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Numerical analysis of thermal cycling during a multi-stage energy pile thermal response test

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ABSTRACT: Energy piles are emerging as convenient alternative to the more traditional borehole heat exchangers (BHEs) to provide heating/cooling to buildings, as they remove the need for special purpose excavations and can accommodate more pipes, thus enhancing energy performance. However, their different aspect ratio compared to BHEs requires different modelling tools and dedicated thermal response testing, to achieve adequate thermal design. In this work, the results of an extended multi-stage thermal response test (TRT) carried out on a single energy pile installed in London Clay are presented in terms of both fluid temperature data and concrete temperature, measured by vibrating wire strain gauges and optic fibre sensors. The results are then explored in detail by means of a finite element numerical code, able to account for both convective heat exchange in the fluid, between the fluid and the solids and transient heat diffusion in the concrete and the ground. Analysis of the TRT field data shows that during the later stages of the test there is clear evidence of cyclic changes in performance. Investigation of these effects using the numerical model raises the possibility that there could be some alteration of the properties of the soil-pile contact during the test. Hypotheses for the observed behaviour are tentatively put forward and discussed with work recommended to further investigate the percieved phenomena.

1 INTRODUCTION

Energy piles, serving the double function of foundations and heat exchangers, have been proposed as a convenient alternative to borehole heat exchangers, as they remove the requirement to make expensive special purpose excavations. Furthermore, their comparatively larger diameter means they can be expected to have a greater energy capacity per drilled metre (Bozis, et al 2011).

Approaches to the thermal design of energy piles tend to be based on analytical (or empirical) methods developed for borehole ground heat exchangers. Such methods assume that the dominant thermal process in the ground is conduction and use analytical solutions to the diffusion equation to relate predicted temperature changes in the ground and the pile to the input of thermal loads in the form of the heating and cooling demand of the building. Typically transient solutions are applied to determine the temperature changes in the ground (e.g Eskilson, 1987, Claesson & Javed, 2011), while steady state solutions based on thermal resistance are used for the borehole or pile itself (e.g. Lamarche et al, 2010). In all these approaches it is assumed that the soil and the concrete that forms the pile are homogeneous and isotropic and that their thermal properties are constant and independent of temperature.

Thermal response testing is an in situ technique to determine the thermal properties of the ground and the thermal resistance of a borehole heat exchanger. It has also been applied to piles, although there are difficulties with doing so for larger diameter piles (Loveridge et al, 2014a). The same analysis methods and assumptions that are used for thermal design can be applied to the interpretation of thermal response tests, although in practice usually the simplest of analytical models, the line source, is adopted. This means that provision of reliable thermal design parameters is also dependent on the assumptions of homogeneous and isotropic conditions with temperature independent behaviour.

This paper will report on the case study of an extended thermal response test of a small diameter energy pile, which shows some indication that cyclic thermal performance could indicate temperature dependent behavior. The test results are explored by a combination of field data (Section 3) and numerical simulation (Section 4), before the relevance and significance of the findings are discussed and tentative conclusions drawn (Section 5). Before describing this work the paper first presents a brief introduction to thermal response testing (Section 2).

2 THERMAL RESPONSE TESTING

Thermal response testing (TRT) is an in situ investigation technique developed for borehole heat exchangers and subsequently extended for use with some energy piles. The test aims to determine the thermal conductivity of the ground and the thermal resistance of the heat exchanger to provide input parameters for thermal design.

In a typical test the ground heat exchanger is connected, via its heat transfer pipes, to a number of heaters and a circulation pump. Circulation of the heated fluid through the borehole or pile allows heat to be injected to the ground at constant rate. The temperature change of the inlet and outlet fluid are monitored throughout the test and the results used with an analytical solution to the diffusion equation to calculate the ground thermal conductivity and heat exchanger thermal resistance. As a minimum, tests include a heat injection stage, but additional information can also be gained by continuing to circulate the fluid and monitor its temperature once the heaters have been switches off, i.e. during a recovery stage.

There are several international and national guidelines for the test to encourage high quality testing and interpretation (Sanner et al, 2005; IGSHPA, 2007; GSHPA, 2011). However, it must be recognised that the accuracy of the test depends on how well the real in situ conditions reflect the assumptions that are inherent in the analytical methods used in interpretation. Well conducted tests carried out in boreholes in reasonably consistent ground conditions can be expected to achieve an accuracy of around 10% (Witte, 2013, Spitler & Gehlin, 2015). However, non-uniform ground conditions can result in more significant errors developing (Signorelli et al, 2006).

3 CASE STUDY

The thermal response test described in this study was carried out on a 300mm diameter and 26.8m length test pile constructed at a London development site (Loveridge et al. 2014b). Beneath an initial concrete slab, the pile was constructed through water saturated London Clay over its entire length. The stratum was described as firm to stiff grey clay and contained some layers of claystones.

A single U-loop of heat transfer pipe was installed in the hole to 26m depth and backfilled with hard pile cementitious grout. The pipes were made from high performance polyethylene material with an external diameter of 32mm and a wall thickness of 2.9mm. The pipes were installed separated by rigid spacers ensuring an even separation of the pipes and a centre to centre spacing between the two legs of the U-tube of around 135mm. The spacers also served as a housing to mount numerous sensors which are described in Section 3.1 below.

Ten days after grouting the pile, a multi-stage thermal response test was carried out. Unusually the test comprised a number of different phases (Figure 1) which were designed to allow investigation of the thermo-mechanical response of the pile (Ouyang, 2014). After an initial circulation phase, a heat injection test (Stage 2) and recovery period (Stage 3) was followed by a heat extraction test (Stage 4) and recovery period (Stage 5). Cyclic testing was then commenced comprising two heat injection phases (Stages 6 and 8) separated by heat extraction phases (Stages 7 and 9). Each test stage followed directly from the preceding phase and measurements were maintained throughout, except for a 4 day period in Stage 6 when repairs were being carried out to a faulty heating unit. Consequently the heat injection of Stage 6 is only seen at the latter part of this time period and there is an extended period of no recorded applied power prior to then (Figure 1). However, during the period when the power was not recorded, some heat was rejected to the system, as is shown by the concrete temperature data (refer to Figure 3 and Section 3.2).

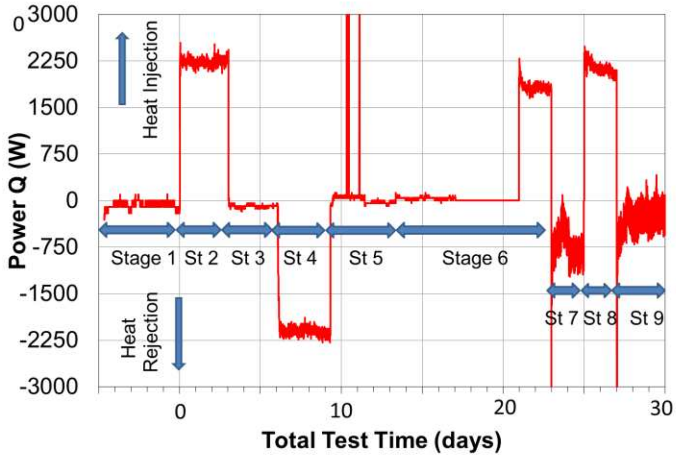

Figure 1. The multi-stage thermal response testing, showing heating power input at each stage.

3.1 Instrumentation & Monitoring

The inlet and outlet heat exchanger fluid temperature T_{in} and T_{out} were measured throughout the test, except at the start of Stage 6 when the heating equipment was faulty. Moreover, the evolution of temperature within the concrete T_c during the TRT was measured in two ways, namely (i) at four locations along the pile depth, by means of temperature sensors associated with vibrating wire strain gauges (VWSG), and (ii) continuously along the pile depth by means of optic fibre sensors (OFS) placed at four positions (Figure 2). Strain was also measured by both the VWSG and the OFS cables, however, consideration of this data is not within the scope of this study. Full description of these data and their interpretation are contained within Ouyang (2014).

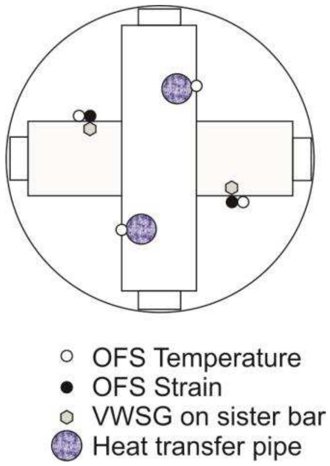

Figure 2. Location of the temperature sensors within the pile cross section.

3.2 Results

The resulting fluid temperatures at the inlet and outlet in response to the applied cycles of heating (Figure 1) are shown in Figure 3. The temperature increases in response to heat injection and reduces in response to heat extraction. It can also be seen that there is a bigger difference between the inlet and outlet temperatures when the applied heating power is greater. Figure 3 also shows as an example the average temperatures recorded by the VWSGs at pile mid-height, which are seen to have reduced amplitudes of variation to the fluid temperatures due to their greater offset from the pipes.

It can be also noticed in Figure 3 that during the second part of stage 5 and the first part of stage 6 the concrete temperature varies unexpectedly, in a way that suggests heat extraction, although this is neither reflected from the fluid temperatures nor from the applied power (Figure 1). A similar pattern is seen in the OFS data, including on those OFS cables located on the heat transfer pipes (Figure 2). This discrepancy is the likely result of the heating system malfunctioning in that period, leading us to presume that fluid temperature measurements are not reliable during stage 5 and the beginning of stage 6.

Temperature measurements were also available from within the concrete from the OFS placed at approximately the same distance from the pipes. It emerged that overall, the VWSG measurements are more stable and consistent compared to OFS measurements, which appear more wavy. After applying a moving average filter to the latter data, comparison of the two types of measurements showed adequate consistency. As an example, in Figure 4 VWSG and OFS data are plotted versus depth for an instant at the end of stage 6. It can be noticed that the two different OFS datasets tend to overlap in correspondence with the locations of spacers. This could indicate that the OFS cables were not perfectly straight along the pile; hence a certain degree of oscillation of OFS temperature measurements might have reflected the variable distance of the cables from the pipes (i.e. changes of position in different cross-sections along the pile).

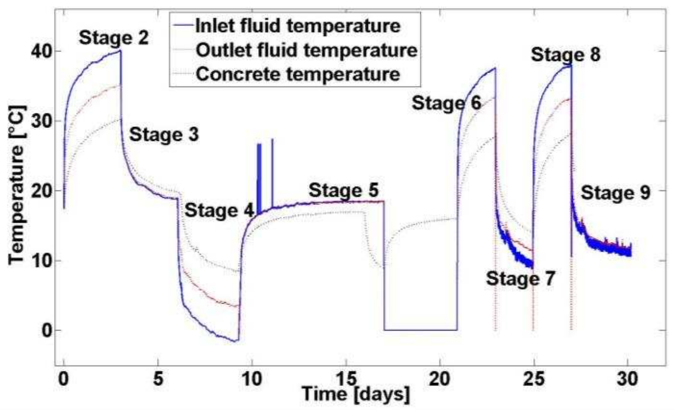

Figure 3. Fluid and VWSG average concrete temperature (at pile mid-height) data throughout the test.

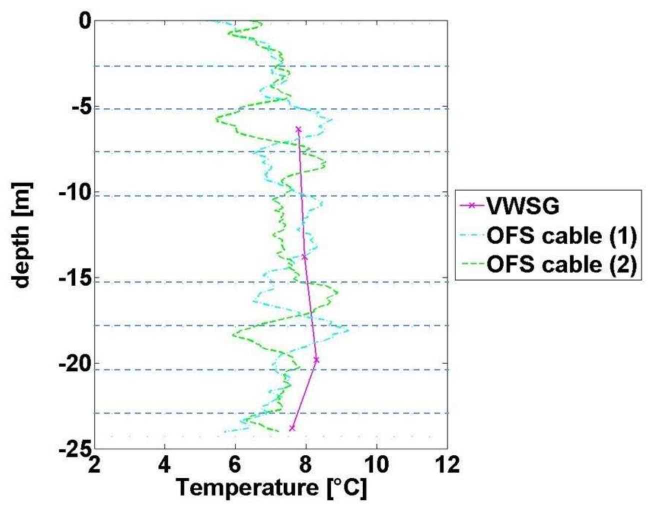

Figure 4. Comparison between OFS and VWSG temperature measurements after application of moving average filter to OFS data. The horizontal dotted lines denote the approximate locations of spacers.

4 NUMERICAL SIMULATION

4.1 Model description

The numerical model (Cecinato and Loveridge 2015, Cecinato et al. 2015) aims at realistically reproducing the main processes behind the heat transfer phenomena taking place in geothermal structures, namely thermal convection between the fluid and the pipe wall, thermal conduction in the grout/concrete, and thermal conduction in the ground. Convective heat transfer in the pore water is not considered. Hence, while the model is always applicable to low-permeability or dry geomaterials, it can only be applied to high-permeability water-saturated materials if the groundwater at a specific site is known to be static.

The transient heat convection-diffusion problem for energy piles was solved using the Finite Element (FE) code ABAQUS to integrate 3D transient conduction through the solids, complemented by writing bespoke user subroutines to model the convective heat transfer at the fluid/solid interface and the temperature changes in the fluid along the pipe, represented within the FE mesh as lines of nodes, where the heat exchange resulting from convection-diffusion in the pipes is concentrated. The 3D nature of the pipes (i.e. the relevant diameter, in addition to length) is properly accounted for via the user subroutines, by multiplying the heat flux corresponding to each pipe node by the corresponding lateral surface area of each pipe segment.

To minimise computational time, while controlling the element aspect ratio and node spacing at key locations to warrant accuracy of heat exchange calculations, the 3D FE mesh was created manually in an axisymmetric fashion using 6-node linear triangular prism and 8-node linear brick diffusive heat transfer elements (Figure 5). The spacing of the nodes representing the ground was progressively increased towards the outer boundary, while the mesh was refined in the exchanger pipe and surrounding pile areas. The size of the domain was determined by numerical experimentation to be much larger than the area actually affected by heat transfer over the time range explored in this study.

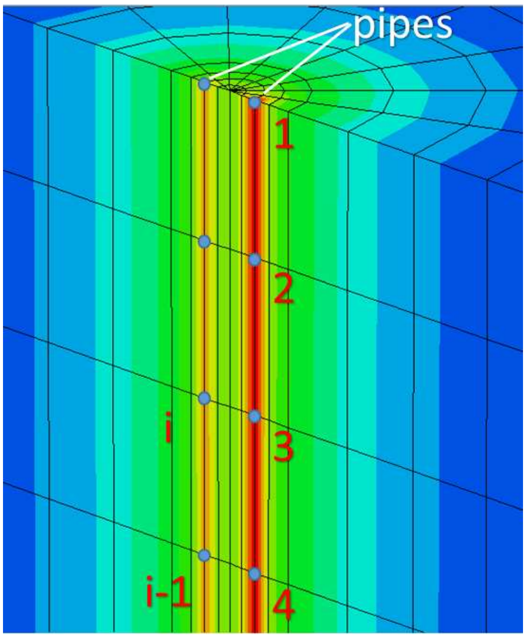

Figure 5. FE mesh representing the pipes (schematised in 1D as a line of nodes), the pile and surrounding ground, with temperature contours. Only half of the domain is considered, to save computational time exploiting symmetry.

To simulate the TRT case study, the inlet fluid temperature was prescribed as a function of time, as a boundary condition for the analysis. At zero heat flux an initial equilibrium temperature for both the fluid and the concrete/ground conditions was specified. The TRT geometry was reproduced in detail in the numerical model as a half domain exploiting symmetry (Figure 5).

Validation of the model has been previously undertaken using fluid data from Stages 2 to 5 of the case study described above (Cecinato and Loveridge 2015, Cecinato et al. 2015). The physical and thermal properties of the materials involved are given in Table 1.

Table 1. Material properties used in the simulation

Material	Parameters	Values	Units
Fluid	Density	1000	kg/m^3
	Kinematic viscosity	1.00E-06	m^2/s
	Specific heat capacity	4200	J/(kg K)
	Mass flowrate	0.108	kg/s
	Thermal conductivity	0.6	W/mK
	Prandtl number	7	
Concrete	Density	2210	kg/m^3
	Specific heat capacity	1050	J/(kg K)
	Thermal conductivity	2.8	W/mK
Pipes	Thermal conductivity	0.385	W/mK
London Clay	Density	1900	kg/m^3
	Specific heat capacity	1820	J/(kg K)
	Thermal conductivity	2.3	W/mK

4.2 Model Development

Although in previous validation of the model it was shown to perform well in reproducing the thermal behaviour of the test pile, subsequent work had shown that the inherent simplification of representing the pipes as 1D lines of nodes in the FE mesh might lead to less accurate calculations when pipes are placed very close together (Loveridge and Cecinato, 2016). To investigate this potential effect, the numerical model was modified by changing both the FE mesh and the user subroutines, to represent the exchanger pipes in 3D. The scheme adopted involves representing each pipe in the pile cross-section with a set of nodes (2, 4 or 8) distributed along the pipe's circumference, so that each node represents a part of the total pipe surface involved in the heat flux (Figure 6). On the other hand, in the original model a single node represents the whole pipe surface in a pile cross-section.

The modified model was then used to run the same TRT simulations from Stage 2 to Stage 5, showing a significant improvement in the RMSE comparing the simulated and measured outlet fluid temperature. For example, for Stage 2, Table 2 shows the general decrease in RMSE, and hence increase in fit, as the number of pipe nodes is increased. This suggests an increase in the accuracy of the simulation due to a more realistic representation of the heat flux spatial distribution across the pipes. Additionally, more symmetrical temperature contours further suggest a progressive improvement in the representative of the heat fluxes (Figure 6).

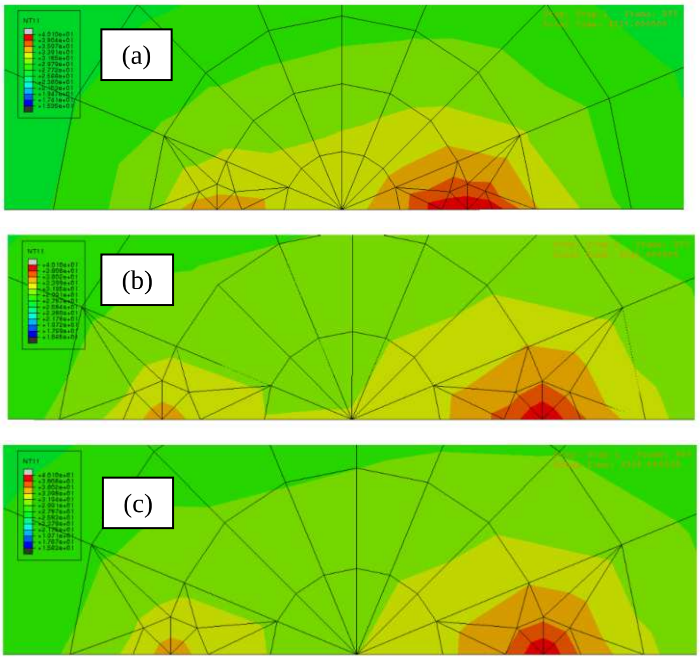

Figure 6. FE mesh representing a cross-section of the pipes area with temperature contours during heat injection, for half of the domain. The model was developed by representing each pipe in the pile cross-section with a set of (a) 2, (b) 4 or (c) 8 nodes instead of a single node as originally proposed (Figure 5).

Table 2 Improved model fit (Stage 2) when using increased number of nodes to represent the fluid pipes

No. Nodes	1	2	4	8
RMSE	0.240	0.202	0.169	0.196

4.3 Simulation of Case Study

The model was now used to reproduce the entire temperature history of the TRT case study over all stages of the test, using the 4 node 3D representation of pipes. This provided an appropriate balance between set up and computational time expended and the output accuracy.

The field measured fluid temperature was used as specified boundary condition and both the evolution of the outlet fluid temperature (T_{out}) and the concrete temperate (T_c) were used to assess fit of the model. Based on the assessment of the OFS field data given in Section 3.2, only the VWSG data were used to assess T_c.

In Figure 7 the simulated and measured outlet fluid temperature are reported for comparison, for all of the TRT stages, leaving out the second part of stage 5 and the early part of stage 6 (due to the above mentioned problems in that part of the TRT with measurements reliability). The numerical simulation effectively reproduces the field measurements for all considered stages of the TRT, however, it could be noticed that it does not approximate all stages with the same accuracy. In particular, the cyclic testing stages (6 to 9) appear to be reproduced less precisely, as can be seen in an enlargement of these stages (Figure 8).

To evaluate further the accuracy of the simulation, the root mean square error (RMSE) of the residuals was calculated, resulting in the values given in Table 3. A tendency for the simulation accuracy to worsen (i) for heat extraction phases (4, 7 and 9) and (ii) generally at later TRT stages is observed, with special regard to the heat extraction phases during thermal cycling. A similar effect was observed by Loveridge et al (2014b) when fitting analytical solutions to the same data. Those authors observed particular misfit of the analytical models in the last four stages of the test. It was suggested that this effect could be the results of the pile thermal resistance may not be constant. It was hypothesised that this could be due to increased contact resistance at the pile-soil boundary when the pile is cooled. However, the authors also showed that this hypothesis could not explain all the observed behaviours of the pile during the test.

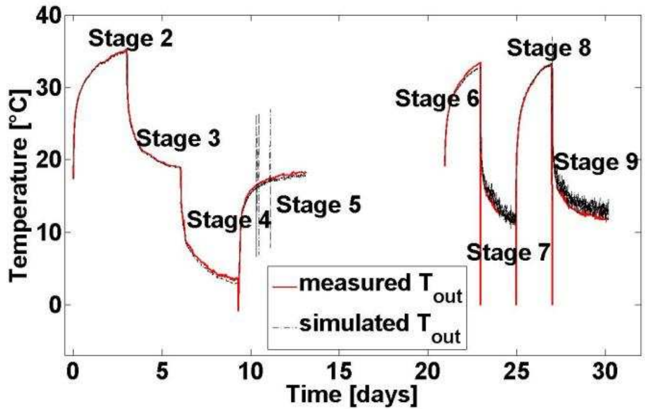

Figure 7. Comparison of measured and simulated outlet fluid temperature during the TRT.

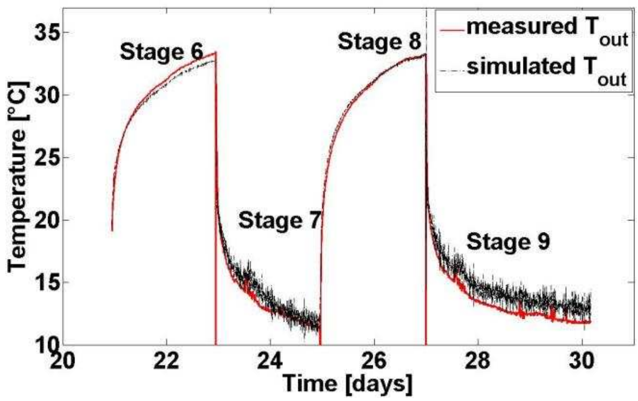

Figure 8. Comparison of measured and simulated outlet fluid temperature during the TRT, enlargement of later stages 6-9.

Table 3 Model fit for the different test stages

Stage	2	3	4	5
RMSE	0.169	0.205	0.504	N/A
Stage	6 (2nd part)	7	8	9
RMSE	0.588	0.993	0.231	1.598

In Figure 9 the VWSG-measured and simulated (using the original 1D pipe scheme, to save computational time yet providing adequate accuracy) concrete temperature values are reported, as an example, at pile mid-height (13.8m depth) throughout the TRT. Simulation #1 was obtained using the measured inlet fluid temperature as boundary condition, and it can be seen that data are not adequately reproduced during stages 5 and 6, during which the fluid temperature measurements have been considered unreliable due a temporary system breakdown. To be able to reproduce the evolution of T_c, the temperature input T_{in} was modified during those stages generating a synthetic temperature history, by means of numerical back-analysis (Piglialepre 2016). This modified T_{in} was used to run Simulation #2, which can adequately reproduce T_c also during stages 5 and 6. The modified T_{in} has a negligible effect on the subsequent stages due to sufficient recovery time prior to the start of heat injection in Stage 6.

In general, the measured concrete temperature evolution is now correctly reproduced using Simulation #2 with synthetic input for Stages 5 and 6 (Figure 8). However a worse fit during the last stages is still observed in both simualtions, with special reference to heat extraction stage 7 (field data were not available for stage 9). This is consistent with what has been observed above for the outlet fluid temperature.

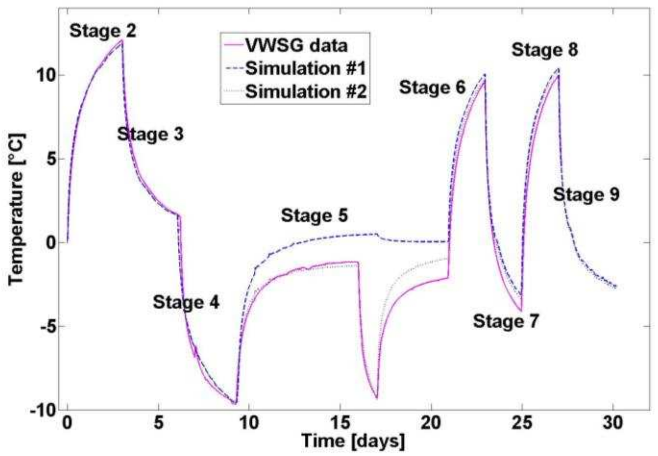

Figure 9. Comparison of measured and simulated concrete temperature during the TRT. Simulation #1 is obtained using the measured T_{out} as boundary condition while Simulation #2 is obtained with a corrected input during stages 5 and 6.

4.4 Cyclic Effects

A sensitivity study was carried out to preliminarily investigate the possible reasons for the particular mismatch between the outlet temperature simulations and data during heat extraction stages 7 and 9. The fact that during those stages less heat than predicted is extracted may suggest that, by virtue of differential contraction between concrete and soil within the elastic regime and/or due to possible thermoplastic effects in the soil upon thermal cycling, contact at the pile-soil interface might be reduced. This in turn could affect the lateral bearing capacity of the pile.

As a first-attempt analysis, the thermo-mechanical pile-soil interaction was not modelled numerically (the FE analysis was kept purely thermal), but its possible effect was accounted for by changing the thermal properties of a thin layer of solid elements (i.e. a 1cm thick ring) in contact with the pile. Possible reduction of contact between pile and soil was simulated by setting for this layer values of density, thermal conductivity and specific heat equal to those of air.

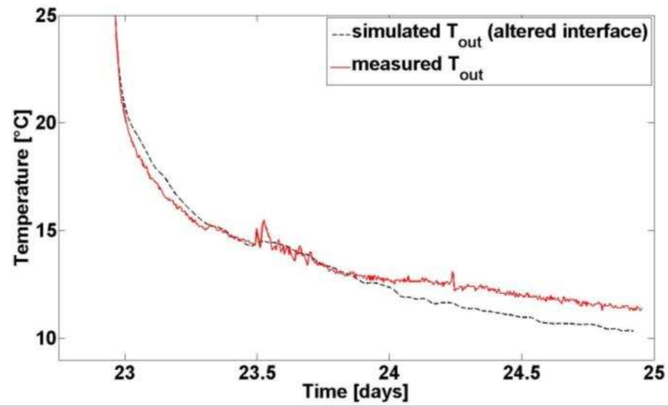

Figure 10. Comparison of measured and simulated outlet fluid temperature during stage 7.

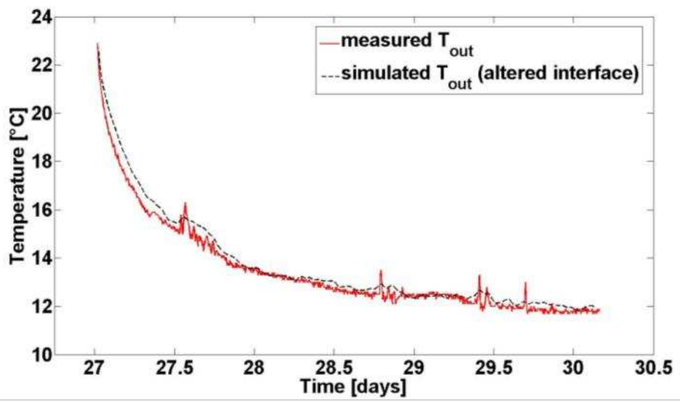

Figure 11. Comparison of measured and simulated outlet fluid temperature during stage 9.

A comparison of simulations of T_{out} obtained with these settings and measurements for stages 7 and 9 is shown in Figures 10 and 11 respectively. In Table 4 the model fit in terms of RMSE is reported for stages 7 and 9 compared to values obtained with the original simulation (cf. Section 4.3). It can be seen that model simulations now can better reproduce field data, especially regarding stage 9, representing the second thermal loading-unloading cycle. This result corroborates the conjecture that pile-soil contact might have been reduced during stages 7 and 9, although further numerical analysis accounting for thermo-mechanical couplings would be needed to adequately support this hypothesis.

Table 3 Model fit for test stages 7 and 9 obtained with the original settings and with the altered interface settings.

Stage	7	9
RMSE (original model)	0.993	1.598
RMSE (altered interface)	0.844	0.703

5 DISCUSSION & CONCLUSIONS

In this work, a recently proposed FE numerical model to interpret the thermal behaviour of energy piles was further developed and validated against field data from a multi-stage thermal response test. Numerical developments, consisting in providing a 3D representation of pipes (instead of the original 1D schematisation), led to significant improvements in the model accuracy.

The comparison of simulations and field data throughout the multi-stage TRT, both in terms of outlet fluid and concrete temperature, highlighted that the simulations provide a very good fit in the early TRT stages, and a worse fit at later stages. In particular, the model accuracy appears to worsen in correspondence with the heat extraction phases. This suggests the presence of cyclic effects in the case study at hand. A similar effect was observed by Loveridge et al (2014b) when fitting analytical solutions to the same data, and by Ouyang (2014) when assessing the effect of pile-soil interaction in the thermal exchange process of the same TRT.

To further investigate cyclic effects, a sensitivity study was carried out by tentatively changing the thermo-physical properties at the soil-pile interface during the last heat extraction phases (stages 7 and 9), to reproduce in a simplified manner the possible formation of an air gap, due to thermally induced (differential) contraction of the pile and soil material. This resulted in an improved fit of outlet temperature data (with special regard to Stage 9, i.e. the last heat extraction cycle), suggesting that a reduction of pile-soil contact may have been possible in this case. However, this mechanism is not proven and should be corroborated by further investigation accounting for thermo-mechanical couplings in a more rigorous manner.

However, care must also be taken in extrapolating this case to general practice for two reasons. Firstly, the pile was not subject to mechanical load during the TRT. As highlighted by Ouyang (2014), the mechanical load would allow the pile to form a better interface with the soil prior to thermal loading, thus preventing the free contraction of the pile in the cooling cycle. Ouyang (2014) also suggest that the interface effects of “weak interaction” could result from the unusually large size of the plastic spacers or the short time delay between pile grouting and testing of the piles. The former could lead to differential thermal expansion effects within the pile, while the latter could have resulted in the grout not having cured completely, hence having different physical characteristics compared with a working pile.

Nonetheless, the possible thermally induced weakening of pile-soil contact is worth additional analysis considering the thermo-mechanical couplings relevant to the suggested mechanisms. This will help to understand whether or not there is a real risk of changing pile-soil interface conditions in operational scenarios.

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