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# Synthetic charts for the thermo-mechanical behaviour of thermoactive piles

## Abaques synthétiques pour le comportement thermo-mécanique des pieux thermoactifs

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**ABSTRACT:** Thermoactive piles constitute innovative technical solution for heating and cooling of buildings. From a mechanical point of view, volumetric strains caused by thermal loading lead to additional displacements and internal forces. Different approaches are henceforth available to predict the behaviour of such structures. However, some questions still stand for complementary issues, such as i) the influence of the stiffness of the supported structure, ii) the consequences of volumetric strains in the surrounding ground and the transient effects linked to the real sequence of thermal loading and iii) the evolution of the behaviour after several operating cycles.

Based on different numerical approaches, synthetic charts for one given configuration are elaborated, to take into account some of the previous phenomena, presenting additional displacements, the maximal variation of normal force and the mobilised geotechnical (base and shaft) resistance.

**RÉSUMÉ:** Les pieux thermoactifs constituent désormais des solutions techniques innovantes pour le chauffage que la climatisation des bâtiments. Du point de vue mécanique, les déformations volumiques engendrées par le chargement thermique induisent des déplacements et des efforts parasites. Des méthodes d'analyse sont désormais reconnues pour apprécier le comportement de ces ouvrages. Néanmoins, des interrogations subsistent vis-à-vis de problématiques mécaniques additionnelles, comme i) la prise en compte de la rigidité de la structure en tête de pieu, ii) l'effet des déformations volumiques des terrains environnant les pieux et des effets transitoires associés au chargement thermique réellement appliqué ainsi que iii) l'évolution du comportement après plusieurs saisons de fonctionnement.

Dans un premier temps, sur la base de différentes approches numériques, des abaques synthétiques valables pour un pieu donné sont proposés afin de tenir compte de la plupart des phénomènes précédemment étudiés, en présentant les déplacements additionnels, la variation maximale de l'effort normal et la mobilisation de la résistance verticale.

**Keywords:** Thermoactive piles, design charts

# 1 INTRODUCTION

Thermoactive geostructures, and especially thermoactive piles, constitute a challenging and promising solution to produce heating and cooling. However, their practical and systematic implementation is confronted to technical and administrative locks. Part of these locks are linked both to the innovative aspect of this technique, and the lack of long-term feedback, both from thermal and mechanical points of view. They are also linked to the variety of phenomena that have to be taken into account when dealing with the mechanical behaviour of these specific piles, the differences approaches available, and the lack of consensual recommendations for their structural and geotechnical design.

Based on different numerical approaches, this paper proposes some synthetic charts for one given configuration, to take into account some of the previous phenomena, presenting additional displacements, the maximal variation of normal force and the mobilised geotechnical (base and shaft) resistance of a thermoactive pile.

# 2 STRUCTURAL AND GEOTECHNICAL ISSUES

## *2.1* Mechanical issues to address

Globally, three main parameters caused by additional thermal loading are studied:

- Variation of axial displacement at the head of the pile $w_h$,
- Variation of normal force $\Delta N$ under thermal loading along the pile (and associated axial stress),
- Variation of the mobilised geotechnical resistance (bearing capacity).

## *2.2* Available approaches

Different authors have proposed a progressive set of approaches to deal with thermoactive piles.

A first simplified approach considers piles as a beam, either fully free or restrained at its two extremities. Although quite rough, it provides an envelope of the expected displacement and variation of normal load.

Progressively, additional approaches may be implemented to take into account soil –structure interaction. However, they require more complex and higher level of ground characterization and modelling tools, which may include:

- The global modelling of the overall overburden structure, taking into account any conventional (not thermoactive) and thermoactive piles (Burlon and al., 2013),
- Thermal strains in the surrounding ground (Bourne-Webb and Freitas, 2016), and actual or predicted time-sequences of temperatures, influence the behaviour of thermoactive piles,
- The behaviour after several subsequent cycles (Rammal, 2017),
- Additional issues, such as group effects or any accidental defects of some thermoactive piles.

### *2.3* Typical behaviour of a single pile

The typical behaviour of a single thermoactive pile is given in Figure 1

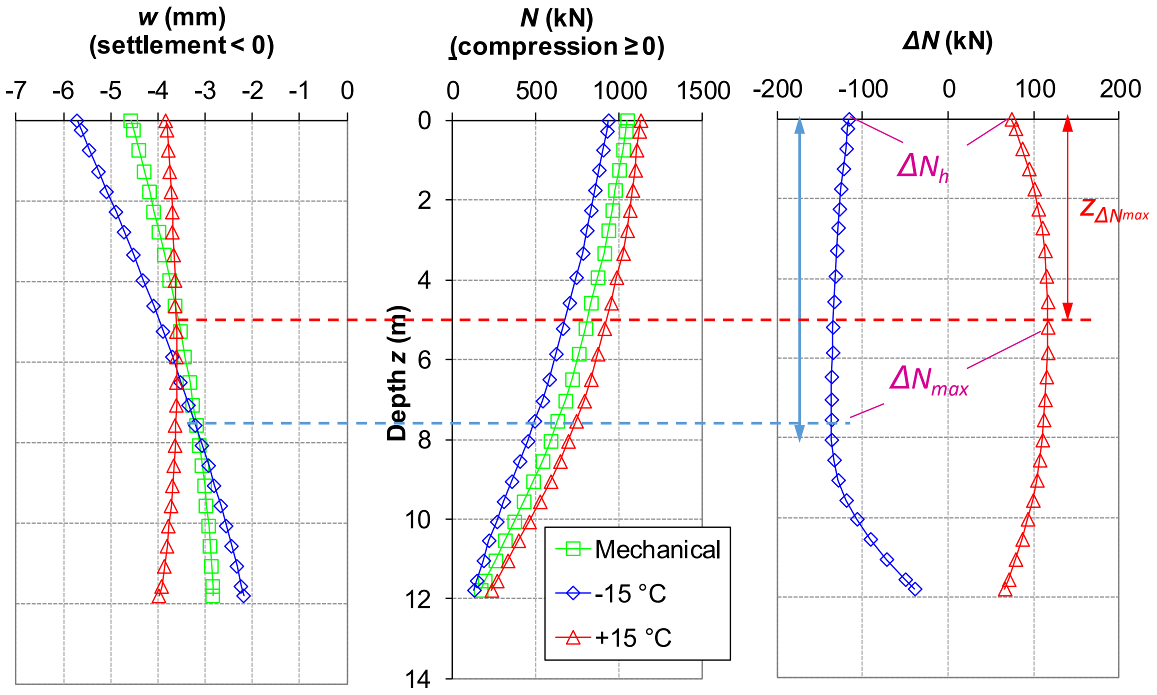

*Figure 1: Typical behaviour of a thermoactive pile*

Hence, the parameters listed previously (§2.1) are completed by the following:

- The variation of normal force $\Delta N_h$ at the head of the pile (also equal to the variation of the mobilised geotechnical resistance), and $\Delta N_{max}$ its maximal absolute variation,
- The maximal variation of the normal load takes place at a specific depth, $z_{\Delta Nmax}$.

## 3 SIMPLIFIED DESIGN CHARTS

In a first part, simplified design charts for a single pile are established, to take into account i) the head rigidity and ii) the volumetric strains in the surrounding ground.

## *3.1* Hypothesis

### *3.1.1* Ground and pile properties

The pile is coming from a full-scale experimental project in Dunkirk (Szymkiewicz and al, 2015). The ground model is given in Table 1, where $z_{base}$ is the base of each layer, $E_M$ the Menard pressuremeter modulus, $q_s$ the unit shaft friction and $q_b$ the ultimate stress under the base of the pile.

*Table 1. Ground model*

| Layer | $z_{base}$ (m) | $E_M$ (MPa) | $q_s$ (kPa) | $q_b$ (kPa) |
|---|---|---|---|---|
| **Silt** | 2.7 | 4 | 30 | - |
| **Sand** | 3.8 | 8 | 70 | - |
|  | 2.0 | 17 | 100 | - |
|  | 3.5 | 30 | 110 | 4620 |

A static axial compression test (MLT - maintained loads test, with constant duration of load increments of 60 minutes) has also been performed on these piles (Figure 2).

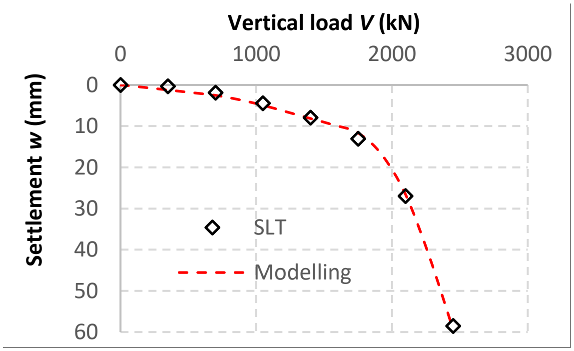

*Figure 2 : Static load test and modelling results*

### *3.1.2* Modelling approach

The pile is modelled through a load transfer approach (Laloui and al., 2006), using commonly accepted transfer curves (Frank and Zhao, 1982). The comparison to the static compression test load results (Figure 2) enables to assess the calibration of the parameters.

### *3.1.3* Thermal loading

The pile temperature variation is assumed to be homogeneous. For the ground, temperature around the pile is time and space dependent. However, in this paper, a homogenous single value of the temperature is chosen, as it has been shown that this choice may cover transient effects (Rammal and al, 2017).

### *3.1.4* Addressed parameters

Parameters presented in § 2.1 and 2.3 are studied. For sake of clarity, normalised parameters are used, according to the following notations:

- Normalised variation of axial displacement at the head of the pile $w_h/(\alpha \Delta T)_p L$,
- Normalised variation of normal force at the pile head $\Delta N_h/(\alpha \Delta T)_p ES$,
- Normalised maximal absolute variation $\Delta N_h/(\alpha \Delta T)_p ES$,
- Normalised depth of the maximal absolute variation of the normal force $z_{\Delta N max}/L$.

Normal variation of normalised axial displacement at the head of the pile and of normal force are equal to 1 if the simplified approach was used (§2.2). Using normalised parameters enables to clearly quantify the optimisation brought by a performing a soil-structure interaction.

## *3.2 Elaboration of synthetic design charts*

### *3.2.1 Charts procedure*

A complete design chart is established to overview the effect of the head rigidity and the thermal variations on the behaviour of thermoactive piles.

This chart is obtained in two separate steps:

1. In a first step, temperature variation is only considered in the pile,
2. In a second step, effects of thermal volumetric variations in the ground are also considered.
    - When cooled, ground materials contract. A single condition is then added, considering $(\alpha\Delta T)_g$ (in the ground) equal to $(\alpha\Delta T)_p/2$ (in the pile).
    - When heated, standard ground materials will expand. However, normally consolidated or slightly overconsolidated clayey soils can suffer a reduction of preconsolidation ratio and subsequently contract (Cekerevac and Laloui, 2003). Consequently, two specific conditions will be added for heating conditions, $(\alpha\Delta T)_g = (\alpha\Delta T)_p/2$ (ground with a standard thermoelastic behaviour) and $(\alpha\Delta T)_g = -(\alpha\Delta T)_p/2$ (clayey soil contracting when heating).

The Figure 3 show the synthetic design chart hence obtained.

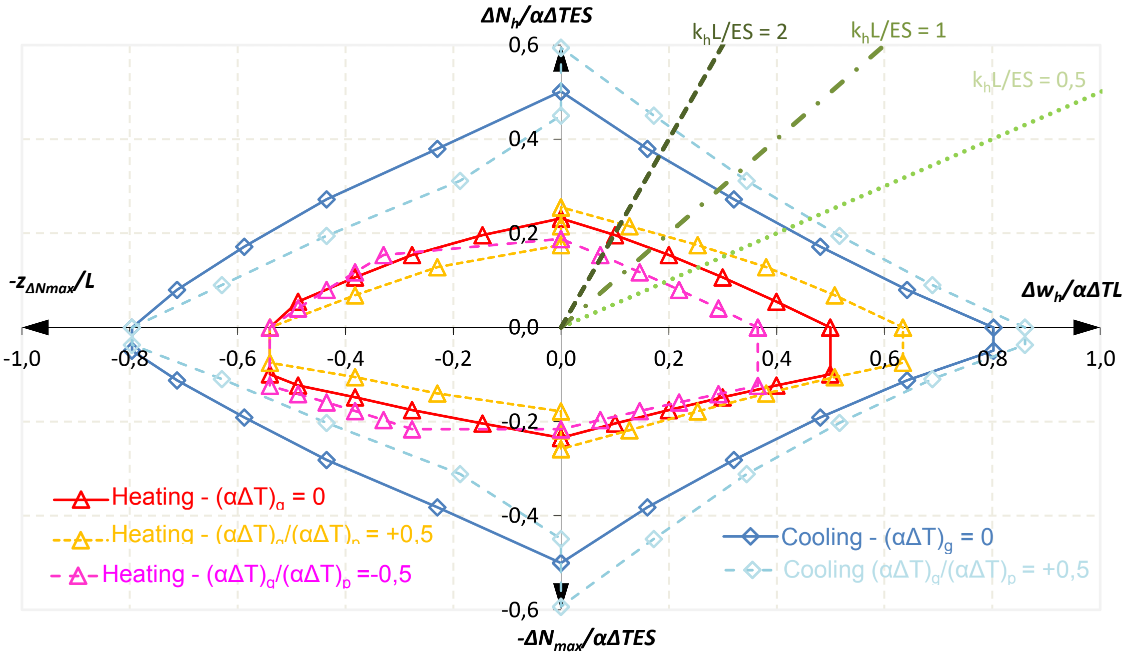

*Figure 3: Synthetic design charts of a thermoactive pile*

# 4 ANALYSIS

### *4.1.1 First step*

If pile thermal variation is only considered, one may notice two main phenomena:

- Two distinct behaviours take place for heating and cooling, due to the irreversible used load transfer curves,
- At the same time, for a given thermal "direction" (heating or cooling), the normalisation by $\Delta T$ enables to obtain one single curve. This is due to the use of Frank and Zhao transfer curves and the small amplitude of displacements. Using smooth t-z curves (Burlon and al., 2016) might lead to significantly different results.

For a given pile and ground conditions, once the normalised rigidity is known, this first chart may be used to derive thermal head displacement and normal load, and then determine maximal variation of normal force and its position.

### *4.1.2 Second step*

Taking into account ground volumetric strain shows the following different phenomena:

a) For conventional ground (not affected by any other phenomena other than contraction when temperature decreases and expansion when temperature increases), taking into account variation of temperature in the ground leads:
  - to higher displacements under thermal loading,
  - globally to higher variation of head normal force and maximal variation of normal force, as soon as head rigidity appears significant (see below).

b) For non-conventional ground (especially normally consolidated or slight overconsolidated clayey soils), taking into account variation of temperature leads to opposite effects.

It appears essential to catch the detrimental effect of ground temperature variation on normal load with head rigidity. The ratio of normalised maximal variation of normal force obtained with temperature variation only in the pile ($(\alpha\Delta T)_g = 0$) and both in the pile and the surrounding ground (here $(\alpha\Delta T)_g = (\alpha\Delta T)_p/2$) is plotted in Figure 4, for cooling condition, for different values of the head rigidity $k_h$. It leads to the following remarks:

- for low values of head rigidity (here $k_hL/ES \leq 0{,}25$), and especially for free head piles, taking into account thermo-volumetric ground variations leads indeed to lower value of variation of normal force;
- for higher values of head rigidity ($k_hL/ES >$ 0,25 for this particular case), on the contrary, it will lead to higher value.

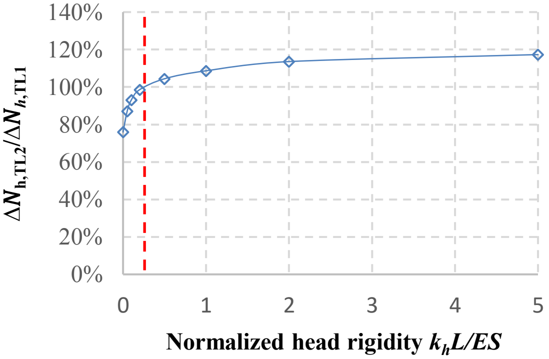

*Figure 4: Influence of head rigidity – cooling of the pile, conventional ground*

## 5 ADDITIONAL PHENOMENA

Synthetic design charts have been established for a single pile in specific ground conditions. Although not given in the charts, additional effects might be addressed separately.

### *5.1 Cyclic Effects*

Effects of successive thermal may be taken into account. An example of typical behaviour is given in Figure 5. A synthetic chart integrating the effect of cycles is given in Figure 6.

For this configuration, taking into account cyclic effects significantly increases variation of head displacement and head normal load. However, effects of subsequent cycles appear to be strongly linked to the choice of the modelling approach and have to be considered carefully

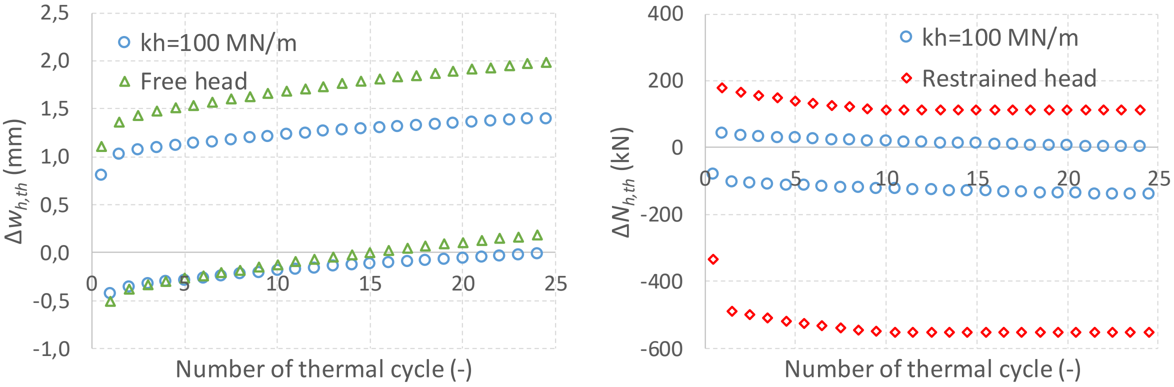

*Figure 5: Typical behaviour of thermoactive pile during several cycles*

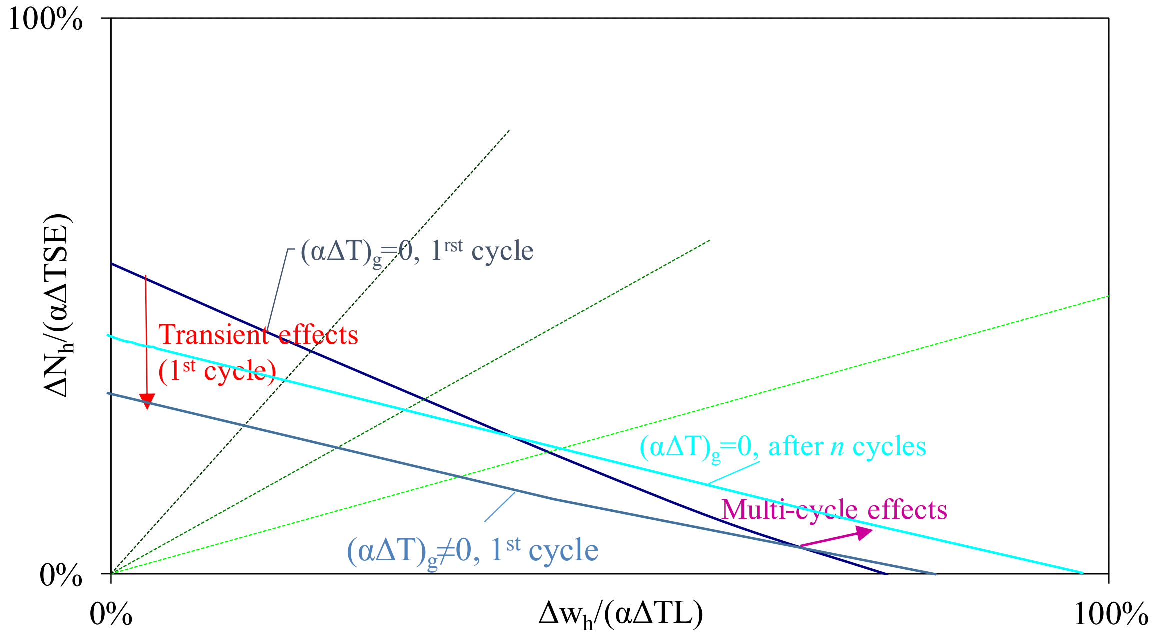

*Figure 6: Effects of successive operating cycles (after Mroueh and al., 2018)*

## 5.2 *Group of piles*

Behaviour of a group of piles is not taken into account in the previous synthetic chart. Group of piles may include both conventional and thermoactive piles.

However, on a first approach, behaviour of a group of piles may be relevantly assessed through a relevant *choice of the head rigidity*.

## 6 CONCLUSION

This paper presents numerical calculations for the elaboration of synthetic charts to assess the behaviour of thermoactive piles

On the one hand, synthesised charts can be determined for a specific ground model and pile conditions. As thermo-mechanical tools appear to be currently unavailable, the use of synthetic charts may benefit to efficiently address all site and pile conditions, using the same input parameters as for conventional piles.

On the other hand, additional guidance is also given to take into account cyclic effects on the behaviour of thermoactive piles.

## 7 ACKNOLEDGEMENTS

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