4th International Conference on DEEP FOUNDATION PRACTICE
July 1999 - Singapore

IN-SITU THERMO-MECHANICAL LOAD TEST ON A HEAT EXCHANGER PILE

Lyesse Laloui[1], Matteo Moreni[1], Antoine Fromentin[2], Daniel Pahud[2], Laurent Vulliet[1]
[1] Soil Mechanics Laboratory, [2] Laboratory of Energy Systems
Swiss Federal Institute of Technology at Lausanne
1015 Lausanne, Switzerland

Abstract

A heat exchanger pile is a deep pile foundation equipped with a channel system, so that a heat carrier fluid can be circulated in order to exchange heat with the surrounding. This paper presents an experimental test showing the effect of the thermal constraints (temperature between 11°C and 40°C) on the pile behavior.

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. As a result, part of the heating requirement is covered by energy that originates from the ground. 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 (direct cooling is realized by connecting the pile flow circuit to the cold distribution). In other terms, part of the thermal loads generated in the building are directly injected into the ground through the heat exchanger piles. Direct cooling enables a thermal regeneration of the ground.

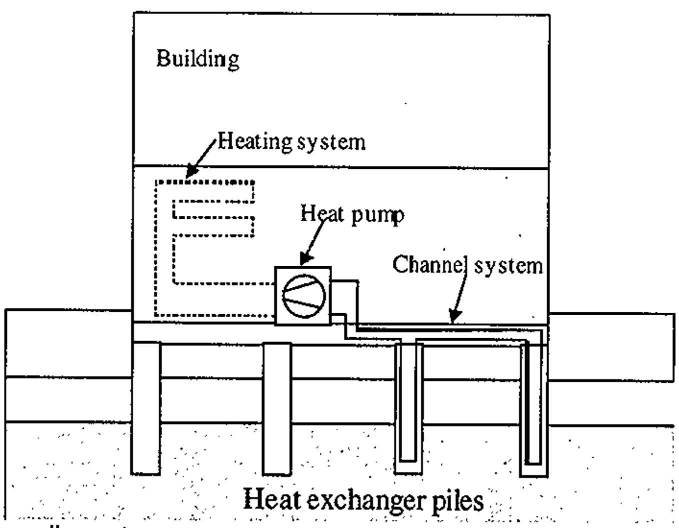

Figure 1 : Heat exchanger pile system

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.

Another constraint of this kind of system is its thermal behavior. In particular, freezing of the piles must be avoided to avoid structural collapse or large settlements. In a safely designed heat exchanger pile system, the fluid temperature in the piles never drops below 0 °C for a long period of time. This temperature constraint influences the size of the heat pump, which in turn affects the heating potential provided by the heat exchanger piles. When direct cooling is performed, the cooling potential also depends directly on the temperature level of the fluid in the cooling system. The annual extracted and injected thermal energy through the piles determinates the evolution of the ground temperature over the years, which in turn may affect the thermal performances of the system. An accurate assessment of the heating and cooling potential offered by heat exchanger piles requests a dynamic simulation of the system, which takes into account both short-term and long-term thermal performances. It requires a good knowledge of the system's thermal characteristics, the local ground conditions and the use of an accurate system simulation tool [1], [2], [3].

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 behavior of the piles has, to our knowledge, not been specifically investigated until now. A first theoretical study [4], [5] has shown that the thermal solicitations (heating) could affect the pile's behavior on two aspects : 1) modification of the friction mobilization 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 mobilization) 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 behavior of heat exchanger piles, an experimental in-situ test has been set-up.

2. Experimental setup

The in-situ test has been designed to gain information on the thermo-mechanical behavior 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 EPFL (Swiss Federal Institute of Technology at Lausanne, Switzerland). This pile is 25.8 m in length and 880 mm in diameter. It has been equipped with a pipe system for the thermal loading and with 58 sensors : one load cell (HCV TELEMAC™), 29 fiber-optic extensometers (SMARTEC™) and 28 vibrating-wire extensometers and temperature-gages (TELEMAC™) (Figure 2). A precision leveling enables to measure the vertical pile head displacement. The mechanical loading is imposed by the monotonic weight increase of the building construction 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 loading (heating and relaxation) after the construction of each level of the building. Under these conditions, eight thermo-mechanical tests have been performed. For the first one, the thermal loading was $\Delta T=22°C$ (with an initial temperature $T_0=11°C$). For the others $\Delta T = 15°C$ was imposed.

Integrity test (PIT™) shows that the section of the pile ($A=6080\ cm^2$) could be considered as constant over 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.

The soil characteristics at the location of the building were analyzed by several geotechnical investigations and two static load-piles [6]. A summary of the data collected during the investigations revealed the geological profile given schematically on the Figure 2. The values of the ultimate shaft friction (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, $q_s = 30$ kPa
- soil C : ground moraine / glacial till, $q_s = 165$ kPa
- soil D : molasse marl / sandstone, $q_s = 300$ kPa, $q_p = 11000$ kPa.

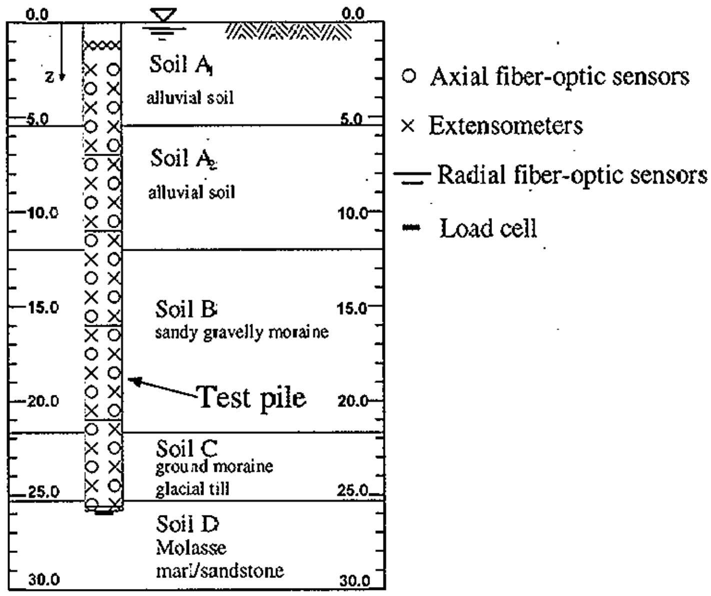

Figure 2 : Stratigraphic profile with position of sensors

3. Test results

3.1 Weight distribution in the pile

The static loading is imposed to the pile by the own weight of the building. The effective head load is determined from the four strain gages installed in the upper section of the pile, knowing the pile's diameter and its elastic modulus.

Figure 3 shows the measured static force at the top of the pile (Q_0) –negative in compression- 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 [7]. This result shows that the use of the dynamic modulus is a good approximation of the Young's modulus.

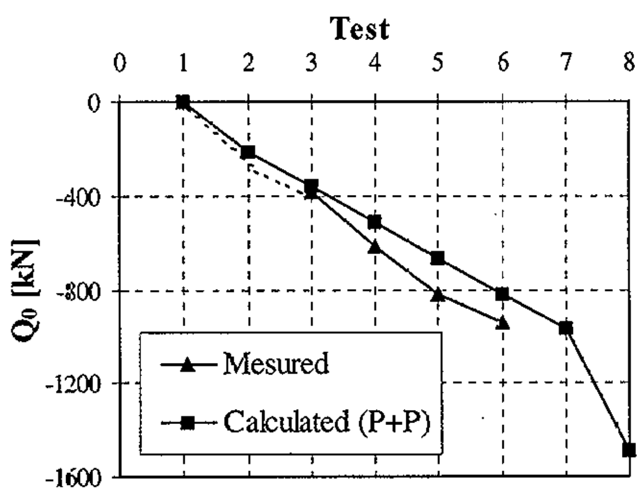

Figure 3 : Loading force at the top of the pile induced by the building during the construction.

The axial (vertical) pile-deformation ε_1 is given by the extensometers and the fiber-optic sensors (Figure 2) placed every meter. The distribution of the normal load with depth is thus:

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

With ε_1 the axial strain, z the down vertical direction, A the pile cross-section and E_{pile} the pile Young's modulus (both assumed constant).

Figure 4 shows the distribution of the normal load with depth for different tests. Note that the compression is negative.

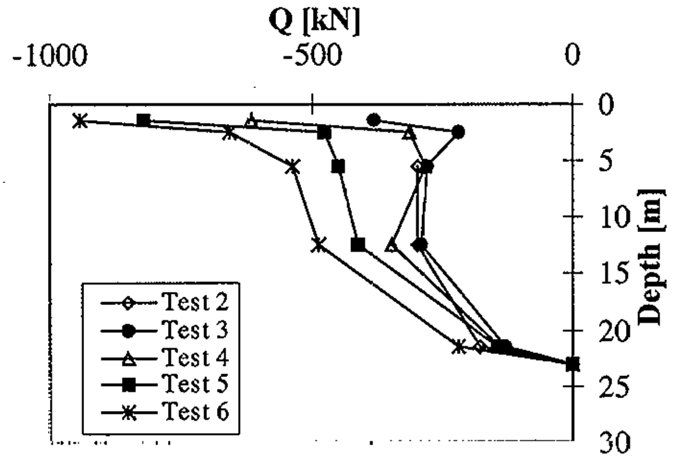

Figure 4 : Distribution of the normal load in pile after the construction of each floor and for the initial ground temperature (≈ 11°C).

3.2 Friction mobilization

During the test 1 the pile is heated with ΔT = 22°C. The building is not yet constructed. Under this condition the pile is supposed free to move at the top, except due to effect of friction mobilization (note that the experimental results show that this effect is reversible). Figure 5 shows the measured strains for different temperatures Test 1. Without the soil-pile friction effect, the axial strain would be uniform and equal to :

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

with β the axial thermal expansion coefficient of the pile estimated constant for the considered temperature range and equal to 10^{-5} °C^{-1}.

If $\varepsilon_1(z)$ is the measured strain, the constrained thermal strain $\Delta\varepsilon(z)$ (due to the friction at the pile-soil interface) is :

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

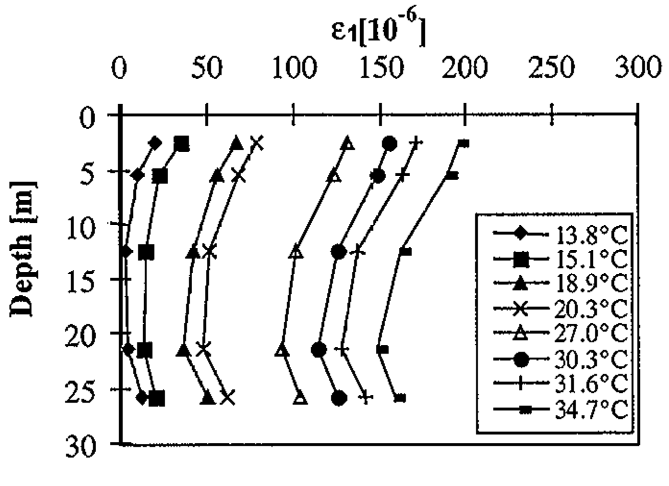

Figure 5 : Strain vs. depth for varying temperature in Test 1

The mobilization curves [8] due to the thermal strains are given by :

$$q_s(z)=\frac{A\cdot E_{pile}}{\pi\cdot D}\cdot\frac{\Delta\varepsilon_1(z)}{\Delta z_i} \qquad (4)$$

where $\Delta\varepsilon_1(z)$ is the measured strain in the pile segment due to the thermal loading, D is the diameter of the pile and Δz_i the thickness of the pile segment (one meter). The pile diameter and the Young's modulus are supposed constant and equal to the nominal values.

The measured lateral friction mobilization in the Test 1 due to the thermal loading of ΔT=22°C (T_0=11 °C) is shown on the figure 6a,b. The displacement is considered as positive when it goes from the bottom to the top.

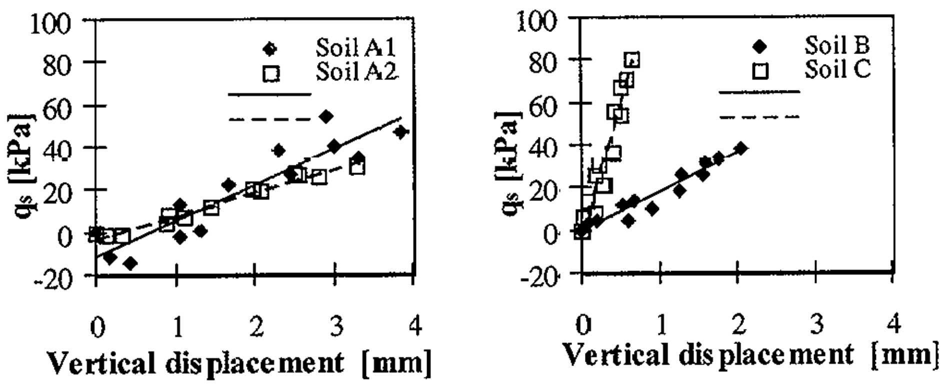

Figure 6a,b : Lateral friction mobilization of the layers A_1, A_2, B et C due to the thermal loading of 22°C.

Table 1 gives a comparison between the lateral friction mobilization due to the thermal loading and the lateral friction mobilization obtained by the static load test [6] and used for the project design.

Layers	Lateral friction mobilization	
	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 mobilization : Test 1 result and project values

Figure 6a,b shows that the thermal loading of 22°C have a significant influence on the mobilization of the lateral friction. In this case the ultimate lateral friction is not reached although the measured values are larger than the design values except for the layer C (Table1).

3.3 Thermal compressive stress

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. Since the pile is in hyperstatic condition, thermal stress is produced in the pile (Figure 7).

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

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

where ε_1 is the measured axial strain. Knowing the value of ΔT (measured with the extensometer-temperature gages) and the coefficient of thermal expansion of the pile, the value of n(z) for each sensor (every meter) can be determined. The obtained average value is :

$$n=0.60\pm0.06 \qquad (6)$$

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

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

and the total compression load in the pile is :

$$Q_{TOT}(z) = Q_T(z) + Q(z) \quad (8)$$

with $Q_T(z)$: the load in the pile due to the thermal variation and
Q(z) : the load in the pile due to the weight of the building.

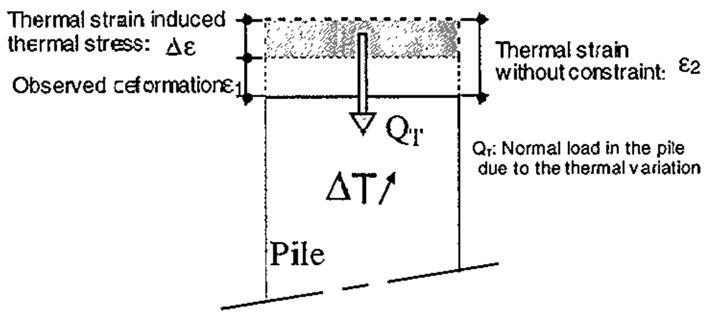

Figure 7 : Thermal stress in the pile

In Test 2, the added thermal load at the top of the pile with ΔT=15°C is Q_T=1000 kN which is more important than the mechanical load corresponding to the first floor (Q≈300 kN, see Figure 3).

4. 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 behavior of a pile foundation. It concerns an in-situ static load test with mechanical (weight of the building) and thermal solicitations.

The results show that the thermal variation has two effects on the mechanical behavior of the pile. The first effect is that the friction mobilization 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 thermal injection (solar collector) is used in summer.

In the case presented, the integrity of the pile and thus of the building have never been threatened by thermal loading.

References:

[1] FROMENTIN A., PAHUD D., JAQUIER C. & MORATH M. 1997. Recommandations pour la réalisation d'installations avec pieux échangeurs. Empfehlungen für Energiepfählesysteme. Rapport intermédiaire, Office fédéral de l'énergie, Bern.

[2] PAHUD D. 1999. PILESIM-LASEN: Simulation Tool for Heating/Cooling systems with Exchanger Pile or Bore-hole heat Exchangers. User Manual. Laboratory of Energy Systems. Swiss Federal Institute of Technology in Lausanne, Switzerland.

[3] FROMENTIN A., PAHUD D., LALOUI L. & MORENI M. 1999. Pieux échangeurs : conception et règles de prédimensionnement, Submitted to Revue française de génie civil.

[4] FROMENTIN A., PAHUD D., LALOUI L., MORENI M. & KAPP C. 1998. Pieux échangeurs-QN EPFL ; étude préliminaire de faisabilité technique et économique. LMS SY40 - LASEN 120.108. EPFL.

[5] MORENI M., LALOUI L., PAHUD D., FROMENTIN A., STEINMANN G. & VULLIET L. 1999. Test en conditions réelles du comportement statique d'un pieu soumis à des sollicitations thermo-mécaniques, Rapport intermédiaire. OFEN, Berne.

[6] DE CERENVILLE GEOTECHNIQUE, 1997. Rapport géotechnique. Extension Quartier Nord Message 96. Ecublens.

[7] PASSERA & PEDRETTI, 1997. Extrait note de calcul. Vérification du pieu N° 68. Bâtiment polyvalent Quartier Nord EPFL. Lugano.

[8] VULLIET L. & MEYER A. 1999. The Vigner Tunnel : Determining contact laws from static load tests on piles. Proc. XIIth European conference on soil mechanics and foundation engineering, Amsterdam, June 7-10, 1999, Balkema.

Acknowledgments

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

The authors wish to thank M. Lucini and M. Passera (Passera & Pedretti Consulting Engineers) whose interest and cooperation made the test possible.