Real-scale test campaign on energy piles for Belgian practice and numerical modelling of their behaviour

Campagne d'essai en grande échelle sur des pieux énergétiques pour la pratique belge et modélisation numérique de leur comportement

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ABSTRACT : During the past decade, thermally activated foundation piles have been installed in several Belgian construction works, mostly for office buildings but also for residential buildings. Despite of the satisfying performance of these energy supplying structures, a breakthrough seems to be blocked by a lack of knowledge and documented experience with regard to the energetic performance of the energy piles. In addition, the potential impact of (cyclic) temperature changes on the pile response in terms of bearing capacity and settlements is still questioned, particularly for piles with a relative small diameter. The present paper describes a real-scale energy pile test setup in Belgium and presents the first results of the thermo-mechanical behaviour of 3 different pile types. Next, the potential of a commonly used Finite Element software package for geotechnical design to model the energy pile behaviour is assessed. The Finite Element model is calibrated based on the in-situ measurements of a thermo-mechanically loaded displacement screw pile and shows good agreement.

RÉSUMÉ : Durant la dernière décennie, des pieux de fondation thermoactifs ont été installés sur différents sites de construction en Belgique, la plupart pour des immeubles de bureaux mais certains pour des bâtiments résidentiels. Malgré les performances satisfaisantes de ces structures énergétiques, l'avancée de cette technique semble bloquée par un manque de connaissance et de retour d'expérience concernant les performances énergétiques de ces pieux. De plus, l'impact potentiel des variations (cycliques) de température sur la capacité portante et sur le comportement en tassement de ces pieux est mis en question, particulièrement pour les pieux de relativement faible diamètre. Le présent article décrit une installation expérimentale en grandeur réelle de pieux énergétiques, réalisée en Belgique. Les premiers résultats décrivant le comportement thermomécanique de trois différents types de pieu sont aussi présentés. Ensuite, le potentiel d'un programme numérique usuel de type éléments finis, dédié au dimensionnement géotechnique, utilisé pour la modélisation du comportement des pieux énergétiques est discuté. Le modèle éléments finis est calibré sur les mesures in situ de pieux vissés soumis à un chargement thermomécanique et montre une bonne correspondance.

KEYWORDS: energy geostructures, energy piles, numerical modelling, finite element modelling, in situ testing

1 INTRODUCTION

Shallow geothermal energy systems (i.e. common depths of about 50 to 150 m in Belgian practice and low temperature levels of about 10 to 12 degrees) have become a widely applied technique during the last decade for the heating and cooling of all types of buildings. The growing potential of shallow geothermal energy is a result of the decreasing heating demand of buildings due to better energetic performance of new and retrofitted buildings. In many cases, the cooling demand becomes an important part of the building energy demand, favouring the thermal balance of the Underground Thermal Energy Storage (UTES) system. UTES is a general term used for closed and open systems, respectively known as Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES) systems. Until now, only BTES systems are referred to when talking about thermally activated geostructures or shortly, energy geostructures.

The trend to a limited thermal energy demand of buildings offers opportunities to underground infrastructure. Even when the installation depth of the geotechnical element is limited and this zone is partly influenced by seasonal temperature variations, energy geostructures – particularly energy piles – have shown their potential all over the world (Pahud and Hubbuch 2007, Brandl 2013). Nevertheless, Belgian building owners and project developers remain rather sceptical, while the wide application of energy piles in e.g. UK shows that it can be a competitive alternative for traditional UTES systems.

Several international studies have investigated the thermo-mechanical behaviour of energy piles, which resulted in a framework of the thermo-mechanical behaviour with respect to the end-restraint boundary conditions and mobilized shaft shear friction (Bourne-Webb et al. 2013). Numerical simulations have also been performed with different numerical methods, e.g. the finite difference method (Suryatriyastuti et al. 2012) and the finite element method (Olgun et al. 2015, Di Donna and Laloui 2014). Some software packages also allow thermal and/or thermo-mechanical pile design (e.g. PILESIM, Thermo-Pile, Oasys PILE and Oasys LS-DYNA).

This paper presents the results of the in situ test campaign on energy piles performed on small diameter piles. Next, a Finite Element (FE) model of the test setup is elaborated in Plaxis 2D and compared to the field measurements.

2 IN SITU TEST CAMPAIGN

2 .1 *Site characterisation and installed pile types*

The full-scale experimental tests were conducted on a site in Ostend (Belgium). Based on several CPTs and drill cuttings the soil profile of the upper 15 m can be characterized as follows (see also the Cone Penetration Test (CPT) profile in Figure 1):

- 0 m – 5 m: soft clay and silt, locally organic
- 5 m – 6 m: peat
- 6 m – 10 m: moderately dense sand
- 10 m – 11 m: silty clay
- 11 m – 14 m: dense sand with local thin silt layers
- 14 m – 15 m: clay

Locally, additional peat layers might be present.

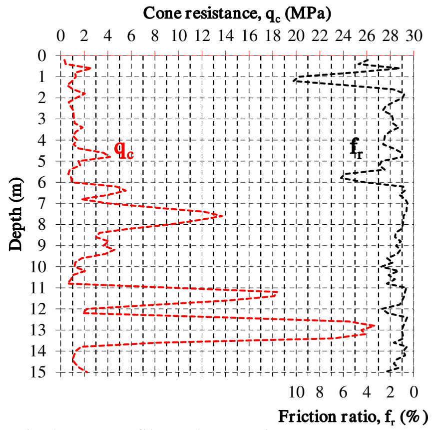

Figure 1. Typical CPT profile at the test site.

In this article the test results of the thermo-mechanical behaviour of 3 energy piles are discussed. Their characteristics are summarized in Table 1. All piles were installed to a depth of 11.5 m and were equipped with a single U loop heat exchanger (PE-Xa 32×2.9 mm) and 2 steel reservation tubes, attached to the reinforcement cage prior to pile execution (Figure 2).

Table 1. Characteristics of the discussed energy piles P1, P2 and P5.

Parameter	*P1*	*P2*	*P5*
Pile type	Displacement screw piles		CFA pile*
Shaft shape	screw	smooth	smooth
Pile diameter (mm)	360/560	435	420

* *Continuous Flight Auger (CFA) pile executed with a temporary casing*

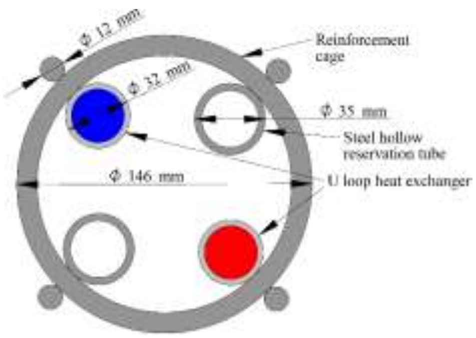

Figure 2. Schematic top view of the reinforcement cage.

2.2 *Overview of the instrumentation*

After pile installation, Fibre Bragg Grating (FBG) strain sensors and thermocouples were inserted in the reservation tubes and fixed with a water/cement mixture. Temperatures are also monitored at different depths inside the heat exchangers and in the surrounding soil. A cross-section of the instrumentation is shown in Figure 3.

2.3 *Mechanical and thermal loading*

The mechanical loading is applied by a reaction system consisting of 2 micropiles installed at both sides of the energy piles (Figure 4). The applied force is measured by a dynamometer. A LVDT measures the pile head displacements.

For the thermal loading, a specific installation has been designed to allow performing Thermal Response Tests (TRT, i.e. supplying a constant temperature difference between inlet and outlet at constant flow rate) as well as supplying a constant temperature between about -5 and +40 °C at the inlet of the energy pile.

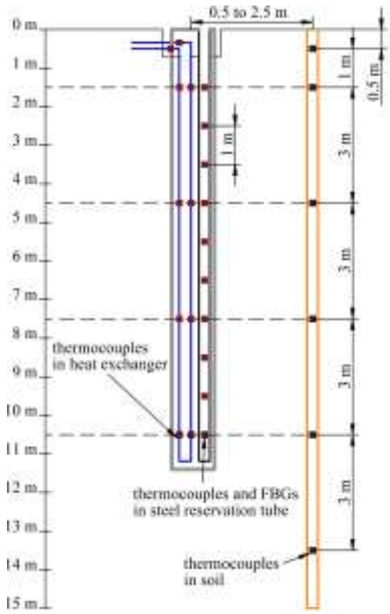

Figure 3. Cross-section of the pile and soil instrumentation.


Figure 4. Energy pile P1 (centre) with mounted reaction frame.

2.4 *Experimental results*

Before applying the mechanical load, all piles have been tested thermally (TRT), in order to determine the thermal pile resistivity and thermal conductivity of the soil. During this preliminary TRT test, compressive axial forces appeared in the pile, due to restrained thermal extension. After the TRT test and prior to mechanical loading some residual compressive strains were present in the piles (see Figure 5 at 0 kN).

Consecutively, the mechanical load has been applied stepwise up to 400 kN (i.e. the reference situation). Under this load, pile head settlements of about 12, 10 and 2 mm were measured for piles P1, P2 and P5 respectively. The limited settlement of P5 is probably due to a concrete bulge just below the pile head. The upper part of Figure 5 shows the depth profile of the axial forces in the 3 piles at 0 and 400 kN. The axial forces were deduced from the measured strains and the combined concrete and steel Young's modulus. Subsequently, the piles were loaded thermally, while the pile load was kept constant at 400 kN. Figure 5 illustrates the resulting axial forces and temperatures at the end of 3 thermal loading steps, for which the temperature at the inlet of the energy pile was maintained constant during at least 3 days at about +40, +30 and -4 °C. Nevertheless, the pile temperatures at the FBG strain sensors (i.e. in the reservation tubes) remained about 5 to 10 °C away from the imposed temperatures at the heat exchanger inlet, resulting in a temperature difference at the FBG sensors of +15, +10 and -10 °C with respect to the undisturbed soil temperature. This shows that it takes a significant time before extreme temperatures in the heat exchangers reach the pile shaft (e.g. to prevent soil freezing).

From Figure 5, it can be deduced that, due to an increasing pile temperature the axial forces in the piles increase. The increase is rather constant along the pile lengths but slightly lower at the upper part of the piles (especially for P1). The high increase of axial forces observed in P5 (CFA pile), despite its execution technique with lower shaft friction, is probably linked to the pile head restraint. This might also explain why the increase of axial force between the temperature steps of +30 and +40 °C is much more pronounced for P5 than for P1 and P2. With regard to the load transfer to the soil, it can be concluded for all three piles that the increasing temperature in the pile leads to a significant decrease of the positive pile shaft friction, which even turns into negative skin friction in the upper part of the pile above the peaty layer. However, this effect is compensated by an important increase of the pile base resistance. The effect of the temperature increase on the pile head displacement is limited to about 1 to 2 mm upwards.

For the cooling phase, the axial forces in the piles decrease and the influence is again most pronounced for P5. At the lower part of the piles even small tensile forces are observed, particularly for P5. Contrary to the heating phase, a more irregular normal load distribution can be observed, especially for piles P1 and P2, which show larger settlements due to cooling. The reason for this is probably the presence of intermediate soft layers in the soil profile.

With regard to the load transfer to the soil, it can be concluded that due to the cooling of the pile the shaft friction generally increases for all piles over there complete length but that the pile base resistance decreases. The effect of the temperature decrease on the pile head settlement is limited to 2 to 3 mm for P1 and P2 and less than 1 mm for P5.

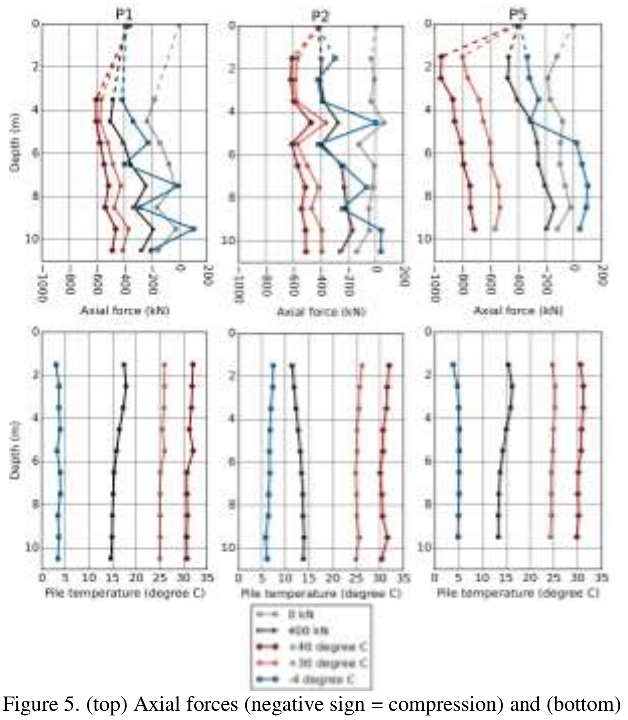

Figure 5. (top) Axial forces (negative sign = compression) and (bottom) temperatures in function of depth for energy piles P1, P2 and P5 at different loading steps. The legend refers to the temperatures at the inlet of the pile heat exchangers.

3 FINITE ELEMENT MODEL DESCRIPTION

In the Finite Element software Plaxis 2D a fully coupled thermo-hydro-mechanical formulation is implemented, as the following balance equations are considered: mass balance equation (including permeability temperature dependence), linear momentum balance equation (including thermal strain effect on effective stresses) and energy balance equation (including advection and convection flux energy). However, thermal plastic strains are not considered and the temperature dependence of the mechanical behaviour is limited to linear elastic thermal expansion. Furthermore, effects of temperature on soil stiffness parameters, yield surfaces and pre-consolidation stresses are not taken into account. To assess the feasibility of Plaxis for modelling the thermal and thermo-mechanical behaviour of energy structures, the test setup on energy pile P1 has been simulated (Allani et al. 2017). It is important to note that the residual stresses due to the preliminary purely thermal loading (TRT) of the pile have not been taken into account in these simulations.

An axisymmetric configuration is considered (Figure 6). The modelled area measures 20 × 20 m² and the mesh comprises 15-node triangle elements. For a better calculation of large stress concentrations and large deformations, a refined mesh zone around the pile-soil interface was adopted. Vertical and horizontal fixities were applied to the base, while horizontal fixity was applied to the left and right boundaries.

The soil stratigraphy as described in paragraph 2.1 has been adopted. A mean pile diameter for P1 of 460 mm is assumed. No installation effects were considered for the pile, which means that the pile was 'wished into place'. For bored piles this approach is realistic. However, for displacement piles an increased horizontal stress along the pile length should be modelled (i.e. by implementing a higher coefficient of lateral earth pressure K_0 or by imposing a certain amount of soil displacement before pile installation). This approach is more complicated (Dijkstra et al. 2011, Broere and Van Tol 2006) and was out of the scope of this work.

For pure mechanical loading, an axisymmetric configuration can be adopted without altering the physics of the problem. The U-shaped heat exchangers imply a 3D representation. This was not possible with the current software and a concentric heat exchanger was thus assumed at the centre of the energy pile by means of a thermal flow boundary, at which the temperature evolution measured inside the heat exchangers was imposed.

The Hardening Soil (HS) Model with Small-Strain-stiffness (HSsmall) is used to model the soil behaviour. The required soil parameters are described by Allani et al. (2017). A rigid interface is considered between the pile and the soil. Initial soil stresses are generated automatically based on the HS model. All calculations are performed using drained analysis for the sand and silt layers and with undrained analysis for the clay layer. The pile is considered as non-porous with a linear-elastic material model.

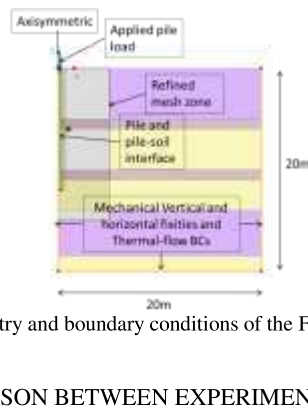

Figure 6. Geometry and boundary conditions of the FE model.

4 COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

4.1 *Mechanical and thermal calibration*

The calibration process of the FE model and the resulting soil and concrete strength and thermal parameters have been extensively discussed by Allani et al. (2017). As expected, the resulting soil strength parameters are slightly higher than for normal conditions, as no installation effects were considered for the displacement pile. A satisfactory matching between the measurements and the numerical simulations was found for the mechanical as well as the thermal response. The low shaft friction generated at the peat layer at about 6 m depth is also observed in the simulations, however less pronounced (Figure 7a). Nevertheless, at the lower part of the pile the simulated mobilized friction is higher, resulting in lower axial forces than measured, which is in this case not surprisingly as the residual stresses due to preliminary TRT testing have been neglected. In Figure 7b the measured and simulated thermal response of the soil at 0.5 m distance from the pile centre are compared before the start of test (T_ref) and at the end of a heating and cooling phase, respectively 40 and -4 °C imposed at the inlet of the energy pile. Above 7 m depth, the agreement is less accurate. At 13.5 m depth, the calculated soil temperature is not affected by the pile heating and cooling, which is also observed in the measurements. The transition between heated soil and earth gradient temperature is well captured in the measurements.

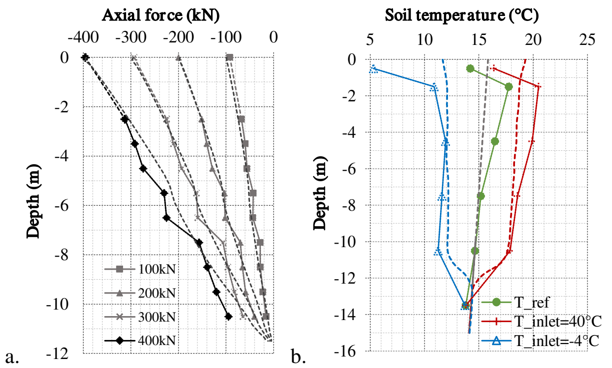

Figure 7. Comparison between the in situ measurements (solid line) and the Plaxis simulations (dashed line). (a) Axial forces in function of the pile depth at different load steps of the static load test on P1 (negative sign is compression). (b) Soil temperature at 0.5 m from the pile centre.

After model calibration, the thermo-mechanical coupling is investigated. Figure 8 shows the comparison between measured and simulated (non-restrained or free) thermo-mechanical deformations along the pile length for different temperature phases. Note that the change of thermal deformation with respect to the 400 kN reference cannot be larger than the thermal expansion coefficient multiplied by the temperature change. Below 6 m depth, a good matching is observed. The increased thermal deformation at the peat layer around 6 m depth (because of the lower shaft friction resistance) is also simulated by the FE model. However, at depths less than 6 m the simulated thermal deformation is systematically larger than the measured deformation. This might be caused by the simplified way in which the pile installation effect has been modelled or the fact that the thermal loading history of the pile is not taken into account.

5 CONCLUSION

The first results of a real-scale experimental test setup on different types of energy piles were presented. The effect of extreme heating (up to +40°C) and cooling (down to -4°C) on the axial forces in foundation piles and on the pile-soil interaction was clearly observed. Even though the temperature variations were very high and the pile sections were rather limited, the concrete stresses and pile head displacements remained within acceptable limits. It is also clearly observed that pile end restraints and soil type significantly influence the energy pile behaviour. This is illustrated by the behaviour of P5, which was believed to have the lowest shaft friction and thus to allow more thermal extension and/or contraction. However, the highest thermally induced forces (for heating as well as cooling) were observed for this pile type, probably due to the end restraints of the pile head (and base). At the time of writing, the test campaign is still on-going to study the effect of cyclic heating and cooling (i.e. simulation of the seasonal varying building energy demand) on the pile behaviour.

In addition, the thermo-mechanical response of energy pile P1 was simulated with a simplified FE model. The results are promising with regard to the feasibility of the FE model to simulate energy pile behaviour. A good understanding will allow to perform parametrical studies of the effect of e.g. pile head and base end restraint and soil type and to model the behaviour of groups of (energy) piles below a building structure.

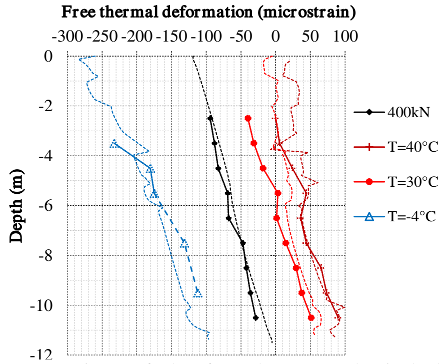

Figure 8. Comparison of the free thermo-mechanical deformation (negative sign is contraction) of the pile P1 as measured (solid lines) and as simulated by Plaxis (dashed lines).

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