Bulletin d'Hydrogéologie No 17 (1999)
Centre d'Hydrogéologie, Universiti de Neuchâtel
EDITIONS PETER LANG

Heat exchanger pile: effect of the thermal solicitations on its mechanical properties

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ABSTRACT

A heat exchanger pile is a pile foundation equipped with a channel system, so that a heat carrier fluid can be circulated in order to exchange heat with the surrounding. Coupled with a heat pump for heating and/or cooling purposes, the advantage of such a system is its ability to use the shallow geothermal resources (in fact solar energy) without too high cost.

One question which remains to be answered with such a technique is the static pile behaviour (and of its interface with the ground) under thermal solicitations. **In** other words, do the thermal constraints imposed by the heat pump have an influence on the fundamental role of a pile, which is to sustain a construction ? This paper will present results of an experimental test under real conditions. **An** heat exchanger test pile ***(25*** m length, 880 mm diameter) has been equipped with different sensors in order to observe its behaviour under both mechanical (load of the building) and thermal constraints. At each step of the building construction, a thermal solicitation (several days with a power up to **9** kW) is imposed to the pile; its deformations, additional constraints, changes of its mechanical characteristic and changes of the friction forces with the surrounding ground is then measured. The first results show an increase of the friction mobilisation with a temperature rise and an added thermal compressive stress in the pile, which should be taken into account when the pile is sized.

KEYWORDS

Heat exchanger pile, thermal solicitation, thermal and mechanical constraints, pile load test

1. Introduction

Heat exchanger piles are foundation piles equipped with a pipe system, where a heat carrier fluid can be circulated to exchange heat with the surrounding ground (see figure 1). The two main functions of the heat exchanger piles are thus to support the loads of the building and to serve as a heat exchanger with the ground. The heat exchanger piles are connected together hydraulically and coupled to a heat pump. During the winter, the heat pump extracts thermal energy from the ground and provides heat to the building. **If** large enough, a regional ground water movement will provide a thermal regeneration of the ground volume which contains the piles from year to year. **If** not, cooling of the ground takes place, which is actually an advantage during the summer when the heat exchanger piles are used for direct cooling, i.e. the pile flow circuit is connected to the cold distribution without a cooling machine in between. Direct cooling enables a thermal regeneration of the ground and is beneficial to heating the next winter.

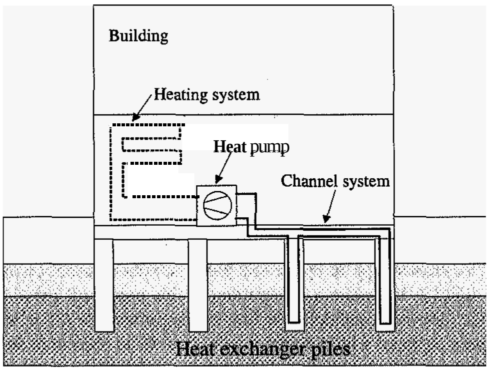

Figure 1: Heat exchangerpile system

The principal constraint on the system is that the thermal solicitations withstood by the piles must not deteriorate their mechanical properties, i.e., their ability to support the loads of the building. This problem is addressed in this paper.

2. In-situ thermo-mechanical test

Despite the fact that this technology has already been **used** quite often (for example in the case of the Main Tower in Frankfurt, 200 meters high), the question of the thermal effect on the mechanical behaviour of the piles has, to our knowledge, not heen specifically investigated until now. **A** first theoretical study (FROMENTIN ***et** al.* 1998: MORENI ***et** al.* 1999) has shown that the thermal solicitations (heating) could affect the pile's behaviour on two aspects: 1) modification of the friction mobilisation along the pile shaft; 2) increase of the compression stress in the pile. Based on theoretical considerations the authors have shown that, since the thermal solicitations are within the natural temperature fluctuation ($\Delta T \approx 15°C$, $T_0=11°C$), the first thermal aspect (friction mobilisation) should not have an important influence on the construction's integrity. However a particular attention should be given to the added thermal stresses in the pile specially for structures with high stiffness, i.e. structures which limit the pile deformation. In order to better understand this problem and to develop a numerical tool to simulate the thermo-mechanical behaviour of heat exchanger piles, an experimental in-situ test has been set-up.

2.1 Description of the experiment

This in-situ test concerns the thermo-mechanical behaviour of a heat exchanger pile. The considered pile is one of the piles **of** the foundation of a new building (100 m long, **30** m wide) with five floors at the QN-EPFL (Swiss Federal Institute of Technology at Lausanne, Switzerland). This pile is 25.8 m long and 880 mm in diameter. It has been equipped with a pipe system **for** the thermal solicitation and with 58 sensors: one load cell (HCV TELEMAC™), 29 fiber-optic extensometers (SMARTEC™) for deformation and 28 extensometers (TELEMAC™) for deformation and temperature (figure 2). A precision levelling enables to measure the vertical pile head displacement. **All** these sensors allow to acquire data for the analysis of the behaviour of the pile submitted to the thermo-mechanical loading. The mechanical loading is imposed by the weight of the building and the thermal loading is imposed by an electric heater. On the practical point of view, the coupled thermo-mechanical loading is obtained by imposing a cyclic thermal solicitation (heating and relaxation) after the construction of each level of the building. In this conditions, we have height thermo-mechanical tests. For the first one, the thermal solicitation was $\Delta T=22°C$ (with an initial temperature, $T_0=11°C$). For the others AT was imposed at 15°C.

Integrity test (PIT™) shows that the section of the pile ($A=6080\ cm^2$) could be considered as constant on all the depth. The Young modulus of the concrete has been evaluated with cross-hole ultrasonic transmission from three 2" steel tubes ($E_{concrete}=23000$ MPa). Taking into account the steel, the Young modulus **of** the pile is $E_{pile}=23900$ MPa. Due to the fact that we haven't a good estimation of a static elastic modulus from the laboratory tests, the dynamic value of the modulus obtained in-situ will be used in the calculations. The soil characteristics in the area **of** the building were analysed by several geotechnical investigations and two static pile load tests (De Ctrenville Gtotechnique 1997).

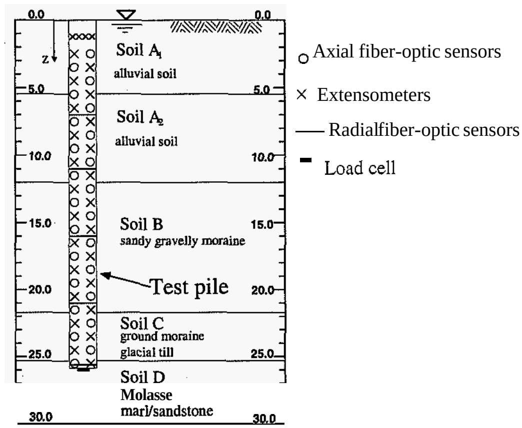

Figure 2: Stratigraphic profile with position of sensors

A *summary* of the data collected during the investigations revealed the geological profile given on the figure **2.** The values of the ultimate lateral frictional resistance (q_s) and the tip capacity (q_p) are:

- soil A_1 and A_2: alluvial soils; $q_s = 0$ kPa
- soil **B:** sandy gravelly moraine, $q_s =$ **30** Wa
- soil C: ground moraine / glacial till, $q_s = 165$ Wa
- soil D: molasse marl / sandstone, $q_s = 300$ kPa, $q_p = 11000$ Wa.

2.2 Experimental results

WEIGHT REPARTITION IN THE PILE

The static loading is imposed to the pile by the building. Knowing the pile's diameter and its elastic modulus, four deformation sensors at the top of the pile allow to estimate this loading.

The figure **3** shows the measured static force at the top of the pile (Q_0) at the end of the construction of each floor of the building (at the initial temperature of 11°C) compared to the calculated value by Passera & Pedretti, the civil engineer of the project (PASSERA & PEDRETTI 1997). This **result** shows that the **use** of the dynamic modulus is a good approximation of the Young's modulus.

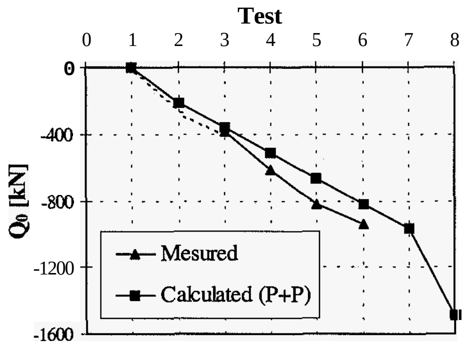

***Figure 3:** Loading force at the top of the pile induced by the building during the construction of the each floor.*

The axial (vertical) pile-deformation ε_1 is known at each meter in the pile (using the extensometers and the fiber optic **sensors, figure 2).** Then it **is** possible to estimate the repartition **of** the normal load with depth by:

$$Q(z) = \varepsilon_1(z) \cdot A \cdot E_{pile} \tag{1}$$

z: the vertical direction

The figure 4 shows the repartition of the weight of the different floors of the building in the pile. This result is obtained with the hypothesis of constant section A and constant elastic modulus **of** the pile E_{pile}. Note that the compression is negative.

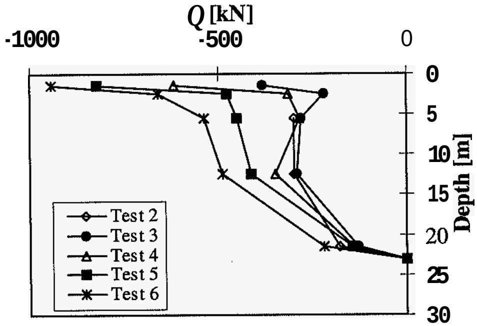

Figure 4: Repartition of the weight in the pile after the construction of each floor and for the initial ground temperature (≈ 11°C)

FRICTION MOBILISATION

During the test 1 the pile is heated with a AT of 22°C. The building is not yet constructed. In this condition the pile is supposed free to move to the top, except due to effect of friction mohilisation (note that the experimental results show that this effect is reversible). The figure 5 shows the measured deformation for different temperatures **for** the test 1. Without the soil-pile friction effect, the vertical pile's deformation is:

$$\varepsilon_2 = \beta \cdot \Delta T \tag{2}$$

with β the axial thermal dilatation of the pile estimated equal to 10^{-5} $°C^{-1}$.

If ε_1 is the measured deformation, the constrained thermal deformation $\Delta\varepsilon$ (due to the friction at the pile-soil interface) is:

$$\Delta\varepsilon = \varepsilon_2 - \varepsilon_1 \tag{3}$$

The mobilisation curves (or contact laws, see VULLIET & **MEYER** 1999) is given by:

$$q_s(z) = \frac{A \cdot E_{pile}}{\pi \cdot D} \cdot \frac{\Delta\varepsilon(z)}{dz_i} \tag{4}$$

where D is the diameter of the pile and dz_i the thickness of the layer i. The pile diameter and the **Young's** modulus are supposed constant and equal to the nominal values.

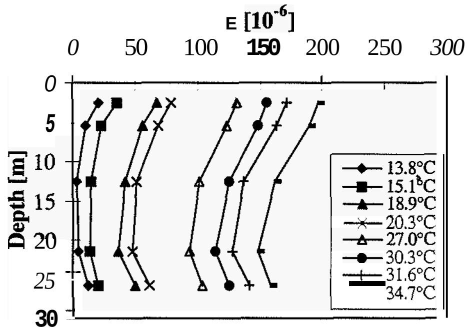

Figure 5: Strain vs. depth for varying temperature in test 1

The measured lateral friction mobilisation in the test 1 due to the thermal loading of $\Delta T=22°C$ ($T_0=11$ °C) **is** shown on the figure 6a,b.

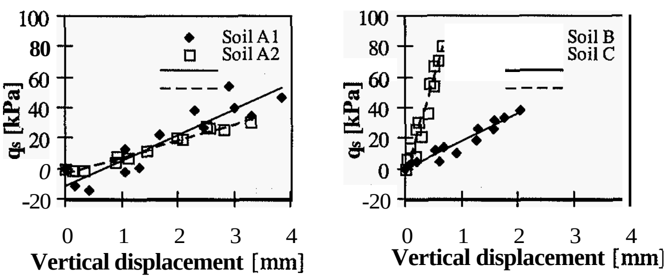

Figure 6a,b: Lateral friction mobilisation of the layers A_1, A_2, B et C due to the thermal loading of 22°C. Test 1

The table 1 gives a comparison between the lateral friction mobilisation due to the thermal solicitation and the lateral friction mobilisation obtained by the static load test (De Cérenville Géotechnique 1997) and used for the project calculations.

The figure 6a,b shows that the thermal loading of 22°C have a significant influence on the mobilisation of the lateral friction. In this case the lateral friction mobilisation is not completely reached in spite of the measured values are bigger than the project values except for the layer C (table1).

	Lateral friction mobilisation	
Layers	Test 1, ΔT=22• C	project values
A_1	≈40 kPa	0
A_2	≈30 kPa	0
B	≈40 kPa	30 kPa
C	≈80 kPa	165 kPa

Table1: Lateral friction mobilisation: Test I result and project values

THERMAL COMPRESSIVE STRESS

The test 2 represents the case where a thermal loading of ΔT=15°C (T_0=11°C) is imposed to the structure in which one floor is built. The pile is in hyperstatic condition. A part of the thermal deformation (deformation due to the thermal effect) is kept by the structure (weight of the building and soil-pile friction) and produces thermal stress in the pile (figure 7).

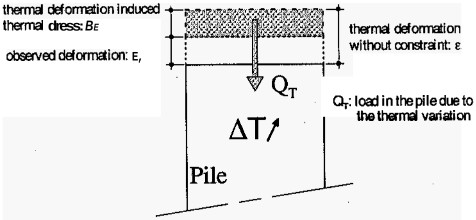

Figure 7: Thermal stress in the pile

The hyperstatic degree of the pile (n) can be estimated from the relation:

$$\varepsilon_1 = n \cdot \beta \cdot \Delta T \qquad (5)$$

where ε_1 is the deformation measured for each sensors. Knowing the value of AT (measured with the extensometers) and the coefficient of thermal dilatation of the pile, it's possible to determine the value of n(z) for each sensor (each meter). The obtained average value is:

$$n = 0.60 \pm 0.06 \qquad (6)$$

The added thermal load due to the thermal variation is then:

$$Q_T = E_{pile} \cdot (n-1) \cdot \beta \cdot \Delta T \cdot A \qquad (7)$$

and the total compression load in the pile is:

$$Q_{TOT} = Q_T + Q \tag{8}$$

with Q_T: the load in the pile due to the thermal variation

Q: the load in the pile due to the weight of the building

In test 2, the added thermal load in the pile with ΔT=15°C is Q_T=1000 kN which is more important that the mechanical load corresponding to the floor one (Q≈300 kN, see figure **3).** The pile capacity must take into account this added thermal effect.

3. Conclusion

Foundation piles offer a good opportunity to use the energy from the environment for heating and/or cooling purposes.

This paper deals with the thermo-mechanical behaviour of a pile foundation. It concerns an in-situ static load test with mechanical (weight **of** the building) and thermal loading.

The results show that the thermal variation has two effects on the mechanical behaviour of the pile. The first effect is that the friction mobilisation **is** increased with the temperature loading. The second effect is that a thermal compressive stress is added in the pile.

These two effects should be taking into account in the design of foundations with heat exchanger pile, especially if a summer thermal injection (solar collector) is used.

However, in our case, the integrity of the pile and thus of the building have never been threatened by thermal loadingss.

Acknowledgements

This work has been conducted with the financial support **of** the Swiss Federal Office of the Energy, the Swiss Federal Office **of** Construction and the Swiss Federal Institute of Technology Lausanne.

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