Thermo-mechanical behaviour of a heat exchanger pile

Comportement thermo-mécanique d'un pieu échangeur de chaleur

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ABSTRACT: The behaviour of a pile subjected to thermo-mechanical solicitations was studied in situ with the aim of quantifying the thermal influence on the bearing capacity of heat exchanger piles. To accomplish this, a pile situated in a building under construction was equipped with a channel system in order to inject heat into it using a special heat pump. Load cells, deformation gauges and thermometers were installed in order to evaluate the behaviour of the pile during seven tests with coupled thermo-mechanical solicitations. The temperature variations applied to the pile were on the order of 15°C and the mechanical load reached 1300 kN. The results obtained permitted the quantification of three significant effects brought about by the temperature increase: i. pile uplift, ii. mobilisation of side friction due to the relative displacement of the pile with respect to the ground, iii. additional load generated in the pile by constrained dilation.

RÉSUMÉ: Le comportement d'un pieu soumis à des sollicitations thermo-mécaniques a été étudié in-situ dans le but de quantifier l'influence de la thermique sur la portance des pieux énergétiques. Pour ce faire, un pieu d'un bâtiment en construction a été équipé avec un circuit hydraulique pour pouvoir lui injecter de la chaleur à l'aide d'un module de chauffage spécial. Des capteurs de force, de déformation et de température ont été installés afin d'évaluer le comportement du pieu au cours de sept tests de sollicitations couplées thermo-mécaniques. Les variations de température appliquées au pieu ont été de l'ordre de 15°C, et la charge mécanique a atteint les 1300 kN. Les résultats obtenus ont permis de quantifier trois effets significatifs induits par l'augmentation de température: i. soulèvement du pieu, ii. mobilisation du frottement latéral due au déplacement relatif du pieu par rapport au sol; iii. effort supplémentaire dans le pieu engendré par la dilatation empêchée.

1 INTRODUCTION

The two main functions of a heat exchanger pile are to transfer construction loads into the ground and to serve as a heat exchanger with the ground. The parallel combination of several heat exchanger piles, usually linked to a heat pump, permits the extraction of warmth from the ground to satisfy the need for heat in winter and to expel excess heat resulting from air conditioning in summer.

This simple yet rational technology has been used in several installations in Switzerland (Pago at Grabs, 600 kW, Kino at Buchs, 70 kW, Malerva apartment complex at Sargans, 70 kW, ...) and in other countries (over 300 in Europe). In spite of a large number of installations, the understanding of the behaviour of piles subjected to thermo-mechanical solicitations remains limited. This represents a handicap when it comes to convincing a project owner of the validity of such technology, especially if it is probable that the temperature increase will lead to a decrease in side friction resistance at the soil-pile interface and generate additional stresses in the building structure. In order to combat this lack of knowledge, a test of the behaviour of a heat exchanger pile under real conditions was carried out at the Swiss Federal Insitute of Technology in Lausanne, EPFL (Laloui et al., 2001). The present article summarises some of the significant results of this study.

2 THE BASIC CONCEPT OF HEAT EXCHANGER PILES

A heat exchanger pile is a foundation pile in which a channel or channel system is installed in order to permit the circulation of a heat carrier fluid to exchange heat with the ground (Figure 1). With a unit length varying from several to several tens of metres, part or all of the pile may be transformed into a "heat exchanger pile" at virtually no extra cost. This is a distinct advantage compared to the construction of geothermal probes at much greater depths.

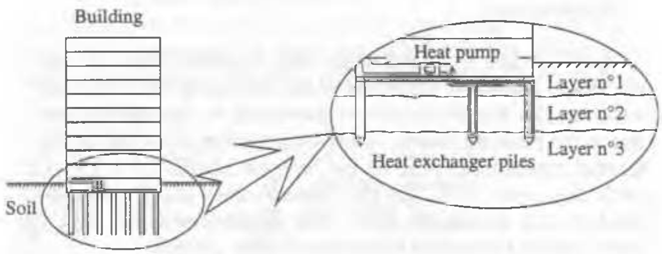

Figure 1. Schematic representation of a heating system with heat exchanger piles

3 THE TEST PILE

A four storey building under construction at the EPFL site (called Bâtiment Polyvalent, « BP ») was chosen for the test site. 100 m in length and 30 m in width, it is founded on piles approximately 25 m long. The test pile was 88 cm in diameter and 25.8 m long. It had been drilled in the soil whose stratigraphic profile is presented in Figure 2 and described in Table 1 (adapted from De Cérenville, 1997). The groundwater table in this zone appears virtually at the ground surface.

4 PILE INSTRUMENTATION

PE tubes were installed vertically (U-shaped configuration) in the reinforcing structure to permit the passage of the heat carrier fluid for the heating and cooling. The instrumentation chosen for the measurement of strain, temperature and toe load in the test pile was made up of 58 gauges placed as indicated in Figure 2.

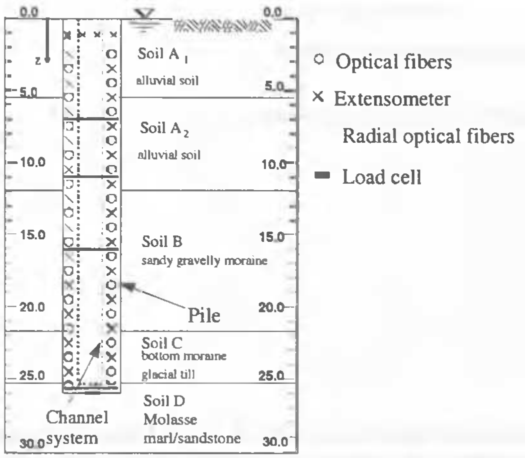

Figure 2. Stratigraphic profile and instrumentation of the test pile

5 LOADING SCHEDULE AND ADDITIONAL TESTS

5.1 *Loading schedule*

The test pile was subjected to two types of solicitations : mechanical and thermal. The mechanical load was applied by the dead weight of the building under construction ; the thermal load was applied by a heating machine which heats and cools the water located in the PE tubes installed in the pile. The solicitations were alternated in order to show the thermo-mechanical coupling clearly. Thus, at the end of the construction of each storey, a thermal loading cycle was applied to the pile (Figure 3). Without taking into account the measurements made during the concreting of the pile (Test 0), seven tests were carried out.

Test 1 differs from the others with regards to the free displacement boundary condition of the pile head. For the other tests, the pile was blocked in its movement by the applied load due to the building storeys under construction. In addition, the thermal solicitations were on the order of ΔT=22°C for Test 1, while they were 15°C for the others (values usually encountered in heat exchanger piles). The measurements for Test 8 were made at the natural temperature of the ground.

5.2 *Additional tests*

On the basis of the results of laboratory tests and cross-hole ultrasonic transmission tests, the elastic modulus of the pile was estimated to be 29'200 MPa.

A check by the reflected wave method to verify pile integrity and geometry was carried out with the PIT™ integrity test. No anomalies were discovered, with the exception of an increase in pile section with depth. For the remaining analyses, the diameter estimated at various depths will be taken into account. Thus the section varied between 7200 et 10800 cm^2.

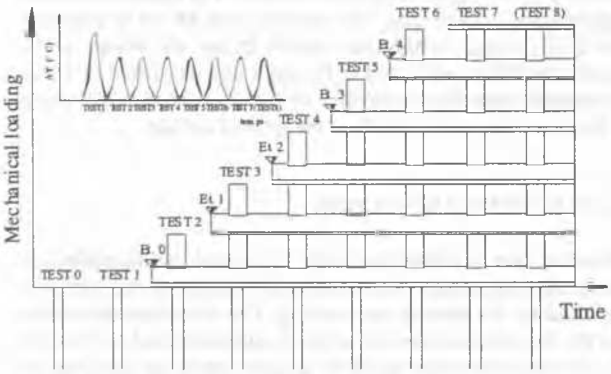

Figure 3. Schedule of thermo-mechanical solicitations

6 INFLUENCE OF TEMPERATURE ON PILE BEHAVIOUR

The entire experimental program was able to be carried out as planned. An important database was, therefore, able to be assembled. In this section, the influence of the temperature on pile behaviour will be studied. In particular, three principal aspects will be addressed : pile uplift, induced loads and side friction.

6.1 *Thermal strains*

The thermal field applied to the pile generated strains. As the pile was free to move in only one direction, the pile dilations occurred upwards. These were not uniform and depended primarily on the friction at the soil-pile interface. In effect, the measurements show the differences according to the type of surrounding soil, and the layer boundaries (A, B, C et D) may be identified in Figure 4.

The representation of the strains during a heating-cooling cycle (Figure 5) indicates thermo-elastic linear behaviour (the same observation is valid for the entire group of gauges). This reversibility of the behaviour means that the displacement of the pile with respect to the soil has not yet reached the threshold where the friction would no longer permit the pile to return to its initial state. The radial strain measurements are similar in that they show no unsticking of the pile with respect to the ground after a thermal cycle.

6.2 *Pile uplift*

Test 1 enabled the measurement of the maximum uplift that a temperature increase of 22°C may bring about in this type of soil. Values obtained by precision levelling are presented in Figure 6. These values are compared to the total displacements measured simultaneously by the extensometers and the optical fibres. The correspondence is remarkable and permits the validation of the measurements made in the pile.

After Test 1, the floor slab, a column wall and the parapet of the ground floor were concreted. Therefore, the fixed point of the precision levelling was moved. Test 2 began with a solicitation of ΔT=14 °C. The rigidity introduced by the structure partially blocked pile displacement. The pile lifted up approximately 1 millimetre and returned to almost its initial

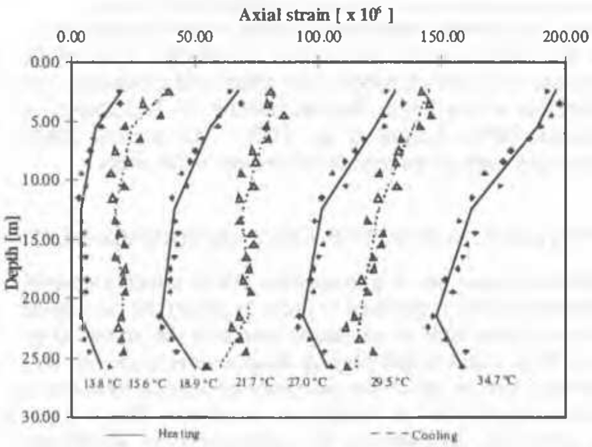

Figure 4. Evolution of strains during Test 1

Tableau 1. Geology at the location of the test pile

	Type of soils	Consistency	Resistance	w [%]	γ_d [kN/m^3]
A	Alluvial soil	Soft	c_{us} = 15-20 kN/m^2	30 %	15
B	Sandy gravely moraine	Soft	c_{us} = 20-30 kN/m^2	20-40 %	13-19
C	Bottom moraine and glacial till	-	c_{us} = 70-150 kN/m^2	14-20 %	18
D	Molasse, marl and sandstone	-	R_c =12 MPa Elastic modulus between 3000 and 7000 MPa	-	-

c_{us} : non-drained shearing resistance determined by vane test ; R_c : unconfined compressive strength ; w : water content ; γ_d : dry unit weight

position after cooling. Then the first floor slab was concreted. This load resulted in settlement of the pile of about one half of a millimetre. A thermal load of ΔT=15 °C was then applied, which lifted up the pile one millimetre (1.5 mm relative displacement). From then on, the settlements due to mechanical solicitations and thermal dilations continued in this manner (Figure 7).

6.3 *Induced loads*

Under the effect of a temperature increase, a pile with free boundary conditions dilates. In the case where it is not entirely free to move (side friction, blocked ends, ...) part or all of the deformation will be prevented. The strain produced in this case, termed the constrained strain ε_g, is a fraction of the strain termed free ε_l which would produce the same temperature difference if the pile were completely free. The ratio of these two vertical strains is termed *n*, degree of freedom of the structure (terminology used by Bochon (1992) and adopted here) :

$$n = \frac{\varepsilon_g}{\varepsilon_l} \qquad (1)$$

The free strain of the pile due to temperature is given by

$$\varepsilon_l = \beta \cdot \Delta T \qquad (2)$$

The blocked strain caused by a temperature difference ΔT is:

$$\varepsilon_g = n \cdot \beta \cdot \Delta T \qquad (3)$$

Where β is the thermal dilation coefficient of the pile.

The prevented vertical strain (the difference between the free and constrained strain) brings about a vertical support reaction, balanced by a proportional increase in the vertical stress in the pile :

$$\sigma = -E_{pile} \cdot (\varepsilon_l - \varepsilon_g) \qquad (4)$$

The negative sign corresponds to compression.

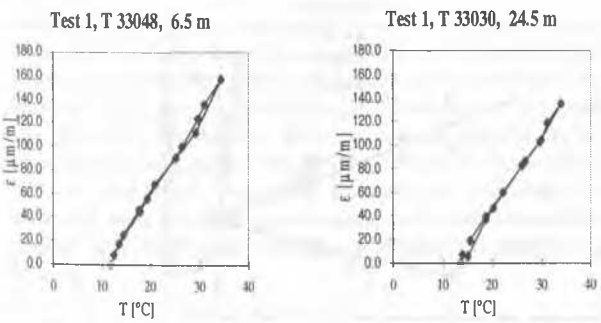

Figure 5. Evolution of strains during thermal solicitation at depths 6.5 and 24.5 m -Test 1

This additional stress depends on the layer of soil i considered as follows :

$$\sigma = E_{pile} \cdot \beta \cdot \Delta T \cdot (n_i - 1) \qquad (5)$$

It is calculated every metre (gauge spacing) and for each construction stage.

The added load in the pile due to thermal solicitations is :

$$Q_T(z) = E_{pile} \cdot (n - 1) \cdot \beta \cdot \Delta T \cdot A(z) \qquad (6)$$

This load evolves during the thermal cycle as shown in Figure 8 for the case of Tests 2 and 6. The representation of the maximum intensities of the thermal loads caused during each test is shown in Figure 9. It should be mentioned that a ΔT of 14°C resulted in a surcharge on the order of 1200 kN at the head of this structure, with a maximum of 2000 kN at the upper limit of layer B. An analysis of the curves of Tests 5 and 6 shows that 1°C results in a difference on the order of 100 kN.

Under normal service conditions, the thermal solicitation of a heat exchanger pile is applied after the completion of the building construction. To represent such a situation, Figure 10 includes, for Test 7, the load caused by the building weight,

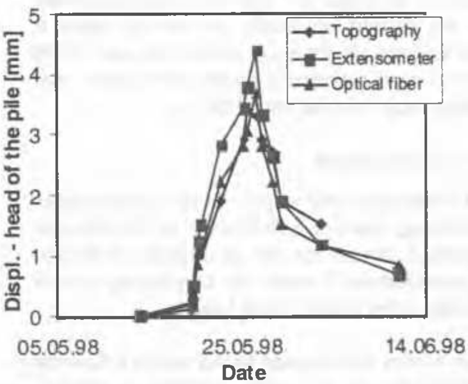

Figure 6. Pile displacement during Test 1

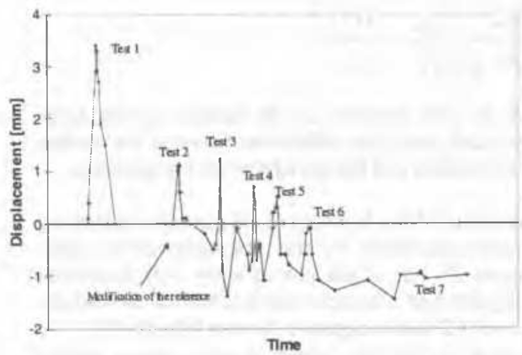

Figure 7. Vertical displacement of the pile head

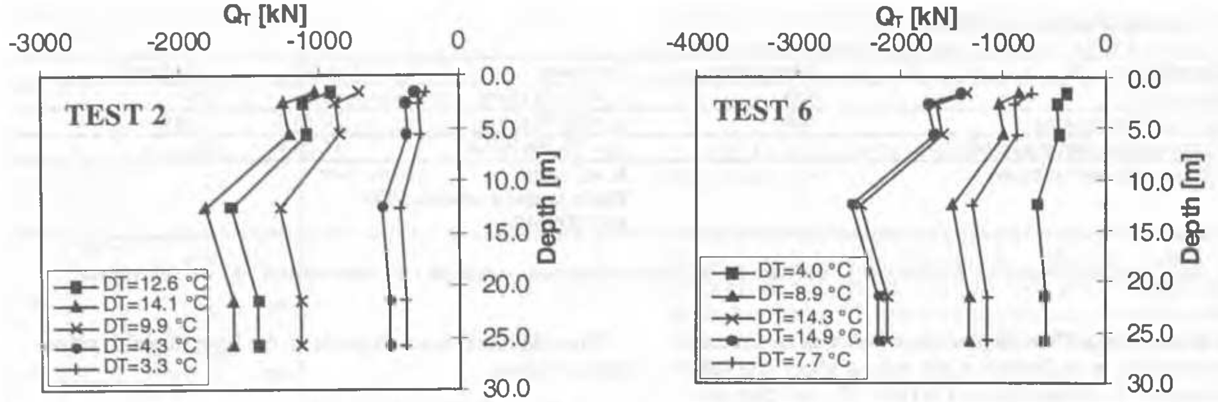

Figure 8. Load evolution during the thermal cycle – Tests 2 and 6

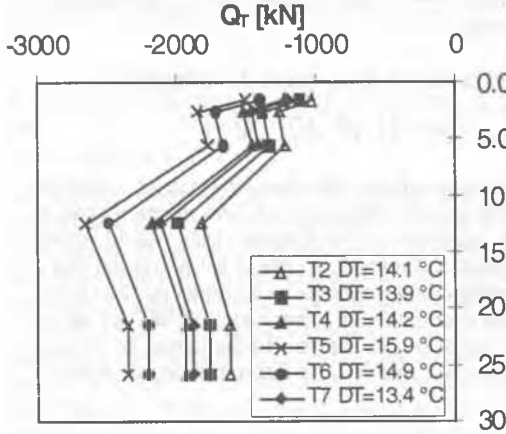

Figure 9. Maximum thermal loads

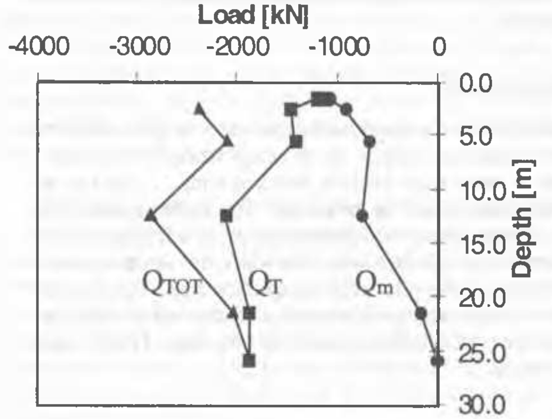

Figure 10. Mechanical (Q_m), thermal (Q_T) and total (Q_{TOT}) loads in the pile after building construction

the maximum thermal surcharge (ΔT= 13.4 °C) and the total load thus obtained. Even though the mechanical load is important at the top (on the order of 1000 kN) and diminishes with depth (the toe carried no load), the thermal load is greater and more uniform. It strongly solicits the toe (2000 kN). Thus, the total load represents double the purely mechanical load, with a large solicitation of the toe.

6.4 *Mobilisation of side friction*

The displacement of the pile with respect to the ground under the thermal effect brings about a mobilisation of side friction at the pile-soil interface. In this section, an analysis of the importance of this mobilisation is made by comparing it with that due to settlement under construction loading.

The shear stress q_s may be obtained based on the following relationship (Bustamante et al., 1991, Vulliet & Meyer, 1999) :

$$q_s(z) = \frac{A(z) \cdot E_{pile}}{\pi \cdot D(z)} \cdot \frac{\Delta\varepsilon(z)}{dz_i} \tag{7}$$

where D is the pile diameter, dz_i the thickness of the layer i in question, and $\Delta\varepsilon(z)$ the difference between the strains measured at the bottom and the top of the layer in question.

The construction of the building results in pile settlement. The side friction mobilised by this displacement is represented in Figure 11. All of the curves show stiff behaviour without having reached complete mobilisation of the friction resistance. Layer A2 shows negative friction (Figure 10).

Test 1, which yielded the largest thermal strains, shows that the friction mobilised in this case remains below limit values (Figure 12 a). Normal service conditions would correspond to Test 7. The mobilisation of friction obtained in this case is shown in Figure 12 b.

Figure 13 shows a superposition of the thermal and mechanical effects for the case of Test 7 for layers A1 and B. Thus, after the settlement phase (1), heating produces uplift. This brings about a decrease in friction mobilisation (2). Since the thermal effect is reversible, the cooling of the pile should return the mobilised friction to points (1).

7 CONCLUSIONS

Heat exchanger piles offer a good opportunity for the use of environmental energy for heating and cooling aspects. In spite of the existence of several installations of this type, the understanding of the thermo-mechanical behaviour is limited at the

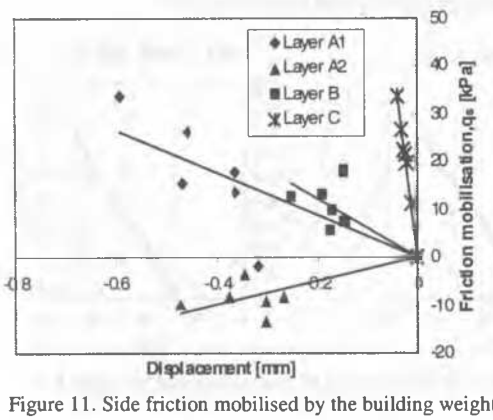

Figure 11. Side friction mobilised by the building weight.

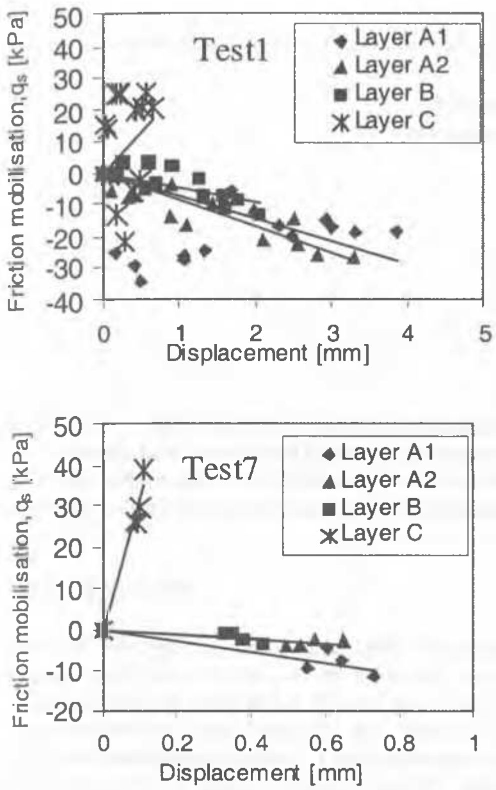

Figure 12. Side friction mobilised by the thermal solicitation (a) Test1; (b) Test7

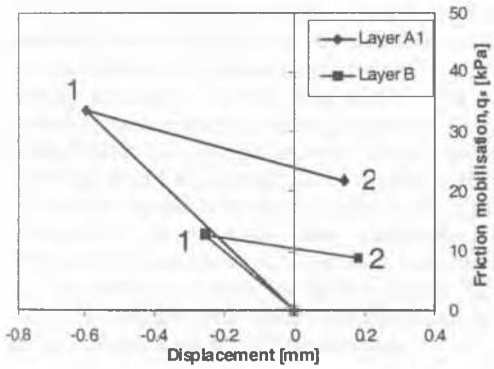

Figure 13 : Mobilisation of side friction by building weight (1) and thermal solicitation (2)

present time. The results presented in this article serve to combat this lack of knowledge.

The different effects of thermal origin were analysed in the case of this in situ test. It was shown that pile strain is of the thermo-elastic type and that its intensity, relatively important, depends on the type of surrounding soil. The additional loads in the pile may be rather large. In addition, due to the uniform nature of the thermal effects, the additional mechanical solicitation loads the toe more strongly in contrast to the loads due to the building weight, which are concentrated at the top and decrease with depth. Finally, the difference in the directions of movement (uplift for thermal and settlement for static) act such that friction resistance is not affected by temperature and relief of side friction mobilisation is seen during heating.

8 ACKNOWLEDGEMENTS

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