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Analysis of Thermo-Mechanical Behaviour of Energy Piles

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ABSTRACT: The use of pile foundations as heat exchangers in combination with heat pump conditioning systems are becoming increasingly popular. Quite a large number of small scale laboratory tests and field scale experiments are available and allow to gain an insight in the mechanisms governing pile-soil interaction under thermo-mechanical loading. In the paper, numerical FEM simulations are carried out on published experimental small scale laboratory tests. The paper focus is on the load-settlement relationship and on the load-transfer curves with depth. The tests show that under purely cyclic thermal loading reversible strains are predominant, while the preliminary application of an axial load causes the development of irreversible deformations during the thermal loading. Numerical FEM simulations carried out with two different constitutive soil models confirm such a finding. A simple procedure to calibrate the model's parameters is proposed and validated.

KEYWORDS: Energy piles; Finite element modelling; Pile testing; Thermo-mechanical behaviour.

1. INTRODUCTION

Shallow geothermal resources use thermal energy stored in the Earth at depths lower than 400m. Rocks and soils are good insulators and at a few meters below the surface ground temperature remains approximately constant during the whole year. At depths ranging between 10 and 20 m, ground temperature fluctuations caused by daily or seasonal variations are not significant; the average value of the yearly temperature keeping practically constant in the range from +5 to +10 °C depending on the geographic location (Brandl, 2006). The constant temperature condition of the ground can be used for cooling and heating purposes in buildings equipped with Ground Source Heat Pumps (GSHP) system connected to the foundation structures -often referred to as ‘‘energy piles’’. The ground obviously act as a heat source in the winter and a cold source in the summer.

Shallow geothermal systems are divided into three main parts: (i) the primary circuit, embedded in piles or alternative underground structures, where the fluid circulates through pipes and exchanges heat with the ground depending on the seasonal operation; (ii) the secondary circuit which is responsible for the heat transfer in the buildings rooms, and (iii) the Heat Pump which connects the two circuits allowing heat transfer and adds further energy in the system depending on the climatization demand.

Thus the GSHP uses ground thermal energy with a small amount of additional electrical power to reach the temperature desired for indoor conditioning purposes. The Heat Pump is characterized by an efficiency coefficient which is defined as the heat released to (or extracted from) the building divided by the external electrical energy provided to the heat pump. The value of this coefficient COP (see eq.1) depends of course on the difference between the temperature of the building and the temperature of the ground system, the larger the difference the smaller the efficiency.

$$COP = \frac{Heat\ outflow\ [kW]}{Energy\ power\ provided\ to\ the\ Heat\ Pump\ [kW]} \qquad (1)$$

It can be shown that in order to make this system really convenient the coefficient COP should be greater than or equal to 4. The sketch in Figure 1 shows the way the GSHP should work with a value of the COP=4. Piles working as heat exchangers are a good solution for the primary circuit. The pile shaft is generally filled with concrete and the closed loop circuit made by polyethylene pipes is usually attached to the reinforcement cage. Some recent studies have outlined the importance of the position of the pvc pipes inside the pile on the efficiency of the heat exchange (Abuel-Naga & Chalabi, 2016; Carotenuto et al., 2017). Concrete has a rather high thermal conductivity which makes it an appropriate medium for heat exchanging. The absence of specific regulations or guidelines on the design of energy piles must be emphasized even if in recent years an increasing number of research and technical papers can be found covering both experimental and theoretical aspects of the behavior of such structures (Bourne_Webb et al., 2009; Mimouni & Laloui, 2014).

The paper focuses on the soil-structure interaction issue which arises when the embedded structure, the pile, is subjected to cooling action (in the winter season) or to heating action (in the summer season) (Amatya et al., 2012) and does not deal further with the GSHP system. In the following sections, after a short literature review, a case history on piles under combined thermo-mechanical loading is back-analysed using FEM. The results obtained under different loading conditions and adopting two constitutive soil models are presented and discussed.

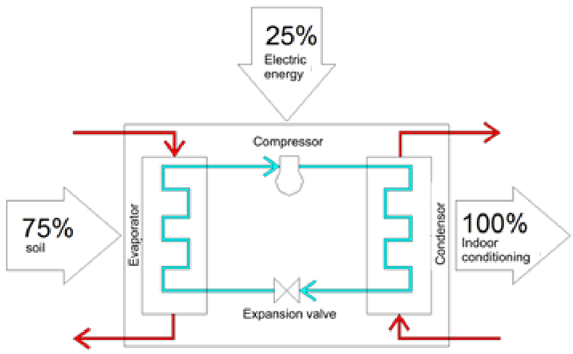

Figure 1 Heat Pump efficiency (heating of the building cycle)

2. CASE STUDIES

In recent years a number of case histories on the thermo-mechanical performance of energy piles have been published. Some of them deal with small model piles in calibration chamber at 1g (g=gravity acceleration) (Kalantidou et al., 2012; Yavari et al., 2014; Yavari et al., 2016; Nguyen et al., 2017) subjected to both mechanical and thermal cyclic loading. Interesting centrifuge tests on different pile types have been carried out by several authors investigating different aspects of pile behaviour at more realistic stress levels (Stewart & McCartney, 2013; Ng et al., 2015; Rotta Loria et al., 2015). Stewart and McCartney (2013) investigated thermal cycle effects on the pile head displacement for end-bearing piles. The influence of temperature variations on the stiffness and the bearing capacity of a single floating pile in medium dense saturated sand was experimentally investigated with centrifuge tests by Ng et al. (2015). Ng et al. (2016) investigated the influence of the installation method on the cyclic response of floating piles in sand. A few thermal experiments on full scale pile foundations with piles used as heat exchangers under combined axial loading may be found in the technical literature (Brandl, 2006; Laloui et al., 2006; Bourne Webb et al., 2009; Mimouni & Laloui, 2014). These are not necessarily the most valuable case histories because sometimes they suffer of only a limited control of the boundary conditions of the experiment which at laboratory scale are more easily controlled and monitored.

A common issue for many of the mentioned case studies is the behaviour of piles under cyclic thermal loading. As a matter of fact, in any real application of the GSHP system, this aspect is very important. Also the combined effects of axial loading, on piles as part of the foundation system, and thermal loading are important and need to be investigated. For both reasons particularly interesting is the case study on models at laboratory scale published by Yavari et al. (2014).

3. EXPERIMENTAL BEHAVIOUR: CYCLIC THERMO-MECHANICAL LOADING

The use of piled foundations as heat exchangers implies a number of soil-structure interaction issues to be addressed at the design stage. An important issue is the amount of additional displacement and/or stress induced by combined thermo-mechanical cyclic loading. On this specific issue the selected case history (Yavari et al., 2014) was considered as a benchmark for the numerical modelling and for proposing a calibration procedure for the model parameters. The experiments were carried out on a model aluminium closed end pipe pile. The length of the pile was 600 mm and its outer and inner diameters were 20 and 18 mm, respectively. The pile was embedded in dry Fontainebleau sand compacted at a dry density of 15.1 kN/m^3 (DR=50 %). Main properties of the Fontainebleau sand are discussed by De Gennaro et al. (1999, 2008). Three sets of experiments were conducted: i) purely mechanical tests, ii) purely thermal tests and iii) thermo-mechanical combined tests. Figure 2 summarizes the full test program. The test E1 was a standard mechanical head load test with a maximum head load of 450 N carried out on a pile at the constant temperature of 20°C. The test E2 was a purely thermal test with the pile submitted only to an overall temperature change of nearly 30°C. The tests from E3 to E7 were all thermo-mechanical combined tests. To monitor the pile behaviour along its shaft, five strain gauges and three temperature sensors were stuck to its external surface.

In Figure 3 the load settlement relationships for the test E1 and for the mechanical part of the other tests (i.e. E3, E4, E5, E6, E7) are reported, demonstrating the repeatability of the mechanical tests. In the purely mechanical test E1, the pile was axially loaded up to conventional failure, fixed at a settlement equal to 10% of the pile diameter d (2 mm). The failure occurred at 450 N following a preliminary loading and unloading cycle at 200 N. Detailed time histories are available for the thermal cycles of the test E2 and the test E6. The temperature as measured at the sensor placed inside (in the middle of) the pile for both tests are plotted in Figure 4. In Figure 5 the measured increase of settlement of the pile head is plotted versus time (left side) and versus pile temperature (right side), this last one as measured by the temperature gauges stuck on the external pile surface. The increase has been plotted negative when the movement of the piled head was directed downwards.

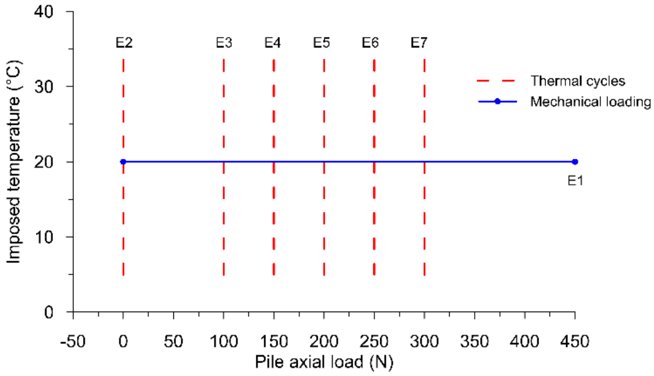

Figure 2 Test program (after Yavari et al., 2014)

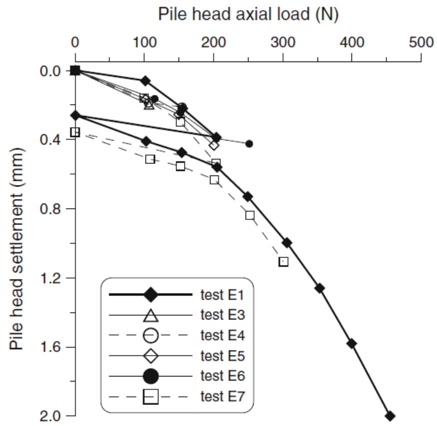

Figure 3 Load settlement relationship for mechanical loading (after Yavari et al., 2014)

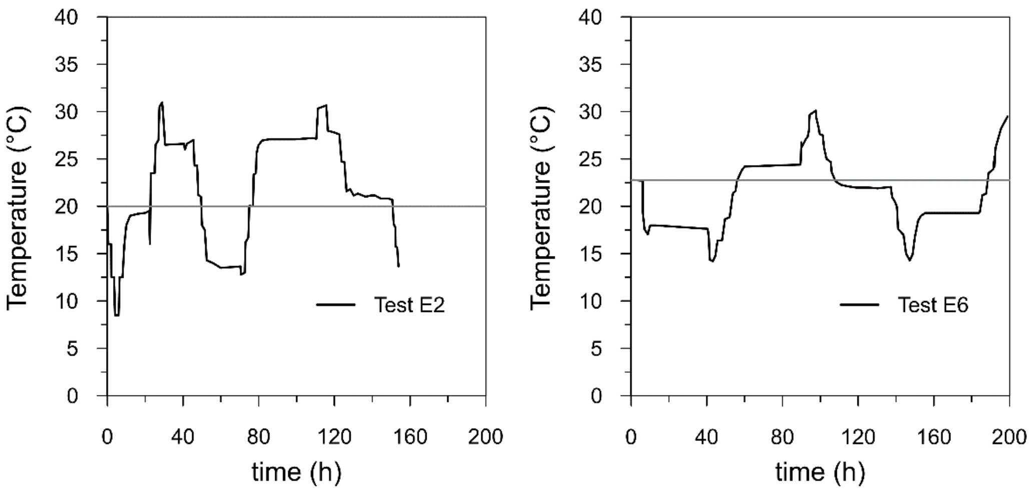

Figure 4 Temperature changes in tests E2 and E6 at pile axis

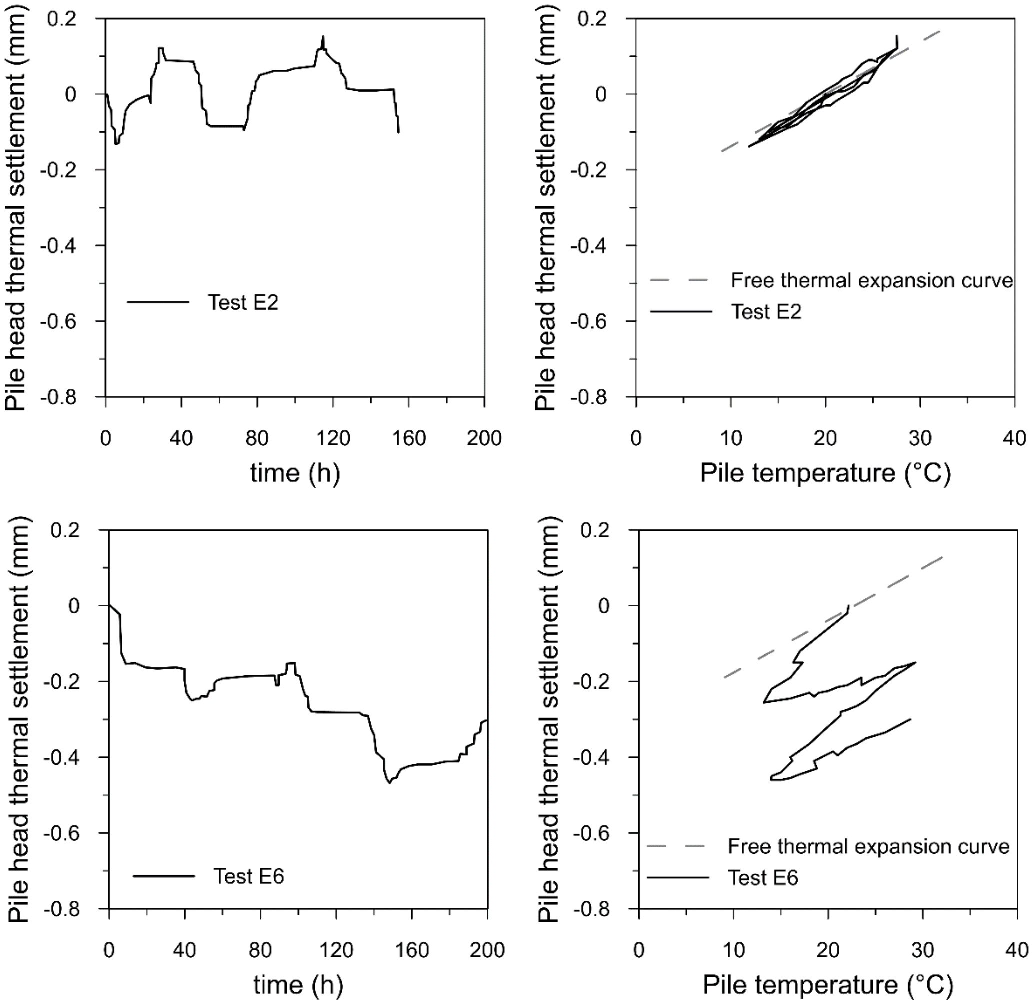

Figure 5 Measured settlement of the pile head vs. time (left) and vs. temperature changes (right) in tests E2 and E6

Interesting feature of the observed behaviour is that at zero mechanical head load (pile test E2), the applied thermal cycle produces fully reversible effects while at larger mechanical loads (pile test E6) the thermal cycles are responsible of not reversible effects. In other words thermo-elastic behaviour is shown at zero head load while thermo-plastic behaviour is exhibited at relatively large head load. The slope of free thermal expansion curve, plotted in Figure 5, is equal to the linear expansion coefficient of aluminium (α= 23 x $10^{-6}\mu\varepsilon/°C$).

4. FEM NUMERICAL MODELLING

Recently several numerical approaches have been proposed to model the coupled thermal, hydraulic and mechanical (THM) effects on energy piles and the surrounding soil (Adinolfi et al. 2016, 2018; Salciarini et al., 2015; Suryatriyastuti et al., 2012). On the other hand, traditional computer codes dedicated to the analysis of pile-soil interaction under axial loadings are not capable of dealing with thermal loadings too.

The case history by Yavari et al. (2014) was thus back-analysed using the FEM package Plaxis 2D. The focus of the back-analyses was on the comparison between the results obtained by means of two different constitutive soil models, the Mohr-Coulomb, more diffused among the practitioners, and the Hardening Soil, more advanced by a mechanical point of view (Schanz et al., 1999; Brinkgreve et al., 2010).

Only recently an explicitly dedicated thermal module was introduced in the FEM package PLAXIS 2D/axi-symmetrical. Yavari et al. (2013) already presented a tentative back-analysis of the experiments using the old version of the code Plaxis (i.e. not including the thermal module) and simply modelling the volume change of the pile induced by the temperature increase. In their simulation thermal interaction between the pile and the soil was thus neglected. In the following the results obtained by the thermal module of the Plaxis 2D are indeed presented. In Figure 6 the FEM model and the boundary conditions adopted are shown. A fine mesh of 3574 triangular (15-noded) elements is used to discretize the soil and the pile in the container. The size of the FEM model has been assumed equal to the size of the experimental container. Interface elements have been adopted to allow slip at the pile-soil contact.

In Table 1, the main physical and mechanical parameters for the Fointanbleu sand as a Mohr Coulomb material are listed. These parameters were deduced by De Gennaro et al. (1999, 2008) who carried out load tests in calibration chamber on very similar piles embedded in the same type of sand. In the case by De Gennaro et al. (2008) the sand was preliminary subjected to a confining isotropic state of stress p'=100 kPa. In the tests by Yavari et al. (2014) no confining stress was indeed applied. For this reason, the parameters reported in Table 1 have been reconsidered as a function of the largely different stress level.

4.1 Calibration of model parameters

The pure mechanical axial load test E1 was used to calibrate the strength and the stiffness parameters of the elastic-plastic M-C model and of the H-S soil model. A classical best fit procedure based on the

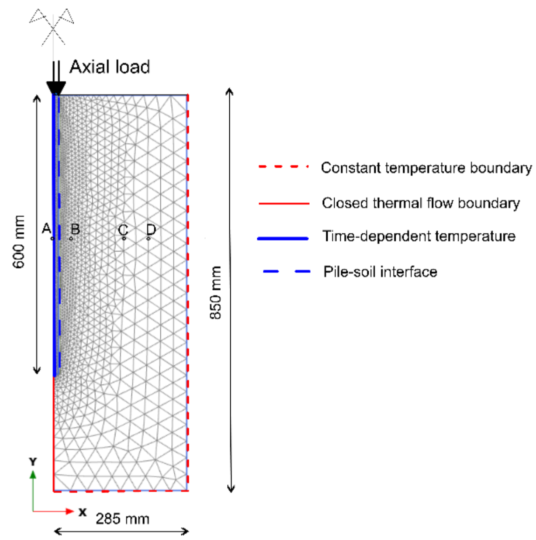

Figure 6 Finite element mesh used for the simulation

trial and error method was adopted to simulate the test E1, which can be considered as an Ideal Load Test according to the definition by Mandolini et al. (2005) and Russo (2013), i.e. a load test where the reaction frame has no interaction with the tested pile and consequently does not influence the back-analysed soil stiffness. This occurs because the selected test is at laboratory scale while in any field scale tests the reaction frame (kentledge system or beam with ground anchors) may have a strong influence on the back-analysed pile-soil relative stiffness.

Table 1 Soil parameters for Fointanbleu sand at DR=50% (De Gennaro et al., 1999)

parameter	Fontainbleu dry sand
γ (kN/m^3)	15
c' (kPa)	0
ϕ (°)	36,5
ψ (°)	6
E (MPa)	34
K_0 (-)	0,5
p'(kPa)	100

After several attempts the trial and error procedure allowed the determination of the set of parameters listed in Table 2. In all the FEM analyses no reduction of the friction angle was assumed for the interface elements compared to the surrounding soil. This was considered the best option since, in order to enhance pile-soil friction, the authors of the experiment had glued a thin layer of sandy grains on the outside of the metal pile shaft.

Table 2 Soil parameters for Fointanbleu dry sand obtained from the calibration procedure and pile properties used in the FEM model

parameter	Fontainbleu dry sand	pile
γ (kN/m^3)	15	20
c' (kPa)	0,1	
ϕ (°)	37	
ψ (°)	7	
E (M-C) (MPa)	4	23000*
E_{50} (H-S) (MPa)	4	
E_{ur} (H-S) (MPa)	12	
p' (kPa)	3,5	

* Elastic material and equivalent modulus for an aluminum pipe pile considered as a solid cylinder

Just to provide an example of the sensitivity study conducted at this stage, three different predictions, M-C (1) to M-C (3), obtained via the M-C model are compared. The differences among the predictions derive from the adoption of three values of friction angle ϕ and of dilatancy angle ψ. M-C (3) is the final prediction which is also the one showing the best agreement with the experimental curve and is obtained by assuming the values reported in Table 2 (i.e. ϕ = 37° and ψ=7°). M-C (1) and M-C (2) are the predictions obtained by assuming respectively smaller values (ϕ=36° and ψ=6°) and larger values (ϕ=38° and ψ=8°) for both friction and dilatancy angles. The three predicted curves plotted in Figure 7 show how large is, at high load levels, the influence of these parameters on the computed axial response.

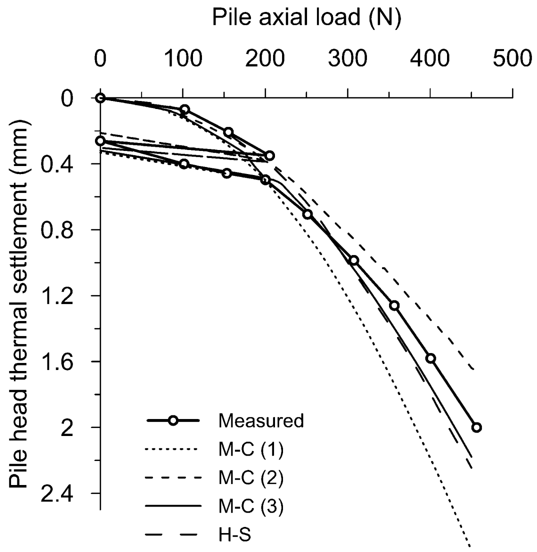

Figure 7 Comparison between measured and calculated load settlement relationship for test E1

As reported in Table 2 the value of the Young's modulus E for the M-C model and of the equivalent modulus E_{50} of the H-S model which produced the best agreement between the computed and the experimental load-settlement relationship was 4 MPa. This value is not in contrast with the value of 34 MPa reported in Table 1 if the largely different stress level is taken into account. The average stress level at mid depth down the model aluminium pile is only about 3 kPa while in the case by De Gennaro et al. (2008), in the calibration chamber, the reference isotropic stress p' was 100 kPa. Furthermore, in the H-S model, the possibility to account for the stress level influence on the moduli E_{50}=E_{oed}=E_{ur}/3 was also used, while the ratio among the values of the three moduli were kept equal to the suggested value (Brinkgreve et al., 2010). The increase with depth (i.e. with the effective stress) of the moduli was fixed as a power function with exponent m=0,5.

The k_0 value was kept constant and equal to 0,5 (Table1) because the pile installation technique was not responsible of significant change in the horizontal stress around the pile compared to the undisturbed lithostatic condition.

In Figure 7 the load settlement relationship obtained by the Plaxis code by using the H-S model is also compared with the experimental curve.

The comparison shows that the agreement with the experiment for both the soil models is satisfactory. It is obviously not surprising considering that the parameters of the soil model have been calibrated with a trial and error best fit procedure. The general trends of both the primary loading and of the unloading-reloading (URL) experimental curves are satisfactorily reproduced by both the models even if the H-S model, as it could be expected, allows a better fitting of the observed behaviour on the URL path.

Summarizing the findings of this section it can be concluded that the two models show the same capability in reproducing the measured experimental behavior, the H-S model being just better in fitting the first unloading branch following the primary loading.

4.2 Thermo-mechanical back-analysis

The two soil models M-C and H-S were then used for back-analysing the thermal experiments E2 and E6. The thermal properties of the dry sandy soil and of the aluminium pile obtained from literature are reported in Table 3.

The thermal histories applied at the model pile in the two tests E2 and E6 are plotted in Figure 4. More precisely in the FEM model (Figure 6) a time dependent thermal boundary condition along the axis of symmetry of the pile was applied. Below the pile tip, the axis of symmetry was defined as a closed thermal flow boundary while the bottom and the right side of the model were set as constant temperature boundaries, the constant selected value corresponding to the environment temperature of the experimental setup.

Table 3 Thermal properties of the soil and the pile in the FEM model

parameter	Fontainbleu dry sand	Aluminium
thermal expansion α ($\mu\varepsilon$/°C)	20	23
thermal capacity c_s (kJ/t/°C)	860	2240
thermal conductivity λ (kW/m/°C)	$3*10^{-3}$	$54*10^{-3}$

The numerical analyses were carried out using the transient flow option being the applied thermal history characterized by rather quick changes of the imposed temperature. The FEM results are also compared with the available experimental measurements in Figure 8. The full time history of the measured pile head settlement is plotted together with results computed via the H-S model and the M-C model for the thermal test E2. The comparison is indeed satisfactory for both soil models. As shown by the plots in the upper part of Figure 8 the observed pile head movements with the temperature change are essentially reversible, the full excursion range being slightly smaller than the theoretical free thermal expansion curve obtained by imposing the thermal change ΔT to an ideally free aluminium pile. This is an expected result considering the soil-pile interaction as a partial constraint to the free expansion of the metal pipe pile. The calculated pile head settlement with both the models are very similar and in good agreement with the experimental data. The largest difference between computed and measured head settlement, however, occurs at the end of the first cooling step and corresponds to around 30% of the measured value.

In the case of test E6 the thermal load was applied under a constant head load of 250 N. which is about one half of the measured axial bearing capacity of the pile. As shown by the bottom part of Figure 8, irreversible settlement occurs already in the first thermal cycle and increases further in the second thermal cycle. Being the thermal cycles very similar to the ones adopted in the test E2, there is a clear coupling between mechanical and thermal loading. In the case of test E6 the comparison between the two models shows that the H-S model is better than the M-C model in predicting the amount of irreversible movements. At the end of the thermal history the H-S computed final settlement is only 20% smaller than the observed value while for the M-C model the difference increases to more than 40%.

In Figure 9 the computed axial load distributions are plotted at different key points of the thermal history. For both the constitutive models in the simulation of test E2 cooling produces tensile stresses in the pile partially constrained by the surrounding soil, while heating produces compressive stresses. In the test E6 the same stresses are induced as increments starting from the mechanical axial load distribution produced by the head load equal to 250 N. In such a case the differences between the two models are not as significant as it was for the pile head settlement.

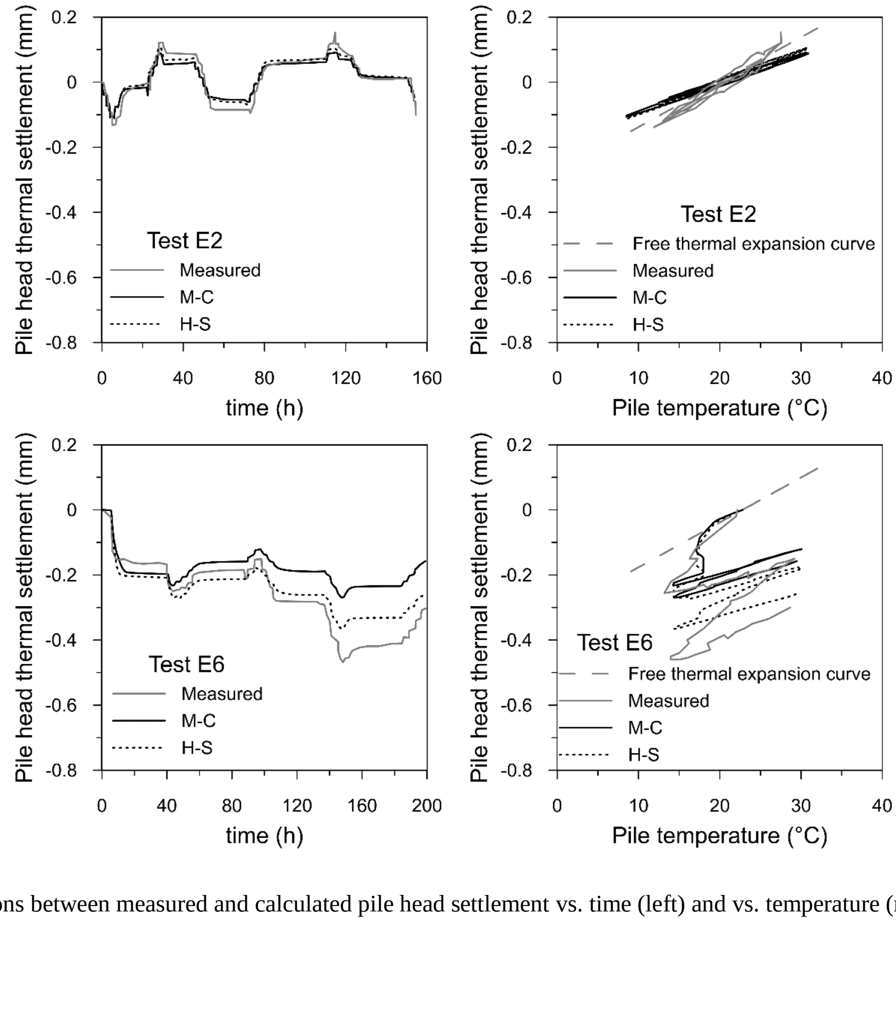

Figure 8 Comparisons between measured and calculated pile head settlement vs. time (left) and vs. temperature (right) for tests E2 and E6

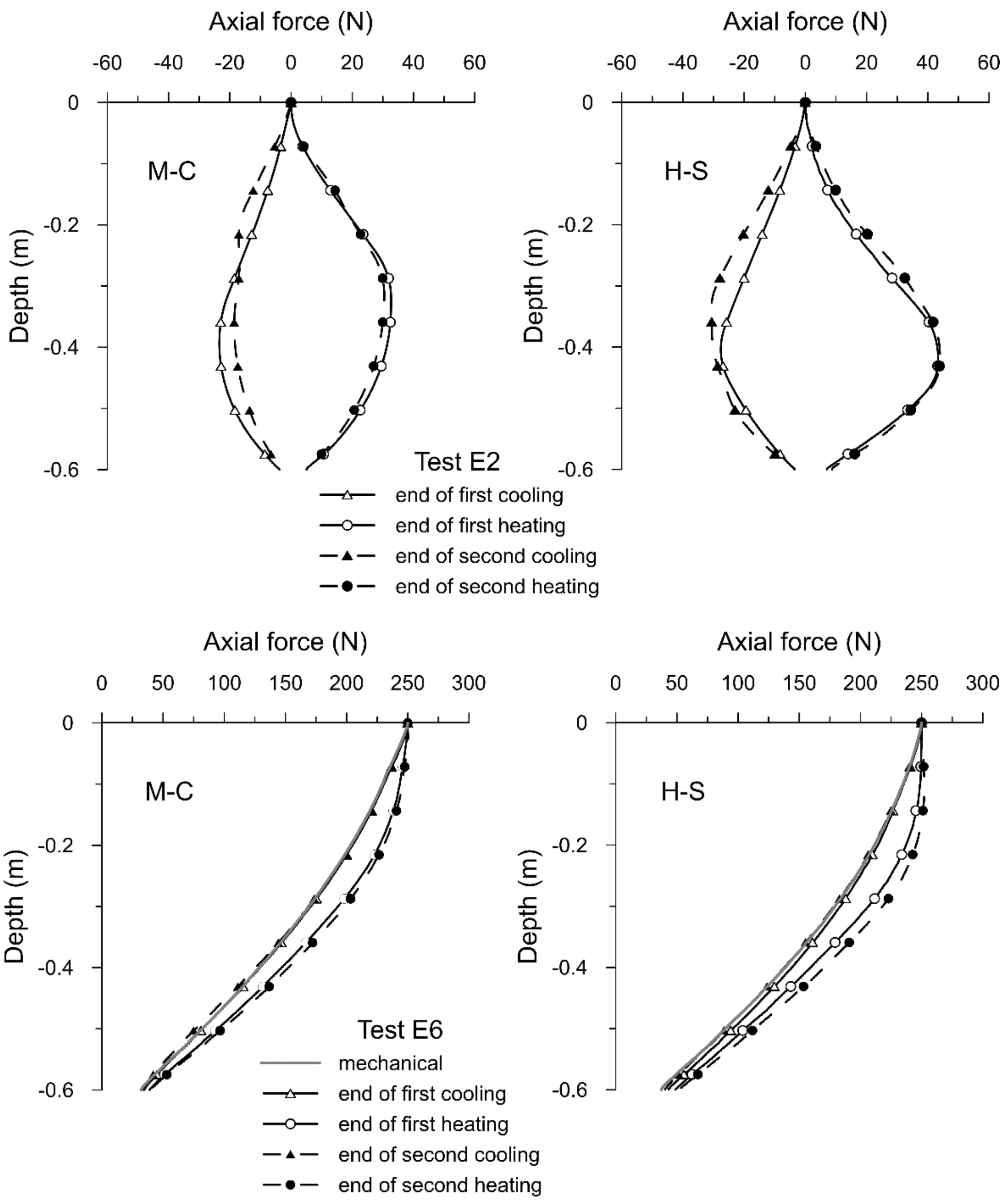

Figure 9 Calculated axial load transfer for tests E2 and E

In Figure 10 the computed (H-S model) axial load distributions are compared with the measured ones only for the thermo-mechanical test E6. The two full lines, referred to the mechanical axial load distribution, show a satisfactory agreement between computed and measured values. The same occurs for the envelopes of the thermal induced changes which are plotted as hatched areas with different crosshatches respectively for the calculated and the measured values.

As highlighted by the Figure 10, the measurements do not cover the full pile length not allowing for an objective comparison at the pile tip. Nevertheless the agreement starting from the pile head down to about 80% of the full pile length is at least satisfactory both for the mechanical induced distributions and for the range covered by the thermal induced ones.

4.3 Cyclic analysis

In order to further elucidate the influence of the thermo-mechanical coupling under cyclic conditions the calculations have been extended for the thermal part of the tests E2 and E6 using only the most

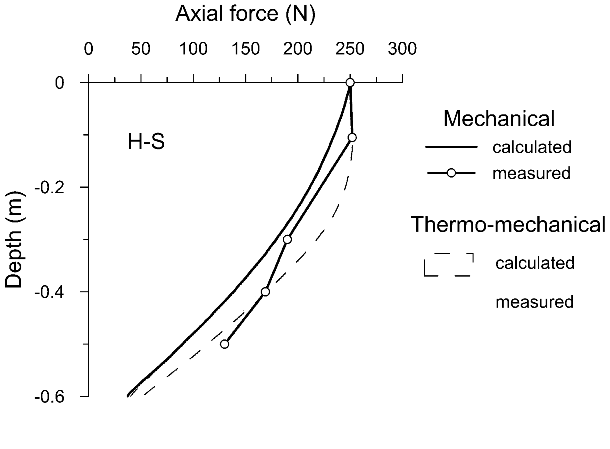

Figure 10 Comparison between measured and calculated axial load transfer for test E6

advanced H-S model. The number of thermal cycles applied to the pile has been extended to 24 simply repeating 12 times the experimental thermal history.

This was the minimum number of cycles, corresponding to nearly 100 days, to get to the stabilisation of the H-S model's response for the test E6. In Figure 11 the settlement computed in both cases are plotted versus the time. The test E2 confirms what was already shown in the simulation of only two cycles: the cyclic effects induced by thermal cycles are fully reversible. In the case of test E6 the settlement of the pile head after 2 cycles was only 0,23 mm while after 20 cycles it reached a value almost three times higher. A first check was done in order to evaluate whether the calculated strain ratcheting could arise from heat accumulation with increasing number of cycles. In Figure 12 the temperature computed at several points in the domain of the boundary value problem (see Figure 6) is plotted versus the time showing clearly that this phenomenon is not occurring. In other words the temperature changes induced by the imposed thermal cycles are perfectly reversible. In Figure 13 the pile base load is plotted as a function of the time. As for the head settlement the base load approaches nearly an asymptotic value after a relatively large number of cycles (i.e. about 15-20 cycles). It can be added that the thermal cycles are responsible for an increase of the load transferred at the pile base while, being the head load constant, the load transferred along the pile shaft decreases. This behaviour has been found and discussed also by Ng et al. (2016) and may have important consequences in the design application of energy piles. In the applications of the GSHP systems there are cyclic conditions linked to the daily operations and cyclic conditions whose period is larger and linked to seasonal operational details. Finally, there are also cyclic conditions whose period is of the order of 1 full year. In the analysed tests by Yavari et al. (2014) the thermal cycles have a duration of tens of hours which may be considered very similar to the daily cycles of a working plant.

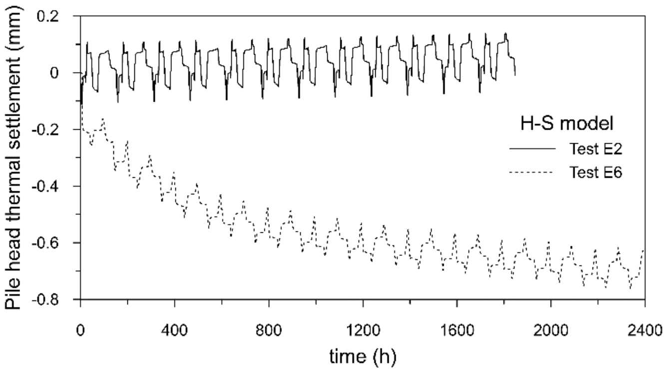

Figure 11 Computed pile head settlements versus time (extended E6 –E2 24 cycles)

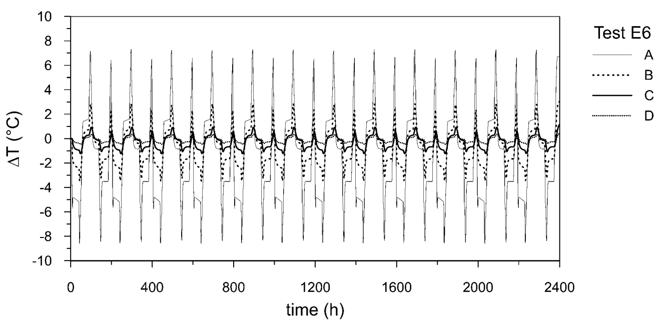

Figure 12 Computed temperature variation at different points versus time (extended E6-24 cycles)

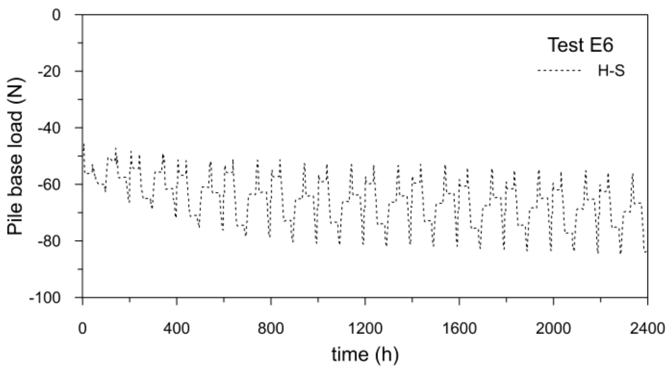

Figure 13 Computed pile base load versus time (extended E6 – 24 cycles)

5. CONCLUSION

The paper provides some useful insight into the bearing mechanisms induced by either pure thermal loading (i.e. temperature variations) or by coupled thermo-mechanical loading in a single energy pile. The pile head is free to move in all the cases discussed in the paper and both experimental results, obtained at laboratory scale, and numerical analyses carried out via the FEM code Plaxis 2D, are used to provide such an insight. During heating and cooling cycles energy piles expand and contract under the partial constraint provided by the soil interaction along the shaft and below the pile tip thus modifying the load sharing between the pile shaft and the pile base. The purely thermal test showed the occurrence of reversible and thus elastic deformation of the system under a temperature variation of 20° C. On the other hand the preliminary application of an axial load induced irreversible deformation in the subsequent cyclic thermal test under similar temperature variation. These experimental findings are confirmed by the FE simulations with two different constitutive soil models, both calibrated on the available head load-settlement relationship. The agreement between the simulation by the hardening elastic-plastic H-S model and the observed behaviour is very satisfactory and better than that for the elastic-perfectly plastic M-C model. The irreversible behaviour under cyclic thermo-mechanical loadings has been further investigated by simulating a larger number of cycles which is a more common condition for the real GSHP applications. The differences between the two tests E2 and E6 are fully confirmed and enhanced by the larger number of cycles. The H-S model show that a stable condition is reached after 15-20 cycles and produces a long term settlement of the pile head which is about three times that computed after only one cycle. Other recent studies (Ng et al., 2016) confirm such a behaviour and suggest that it is taken into proper account when designing energy piles for GSHP systems because of the expected large number of thermal cycles. Experimental observations on piles subjected to large number of thermal cycles are badly needed to better evaluate the amount of accumulation of pile head settlement and the amount of modification of pile-soil load transfer under coupled thermo-mechanical loading.

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