depending on the duration of the application of the transient themal loading. One can observe that for the first six periods (from 1 sec up to 1 month) the temperature measured at point B remains contant and equal to the initial value (12 °C). The perception of temperature variation is manifested only within the 1 year time duration, with an initial delay of roughly 10% of the total period.

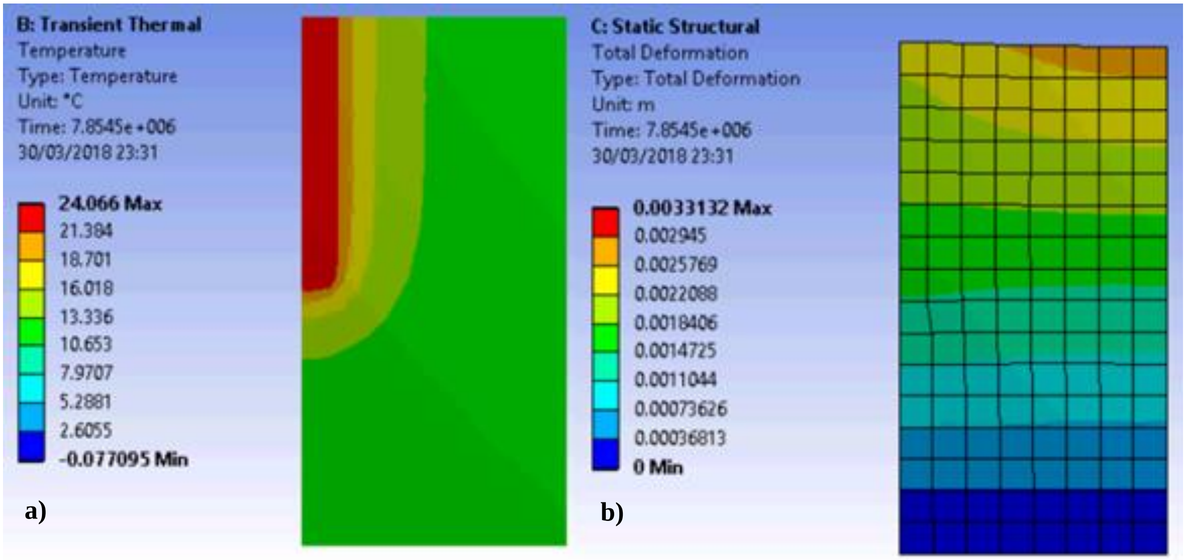

Figure 5. Effects of heating (24 °C) on (a) temperature propagation, and (b) displacements during 1 year

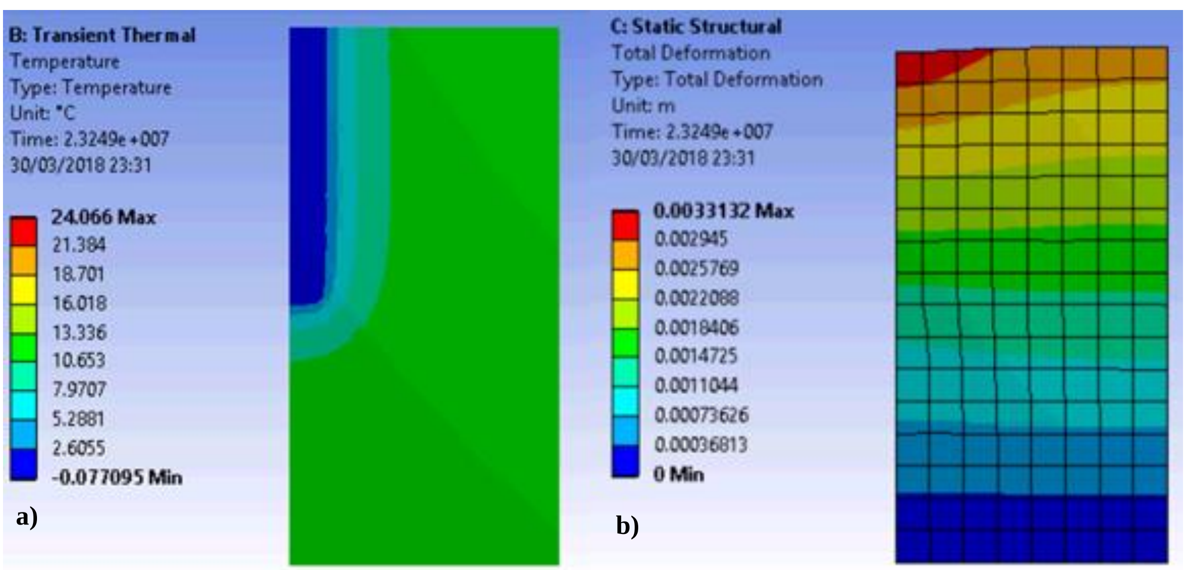

Figure 6. Effects of cooling (0 °C) on (a) temperature propagation, and (b) displacements during 1 year

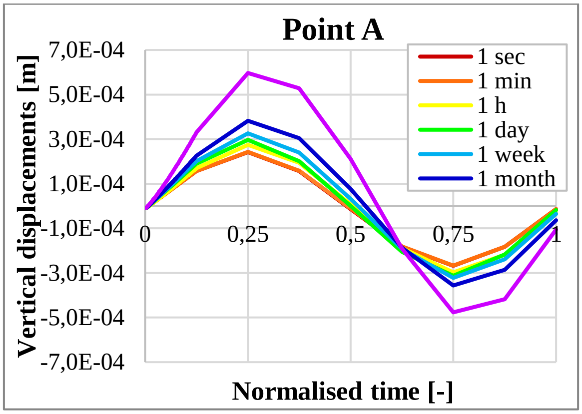

Figure 7. Effect of the duration of the transien themal loading application on the vertical displacements' magnitude at the pile's head

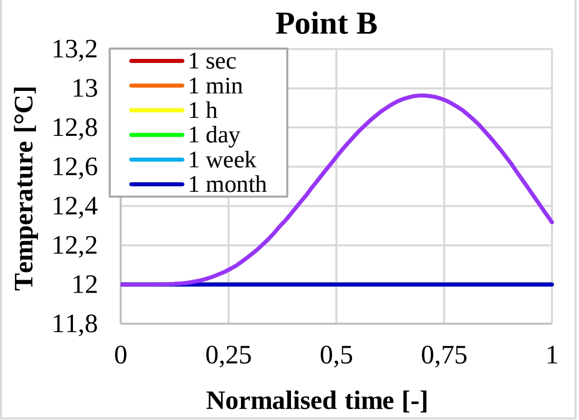

Figure 8. Effect of the duration of the transien themal loading application on the temperature propagation at a point "far away" from the pile

5 CONCLUSIONS

A series of transient thermo-mechanical FE simulations have been performed by using the commerical software ANSYS v. 19.0. The results presented in this paper show how the duration of the applied transient thermal loading affects the soil-structure interaction in terms of displacements and heat propagation in the soil.

As the period of thermal loading cycle increases, the pile head undergoes to further and further vertical displacements and the deformation's recovery requires longer time. Moreover, heat propagation gradients, and so cosequent settlement gradients, are higher in soil's portions closer to the pile's surface, therefore decreasing going far away from the soil domain, i.e. point B. Thermal variations can be perceived at "far away" regions only after long periods of thermal loading application, i.e. 1 year.

Cases in which the thermal cycle is applied for very short durations, i.e. 1 sec and 1 min, show similar outcomes with the steady-state load-transfer thermo-mechanical coupled finite element analyses. Therefore, steady-state themo-mechanical numerical models are not suitable for studying long-term transient heat propagation problems.

The practical engineering significance of this study is that computational tools that ignore radial thermal propagation (such as the beam-spring load-transfer method) are not appropriate for long-term temperature cycles that allow radial temperature propagation.

6 AKNOWLEDGEMENTS

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