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Investigations on the mechanical behaviour of a Heat Exchanger Pile

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ABSTRACT: The geothermal use of concrete geostructures (piles, walls and slabs) is an environmentally friendly way of cooling and heating buildings. With such geothermal structures, it is possible to transfer energy from the ground to fluid-filled pipes cast in concrete and then to building environments. A comprehensive research work was carried out at the EPFL (Switzerland) to improve the knowledge in the field of geothermal structures and to quantify the thermal influence on the bearing capacity of heat exchanger piles. In this paper, some features of the behaviour of a pile subjected to thermo-mechanical loads are presented. Numerical finite element results are supported by in-situ measured values.

1 INTRODUCTION

This paper deals with the development of a new sustainable technology for the intermittent storage of energy in soils. The goal of our research work is to contribute, by a geotechnical approach, to obtaining reliable, environmentally and resource friendly heating and cooling of residential, office and commercial buildings at low additional cost. The idea behind energetic geostructures is to take advantage of the thermal storage capacity of the ground as an energy storage system by using the foundation of a building (e.g. piles or retaining walls). The key factor in the sustainability of such system is the use of the building elements which are already needed for structural reasons. The parallel combination of several heat exchanger piles, hydraulically connected and 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 (Figure 1). With this geothermal use of geostructures, buildings can be cooled at minimal cost and cheaply heated with a heat pump, using the available geothermal energy in the ground and the natural thermal properties of the concrete. From a geotechnical point of view, heating of foundations may also have an important advantage in the improvement of the soil characteristics (Cekerevac and Laloui, 2004). This may result in a reduction in foundation cost. Another potentially significant practical and technological aspect concerns our recently obtained results showing that the thermal pre-treatment of clays may have a very positive effect on their resilience under cyclic loading, which results in higher resistance of the buildings against earthquakes (Laloui et al., 2005). In any case, freezing of the piles is to be avoided by continuous monitoring and control systems to prevent thaw-induced defects.

The heat exchanger technology, although very successful in Switzerland (e.g. Zürich Airport) and world-wide (more than 300 installations in Europe), faces the lack of rational knowledge of the thermal effects on the behaviour of the foundations. In particular, no analytical, physical or numerical tools are yet available to consider the complex interactions between thermal storage and the mechanical behav-

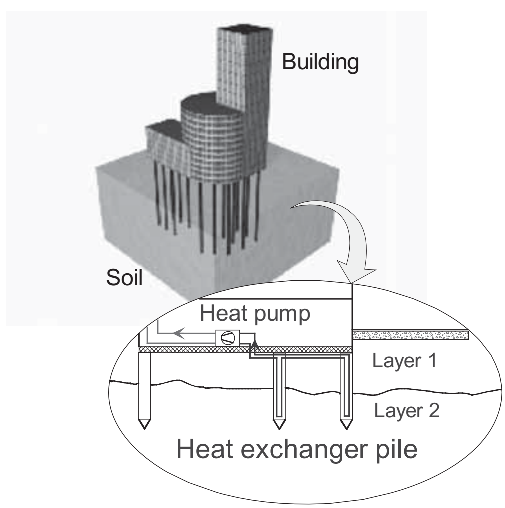

Figure 1. Schematic representation of a heat exchanger pile system.

iour of geostructures. This paper highlights some features of the behaviour of a heat exchanger pile. The thermal transfers in the pile and soil will not be quantified here.

2 EXPERIMENTAL IN SITU TEST ON A HEAT EXCHANGER PILE

2.1 *Test site*

A four storey building under construction at the Swiss Federal Institute of Technology (EPFL) in Lausanne (Switzerland) was chosen for an in-situ test of a heat exchanger pile (Laloui et al., 2003). The building is 100 m in length and 30 m in width and is founded on 97 piles approximately 25 m in length. The tested pile was located at the side of the building. The drilled pile diameter was 88 cm and the length was 25.8 m. The schematic soil stratigraphy profile is presented in Figure 2. The groundwater table in this zone is very close to the ground surface. Polyethylene (PE) tubes were installed vertically in the reinforcing structure with a U-shaped configuration to permit the circulation of the heat-carrying fluid. The instrumentation chosen for the measurement of strain (Inaudi et al., 2000), temperature and load in this in situ test was made up of 58 gauges placed as indicated in Figure 2.

2.2 *Loading history*

Seven thermo-mechanical loading conditions were applied to the pile. The loading principle was to apply a mechanical load (dead weight of superstructure at the construction of each storey) and a temperature variation controlled by a heating device. The two types of loads were applied separately and alternately in order to decouple the thermal and mechanical effects. Test 1 differs from the others with regard to the free displacement boundary condition of the pile head. For the other tests, the pile was blocked in its movement by the applied mechanical load (weight of the building under construction).

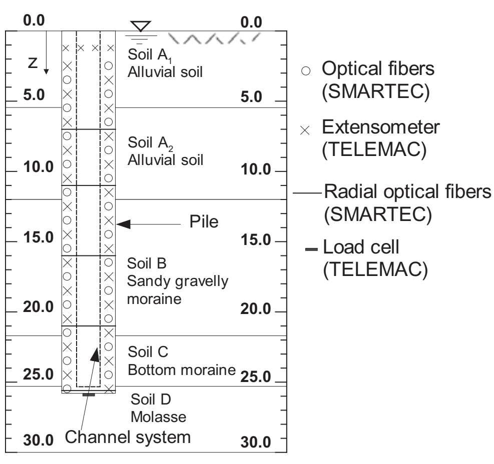

Figure 2. Soil profile and instrumentation of the tested pile.

3 FINITE ELEMENT MODEL

A thermo-hydro-mechanical (THM) model for saturated porous media is used to simulate the behaviour of the heat exchanger pile and the surrounding soils.

Readers may refer to (Laloui 1993, Laloui et al., 2006) for the complete mathematical formulation. It is chosen to model a single vertical pile using an axisymmetric geometry (Figure 3). The finite element nodes of the pile and the soil at the interface are assumed to have no relative movement. The contact area being modeled as the soil material, a refinement of the finite element mesh around this zone is required.

3.1 *Material characteristics*

Due to the length limitation of the paper, the material parameters are not given here. The interested reader may find them in Laloui et al. (2006). The soil is represented by five layers obeying the Drucker-Prager thermo-elastoplastic model. The pile itself is modelled with solid elements and behaves as a thermo-elastic material. The mechanical parameters were determined from triaxial tests at three confining pressures for each soil layer. The pile is considered impervious, as is the layer D (molasse formation) while the other soil layers are considered drained. The horizontal permeability coefficients were determined from in situ measurements and isotropic permeability was further assumed. The thermal parameters were estimated based on the geotechnical characteristics while the porosity of each layer was determined experimentally.

3.2 *Initial and boundary conditions*

Besides the mechanical boundary conditions defined in Figure 3, the hydraulic boundary conditions were imposed as follows:

- Layer D and pile are impervious (undrained conditions)
- Elsewhere, layers are saturated with the water table located at the top surface. Drainage takes place at the top surface and at the right hand side of the mesh.

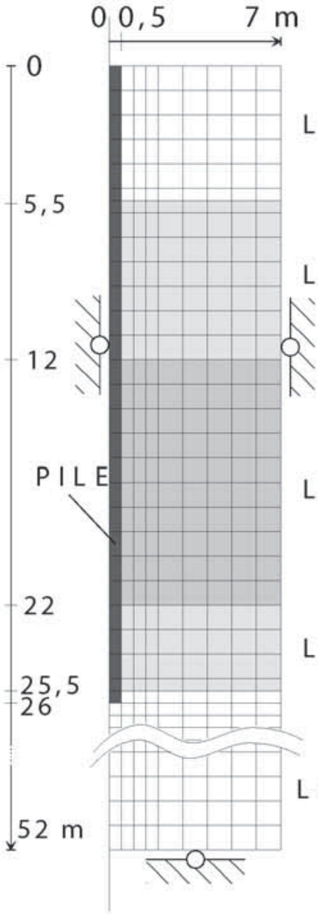

Figure 3. Finite element mesh (534 elements) and mechanical boundary conditions.

The thermal boundary conditions consist in allowing the heat to flow through the right-hand side of the mesh as well as through the bottom of the mesh.

Constant temperatures were imposed on the top surface of the mesh and the heat flux was supposed null along the axis of symmetry.

4 NUMERICAL/EXPERIMENTAL RESULTS

In this section, some of the finite element results are presented and compared with the experimental ones. We mainly focus here on the behaviour of the concrete pile. For the presented example the considered thermal loading in the pile is a heating-cooling cycle: 12 days of heating with a variation of temperature of 21°C then 16 days of cooling (Figure 4).

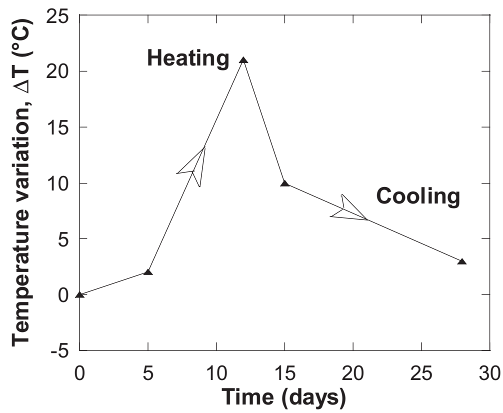

Figure 4. Temperature values imposed in the pile.

4.1 *Thermal strains*

In the case of Test 1, the thermal heating-cooling cycle was applied to the pile. No mechanical load was imposed at the pile top and the pile was free to move upwards. The imposed thermal field generated strains. Figure 5a compares the simulated thermo-elastic vertical strains with respect to the measured ones for the heating and cooling periods. Strains are not uniform during the heating period and are influenced by the friction along the pile shaft. In fact, the measurements show different straining according to the type of surrounding soil, and the layer boundaries (A, B, C and D) may be identified in Figure 5a. The model is able to reproduce this effect.

Thermo-elastic linear behaviour is observed and computed during the cooling phase. This reversibility 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 modeled radial strains fit the measured ones well, as may be seen for one of them (at depth of 16 m) in Figure 5b. The radial strain behaviour shows that lateral contact is still maintained between the pile and the ground after a thermal cycle.

It should be noted here that the final temperature values are different from the initial ones; this explains why the strains do not return to zero at the end of the heating-cooling cycle.

4.2 *Induced thermo-mechanical stresses*

In the case where the pile is not entirely free to move (e.g. due to side friction or blocked head and toe), part or all of the induced thermal deformation will be prevented. The constrained strains produce thermal stresses. Figure 6 gives the vertical stress profile

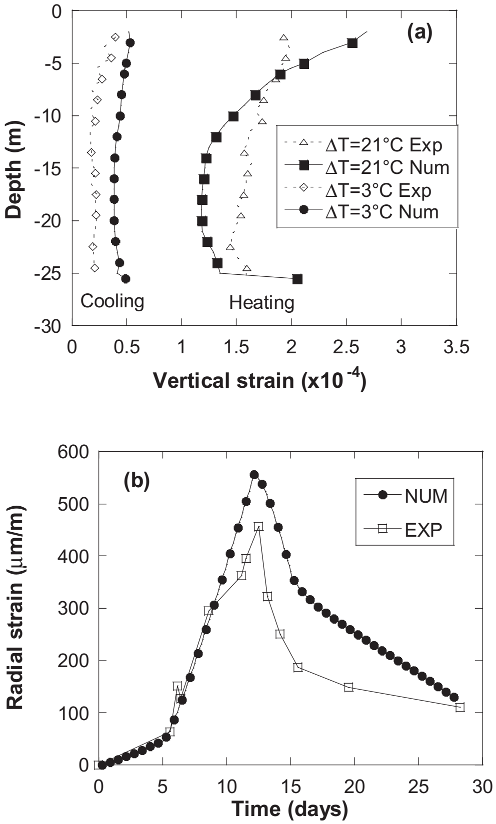

Figure 5. Thermal strains in the pile during a heating and cooling period.

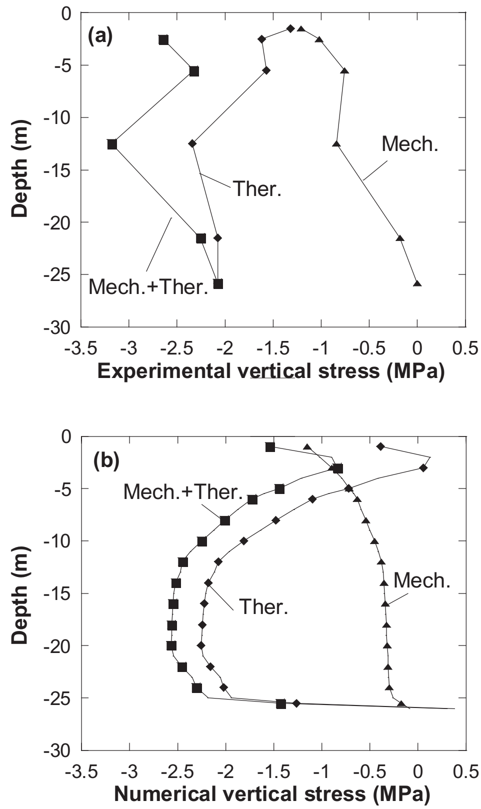

Figure 6. Thermo-mechanical vertical stresses in the pile (ΔT = 13.4°C): (a) experimental results; (b) numerical simulations.

along the pile axis due to the thermo-mechanical load in the case where the building is constructed.

The experimental results clearly show the differences between the effects of the mechanical and the thermal loading (Figure 6a). Even though the mechanical axial stress is large at the pile top (on the order of 1.3 MPa) and diminishes with depth (the toe carries almost no load), the thermal load is larger and rather uniform. This results in an overstress on the order of 1.2 MPa at the pile head and strongly loads the toe (2 MPa). An analysis of other tests shows that a temperature increment of 1°C results in an additional temperature-induced load on the order of 100 kN.

As a consequence, the total axial load in the pile is twice as large as the one due to purely mechanical loading, with a large vertical stress in the toe. The numerical model is able to reproduce the decrease in the mechanical vertical stresses with depth as well as the increase in the thermally-induced vertical stresses with depth (Figure 6b).

5 CONCLUSION

Using experimental results from local full-size in-situ test of one heat exchanger pile, a coupled displacement-temperature finite element analysis was carried out. It was assumed that : i. the concrete and the soil were governed by a thermo-elastoplastic law, and ii. the heat flow followed Fourier's law. The numerical calculations reproduce quite well the experimental results.

The thermo elastic straining of the pile presents the following main behaviours:

i. The pile deformation depends on the type of surrounding soil.

ii. Whereas the mechanical load affects mostly the top of the pile, the thermal load creates rather large axial stresses at the toe.

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