Accounting for transient effects in energy pile design

Prise en compte d'effets transitoires dans le calcul d'un pieu géothermique

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ABSTRACT: The use of energy geostructures has been increasingly grown across the world due to the combination of their traditional role as bearing elements and their environmental benefits. Nevertheless, the different steps of the design of these structures are not completely defined. In particular, energy geostructures are designed by considering only permanent calculation situations. In most cases, only the greatest temperature difference as an extreme condition is considered, so that the transient effects due to the temperature variations are neglected. Furthermore, only the energy geostructures are assumed to be submitted to temperature variations and no contraction or expansion of the surrounding ground is taken into account. Based on static load tests on both conventional piles and energy piles, the transient behaviour of a pile into sandy soils is analyzed through a numerical parametric study. The contractions and the expansions of the ground around the pile are analyzed in details. The aim is to provide a better understanding of energy piles in transient conditions. The variations of the pile head displacements and the normal forces into the pile are assessed and practical considerations for the design of energy piles are proposed.

RÉSUMÉ: Les géostructures énergétiques sont de plus en plus utilisés dans le monde de par leur rôle traditionnel de fondation ou de soutènement et leurs avantages environnementaux. Néanmoins, les différentes étapes de la conception de ces ouvrages ne sont pas complètement définies. En particulier, ces structures sont seulement justifiées pour des situations de calcul permanentes. En général, seulement les différences extrêmes de température sont considérées et les effets transitoires dus aux variations de température sont négligés. Par ailleurs, seule la structure énergétique est soumise à des variations de température et aucune contraction ni expansion du sol encaissant n'est prise en compte. A partir d'essais sur des pieux conventionnels ou énergétiques, le comportement d'un pieu en situation transitoire dans un terrain sableux est analysé. Plusieurs situations sont comparées afin de souligner les effets de la diffusion de température dans le pieu et dans le sol. La contraction et l'expansion du sol autour du pieu sont analysées en détail. L'objectif est de fournir une meilleure compréhension des pieux énergétiques en conditions transitoires. Les variations du déplacement en tête de pieu et d'effort normal sont estimées et des considérations pratiques pour la conception des pieux énergétiques sont proposées.

KEYWORDS: Energy piles, thermal loading, transient analysis.

MOTS-CLES: Pieux énergétiques, chargement thermique, analyse transitoire.

1 INTRODUCTION

Geothermal structures present a promising technology through their double role as bearing elements for superstructures and heat exchangers supplying the supported buildings with their thermal needs. Many studies have been carried on geothermal structures and especially on energy piles. Experimental tests (Wang et al. 2016, Yavari et al. 2014), full scale in-situ tests (Bourne Webb et al. 2009, Laloui et al. 2006), and numerical modeling (Suryatriyastuti 2013, Rotta Loria et al. 2015); all were carried out to study the behaviour of piles under thermal and mechanical loading. In most cases, only the largest temperature difference is considered (Bourne Webb et al. 2009), so that the transient effects due to temperature variations are neglected. In this paper, the transient behaviour of energy piles installed in sandy soil is analyzed through numerical models and full scale tests on energy piles (Szymkiewicz et al. 2015). The objective of this work is to provide a better understanding of the behaviour of energy piles under transient conditions.

2 SITE PRESENTATION AND EXPERIMENTAL RESULTS

The load tests used for this study have been performed in the north of France, near Dunkerque (Szymkiewicz et al. 2015) and include both mechanical and thermal loadings. The considered energy pile is a continuous flight auger (CFA) pile of 12 m length and 0.52 m in diameter.

Concerning the soil, at the top, till a depth 2.7 m the soil is silty, and the rest is a clean and very homogeneous sandy soil. The water table is located at a depth of 1.6 m and water flows in a hydrostatic regime.

In the full scale tests, two piles have been used. The first one has been loaded only mechanically and used to perform the static load test. Pile 2 has been preloaded first to 900 kN (37% of the limit pile capacity), and then subjected to a thermal loading through imposing a constant temperature in the pile.

Each thermal cycle consists of 4 phases; cooling-rest-heating-rest where each phase has a duration of 7 days. The temperature imposed in the pile during the cooling and the heating cycles is 2 °C (decrease by 12°C from the average soil temperature) and 29 °C (increase by 15°C from the average soil temperature) respectively, whereas in the rest phase, the pile temperature varies freely with time.

3 NUMERICAL MODELING OF THE MECHANICAL BEHAVIOUR OF THE PILE

3.1 *Finite difference approach*

The geothermal pile is modeled using a 3D finite difference model (FLAC3D, 2012). The modeled pile has an equivalent square section B=0.44 m. Regarding the boundary conditions, only half of the domain is modeled due to symmetry and Figure 1 shows the considered mechanical boundary conditions. The energy pile is considered as a concrete structure, thus the conventional mechanical properties of concrete are adopted for the pile. The pile installed in sandy soil with a water table at a depth 1.5 m from the surface. The ground is considered homogeneous, where the silty layer is neglected since the unit weights of silt and sand are almost the same. The soil is assumed to have a plastic behaviour with a Mohr-Coulomb failure criterion. The cohesion, friction angle, and the density are taken from the results of the performed laboratory tests (Szymkiewicz et al. 2015). Several parametric studies have been performed in order to determine the elastic modulus and the dilation angle best fitting the experimental data. Table 1 presents the mechanical properties of soil and concrete. Figure 2 represents the results of the static load test where the soil with E=52 MPa was found to have a good agreement with the load-head settlement curve of the soil in the considered site. It is important to note that perfect contact is considered between the pile and the soil, therefore no interface elements are considered. The difference between numerical results and experimental data is not negligible but can be assumed to be sufficiently low for the following of the study, especially, as the mechanical load applied is equal to 900 kN.

3.2 *t-z load transfer approach*

A t-z load transfer approach is then used to model the geothermal pile by solving the following equation:

$$E_y A \frac{d^2 w_p}{dz^2} + f_{pile-soil}(z, w_p)\, w_p = 0 \qquad (1)$$

where E_y is the Young's modulus of the pile, A is the pile area, w_p is the vertical pile displacement, and f_{pile_soil} is the t-z curve corresponding to the mobilised shaft friction or the mobilised base resistance taking into account the properties of the soil-pile interface. For each pile section, the load transfer method gives the following results: displacement, normal stress, axial strain, mobilised shaft friction and mobilised base resistance. The t-z curves have been calibrated in order to obtain the best fitting between the experimental data and the numerical results.

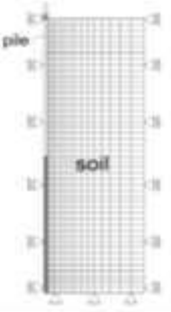

Figure 1. Mechanical boundary conditions.

Table 1. Mechanical properties for the pile and soil.

	Soil		Pile
Density ρ (kg/m^3)	0-1.5m	1581	2500
	1.5-24m	1910	
Elastic modulus E (MPa)	52 MPa		20000
Poisson's coefficient ν	0.3		0.2
Cohesion c (kPa)	3		-
Friction angle φ	31		-
Dilation angle ψ	6		-

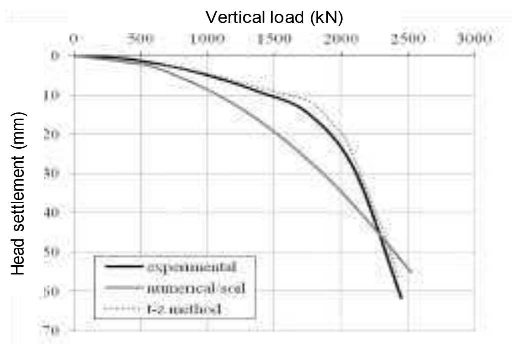

Figure 2. Pile head settlement (experimental=black line, numerical=grey line, t-z method=dotted grey line).

4 THERMAL ANALYSIS

4.1 *Thermal analysis using the finite difference method*

A coupled thermo-mechanical analysis is carried in order to study the transient effects on the mechanical behaviour of the energy pile. Table 2 lists the thermal properties of soil and concrete. The thermal load applied to the pile consists of four phases: cooling-rest1-heating-rest2. The temperature into the pile is allowed to naturally vary between each cooling and heating phases. Rest phases are considered since in many real cases, there is a period of time where the energy geostructure will function without the aid of the heat pump (the temperature delivered through the thermal exchange with the ground is enough to provide the building with its thermal needs). The variation of the pile temperature as well as the soil temperature with time at different distances from the pile edge is presented in Figure 3. The soil temperature has a similar trend of variation as that for the pile with some damping effects due to the thermal diffusion. For a distance of approximately 3 m from the pile edge, the soil temperature is constant and equals to 14°C (initial ground temperature) and does not vary with time.

Concerning the variation of the pile head displacement with the thermal cycle, it is represented in Figure 4 for two different conditions: with and without a preload; in this figure, positive displacement indicates pile head heave while negative displacement indicates pile head settlement. The preload is equal to 900 kN which corresponds approximately to SLS load resistance of the pile (safety factor equal to 2.7). With the thermal phases, the thermally induced settlement increases during the cooling phase due to pile contraction, then tends to decrease in the following rest phase since the pile is allowed to freely vary its temperature. After that, the pile heaves in the next heating phase inducing a positive displacement and then it shows a decrease in the head heave in the following rest phase.

Table 2. Thermal properties of the pile and the soil.

	Soil	Pile
Thermal conductivity λ (W/m.K)	1.8	2
Specific heat capacity (J/kg.K)	880	1000
Linear thermal expansion coefficient α (/°C)	$12x10^{-6}$	$5x10^{-6}$

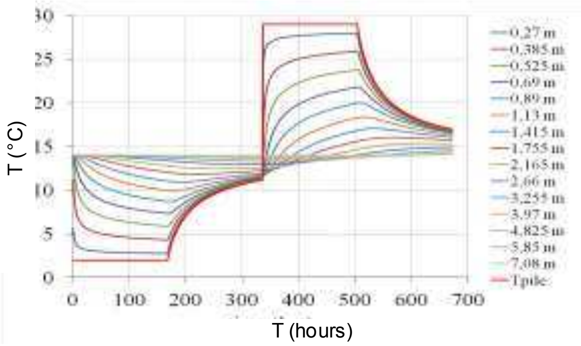

Figure 3. Pile temperature variation during a thermal cycle.

This variation has the same profile for both cases (with and without a preload). It's important to note that the thermally induced head displacement experience a rapid increase or decrease at the beginning of the each phase. The obtained results show that the pile head displacements depend on the mechanical preloading with an increase in the presence of a preload. This result agrees with the experimental work of Wang et al. (2016) and Kalantidou et al. (2012). This can be related to the impact of preloading on the mobilized strength at the pile-soil interface. The preload induces a decrease in the global stiffness of the pile due to the development of plasticity. Anyhow, the thermally induced displacement values remain small and do not exceed 3% of the allowable mechanical settlement (10% of the pile's diameter). They are almost reversible even if they tend to accumulate when a pre-loading is considered. As a comparison, Wang et al. (2016) considers a thermal cycle consisting of a heating phase followed by a natural recovery and then a cooling phase. For the case of no vertical load, the settlement is found to be reversible while it is cumulative in the presence of a vertical load. Kalantidou et al. (2012) shows that for small vertical loads (<40% of limit resistance) the head displacement is reversible whereas for higher loads, the displacement is no more reversible.

The variation of the axial stress $\Delta\sigma_{th}$ induced by the thermal loading along the pile depth is represented in Figure 5. Normally, under the effect of thermal loading only, cooling produces positive axial stress in the pile (tensile stress), while heating leads to the development of negative axial stress (compressive stress) (Bourne-Webb et al. 2009). In the present study, tensile axial stress was developed during the cooling cycle. In the following phases, the thermally induced axial stress becomes compressive and increases more in the next heating phase. For the last rest phase, as time increases, the normal stress decreases and it becomes tensile for the zones below the middle of the pile. The main variations in terms of thermal stress occur at the beginning of the cooling or the heating phase. Due to the thermal diffusion, the amplitude of this stress variation decreases corresponding to an increase of the amplitude of pile head displacements. It is similar to relaxation effects for the axial stress and creep effects for the pile head displacement.

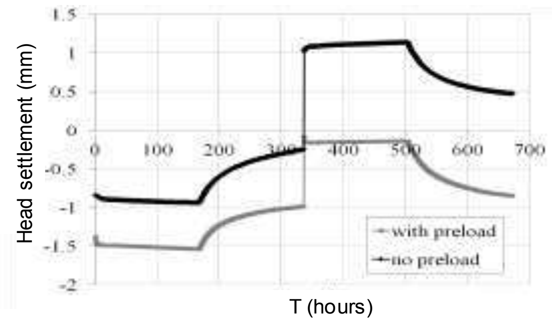

Figure 4. Variation of the thermally induced pile head displacement.

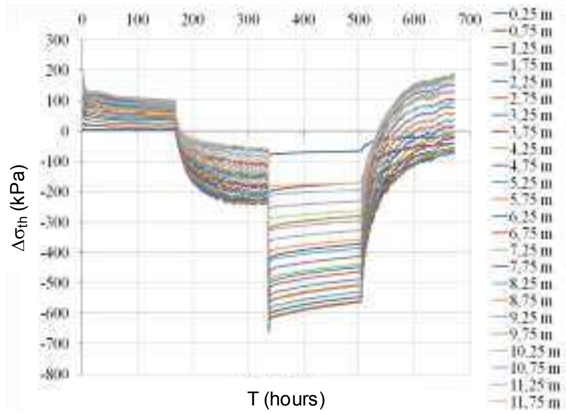

Figure 5. Variation of the thermally induced normal stress with time.

4.2 *Thermal analysis using the t-z load transfer approach*

Thermal strains in the surrounding soil are taking into account through a free vertical displacement of the soil $w_{s,th}$. A slight change in the equilibrium equation is needed, as stated below:

$$E_y A \frac{d^2 w_p}{dz^2} + f_{pile-soil}(z, w)\left[w_p - w_{s,th}\right] = 0 \qquad (2)$$

The free vertical displacement of the soil $w_{s,th}$ can be easily determined with the average temperature variations around the pile. The evolution of the ratio of the thermal induced head displacement to the mechanical head displacement $w_{mec,h}$ and the additional thermal vertical stress is given in Figures 6 and 7. The x-axis represents the ratio of the variation of temperature into the soil to the variation of temperature into the pile. These temperature variations are obtained from the previous numerical calculation where the temperature distribution is calculated according to the time. During heating, pile head displacement increases corresponding to a decrease of the normal load. During cooling, pile head displacement decreases.

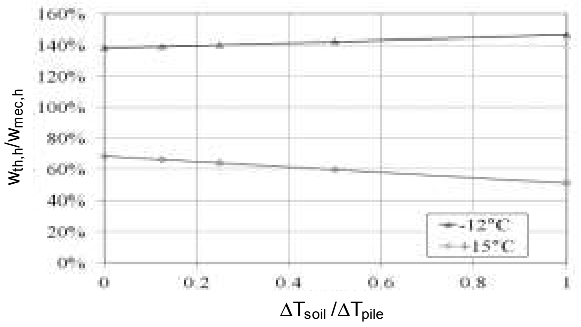

Figure 6. Evolution of the thermal displacement with imposed temperature.

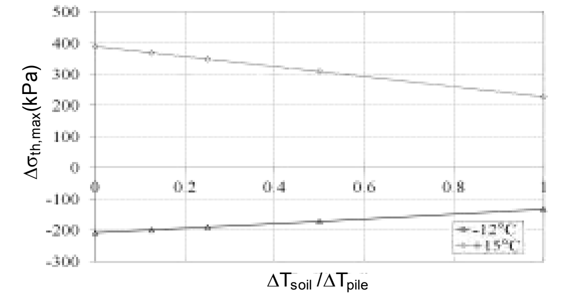

Figure 7. Variation of the maximum thermal normal stress with temperature.

5 COMPARISON OF THE TWO APPROACHES

The two approaches are compared during a cooling phase in terms of the ratio of the normal force variation at time t to that at t=0 (Figure 8). The free vertical displacement $w_{s,th}$ is then calculated using a weighted temperature in the surrounding soil $\Delta T_{s,eq}$, using the following formula:

$$\Delta T_{s,eq} = \frac{\int_{r=B/2}^{r=+\infty} \frac{\Delta T_s(r)}{r} dr}{\int_{r=B/2}^{r=+\infty} \frac{1}{r} dr} \quad (3)$$

where T_s is the soil temperature and r is the soil radius.

The two approaches give very close results and show that it is possible to take into account transient thermal effects using t-z transfer curves. The normal load into the pile increases significantly just after the beginning of the cooling phase and then decreases due to the thermal diffusion. This result is interesting since it shows that the effects of the temperature variations on the normal forces are very transient. In terms of design, it shows that it is legitimate to consider only a part of the total temperature variation; for example in this case, after six hours of cooling, the variation of the induced thermal stress becomes constant.

6 CONCLUSION

In this paper, a thermo-mechanical analysis of an energy pile installed in sandy soil is carried out to study the transient effects on the mechanical behaviour of energy piles. Two main results can be underlined from this work

The first one concerns the thermal stress variations that are the largest at the beginning of a cooling or a heating period and then decrease due to thermal diffusion. This kind of behaviour is similar to relaxation effects. From the viewpoint of the designer, this important result means that only a part of the thermal stress variation has to be considered when the calculation is performed for a quasi-permanent combination.

The second finding is related to the additional pile head displacements that depend on the loading level. They are reversible when a low mechanical load is applied and increase with larger mechanical applied loads. The amplitude of these displacements increases with the time both for cooling and heating. Nevertheless, the displacement amplitude is low and may not induce any disorders on the structure supported by the energy piles.

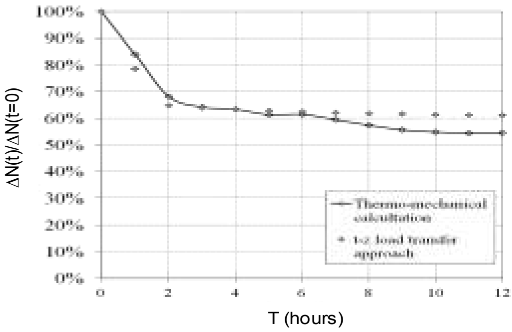

Figure 8. Ratio of the normal force variation at time t to that at t=0 during the cooling phase for the thermo-mechanical calculation (black), and t-z method (grey).

7 REFERENCES

Wang C.L., Liu H.L., and Kong G.Q. 2016. Model tests of energy piles with and without a vertical load. *Environmental Geotechnics* 3(EG4), 203-213.

Yavari N., Tang A.M., Pereira J.M., Hassen G. 2014. Experimental study on the mechanical behaviour of a heat exchanger pile in physical model . *Acta Geotechnica* 9, 385-398.

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

Laloui L., Nuth M., and Vulliet L. 2006. Experimental and numerical investigations of the behaviour of a heat exchanger pile. *International Journal for Numerical and Analytical Methods in Geomechanics* 30, 763-781.

Suryatriyastuti M.E. 2013. Numerical study of the thermo-active piles behaviour in cohesionless soils. Doctoral thesis.

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

Szymkiewicz F., Burlon S., Guirado C., Minatchy C., and Vinceslas G. 2015. Experimental study of heating-cooling cycles on the bearing capacity of CFA piles in sandy soils. *Problematic materials, environment, water and* energy 5(409).

Itasca 2012. FLAC3D Version 5.0. Theory and Background. Itasca Consulting group, Inc. Minnesota, USA.

Kalantidou A., Tang A.M., Pereira J.M., and Hassen G. 2012. Preliminary study on the mechanical behaviour of heat exchanger pile in physical model. *Géotechnique* 62(11), 1047-1051.