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Towards a design approach of bearing capacity of thermo-active piles

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ABSTRACT

Thermo-active piles are subjected to thermo-mechanical loads that differ from conventional loads. This paper proposes a modelling method to design the thermo-active piles based on a conventional approach for the calculation of deep foundations. Numerical modelling of a single thermo-active pile is conducted to analyse its behaviour under combined mechanical load and additional thermal contraction or dilatation. The results are presented in terms of displacement of the pile head, normal forces in the pile sections and variations of shaft friction. The analysis of the numerical results obtained permits to outline some design rules for the thermo-active foundations that could be included in the design standards.

1. INTRODUCTION

In order to reduce the consumption of fossil energy sources and the energy bill, thermo-active piles are a very interesting technology for heating and cooling buildings. By integrating heat exchanger elements into deep foundations, these piles offer an advantage of minimising drilling cost in comparison with vertical geothermal probes. This technology has been used for almost 25 years in Austria and in other countries such as Switzerland, Germany or England: Main Tower in Frankfurt-Germany on 1999 (Quick et al. 2005), Keble College in Oxford-UK on 2001 (Kefford et al., 2010), Dock Midfield Zurich Terminal Airport-Switzerland on 2003 (Pahud et al., 2007), and Lainzer Tunnel Vienna-Austria on 2004 (Adam et al., 2009).

Compared to the classical deep foundations, the heat exchanger fluid circulating in thermo-active piles induces temperature variations in the pile and thus generates contraction and dilation. Up to this moment,there is no precise design method yet to justify the geotechnical resistane of the thermo-active piles. For years, contractors have been constructing the buildings with the thermo-active piles based on an empirical consideration or on a conservative design by increasing the safety factor of the piles (Boënnec, 2009, Knellwolf et al., 2011,).

This paper presents a methodology of thermo-active pile design according to Eurocode 7. The first part of the paper describes the pile behaviour and explains how temperature variations can be easily taken into account into the design according to the hydraulic flow and the heat transfers in the ground. In the second part, different calculations are conducted to observe the effects of temperature variations in thermo-active piles: normal force, axial pile displacement, mobilised shaft friction and base resistance.

2. DESIGN OF CONVENTIONAL PILE FOUNDATIONS

2.1. General principles

When a pile is subjected to an increasing axial load, a settlement of the pile head can be observed. When the value of the pile displacement reaches 10 % of its diameter, the ultimate pile bearing resistance R_c is conventionally defined. Instrumentation of the pile shaft with extensometers or strain gauges permits to estimate the ultimate base resistance R_b and the ultimate shaft resistance R_s, with $R_c = R_b + R_s$.

The conventional method to design a pile consists in limiting the service load V applied on the pile to a part of its total bearing capacity: $V < R_c / \gamma_R$ where γ_R is a partial factor greater than 1.0. The value of this partial factor depends on the combinations considered: either the serviceability limit service (SLS) or the ultimate limit service (ULS). It depends on the model calculation used to estimate the total bearing capacity. According to Eurocode 7, each country in Europe can choose the value which seems more relevant. Other criteria such as the axial pile displacement w and the normal force N in the pile have to be verified.

2.2 Load transfer method

The verification can be done by modelling the soil-pile interaction by the load transfer method. This method is performed by solving the following equation:

$$E_y A \frac{d^2 w}{dz^2} + f_{pile-soil}(z,w)w = 0 \quad [1]$$

where E_y is the Young's modulus of the pile, A is the pile area, w 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 integration along the pile length of the mobilised shaft friction and the mobilised base resistance provides the mobilised shaft resistance $R_{s;m}$ and the mobilised base resistance $R_{b;m}$. Calculations of the ratios $R_s/R_{s;m}$, $R_b/R_{b;m}$ and $R_c/(R_{s;m} + R_{b;m})$ give the values of safety factor noted F_s, F_b and F_c, respectively. These values can be compared to the inverse of the partial factor γ_R according to the ultimate state considered.

In France, the *t-z* curves may be defined according the standard NF P 94-262 devoted to the design of deep foundations which is compatible to Eurocode 7. The curves currently used for the base resistance and shaft friction are shown in Figures 1 and 2 (Frank and Zhao, 1982). These curves are resulted from full scale in-situ loading tests and can be defined by the Menard pressuremeter tests:

- the initial tangent slope of the t-z curve is a function of the Menard pressuremeter modulus E_M, the types of soil and the types of pile. Values of initial tangent slope K_p for the base and K_t for the shaft friction are given for bored piles in Table 1.

- the value of the ultimate shaft friction q_s or the ultimate base resistance q_b is a function of the Menard pressuremeter limit pressure p_{LM}*. Note that the base resistance can be less than zero and could be neglected if the displacement at the pile base is not greater than zero.

Various models of t-z curve also exist, for example the curves with a continuous non-linear model (Hirayama 1990, Monnet 2000).

2.3. Temperature variation effects on the pile

In the case of thermo-active piles, it is necessary to take into account the temperature variations that induce dilations or contractions of the pile. Figure 3 shows the two types of the expected during heating or cooling phase. The pile tries to dilate or contract, which induces an increase or a decrease of the pile length. According to the principles of the load transfer method in Equation [1], the variation of the pile length may significantly affect the mobilization of the shaft friction and the base resistance, and thus conduct to a variation of the normal stress in the pile. Thermo-active pile design requires therefore a study of three major questions. The first question deals with the pile displacements induced by contractions and dilations related to the movements at the base of the buildings supported by the thermo-active piles. The second question concerns the normal stress variations in the piles induced by the constrained dilations and contractions. The third question is related to the evolution of the base resistance of the piles and mobilised shaft fiction at the soil-pile interfaces.

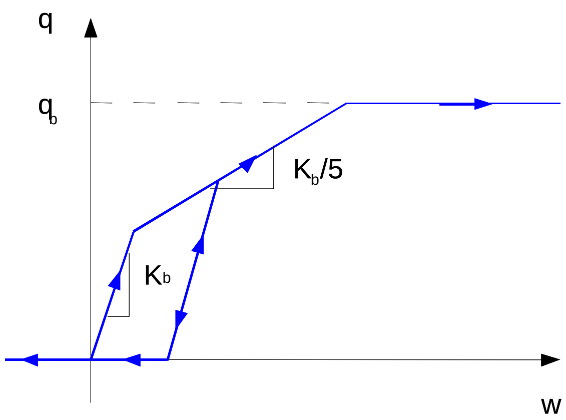

Figure 1: mobilization of base resistance

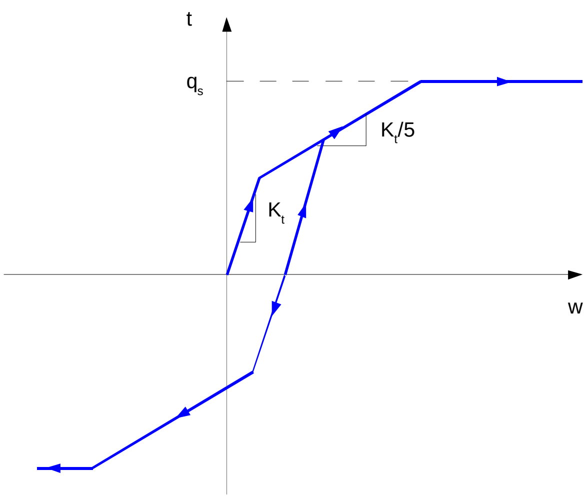

Figure 2: mobilization of shaft resistance

Table 1: Values of modulus K_p and K_t

	Symbol	Cohesive soils	Granular soils
Base resistance	K_b	11 E_M/B	4,8 E_M/B
Shaft friction	K_t	2 E_M/B	0,8 E_M/B

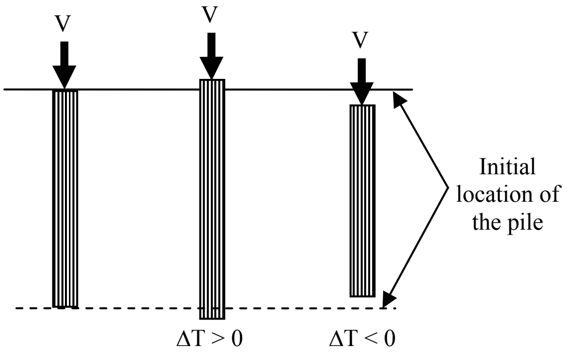

Figure 3: thermo-active pile submitted to heating (ΔT > 0) or cooling (ΔT < 0)

3. MODELLING THERMOACTIVE PILES

3.1. General principles

Thermo-active pile behaviour can be modelled by means of load transfer approach. The calculation principle is based on the decomposition of the total deformation ε into an elastic part ε^e and a thermal part ε^{th}, as stated in Equation [2].

$$\varepsilon = \varepsilon^e + \varepsilon^{th} \qquad [2]$$

The pile is supposed to behave elastically. The thermal part of the deformation ε^{th} will be introduced assuming the evolution of temperature ΔT is homogeneous in the pile with a thermo-elastic behaviour, as shown in Equation [2]

$$\varepsilon^{th} = \alpha_T \Delta T \qquad [3]$$

where α_T is the coefficient of thermal expansion of concrete or steel. In the case of concrete, it is equal to $1.2\ 10^{-5}$ °C^{-1}. These hypotheses are validated by bi-function pile loading test (Bourne-Webb et al., 2009).

By the mechanical equilibrium of the pile, as given in equation [1], the vertical displacement w depending on the depth z is then obtained as the solution of the differential equation.

Several comments must be made to the definition of the thermal deformation ε^{th}. Only the pile undergo a temperature variation and the temperature of the ground is assumed to remain constant, considering that the hydraulic flow is sufficiently strong to diffuse the heat. Moreover, as the range of temperature commonly used are between 0° and 40°C, the thermal effects on the mechanical properties of the soils might be neglected (Laloui 2003, Laloui, 2011). Previous studies on that topic showed that the mechanical properties are rather constant in these ranges of temperature. Only the pre-consolidation pressure seems to slightly decrease when fine soils are heated. Cyclic effects induced by dilation or contraction are neglected if the mobilised resistance is less than the limit value defined by the standard. In France, the limit value concerns only the total bearing resistance of the pile. This assumption is commonly used for the calculation of axial pile displacement.

3.2. Head limit conditions

Three different types of pile head condition are considered. The first two conditions (i) free head pile (zero head axial stiffness) (ii) restrained head pile (infinite head axial stiffness) correspond to the extreme cases but allow us to understand the main behaviours of the thermo-active piles.

In general, the stiffness at the pile head k_h is complex to estimate. It depends on the geometric configuration of the building, on the slab stiffness and on the interaction factor with other piles in a group of foundations. Therefore, different values of stiffness at the head of thermo-active piles have to be taken into account. They can be modelled by a linear spring with a stiffness k_h.

3.3. Examples

The example considered corresponds to a single thermo-active pile with a square section B = 60 cm and a length H = 15 m. The pile is founded on a soil mass composed by 12 meters of fine soil and 3 m of granular soil. The loading is systematically performed in two stages: (i) the initial stage with a mechanical loading and (ii) the second stage with a thermal loading. The mechanical load applied on the pile is equal to 50% of the ultimate bearing capacity of the pile. This value corresponds more or less to the maximal load allowed by the French design standards for deep foundations. During the thermal loading stage, a homogeneous temperature variation is imposed, varying between –12°C and +15°C.

Following these assumptions, the evolution of normal force N, vertical displacement w and mobilised shaft friction q_s can be calculated for both free head pile and restrained head pile, given in Figures 3 and 4.

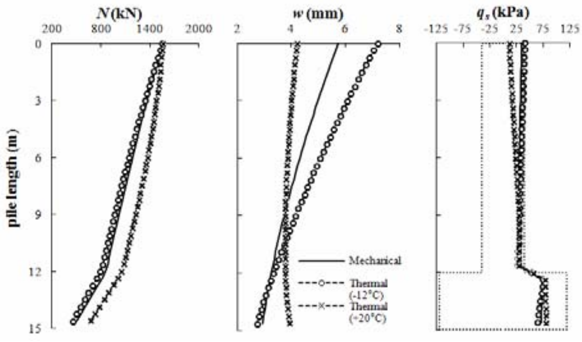

Figure 3: Free head pile.

For a free head pile, the cooling pile in winter induces a reduction in normal forces over the entire pile length and an additional settlement of the pile head. In some cases, it can lead to tensile stress. Due to the pile contraction, shaft frictions increase in the upper part of the pile and decrease in the lower part of the pile. The heating pile in summer leads to an uplift displacement of the pile head and an increase in normal forces in the pile sections. Due to pile dilation, shaft frictions decrease in the upper part of the pile and increase in the lower part of the pile.

For a restrained head pile, the heating phase induces an additional load at the pile head and an increase in normal forces and shaft friction. Due to the pile dilation, the base resistance increases. The cooling phase leads to a global reduction in normal forces and shaft friction. Due to the pile contraction, the base resistance decreases.

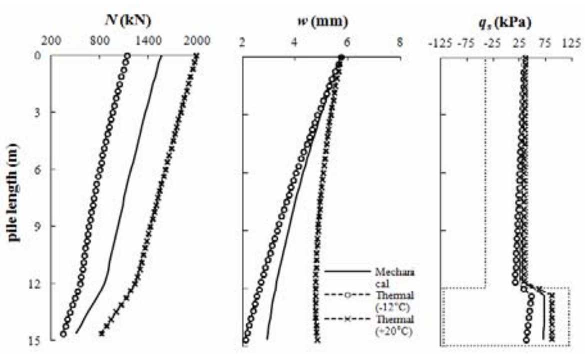

Figure 4: Restrained head pile.

Finally, for these two cases (free head pile and restrained head pile) and for others with various stiffness values at the pile head, it is interesting to present the variations in the ratio of the mobilised resistance to the ultimate resistance induced by temperature variations for both the pile base resistance $R_{b;m}/R_b$ and for the pile shaft resistance $R_{s;m}/R_s$ (Figure 5). During heating, the base resistance mobilised systematically increases. The shaft resistance may increase or decrease according to the stiffness at the pile head. During cooling, the base resistance mobilised systematically decreases. As previously, the shaft resistance may increase or decrease according to the stiffness at the pile head. This type of analysis is very useful to control the pile dimensioning if the mobilised base resistance and shaft resistances are not too important according to the design standard for deep foundations.

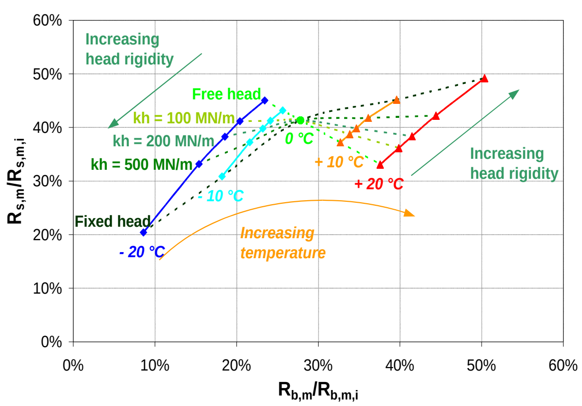

Figure 5: Ratios $R_{b,m}/R_{b,m,i}$ and $R_{s,m}/R_{s,m,i}$ for different temperatures and head conditions

4. CHARTS FOR THERMO-ACTIVE PILE DESIGN

The previous example shows that the thermo-active pile design should take into account axial pile displacements, variations of normal force and mobilised pile-soil resistance. In order to analyse these different elements in the design of thermo-active pile, authors have made some design charts that taking into account various values of stiffness at the pile head and several conditions of heating and cooling in Figures 6 to 9. The horizontal and the vertical axes correspond to a free head pile and a restrained head pile condition, respectively.

From the previous example, Figure 6 presents the overall behaviour of a thermo-active pile in terms of axial displacement w_h and axial force N_h at the pile head. From this chart, it is possible to analyse the thermo-active pile behaviour by considering different assumptions of stiffness at the pile head and of temperature variations.

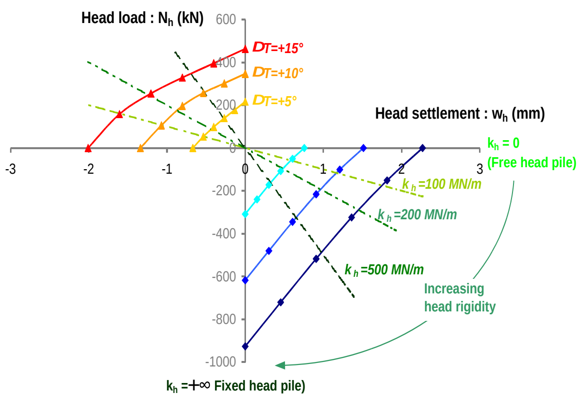

Figure 6: Design chart for a thermo-active pile

Figures 7 to 9 show the variations in mobilised resistances during heating or cooling for the total resistance, the base resistance and also the shaft resistance of the pile. The results are presented in terms of ratios of the thermally induced mobilised resistance due to temperature variation ($R_{c;m}$ for the total resistance, $R_{b;m}$ for the base resistance and $R_{s;m}$ for the shaft resistance) to the initial mobilised resistance at the mechanical loading stage ($R_{c;m;i}$ for the total resistance, $R_{b,m;i}$ for the base resistance and $R_{s;m;i}$ for the shaft resistance).

From the previous example, the total resistance mobilised remains constant for the free head pile condition but increases with the stiffness at the pile head (Figure 7). This increase can reach 50 % during heating for the restrained head condition. In contrast, the total mobilised resistance gets lower during cooling for the restrained head condition.

Figure 8 shows the variations in the base mobilised resistance. It increases with the temperature and with the stiffness at the pile head. These variations are more important for the restrained head condition.

Figure 9 depicts the variations in the shaft resistance. During heating, it increases with the stiffness at the pile head while decreases during cooling. For the pile with a medium value of stiffness, the shaft mobilised resistance remains constant due to the opposite variations in shaft friction over the upper-half part and lower-half part of the pile.

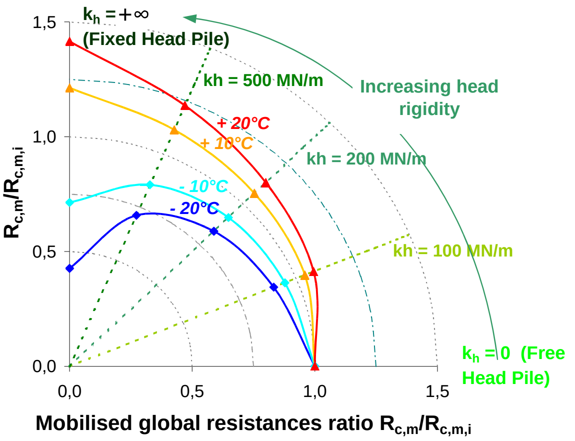

Figure 7: Mobilised global resistances

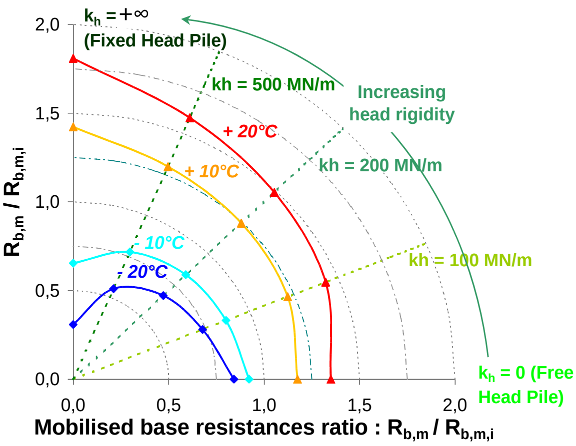

Figure 8: Mobilised base resistances

5. STANDARD ELEMENTS FOR THERMO-ACTIVE PILE DESIGN

Currently, the standards used to calculate the conventional deep foundations do not take into account thermal loading and do not permit to rationally design the thermo-active piles. From the different results obtained in the preceding section, it seems possible to define a design methodology based on four components : the definition of the temperature variation, the displacements of the pile head, the resistance of the pile and the resistance of the soil.

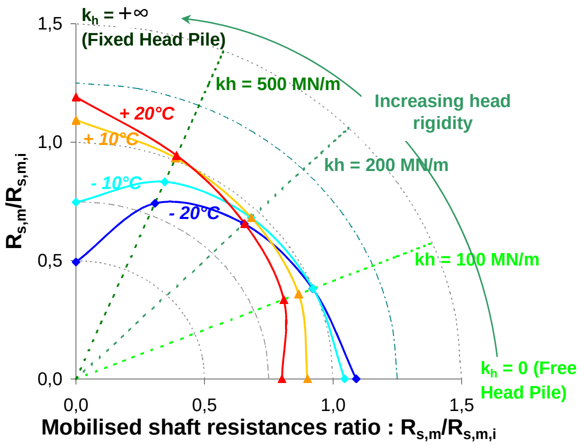

Figure 9: Mobilised shaft friction resistances

5.1. Definition of thermal actions

It is necessary to define thermal actions in comparison with common actions on structures (e.g. self-weight of structures, overload, wind, etc.), either as permanent or transient loads. One can take for granted that the thermal loading is such variable actions, from which characteristic value is commonly noted Q_k.

Partial factors has to be determined to define the accompanying value of the thermal loading, noted $\psi_i Q_k$, as defined for structure design in EN 1990. This step means to determine a combination value $\psi_0 Q_k$ for ULS, a frequent value $\psi_1 Q_k$ and a quasi-permanent value $\psi_2 Q_k$ for SLS, in respect to Equation [4].

$$\psi_i \leq 1 \quad [4]$$

Based on the temperatures monitored in thermo-active piles during the operational time, authors propose the following values for factors ψ_i: $\psi_0 = 0.6$, $\psi_1 = 0.5$ and $\psi_2 = 0.2$.

5.2. Displacements of the upper structure

The obtained displacements have to be compared to the maximum acceptable total displacements. The analysis shall also show that the differential displacements and relative rotations are inferior to the limit values. EN 1997-1 presents some guidelines for these values, depending on the upper-structure type.

It is also useful to compare the differential displacements to those of the classic piles without additional thermal loads. Hence, one can note that for almost structure built on deep foundations, the differential settlements obtained are in the range of few millimetres due to differences in terms of pile diameter, pile length and mechanical load applied on piles.

Several calculations performed on different projects show that displacements induced by thermal loading are inferior to prescribed acceptable values.

5.3. Pile resistance

For concrete piles, the rules and common safety levels used for the classic piles appear pertinent. In particular, apparition of tensile zones during cooling should be avoided according to the French design standard. The deformation modulus of concrete must also be fixed. Based on the observed time operation of the thermal loadings, authors propose to use the middle term deformation modulus, which can be approximate to 20000 MPa.

5.4. Soil resistance

The last step consists in verifying that the limit state is not exceeded in the ground around the pile, which is rather complex, because the mobilised shaft and base resistances are altered cyclically during the thermal loading. However, with the modelling method previously described, it is possible to obtain the mobilised resistance at pile shaft and at pile base. As the total resistance may remain constant in the case of free head pile, the authors propose to calculate distinctly the shaft resistance and base resistance, then to fix specific limits for both of these terms in order to limit their amplitudes of variation.

7. CONCLUSIONS

Thermo-active piles are subjected to thermo-mechanical loads that differ from conventional loads. Modelling methods proposed in this paper allow to estimate the displacements, axial normal forces and mobilised resistance induced by temperature variations in the thermo-active piles. The understanding of the observed phenomena permits to outline some design rules for thermo-active foundations that could be included in standards.

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