A new modelling approach for piled and other ground heat exchanger applications

Une nouvelle approche de modélisation pour pieux et autres applications géothermiques

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ABSTRACT Pile heat exchangers have an increasing role to play in the delivery of renewable heating and cooling energy. Traditionally the thermal design of ground heat exchangers has relied upon analytical approaches which take a relatively simple approach to the inside of the heat exchanger. This approach is justified while the heat exchanger diameter remains small. However, as larger diameter piled foundations are used as heat exchangers, the transient heat transfer processes operating within the pile become more important. To increase our understanding of these processes and ultimately lead to improved thermal design approaches for pile heat exchangers it is important to examine the heat transfer within the pile in detail. To accomplish this, a new numerical approach has been implemented within the finite element software ABAQUS. Coupling of the convective heat transfer due to fluid flow within the heat transfer pipes and the heat transfer by conduction within the pile concrete is the most important facet of the model. The resulting modelling approach, which is ready to generalise to other geothermal applications and to assess thermo-mechanical couplings, has been validated against a multi-stage thermal response test carried out on a test pile in London Clay.

RÉSUMÉ Le rôle des pieux géothermiques pour la climatisation écologique des bâtiments devient de plus en plus important. Traditionnellement, la conception thermique des échangeurs de chaleur géothermiques s'est fondée sur des approches analytiques simplifiées. Cette approche est justifiée tandis que le diamètre de l'échangeur de chaleur est faible mais, pour pieux de grand diamètre, les procédés de transfert de chaleur transitoires deviennent plus importants. Afin d'améliorer notre compréhension de ces phénomènes et améliorer les méthodes de conception géothermique, il est important d'examiner en détail le transfert de chaleur à l'intérieur du pieu. Pour réaliser ceci, une nouvelle approche numérique a été mise en œuvre dans le logiciel ABAQUS. Le couplage du transfert convectif de chaleur dans les tubes et le transfert de chaleur par conduction dans le béton du pieu est l'aspect le plus important du modèle. L'approche de modélisation qui en résulte, qui est prêt à être généralisée à d'autres applications de géothermie et à évaluer les couplages thermomécaniques, a été validée avec un test de réponse thermique à étages multiples réalisé sur un essai de pieu installé dans l'argile de Londres.

1 INTRODUCTION

Ground source heat pump systems have been developed in recent decades as an efficient way to provide heating/cooling to buildings. Traditional borehole heat exchangers have been the subject of extensive studies, both experimental and theoretical/numerical (e.g. Spitler 2005), aimed at improving their efficiency. More recently 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).

Most energy pile design tends to be carried out using analytical or empirical methods developed for borehole ground heat exchangers. However, there are important differences between the two types of geothermal systems. For example, energy piles typically have a different aspect ratio from borehole heat exchangers. Further, large diameter piles take a long time to reach steady–state, and can accommodate

multiple U-loops, so that bespoke tools are needed to account for their transient and three-dimensional thermal behaviour. Few studies (e.g. Lee & Lam, 2013) have focused on the optimization of energy pile design, mostly employing (semi) empirical methods.

In this work a new 3D modelling approach is described (Section 2) which is able to capture accurately the different aspects of transient heat transfer for energy piles. The model is then validated (Section 3) against field data from a thermal response test (TRT), and a sensitivity analysis is carried out to back-calculate the field thermal properties. Applications of the proposed model in improving the design of energy piles and other ground heat exchanger applications are discussed in Section 4.

2 MODEL FORMULATION

The numerical model described herein aims to reproduce 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 convection-diffusion equation that applies to the heat exchanger fluid, neglecting the contribution of friction heat dissipated by viscous shear, can be expressed in terms of heat flux quantities as

$$\rho_f c_{pf} \dot{T} - \nabla\left(\lambda_f \nabla T\right) + \dot{m} c_{pf} \nabla T = h \Delta T \qquad (1)$$

where ρ_f and c_{pf} are the fluid density and specific heat capacity, λ_f the fluid thermal conductivity, $\dot{m}$ the mass flow rate, A the pipe cross-sectional area, h the convective heat transfer coefficient, and $\Delta T = (T_s - T_f)$ the temperature difference between the solid interface (pipe wall) and the fluid.

Equation (1) can be simplified for the purposes of our analysis, by assuming that (i) convection due to fluid flow occurs as a quasi-static phenomenon, and (ii) conductive heat transfer along the flow direction can be neglected compared with both the radial heat transfer at the fluid/pipe wall interface and the convective transfer. These simplifying hypotheses were shown to yield accurate results for the purpose of vertical ground heat exchanger simulation (Choi et al. 2011). Furthermore, as shown in Section 3, the simulation results obtained assuming this assumption can closely reproduce temperature field measurements for the full operating time range of a pile TRT.

Heat transfer through the pipe wall, concrete/grout and the ground is governed by standard transient heat conduction:

$$\rho_s c_{ps} \dot{T} = \nabla\left(\lambda_s \nabla T\right) \qquad (2)$$

where ρ_s, c_{ps} and λ_s are respectively the density, specific heat capacity and thermal conductivity of the considered solid material.

The transient heat convection-diffusion problem for energy piles outlined above was solved using the Finite Element Method. The model was implemented using 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.

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 1). 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.

A single energy pile was represented in the mesh, with the possibility of selecting the position and number of embedded pipes and the type of hydraulic connection between the loops.

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.

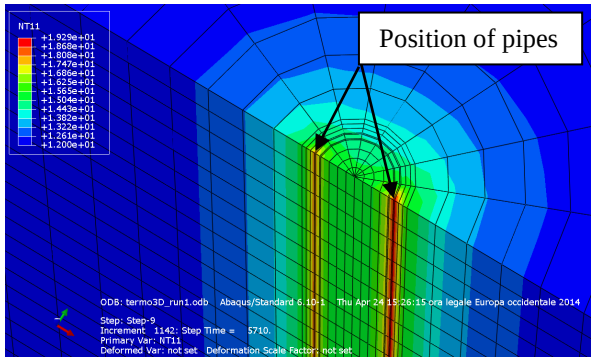

Figure 1. Example of 3D FE mesh for one energy pile with a single U-pipe, with sample calculated temperature contours.

3 MODEL VALIDATION

The proposed numerical model was tested by reproducing a multi-stage thermal response test (TRT) carried out in London on a 300mm diameter, 26.8m length test pile (Loveridge et al. 2014). The pile was equipped with a single U-loop and was installed through water-saturated London Clay. The heat exchanger fluid flowrate and temperature were measured throughout the test. The test started with an initial isothermal circulation (stage 1) and then comprised different stages where a heat injection test (stage 2) and recovery period (stage 3) were followed by a heat extraction test (stage 4) and recovery period (stage 5).

The TRT geometry was reproduced in detail in the numerical model as a half domain exploiting symmetry (Figure 1). The physical and thermal properties of the materials involved were taken, generally, from published data.

Particular attention was paid to the choice of parameters governing transient heat diffusion, i.e. the thermal conductivities λ_c and λ_g, and specific heat capacities c_c and c_g, of the concrete and ground respectively. Specific heat capacities are rarely considered in practical geothermal studies as they are relevant only to transient analyses, while λ_g is frequently measured in the field, as it features in the simplified analytical or empirical formulae that are routinely used to interpret thermal response tests.

For a first-attempt simulation (#1), thermal properties of the concrete pile were chosen following Choi et al. (2011). The specific heat capacity of the ground was deduced, assuming the clay to be fully saturated, from the values of specific heat capacity of water (4200 J/kgK) and of solid particles (800 J/kgK), assuming porosity n=0.3 . The soil thermal conductivity, which generally varies depending upon soil type and saturation, was set to 2.3 W/mK, as obtained by interpreting stages 2 and 3 of the TRT (Loveridge et al. 2014). A complete list of parameters adopted for all materials involved in the simulation is given in Table 1.

Table 1. Material parameters, simulation #1.

Materials	Parameters	Values	Units
Water/ circulating 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
PE (pipe material)	Thermal conductivity	0.385	W/mK
Soil	Density	1900	kg/m^3
	Specific heat capacity	1820	J/(kg K)
	Thermal conductivity	2.3	W/mK

As an initial condition, the equilibrium temperature of all materials was set to 17.4°C, corresponding to the isothermal circulation stage of the test. As a boundary condition, the inlet fluid temperature history measured in the actual TRT was imposed at the first node of the U-pipe throughout the simulation time (about two weeks).

The simulation results in terms of the calculated outlet fluid temperature are compared with the corresponding measured values in Figure 2 for TRT stages 2 through 5. The numerical simulation effectively reproduce the field measurements for all stages of the TRT.

To evaluate further the accuracy of the simulation, the root mean square error (RMSE) of the residuals was calculated, resulting in $RMSE_{2\text{-}5}$=0.6586 for stages 2-5, and $RMSE_{2\text{-}3}$=0.2308, $RMSE_{4\text{-}5}$=0.8653 for stages 2-3 and stages 4-5 respectively. It can be inferred that a somewhat better fit to the experimental data is achieved for the first two test stages

than the second two. This is consistent with the findings of Loveridge et al (2014), who in using analytical and empirical methods to match the TRT output and estimate the ground thermal conductivity, obtained slightly different back-calculated values of λ_g for the different test stages.

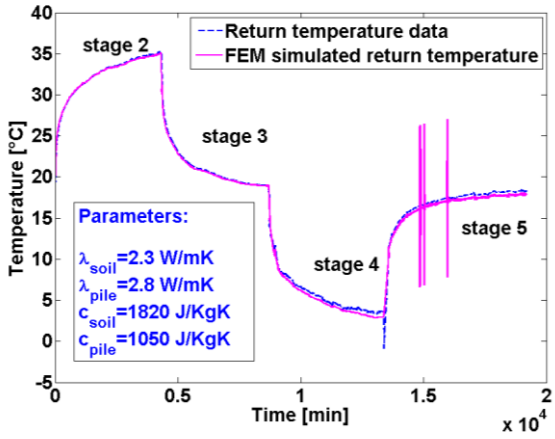

Figure 2. Calculated outlet fluid temperature (solid line) compared to measured outlet fluid temperature (dashed line) for TRT stages 2 through 5.

To compare the numerical results with those obtained using empirical methods, RMSEs were also calculated considering the 'average fluid temperature' (computed as the average between the measured inlet and simulated outlet temperature), resulting in an improved fit: $RMSE_{AVG,2\text{-}5}$=0.3293 for stages 2-5, and $RMSE_{AVG,2\text{-}3}$=0.1154, $RMSE_{AVG,4\text{-}5}$=0.4326 for stages 2-3 and stages 4-5 respectively. These values compare favourably with the corresponding RMSEs obtained by parameter estimation presented by Loveridge et al. (2014), suggesting the better accuracy of a numerical method that accounts for transient diffusion than simpler steady-state methods.

Next, the numerical model was used to carry out a sensitivity analysis, in an attempt to back-calculate the main geothermal material parameters from the London TRT data. This was done by means of the statistical-based Taguchi method (see Appendix). Many simulations were run in which the four parameters of less certain determination, i.e. λ_c, λ_g, c_c and c_g, were varied within a realistic range (Table A1) while the other model parameters were kept constant as per Table 1.

The sensitivity analysis identified (1) λ_c and (2) λ_g the two most important parameters in minimising the RMSE between the simulated and measured outlet temperature, suggesting a ranking of importance of the parameters in influencing the accuracy of prediction of field data. The outcome of this sensitivity analysis served as a reference to select the best-fit parameter values.

Further simulations were run (Table 2), as a refinement of the sensitivity study. All of these runs yield very small RMSE values, suggesting the existence of multiple minimums in the problem. This results from co-linearity of the two key parameters and has been identified by other authors in similar problems (e.g. Wagner et al, 2012, Marcotte & Pasquier, 2008).

It can be observed that the best-fit parameters (simulation #3 in Table 2) do not differ significantly from those initially chosen for simulation #1, resulting in an only slightly lower global RMSE that can be considered negligible for practical purposes. This also indicates close agreement between the best-fit values of λ_g obtained with our numerical model and with empirical and analytical methods presented by Loveridge et al (2014).

Table 2. Simulations to identify best-fit values of thermal parameters for different TRT stages. Conductivities are expressed in W/mK and specific heat capacities as J/kgK. The global RMSE refers to all TRT stages (2 through 5).

Simulation #	TRT stages	λ_c	λ_g	c_c	c_g	RMSE	Global RMSE
1	*2&3*	*2.8*	*2.3*	*1050*	*1820*	*0.2308*	*0.659*
	4&5	*2.8*	*2.3*	*1050*	*1820*	*0.8653*	
2	2&3	2.5	2.3	1050	1820	0.2826	0.670
	4&5	2.5	2.3	1050	1820	0.8686	
3	**2&3**	**2.8**	**2.2**	**1000**	**2100**	**0.2312**	**0.652**
	4&5	**2.8**	**2.2**	**1000**	**2100**	**0.8557**	
4	2&3	2.6	2.3	1050	2100	0.2532	0.669
	4&5	2.6	2.3	1050	2100	0.8750	
5	2&3	2.55	2.6	1000	2100	0.2917	0.666
	4&5	2.55	2.6	1000	2100	0.8635	

The parameter λ_c does not feature directly in the empirical analysis, but it is covered indirectly via the pile thermal resistance parameter R_c. R_c can be calculated by the method of Hellstrom (1991):

$$R_c = \frac{1}{4\pi\lambda_c}\left[\ln\left(\frac{r_b}{r_o}\right)+\ln\left(\frac{r_b}{s}\right)+\sigma\ln\left(\frac{r_b^{\,4}}{r_b^{\,4}-\left(s/2\right)^4}\right)\right] \qquad (3)$$

where r_b is the pile radius, r_o is the pipe radius, s is the centre to centre spacing of the pipes and σ is given by the expression:

$$\sigma = \frac{\lambda_c - \lambda_g}{\lambda_c + \lambda_g} \quad (4)$$

Applying equations 3 & 4 to the results of the simulations gives a value of pile thermal resistance of 0.067 mK/W. This is ~ 90% of the value (R_c=0.075 mK/W) determined by empirical methods. No direct comparison can be made of our estimation of c_c and c_g, since these parameters do not directly feature in empirical equations.

4 DISCUSSION & CONCLUSIONS

The 3D numerical model presented above can provide a realistic interpretation of the key aspects of heat transfer in energy piles. While the non-negligible computational expense (tens of minutes to a few hours with an ordinary laptop) makes the model inappropriate for rapid practical design, it can be usefully employed to investigate the design aspects that are generally disregarded by standard analyses.

First, the model can be used to aid thermal parameter estimation during TRT tests. Usually, the temperature change of the fluid during heat injection is used to calculate the soil thermal properties by application of analytical or (semi)empirical methods. This typically leads to determination of the two main parameters used for routine geothermal design, namely the soil thermal conductivity and steady-state pile thermal resistance. While the former can be obtained by calibrating our model to match field measurements, the latter would need to be determined from Equation 3. However, the advantage of this approach is in the direct determination of the underlying pile physical properties.

Further insight can be gained using the 3D model to investigate the role of transient heat transfer in the pile performance, which is expected to depend on the pile geometry and thermal properties which are usually disregarded in standard design. The larger the pile diameter, the more significant the short term transient behaviour is expected to be. This increases the importance of the role of concrete properties.

The numerical model can be thus used to estimate the thermal properties of both the soil and concrete and to aid development empirical design tools that can more accurately account for transient conduction effects and 3D effects due to the length of pipe circuit and pipe to pipe interactions. Moreover, our model can be used to carry out parametric analyses to produce practical recommendations aimed at improving energy pile design; identifying, among design factors that can be easily engineered, the most important ones to enhance energy efficiency, yet complying with geotechnical design requirements.

In addition, the numerical model can easily be employed to assess thermo-mechanical interactions, i.e. to explore any effects of the induced temperature variations in the pile mechanical behaviour. For example, the effect of differential thermal expansion between concrete and soil, possibly inducing a significant increase of axial load in the pile, can be readily assessed for single energy piles or pile groups. Further, an appropriate thermo-mechanical elasto-plastic constitutive law can be implemented, to assess any irreversible differential deformations occurring on temperature cycling, that may lead to changes in pile settlements and bearing capacity.

It is finally worth remarking that despite the focus of this work being on energy piles, the proposed numerical model is very flexible, and can easily be applied, upon modifying the mesh and the material properties, to the study of diverse geothermal systems such as diaphragm walls and tunnel linings.

APPENDIX

The sensitivity analysis was aimed at identifying the parameters most influencing the fit between the calculated and the experimental outlet temperature curves. Four parameters of uncertain determination λ_c, λ_g, c_c and c_g were varied while the remaining model parameters were kept constant, equal to those adopted in simulation #1 (Table 1). Based on preliminary numerical testing and TRT field experience with the materials at hand, to maximise the chance of possibly achieving a better fit than simulation #1 (Table 1), a relatively narrow range was chosen for the parameters: $2.2 \leq \lambda_g \leq 2.4$ W/mK, $2.6 \leq \lambda_c \leq 3.0$ W/mK, $2050 \leq c_g \leq 2150$ J/kgK, $950 \leq c_g \leq 1050$ J/kgK.

The sensitivity analysis was designed following the Taguchi method (e.g., Peace 1993, Cecinato and Zervos 2012). Three levels for each parameter were

selected, i.e. the upper-bound, the lower-bound and a mid-range value. The Taguchi orthogonal array chosen for this analysis was the conventional "L9", involving a total of 9 simulations to explore the effect of four three-level factors. The simulation response was expressed as the RMSE quantifying the discrepancy between the measured and simulated outlet fluid temperature, limited to the reproduction of TRT stage 2 (Figure 2).

Table A1. Taguchi orthogonal array "L9" with parameter settings. In the rightmost column the output in terms of calculated RMSE between the measured and simulated outlet fluid temperature.

Run	λ_g	λ_c	c_g	c_c	RMSE
#	W/mK	W/mK	J/kgK	J/kgK	
1	2.2	2.6	2050	950	0.2330553
2	2.2	2.8	2100	1000	0.1998981
3	2.2	3	2150	1050	0.2913251
4	2.3	2.6	2100	1050	0.2129381
5	2.3	2.8	2150	950	0.2317168
6	2.3	3	2050	1000	0.306722
7	2.4	2.6	2150	1000	0.2223933
8	2.4	2.8	2050	1050	0.2478095
9	2.4	3	2100	950	0.353036
confirmation	*2.2*	*2.6*	*2150*	*1000*	*0.219218*

Table A2. Response table for the parametric analysis, showing in the bottom line the ranking of importance of parameters, from the strongest to the weakest effect.

RESPONSE TABLE (RMSE of predicted vs measured temperature)				
Level/par.	λ_g	λ_c	c_g	c_c
Min	0.241	0.223	0.263	0.273
Med	0.25	0.226	0.255	0.243
Max	0.274	0.317	0.248	0.251
Effect of parameter (Delta)	0.033	0.094	0.014	0.03
Ranking	2	1	4	3

The parameter settings and the output for each of the nine runs are reported in Table A1. It can be seen that the parameter combination in run #2 gives the lowest RMSE. Next, the RMSE output values were interpreted with a level average analysis (e.g., Peace 1993), to establish a ranking of most influential parameters in the model response, with the results summarised in Table A2. It emerges that the two most important parameters in minimising RMSE are (1) λ_c and (2) λ_g, hence their selection deserves most attention when the numerical model is used to back-calculate field thermal properties by fitting TRT data. Finally, a reliability check (e.g., Peace 1993) was carried out, an estimate of the simulated response with optimal parameter settings and comparing it with a confirmation run (bottom line of Table A1) using the same settings of the parameters. The reliability check corroborates the validity of this analysis, since the estimated and numerically calculated RMSEs are close, resulting in 0.189 and 0.219 respectively.

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REFERENCES

Bozis, D., Papakostas, K., & Kyriakis, N. 2011. On the evaluation of design parameters effects on the heat transfer efficiency of energy piles, *Energy and Buildings* **43 (4)**, 1020-1029.

Cecinato, F., & Zervos, A. 2012. Influence of thermomechanics in the catastrophic collapse of planar landslides, *Canadian geotechnical journal* **49**, 207-225.

Choi, J.C., Lee, S.R. & Lee, D.S. 2011 Numerical simulation of vertical ground heat exchangers: Intermittent operation in unsaturated soil conditions, *Computers and Geotechnics* **38**, 949-958.

Hellstrom, G. 1991. *Ground heat storage theory, Thermal Analysis of Duct Storage Systems.* Department of Mathematical Physics, University of Lund, Sweden.

Lee, C. K., & Lam, H. N. 2013. A simplified model of energy pile for ground-source heat pump systems, *Energy*, **55**, 838-845.

Loveridge F., Powrie W. & Nicholson, D. 2014. Comparison of two different models for pile thermal response test interpretation, *Acta Geotecnica* **9** (3), 367 – 384.

Marcotte, D. & Pasquier, P. 2008. On the estimation of thermal resistance in borehole thermal conductivity tests, *Renewable Energy*, **33**, 2407-2415.

Peace, G.S. 1993. *Taguchi methods: a hands-on approach*. Addison-Wesley, Reading, Mass.

Spitler, J. D. 2005. Editorial: Ground-Source Heat Pump System Research—Past, Present, and Future, *HVAC&R Research* **11** (2), 165-167.

Wagner, V., Bayer, P. Kubert, M. & Blum, P. 2012. Numerical sensitivity study of thermal response tests, *Renewable Energy*, **41**, 245-253.