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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 the last 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).

The bulk of energy pile design tends to be carried out using analytical or empirical methods developed for borehole ground heat exchangers. However, important differences exist between the two types of geothermal systems. For example, energy piles typically have a different aspect ratio than 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), able to accurately capture 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 accurately 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 finally discussed in Section 4.

2 MODEL FORMULATION

The numerical model hereby described aims at reproducing the main processes behind the heat transfer phenomenon 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. It should be noted that 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 be applied to high-permeability water-saturated materials only if the groundwater at a specific site is known to be in static conditions.

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

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

where ρ_f and c_{pf} 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 $\Delta T = (T_s\text{-}T_f)$ 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 to 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 purposes of vertical ground heat exchangers simulation (Choi et al. 2011). Furthermore, as shown in Section 3, the simulation results obtained with this assumption can accurately reproduce temperature field measurements for the full operating time range of a pile TRT.

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

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

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

The above outlined transient heat convection-diffusion problem applied to energy piles was solved by resorting to the Finite Element Method. The model was implemented by employing 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, yet controlling the element aspect ratio and node spacing at key locations to warrant accuracy of heat exchange calculations, the 3D FE mesh was created via manual input in an axisymmetric fashion, consisting of 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 chosen by numerical experimentation to be much larger than the area actually affected by heat transfer, for 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.

As boundary conditions, the inlet fluid temperature is prescribed with the relevant time history. Natural boundary conditions are adopted for the outer domain bounds. As initial conditions, no heat flux and a unique equilibrium temperature for both the fluid and the concrete/ground are set.

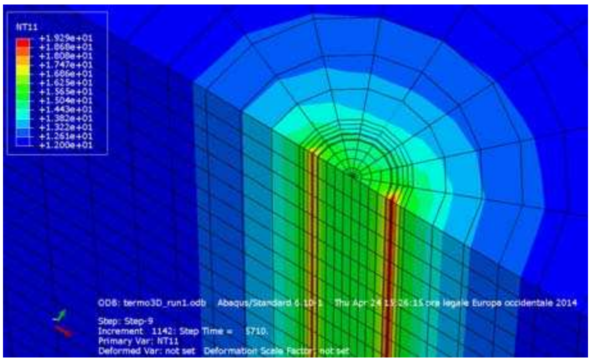

Figure 1. Example of 3D FE mesh for one energy pile with a single U-pipe, with sample calculated temperature contours.

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 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) was followed by a heat extraction test (stage 4) and recovery period (stage 5).

The TRT geometry was reproduced in detail in the numerical model, referring to half of the domain for symmetry reasons (Figure 1). The physical and thermal properties of the materials involved were taken, wherever possible, from published data.

Particular attention was given to the choice of parameters regulating transient heat diffusion, namely thermal conductivities λ_c and λ_g, and specific heat capacities c_c and c_g, of concrete and the ground respectively. Specific heat capacities are rarely considered in practical geothermal studies, as they are peculiar to transient analyses only, while λ_g is frequently measured in the field, since 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 constituting the solid body of the pile were chosen after 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 n=0.3 as a reasonable value of porosity. The soil thermal conductivity, which generally varies depending upon soil type and saturation, was set to 2.3 W/mK, as obtained by interpreting TRT stages 2 and 3 (Loveridge et al. 2014). A complete list of parameters adopted for all materials involved in the simulation is given in Table 1.

Table 1. List of parameters adopted for all materials involved in 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 for all materials was set to 17.4°C, corresponding to the isothermal circulation stage of the test. As a boundary condition, the measured inlet fluid temperature history was imposed at the first node of the U-pipe throughout the simulation time (equal to about two weeks).

The simulation results in terms of predicted outlet fluid temperature, compared to the corresponding measured values, are presented in Figure 2 for TRT stages 2 through 5. It can be observed that the numerical simulation effectively reproduce the field measurements for all stages of the TRT.

To further evaluate the accuracy of the simulation, the root mean square error (RMSE) of the residuals was calculated, resulting in $RMSE_{2-5}$=0.6586 for stages 2-5, and $RMSE_{2\text{-}3}$=0.2308, $RMSE_{4\text{-}5}$=0.8653 considering stages 2-3 and stages 4-5 respectively. It can be inferred that a somewhat better fit of experimental data is achieved for the first two test stages compared to the second two. This outcome is in line with the findings of Loveridge et al (2014), who used analytical and empirical methods to match the TRT output and estimate the ground thermal conductivity, obtaining slightly different back-calculated values of λ_g for the different test stages.

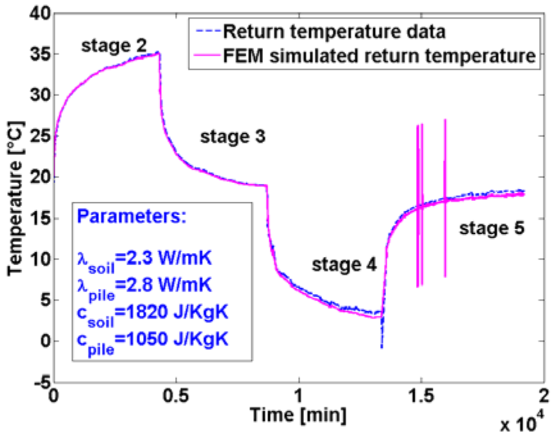

Figure 2. Predicted outlet fluid temperature (solid line) compared to measured outlet fluid temperature (dashed line) for TRT stages 2 through 5.

To compare our numerical results with those obtained from 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 RMSE values obtained by parameter estimation presented by Loveridge et al. (2014), suggesting the better accuracy of prediction of a numerical method that accounts for transient diffusion compared to simpler steady-state methods.

Next, the numerical model was employed to carry out a sensitivity analysis, in an attempt to accurately 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). A significant number of simulations was run in which the four parameters of less certain determination, namely 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, thus 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 those 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 of 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 a good 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). 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):

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

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:

$$\sigma = \frac{\lambda_c-\lambda_g}{\lambda_c+\lambda_g} \tag{4}$$

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

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	

4 DISCUSSION & CONCLUSIONS

The 3D numerical model presented above has been shown to provide realistic interpretation of the key aspects related to 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 quick practical design, it can be fruitfully 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 soil's thermal properties resorting to analytical or (semi)empirical methods. This typically leads to determining the two main parameters used for routine geothermal design, namely soil's 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's geometry and thermal properties that 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 both soil and concrete thermal properties and to aid developing 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 employed 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.

In addition, the numerical model can be easily employed to assess thermo-mechanical interactions, i.e. to explore any effects of the induced temperature variations in the pile's mechanical behaviour. As an example, the effect of differential thermal dilation between concrete and soil, possibly inducing 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 upon temperature cycling, that may lead to changes in the pile's 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 be promptly 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 most influential parameters in best fitting the experimental outlet temperature curve. Four parameters of uncertain determination were chosen, namely λ_c, λ_g, c_c and c_g, to be varied while the remaining model parameters were kept constant, equal to those adopted in simulation #1 (Table 1). Based on preliminary numerical testing and on 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≤ λ_g≤2.4 W/mK, 2.6≤ λ_c≤3.0 W/mK, 2050≤c_g≤2150 J/KgK, 950≤c_g≤1050 J/KgK.

The sensitivity analysis was designed resorting to the Taguchi method (e.g., Peace 1993, Cecinato and Zervos 2012). Three levels for each parameter were selected, namely 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 of run #2 is the one giving 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, whose results are 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 choice 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 performed, calculating an estimate of the predicted 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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