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Experimental behavior and numerical analysis of energy piles

Comportement expérimental et analyse numérique des pieux thermiques

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ABSTRACT: The use of pile foundations as heat exchangers in combination with heat pump conditioning systems are becoming increasingly popular. This occurs for a number of reasons mainly related to the developments of more efficient and environmentally friendly solutions for the building conditioning. A relatively large number of small scale laboratory tests and field scale experiments are available and useful to get an insight in the mechanism governing pile-soil interaction under thermo-mechanical loading. On the other hand numerical analysis represents a powerful tool to simulate even complex thermo-mechanical tests. In the paper numerical FEM simulations are performed for published experimental investigations. The paper focus is on the load-settlement relationship and on the load-transfer curves with depth for piles subjected to combined mechanical and thermal loadings. A simple procedure to calibrate the stiffness and the strength parameters of the soil model is proposed and validated.

RÉSUMÉ: L'utilisation de fondations sur pieux comme échangeurs de chaleur en combinaison avec des systèmes de conditionnement de pompes à chaleur devient de plus en plus populaire. Cela se produit pour diverses raisons principalement liées au développement de solutions plus efficaces et plus respectueuses de l'environnement pour le conditionnement des bâtiments. Un nombre relativement important d'essais en laboratoire et d'expériences sur le terrain à petite échelle sont disponibles et utiles pour mieux comprendre le mécanisme qui régit l'interaction pieu-sol sous un chargement thermomécanique. D'autre part, l'analyse numérique représente un outil puissant pour simuler des tests thermomécaniques complexes. Dans le document, des simulations FEM numériques sont effectuées pour des enquêtes expérimentales publiées. L'accent est mis sur la relation charge-tassement et sur les courbes de transfert de charge avec la profondeur pour les pieux soumis à des charges mécaniques et thermiques combinées. Une procédure simple pour calibrer les paramètres de rigidité et de résistance du modèle de sol est proposée et validée.

Keywords: Energy piles, Fully coupled thermo-hydro-mechanical analysis, Free Head Pile, Fully Fixed Head

1 INTRODUCTION

The increase of costs and the difficulties of supplying of oil and gas coupled with pollution problems have increased the interest in new technologies for renewable energy sources. In this field, the ground, that is characterized by a constant temperature starting from 5-10 m of depth, can be used, according to energy demand, as heat source or heat sink. Furthermore the ground is the only available renewable energy on the side of cooling actions. Geothermal energy can be exploited by thermo-active ground structures like piles, barrettes, diaphragm walls, basement slabs or walls, tunnel linings (Brandl 2006).

These structures are characterized by absorber pipes filled with a heat carrier fluid that are installed within conventional structural elements (Brandl 2006).

Among thermo-active ground structures, the paper is focused on energy foundations and in particular on so called energy piles. These elements have a double action: they act as deep foundations and as heat exchangers. This makes their design challenging and more complex with respect to conventional projects (Laloui et al. 2013). Energy piles design deals with different kind of problems linked to the interaction between soil and foundation and to the energy demand and thermal efficiency. Some studies deal on the effects of temperature on soil-pile interaction and others keeps the focus on the energy aspects and heat exchanging

To better understand the mechanisms of the response of a pile foundation under thermo-mechanical loads literature provides several small scale tests (Yavari et al., 2014) and field trials (Laloui et al. 2006, Bourne-Webb et al. 2009).

In this paper, results from the field test performed in London, by Bourne-Webb et al. (2009), are synthesised and used to validate thermo-hydro-mechanical analysis with the finite elements program PLAXIS 2D.

It has been found that the software is able to reproduce the main features of the experimental observed response even with very simple constitutive models.

With the aim of investigating the response of a virtual energy pile installed in the area of Naples, numerical simulations with the same FEM code PLAXIS 2D have been performed. The numerical model has been calibrated, considering a pile load test, through a trials and errors procedure. Rather simple but realistic daily thermal cycles have been simulated showing the coupling between thermal and mechanical effects. Different restrained conditions at the head of pile were considered: F*ree* H*ead* P*ile* (FHP) and F*ully* F*ixed* H*ead* P*ile*(FFHP).

2 THERMAL FIELD PILE TEST: LAMBETH COLLEGE (LONDON)

In order to validate the fully coupled thermo-hydro-mechanical module of FEM package PLAXIS 2D, the experimental data of Lambeth College pile test in London (Bourne-Webb et al.2009) are compared with numerical results. The thermal pile was installed as part of the foundation of a five-storey building in Clapham Common in South London. The testing carried out consists in cooling and heating cycles applied with a maintained live head load.

An extensive instrumentation set-up was employed to monitor the test pile behaviour throughout a period of 53 days. Vibrating wire strain gauges and optical fibre sensors were installed to obtain point measurements and continuous distributed temperature and strain profiles. The test pile was designed as a friction pile based on the working load of 1200 kN with an overall safety factor of 2.5 and without any restraint at the pile head. The test pile was 23 m long and had a diameter of 550 mm.

Two U-shaped heat exchanger pipes were attached to the reinforcement cage together with 18 vibrating-wire strain gages (VWSGs), 6 thermistor and optical fibre sensors (OFSs). Temperatures were also recorded in a borehole and anchor piles located respectively 0.5 and 2 m away from the pile. The vertical displacement of the pile head was measured by means of LVDTs. The mechanical load on the pile was controlled using a load cell and a hydraulic jacket, while the thermal load was applied by a heat pump. The range of applied fluid temperature, in cooling and heating cycles, fluctuated between -6°C and +40°C. Thermal and mechanical load time history is illustrated in Figure 1.

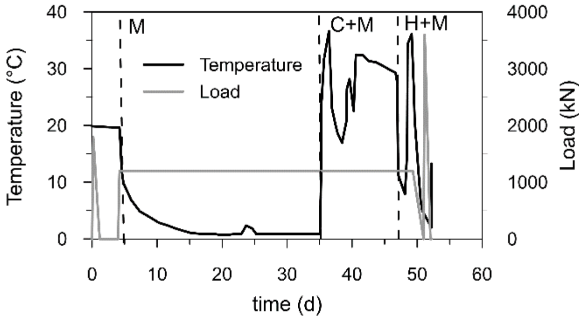

Figure 1. Pile load and temperature recorded in the Lambeth College test pile vs. time (d).

The thermal loading considered was the temperature recorded by the thermistors inside the test pile, which show a constant profile of temperature inside the pile with depth.

The test consisted of the following stages: (a) initial loading to 1800 kN, followed by unloading, (b) reloading to 1200 kN, (c) pile cooling with constant pile load, (d) pile heating with constant pile load, (e) final loading to 3600 kN. In Figure 1 three moments are outlined: the end of reloading stage (M) at constant temperature, the end of the cooling phase under constant load (C+M) and the end of heating phase (H+M).

In the original paper by Bourne-Webb et al. (2009) more details on the soil investigations may be found. Here it is only recalled that the ground is basically consisting of a thick layer of London Clay underlying a 4 m thick alluvial deposit. The groundwater table was found at 3 m below the ground level. The ground temperature measured at the site before the pile test was in the range 18°-20°C.

3 FEM BACK ANALYSIS OF LAMBETH COLLEGE TEST

Fully coupled thermo-mechanical axisymmetric analyses are reported in this paper to back-analyse the Lambeth College pile test. Figure 2 shows the finite element mesh and the thermal boundary conditions adopted for the analyses. Two different constitutive models were used: a simple L*inear* E*lastic* (LE) model and a linear elastic -plastic model with a M*ohr*-C*oulomb* failure surface (M-C).

The material properties are reported in table 1 and are the same adopted for the back-analyses performed by other authors (Gawecka et al. 2017, Adinolfi et al. 2018). The Young's modulus of alluvial deposit and of London clay are taken from Yavary et al. (2014). The pile stiffness EA is calculated on the basis of the back-calculated value of the Young's modulus E, equal to 40 GPa (Bourne-Webb et al., 2009), and, obviously of the transverse area A of the pile section.

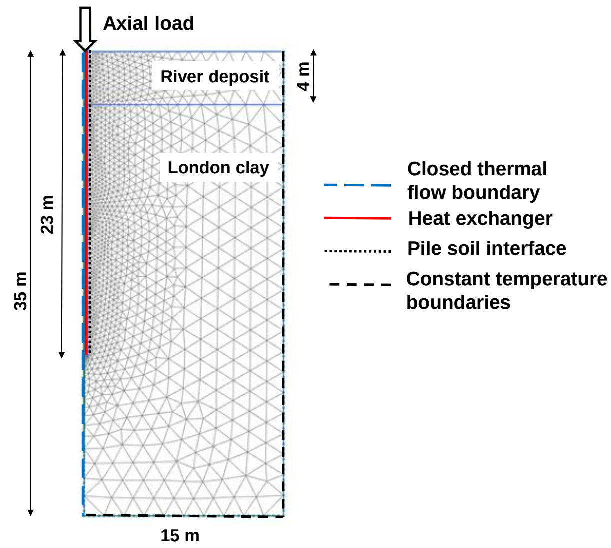

Figure 2. Finite element mesh used for the Lambeth College test.

The coefficient of thermal expansion of the concrete pile α equal to 8.5 x 10^{-6} is also the result of back analysis from the OFS data (Bourne-Webb et al. 2009). The initial temperature of 19.5 °C is assumed to be constant over the whole finite-element mesh.

The numerical analysis for the London case reproduce the same conditions occurred during the experiment. All the stages were simulated using a fully coupled-thermo-hydro-mechanical analysis. The pile temperature history was taken constant during the mechanical loading, unloading and reloading phases and equal to the thermistors records during the cooling-heating phases. In the FEM mesh the thermal boundary condition was applied at the location of the U-shaped pipes.

The results of the LE and M-C analyses are compared to measurements on site in terms of pile head vertical displacement throughout the test, Figure 3 a), and pile axial load, Figure 3 b). Figure 3 a) shows that there is a good agreement between the two analyses and the experimental results. Although the displacement of the pile head during the initial loading is over predicted in the two analyses, during the subsequent unloading phase the M-C analysis is able to better reproduce the measures, while the LE model still over predicts the displacement. On the contrary during the cooling phase the M-C model seems to overestimate the pile head settlement, while the LE model is able to accurately reproduce it. The subsequent heating phase is better reproduced by the M-C model. In both cases the displacements are over predicted in the heating phase and this is probably due to the fact that constant stiffness (i.e. not depending on the strain level) is a feature of both models.

Figure 3 b) shows the axial load profiles calculated with the two soil models together with field data measured by OFS and VWSG in the three significant moments defined in the previous section. The numerical data are in very good agreement with measurements. The difference between the LE and M-C results is due to the residual stresses locked in the pile after the unloading phase.

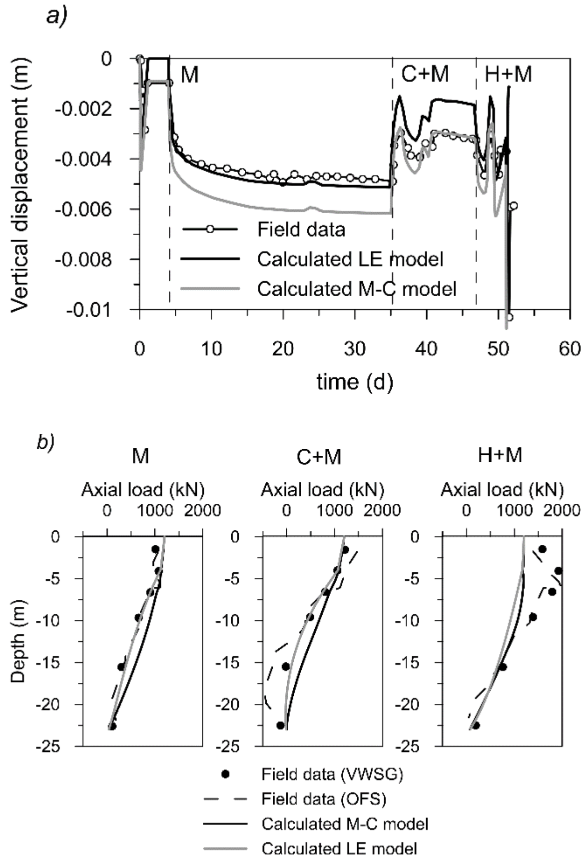

Figure 3. a) Pile head vertical displacement for the London case; b) axial load profiles

Table 1. Material parameters used for the back-analysis of the Lambeth College Test

	Pile	**River deposits**	**London clay**	**units**
Unit weight (γ)	20	19	19	[kN/m^3]
Young modulus (E)	40000	13	70	[MPa]
Thermal expansion coefficient (α_s)	8.5 x 10^{-6}	1.7 x 10^{-5}	1.7 x 10^{-5}	[m m^{-1} K^{-1}]
Thermal conductivity (λ_{eff})	2.33	1.40	1.79	[W m^{-1}K^{-1}]
Specific heat capacity (c_s)	960	950	910	[J kg^{-1} K^{-1}]
Permeability (k)	-	1 x 10^{-5}	1 x 10^{-9}	[m/s]
Cohesion (c')	-	1	5	[kPa]
Friction angle (ϕ')	-	35	25	[°]
Dilatancy angle (ψ')	-	17.5	12.5	[°]

4 MECHANICAL FIELD PILE TEST: AUCHAN SITE (NAPOLI)

The loading tests carried out in the framework of the design of the foundations of a new big trade centre are presented by Russo (2013).

Three CO*nventional* top-down static L*oad* T*ests* (COLTs) and two O*sterberg's* cell L*oad* T*ests* (OLTs) on the same pile type (CFA piles) in the same subsoil conditions were described. The five design tests were all carried out on piles, instrumented to measure axial strains along the shaft, slightly different in lengths and diameters and all socketed in the grey tuff bedrock (Russo & Marone 2018). The test site is located in the plain east of Napoli where the subsoil is composed by products of the Vesuvius and Phlegrean volcanoes. The groundwater table is located close to the ground surface. Made ground is first found with thickness ranging between 1 m and 3 m. A second layer with a total thickness ranging between 8 and 11 m consists of pyroclastic sandy soil. Finally, at a depth ranging between 10 and 12 m below the ground surface, the bedrock of volcanic grey tuff is encountered.

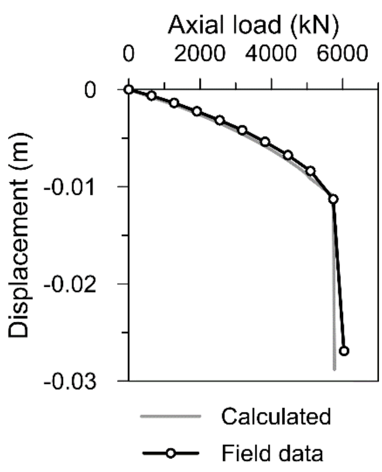

Figure 4. Auchan site: experimental results from in situ pile load test (Field data) and PLAXIS Modelled by FEM (Calculated).

The shear strength of the pyroclastic sandy layers, as derived from the CPTs and SPTs carried out in the test site, is fully reported by Russo (2013). The underlying layer of volcanic tuff represents a well-known formation in the area of Napoli and it is typically characterised by a Mohr-Coulomb envelope with an effective cohesion c'=400-800 kPa and a friction angle ϕ'=27°-28°.

From the results of the load tests, showed by Russo (2013), the shaft resistance was fully mobilised only for one pile. This occurred for the COLT performed on a CFA pile 13 m long and with a diameter of 0.6 m.

In figure 4 the experimental load-settlement curve (Field data) is plotted and compared with the calculated FEM one (Calculated).

5 FEM BACK ANALYSIS OF AUCHAN LOAD TEST

The FEM back analysis of the COLT was undertaken using PLAXIS 2D. The results of the load test and the site investigations available were used to calibrate the mechanical parameters of M-C model and of the H*ardening* S*oil* model (H-S). The trials and errors procedure allowed the determination of the constitutive models parameters (table 2) and the agreement between calculated and experimental curve is indeed satisfactory as shown by Figure 4.

The geotechnical model used in the numerical simulations consists of three different layers of pyroclastic sands until 10 m of depth and a layer of grey tuff from 10 m to 30 m (Figure 5). For the three layers of pyroclastic sands the H-S model was adopted, while, for the tuff layer and the pile, M-C constitutive model was used. The ground water level is 1 m below the ground surface.

The axisymmetrical FEM model is shown in Figure 5. In the H-S model the possibility to account for the stress level influence on the moduli, E_{50}, E_{oed} and E_{ur} ,was also used, while the ratio among the values of the three moduli were kept equal to the suggested value $E_{50}=E_{oed}=E_{ur}/3$ (Brinkgreve et al. 2010). At the contact between the pile and the surrounding soil the interface was included. M-C model was used for the interface considering a shear strength as deduced by the friction angle of the adjacent soil.

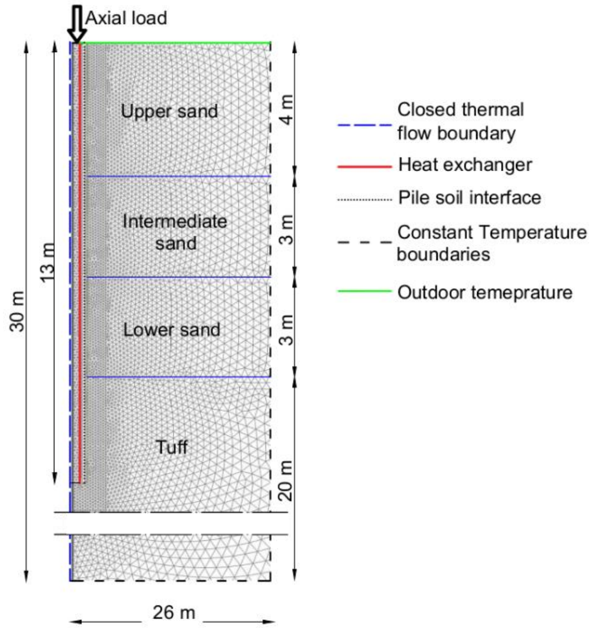

Figure 5. Finite element mesh used for the Auchan (Naples) simulations

5.1 Thermal analysis by FEM

Once the parameters of the M-C model and H-S model were successfully defined, fully coupled thermo-hydro-mechanical analyses, for the same pile and subsoil conditions, were carried out. In a first step a mechanical load equivalent to 40% of the pile bearing capacity was applied at the head of the pile. This load was kept constant while a “thermal load” was assigned to the pile in the form of a temperature variation applied along a cylindrical surface located in the typical place of the primary circuit in a real pile prototype. The temperature was applied uniformly along the pile length neglecting the minor variations which occur in real prototypes along the exchangers pipes. This assumption is considered acceptable because the difference between the inlet and the outlet temperature is usually less than 4°C (Rammal et al. 2018).

The temperature variations were defined considering a typical daily cycle in both cooling and heating mode for a GSHP. Crenel temperature variations were considered because they conservatively lead to higher displacement and axial forces (Rammal et al., 2018) if compared to more realistic temperature fluctuations.

The ground surface, corresponding to the top boundary of the model, was considered as exposed to external air temperature and two different outdoor sinusoidal temperature functions were assigned. For the cooling mode of the building, which occurs during summer, a typical daily outdoor temperature variation was applied at the ground surface. The same was done for the heating mode of the building, of course considering a typical daily outdoor temperature variation referred to winter season.

The model was submitted to a constant initial temperature of 17°C that corresponds to an average temperature as measured in the groundwater in the city area of Naples below 5 to 10 m.

The thermal boundary conditions and the applied temperature functions are shown respectively in Figure 5 and 6 a) and b). The thermal properties of the pyroclastic soil and of the concrete pile are summarised in Table 2.

The thermo-hydro-mechanical analyses were performed considering two different constraints at the head of the pile: F*ree* H*ead* P*ile* (FHP) and F*ully* F*ixed* H*ead* P*ile* (FFHP). The former condition can be representative of an isolated pile. The latter condition can be representative of a pile in a foundation system where the surrounding piles are not equipped with heat exchangers. For both options (i.e. head constraint) three cases are reported: Mechanical case, (M), in which only mechanical load at constant temperature was applied and two thermo-mechanical cases, (M+C) and (M+H), in which mechanical load was applied first followed by respectively a cooling cycle or a heating cycle.

For both M+C and M+H cases axial forces with depth are plotted in figure 6c. The plots refer to the calculated values at 0,6d (cooling and heating) and 1 d (end of cooling and end of heating) for both operation modes.

In the FHP case, heating and cooling phases lead, respectively, to an increase or a decrease of the compression axial force starting from the initial value due to the mechanical load (M). At the end of heating and cooling a significant recover of the axial force distribution occurs and it is almost coincident with the purely mechanical case, apart from a small amount of residual force near to the pile tip.

For the FFHP, heating produces a strong increase of the compression force doubling the value produced by the mechanical load. The reverse occurs, obviously, for the cooling analysis hence producing a reduction of the axial force. For the FFHP neither the heating nor the cooling show reversible behaviour. The amount of irreversible forces is larger in the cooling case than in the heating case and should be taken into account at the design stage.

The amount of residual forces could be of course increased by repeated daily cycles which is a more realistic way to function of Ground Source Heat Pump System.

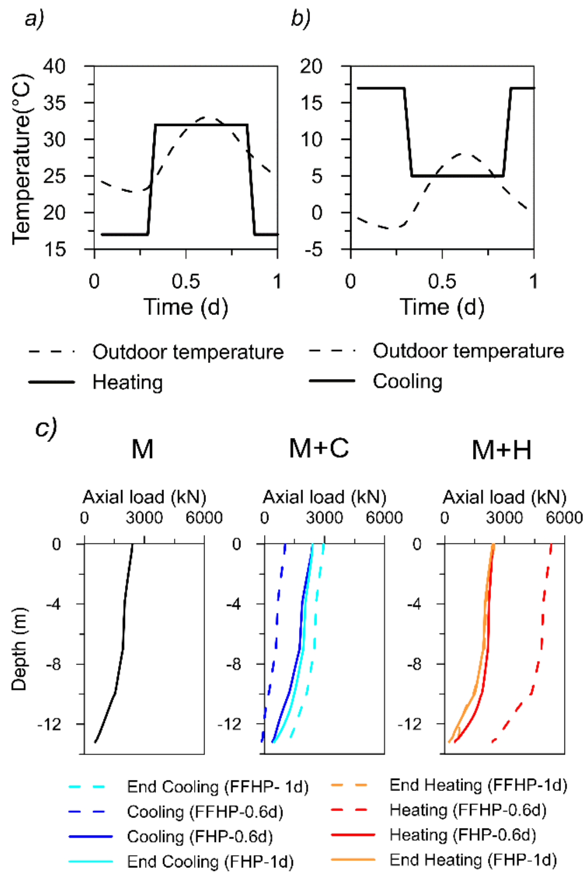

Figure 6. Auchan site: a) Heating mode; b) Cooling mode: outdoor temperature and assigned temperature; c) Axial force along the pile depth

Table 2. Material parameters used for the-analysis of the Auchan site

	Pile	**Upper sand**	**Intermediate sand**	**Lower sand**	**Tuff**	**units**
Unit weight (γ)	24	19	18	19	17	[kN/m^3]
Young modulus (E_{50})	30000	31.85	9.10	53.30	5000	[MPa]
Young modulus (E_{ur})	-	95.55	27.30	159.90	-	[MPa]
Thermal exp. coefficient (α_s)	1.2x 10^{-5}	4x 10^{-5}	4x 10^{-5}	4x 10^{-5}	4x 10^{-5}	[m m^{-1} K^{-1}]
Thermal conductivity (λ_{eff})	2.4	2.4	2.4	2.4	1.4	[W m^{-1}K^{-1}]
Specific heat capacity (c_s)	100	1000	1000	1000	1300	[J kg^{-1} K^{-1}]
Permeability (k)	-	1 x 10^{-5}		1 x 10^{-5}		[m/s]
Cohesion (c')	-	10	-	-	100	[kPa]
Friction angle (ϕ') [°]	-	37	32	37	28	[°]
Dilatancy angle (ψ') [°]	-	7	2	7	-	[°]

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6 CONCLUSIONS

The paper has analysed, via FEM and with three different constitutive models, field tests on 2 cases of thermo-mechanically loaded piles. In the first case at Lambeth College LE and M-C models have been adopted showing an overall sufficient agreement with the observed behaviour. The major differences between computed and observed results refer to axial force distribution with depth during heating phase while under purely mechanical load and cooling mode the agreement is very satisfactory. For the second case at Auchan site both FHP and FFHP have been analysed using M-C and H-S soil models. It should be kept in mind that a real pile in a foundation system is somewhat intermediate between the two above mentioned conditions. At the design stage different aspects must be considered. If the structural issues are the focus, the amount of axial forces developed along the pile could be evaluated, avoiding an excess of conservatism, with a degree of constraint intermediate between FHP and FFHP. This evaluation should take into account at least the stiffness of the foundation system and the geometrical arrangement of the energy piles. When dealing with a real foundation system of course also the boundary condition at the ground surface should be carefully evaluated, the outdoor temperature being not necessarily an accurate assumption.

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