Evaluation of analytical design methods for energy pile groups using a screw-pile case study in Australia

Évaluation des méthodes analytiques de conception pour les groupes de pieux énergétiques à l'aide d'une étude de cas sur pieux vissés en Australie

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ABSTRACT: The usage of shallow geothermal energy systems has already proven to be a viable alternative for reducing fossil-fuel derived heating and cooling energy consumption of buildings, particularly when installing the closed pipe circuits within the building's supporting piles (forming "energy piles"). However, the novel use of short screw piles connected in series to form an equivalent longer ground heat exchanger raises the need for a better understanding of the thermal behaviour of these piles, specifically regarding the thermal interactions between them. This paper utilises 3D finite element modelling in combination with experimental data of energy screw piles installed in series under a building in Melbourne, Australia, to assess their thermal performance and compare against results obtained from common analytical design models proposed in the energy pile literature. The results obtained indicate that the group of piles perform similar to an equivalent borehole under thermal loads favourable to geothermal systems (e.g. fairly balanced loads); and while the existing analytical tools may be suitable to estimate thermal performance and for design, the thermal interaction between the piles is significant and a case-by-case consideration is required.

RÉSUMÉ : L'utilisation de systèmes d'énergie géothermique peu profonde s'est déjà avérée être une alternative viable pour réduire la consommation d'énergie pour la climatisation des bâtiments dérivée des combustibles fossiles, en particulier lors de l'installation de la canalisation dans les pieux du bâtiment (formant des "pieux d'énergie"). Cependant, l'utilisation nouvelle de pieux vissés courts connectés en série pour former un échangeur de chaleur plus long soulève le besoin d'une meilleure compréhension du comportement thermique de ces pieux, en particulier leurs interactions thermiques. Cet article utilise la modélisation par FEM 3D avec des données expérimentales de pieux vissés énergétiques installés en série sous un bâtiment à Melbourne, en Australie, pour évaluer leur performance thermique et les comparer aux résultats obtenus à partir de modèles de conception analytique courants proposés dans la littérature. Les résultats indiquent que le groupe de pieux se comporte de manière similaire à un sonde équivalent sous des charges thermiques favorables aux systèmes géothermiques (assez équilibrés); et bien que les méthodes analytiques existants puissent convenir pour estimer et concevoir les performances thermiques, l'interaction thermique entre les pieux est importante et une égard au cas par cas est nécessaire.

KEYWORDS: Energy geostructures; numerical modelling; analytical methods; energy piles; screw piles.

1 INTRODUCTION.

Ground-source heap pump (GSHP) systems are a reliable and renewable alternative for providing thermal comfort to buildings, which is one of the key drivers of the recent global increase in CO_2 emissions (IEA, 2020). The use of GSHPs along closed loop underground heat exchangers, typically high-density polyethylene (HDPE) pipes, is the most popular shallow direct geothermal system (Lund & Boyd, 2016). These underground HPDE pipes exchange heat with the soil by circulating a carrier fluid (e.g. water), harnessing or rejecting heat according to the building's thermal needs (Johnston, Johnston, Narsilio, & Colls, 2011). Heat may accumulate in the soil during summer operation, which represents energy savings in winter, when the system harvests thermal energy from the soil making it susceptible to absorb heat again in the following summer. This yearly cycle repeats itself for the lifespan of the system.

Even though GSHP system operation typically represents an economic advantage when compared to other traditional thermal comfort technologies, the heat exchangers' construction and drilling costs undermine its feasibility (Lu & Narsilio, 2019). Recently, the installation of the HDPE pipes within geotechnical support structures has emerged as a solution to mitigate these costs (Makasis, Narsilio, Bidarmaghz, & Johnston, 2018), forming energy structures such as energy piles. The underground pipes are installed during construction, "eliminating" the excavation costs involved, since they already are part of the structural budget. Energy pile similarities to traditional borehole heat exchangers (BHE) allowed importing a series of analytical models for thermal design and parameter estimation. However, there are differences that impact the heat exchange, which requires pile-specific analytical methods (Loveridge & Powrie, 2013, Jensen-Page, Loveridge, & Narsilio, 2019). Alternatively, the usage of finite element modelling tools for energy pile evaluation, that provides more accurate results at a cost of higher computational demand, has grown in popularity (Loveridge, McCartney, Narsilio, & Sanchez, 2020). The most popular analytical models that concern energy piles are presented in Table 1, where the general equation for calculating the change in fluid temperature (T_f) in Celsius degrees with time (t) takes the following form:

$$T_f(t) = T_i + \frac{Q}{H} R_b + \frac{Q}{2\pi\lambda_g H} G(t,r) \quad (1)$$

where T_i is the initial fluid temperature (°C), Q the heating power injected (W), H the BHE length (m), R_b the heat exchanger thermal resistance (°C/W), λ_g the ground thermal conductivity W/(m·K) and G(t,r) the ground response function, determined accordingly to the analytical model adopted, typically named as *G-function* (Eskilson, 1987; Loveridge et al., 2020).

Table 1. Main analytical ground heat transfer models.

G-function model	*Reference*
Infinite Line Source (ILS)	Carslaw and Jaeger (1959)
Infinite Cylindrical Source (ICS)	Carslaw and Jaeger (1959)
Finite Line Source (FLS)	Zeng, Diao, and Fang (2002), Lamarche and Beauchamp (2007)
Pile G-functions	Loveridge and Powrie (2013, 2014)

Since the piles' primary purpose is to support the building, their numbers, geometries, and positions are determined by the geotechnical foundation design and adjustments are limited. Therefore, designing an energy pile based GSHP system requires an approach of estimating how much thermal energy the system can provide (Makasis, Narsilio, & Bidarmaghz, 2018). Energy pile systems end up with several heat exchangers connected in a mix of circuits, both in parallel and in series, significantly affected by thermal interactions (Katsura et al., 2009, Loveridge & Powrie, 2014).

The complexity of the thermal interactions involved are hard to capture using the analytical methods. Eskilson's (1987) work provides a series of *G-functions* to be used for several configurations of multiple boreholes and Loveridge and Powrie (2013 & 2014) used the same approach to provide suitable equations for piles; each case requires the determination of a specific function that accounts for the ground response and thermal interaction. Additionally, Katsura et al. (2009) developed an algorithm that accounts for thermal interactions using traditional *G-functions* for energy piles. However, there is no verification for the long term (i.e., years) performance of these methods considering a real application scenario. This work intends to use a combination of full-scale experimental data from a group of energy screw piles built in Melbourne, Australia and state-of-the art finite element modelling techniques for energy structures to investigate the suitability of analytical models in evaluating the energy field of energy pile groups. Then, the thermal performance of the energy pile group is compared to an equivalent BHE.

2 METHODOLOGY

2.1 *Field test set-up*

The Plumbing Industry Climate Action Centre (PICAC) campus located in Narre Warren (VIC, Australia) is a building with a GSHP system in operation. There are 192 13-meter-deep energy screw piles filled with thermal grout and 28 100-meter-deep boreholes acting as heat exchangers. On-site soil strata conditions consist of grey-brown over-consolidated clay for the upper 42 meters and the groundwater level 7 m below surface. As part of the experimental testing and research program, a group of 8 energy screw piles connected in series were instrumented with temperature sensors (thermistors) attached to the pipe wall at the bottom of each pile. Details are presented in Figure 1.

A thermal response test (TRT) (see for example EklÖF and Gehlin, 1996; Jensen-Page et al. 2019) was performed in the whole group simultaneously. First, only the water pump of the testing unit was turned on to homogenise the water temperature in the group and to measure the initial ground temperature T_i, then a nominal heating power of 5,500 W was applied to the energy pile circuit. The test duration was 72 hours, with the heating units on for more than 66 hours. The TRT unit registered the inlet and outlet water temperatures and the input power; a problem occurred with the flow meter that hindered the flow rate measurements. Thus, the flow rate was obtained using Eq. 2. A separate datalogger registered data from the thermistors B1-1 to B1-8 and an ambient temperature sensor.

$$Q = qC_{p_w}\rho_w \Delta T \quad (2)$$

where Q is the heating energy imputed in the heat exchanger, q is the volumetric flow rate, C_{pw} is the water specific heat capacity, ρ_w is the water density and ΔT is the difference of inlet and outlet temperature measurements.

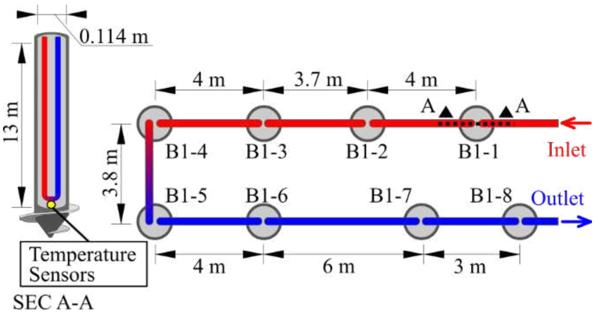

Figure 1. Scheme of the tested energy screw piles group distribution and instrumentation with temperature sensors B1-1 through B1-8 at the bottom of each HDPE U-loop inside the energy screw piles (out of scale).

As described by Loveridge et al. (2015), thermal response tests in energy pile groups can be interpreted as done in an equivalent borehole, even though thermal interactions can affect the results. Since the magnitude of the thermal interference between the energy piles in this case was not known before performing the numerical analysis, an analytical interpretation of the test was undertaken to obtain an estimate for the ground thermal conductivity.

2.2 *Numerical modelling*

A 3D FEM model that represents the energy screw pile group was built in COMSOL Multiphysics, building on models developed within the University of Melbourne (Bidarmaghz, 2014, Makasis, 2018). The model was validated by simulating the TRT test and comparing the results with the experimental measurements. The simulation was used to assess the ground thermal conductivity (λ_g) and the screw pile thermal resistance (R_b). The mesh and boundary conditions are presented in Figure 2 and the input parameters in column 2 in Table 2. All inter-connecting surface pipes were considered as perfectly insulated.

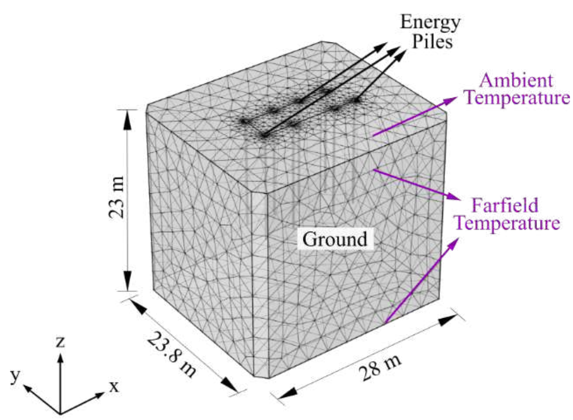

Figure 2. FEM model mesh and boundary conditions.

In order to calibrate the numerical model, the results of a series of TRT simulations using different ground thermal conductivity values are compared to the experimental ones, starting from the value obtained analytically. The thermal conductivity that provided the lower root mean squared error (RMSE) and the mean absolute error (MAE) (Eq. 3 and Eq. 4) values for the mean fluid temperature is then compared to the value obtained analytically and used in the following analysis.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(T_{fmean(i)}^{predicted} - T_{fmean(i)}^{measured}\right)} \tag{3}$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left(\left|T_{fmean(i)}^{predicted} - T_{fmean(i)}^{measured}\right|\right) \tag{4}$$

The inputs in the numerical model are then modified to simulate the screw piles group under real operating conditions. A fairly balanced yearly thermal load distribution is used herein, suitable for a typical two-bedrooms residential dwelling located in Adelaide, Australia (Aditya, Mikhaylova, Narsilio, & Johnston, 2020) and satisfied by two pile groups (Figure 3). This is selected as the reference case for this study, to evaluate the performance of different analytical models as energy pile design tools. The numerical model simulates five years of the pile group daily operation, using the presented thermal load and applying "thermal insulation" as the top boundary condition to reproduce the building's presence. The third column in Table 2 presents the other input parameters. The result of this simulation is used as a benchmark for the evaluation of the analytical methods.

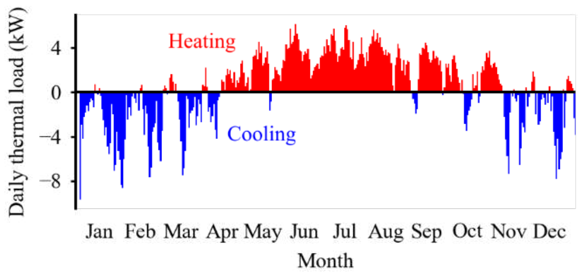

Figure 3. Thermal load case analysed in this work.

Table 2. Numerical model input parameters.

Parameter	*TRT simulation*	*Operation simulation*
Farfield temperature	17.85 °C	18.7 °C (Aditya et. al. 2020)
Pile grout density	2250 kg/m³	2250 kg/m³
Soil density	2000 kg/m³	2000 kg/m³
Pile thermal conductivity	1.4 W/(m·K)	1.4 W/(m·K)
Soil thermal conductivity	1.4 to 1.9 W/(m·K)	1.72 W/(m·K)
Pile heat capacity	890 J/kgK	890 J/kgK
Soil heat capacity	830 J/kgK	830 J/kgK
Fluid flow rate	20.8 L/min	17.5 L/min
Pipe inner diameter	26.9 mm	26.9 mm
Pipe thickness	2.3 mm	2.3 mm

2.3 *Analytical Methods*

To evaluate the performance of the different analytical methods, the same five-year long scenario is modelled analytically. Considering the heat demand variation with time and the thermal interactions between the screw piles in the analytical method, Eq. 1 was modified (as shown in Eq. 6) to incorporate the superposition of effects in time (Eq. 7) (Loveridge & Powrie, 2013; Spitler & Bernier, 2016) as well as in space, from other heat exchangers (Eq. 8) (Katsura et al., 2009). The average fluid temperature of the system, T_f is obtained for each one of the piles, and the fluid temperatures entering and leaving the circuit are then obtained using Eq. 10 and Eq. 11 respectively, modified from Eq 2. This framework is utilised to test four different analytical models in this work. Each model from Table 1 provides a G-function which is used to evaluate the individual ground thermal response for each pile (Eqs. 7 & 8), noting that for Eq. 8 only the ILS model G-function was incorporated, due to its lower computing cost.

$$T_f(t) = T_i + \Delta T_f^{pile}(t) + \Delta T_f^{interferences}(t) \tag{6}$$

$$\Delta T_f^{pile}(t) = \sum_{j=\tau}^{t} Q(j)R_b + \frac{1}{\varphi(j)}\begin{pmatrix} G\left(\left(t-(j-\tau)\right), r_b\right) \\ -G\left((t-j), r_b\right) \end{pmatrix} \tag{7}$$

$$\Delta T_f^{interf}(t) = \sum_{j=\tau}^{t}\sum_{i=1}^{n} \frac{1}{\varphi(j)}\begin{pmatrix} G_i\left(\left(t-(j-\tau)\right), r_i\right) \\ -G_i\left((t-j), r_i\right) \end{pmatrix} \tag{8}$$

$$\varphi(t) = \frac{2\pi\lambda_g H}{Q(t)} \tag{9}$$

$$T_{in}(t) = T_f(t) + \frac{Q(t)}{2qC_{pw}p_w} \tag{10}$$

$$T_{out}(t) = T_f(t) - \frac{Q(t)}{2qC_{pw}p_w} \tag{11}$$

where τ is the time step, n is the number of interacting piles, r_b is the pile radius and r_i is the distance of each on to the pile from which T_f is being calculated.

The thermal resistance value R_b was obtained from Eq. 12 using the numerical model results, considering only the steady state phase (i.e., constant value) for all cases. It is important to note that the Pile specific *G-functions* (Loveridge & Powrie, 2013) presents a concrete G-function, responsible for considering the transient effect of the thermal resistance from the steady state value (Eq 13). Thermal interference from piles further away than H/2 from each other were not considered (Loveridge & Powrie, 2014).

$$R_b = \frac{H}{Q}\left(\overline{T_f} - \overline{T_b}\right) \tag{12}$$

$$R_b^*(t) = R_p + R_c \cdot G_c(t, r_b) \tag{13}$$

where $\overline{T_f}$ and $\overline{T_b}$ are the integral mean values of temperature across all pipes within the screw pile and over the outside pile surface, respectively. R_b^* is the thermal resistance value used exclusively in the tool that uses the *pile G-functions*. R_p and R_c are the pipe and concrete thermal resistances, respectively, and G_c is the concrete G-function.

All calculations were done using the Python programming language, with support of the SciPy library to solve the Bessel functions and integrals (Jones, Oliphant, Peterson, & others, 2001). For the FLS model, calculations were undertaken following Lamarche & Beauchamp (2007). The heat energy per pile (Q) is considered as constant in this work, using the mean for all piles. Despite minor variations in Q between piles, due to the connection in series, the potential error is small, as also shown by Katsura et al. (2009), who mention that heat exchangers connected in series can be considered as a single long heat exchanger without significant error.

The results of the four different analytical tools, where the only difference between them was the *G-function* used in Eq. 8, were compared one by one to the numerical simulation output. Besides comparing the fluid temperature values directly, the error metrics RMSE and MAE calculated for the average temperature value were used to define which method performs best for this case study.

2.4 *Performance assessment*

As a final analysis, this work compares the thermal performance from the energy pile group to an equivalent vertical BHE. The results from the previous analytical simulation for the screw pile group are compared against results for a 104-meter BHE using the analytical model that provided the best result in the previous analysis. It is important to note that when designing GSHP systems, the entering water temperature (EWT) into the heat pump is the key parameter regarding the system operation and performance. Most of the heat pumps cannot operate with an EWT outside the range of 0 °C < EWT < 40 °C and the coefficient of performance (COP) for heating and cooling operations are directly related to this value. Therefore, a performance assessment is undertaken within this analysis, comparing the outlet fluid temperature of the heat exchangers (T_{out}), equivalent to the EWT.

3 MODEL CALIBRATION & VALIDATION

The TRT test was performed as per description in section 2.1. The unit registered an average heating power Q of 4,667.8 W applied to the whole circuit, resulting in an average flow rate q of 20.8 L/min. The analytical evaluation of the results following Loveridge et al. (2015) provided a ground thermal conductivity value λ_g of 1.44 W/(m·K), considering only the steady-state period of the test and assuming the piles form a single borehole of equivalent length. This do not consider the thermal interaction between the piles.

For the calibration of the energy screw pile group numerical model, the TRT was simulated as described in section 2.2, using as input the measured inlet temperature and mean (constant) flow rate. Figure 4 presents the RMSE and MAE results of the outlet fluid temperature for each one of the simulations run with different values of ground thermal conductivity. The best fit between numerical and experimental results occurred for a thermal conductivity λ_g of 1.72 W/(m·K).

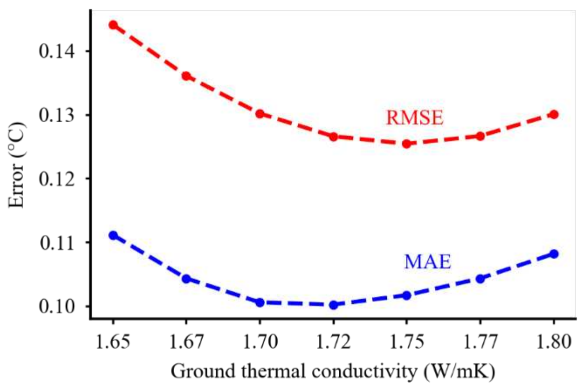

Figure 4. RMSE and MAE of the average fluid temperature obtained from the experimental TRT and numerical simulations for different ground thermal conductivity values.

Figure 5 presents the temperatures measured in the TRT test and the equivalent outputs of the FEM simulation, for a ground thermal conductivity of 1.72 W/(m·K). The uncertainties involved in the measurements of the thermistors B1-1 to B1-8 are significantly higher than the ones from the fluid temperature sensors on the TRT unit, with precision and data quality affected. It is highly likely that the contact between the sensors and the pipe is affected by the grout pouring during the construction process, possibly dislocating the sensors up to a few centimetres away from its original position. The numerical results show an average drop of approximately 2 °C from the pipe wall in the bottom of the pile to a point just 10 mm away. Considering these observations and the nature of the following simulations, the outlet fluid temperature sensors was chosen as the primary model validation parameter. As presented in Figure 5, the thermistors measurements are within the range of possible results obtained numerically considering up to 10 mm dislocation of the sensors. Therefore, the results presented in Figures 4 and 5 accredit the numerical model as a reliable simulation tool for the group of energy screw piles, and the ground thermal conductivity assumed as 1.72 W/(m·K) in the following analyses. The value is 19% higher than the one obtained analytically by traditional means.

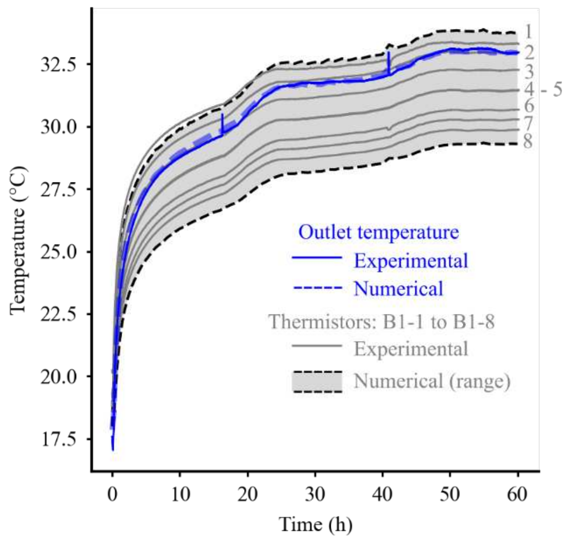

Figure 5. Comparison of numerical and experimental TRT temperature results, for a ground thermal conductivity of 1.72 W/(m·K).

4 ANALYTICAL G-FUNCTIONS

Before presenting the comparison of the results from both numerical and analytical models, some considerations must be noted. Regarding the *Pile G-functions* method, it is important to state that the work from Loveridge and Powrie (2013) presents functions for a range of pile aspect ratios (AR = Pile length / Pile diameter), where the upper limit is 50. Since the screw piles used in this work have AR ≈ 114 and it is not within this work's scope to calculate new *G-functions*, the curve fitting parameters presented for AR = 50 are used herein. The application of the *pile G-functions* also demands considerations regarding other characteristics of the problem (e.g. number of pipes, concrete cover, concrete and ground thermal conductivity; refer to the original work for more details). This work presents the results for the lower boundary *pile G-functions*, considering the pipes are positioned in the centre of the piles, which the authors considered the best fit to this case. However, the results for all four possibilities of *pile G-functions*, formed by combining the previous assumptions with the upper bound option and considering the pipes near the edge of the pile section did not show any significant differences between them.

All the analytical methods *G-functions* used provided reasonable results for the ground response when compared to the numerical model (Figure 6). The usage of the thermal resistance and ground thermal conductivity values obtained numerically clearly contribute for the results' high accuracy. The RMSE value was the highest for the *Pile G-functions* method, probably due to application outside its valid AR range. The lowest error was found using the FLS model *G-function* possibly because it considers the energy pile length and its axial heat exchange, which are not considered in the ILS and ICS models.

Figure 7 presents the evolution of the RMSE per year of analysis for each one of the analytical models. The errors from ILS, ICS and FLS for the first year are similar, while the *Pile G-functions* method presents higher errors due to reasons previously explained. However, both ILS and ICS models' errors tend to increase with time, in opposition to the results arising from using the G-functions derived from the FLS and *Pile G-functions* errors. This emphasises the importance of considering axial heat transfer for short energy piles in long term analyses. Hence, the FLS model was used in the analytical calculations undertaken ahead in section 3.3.

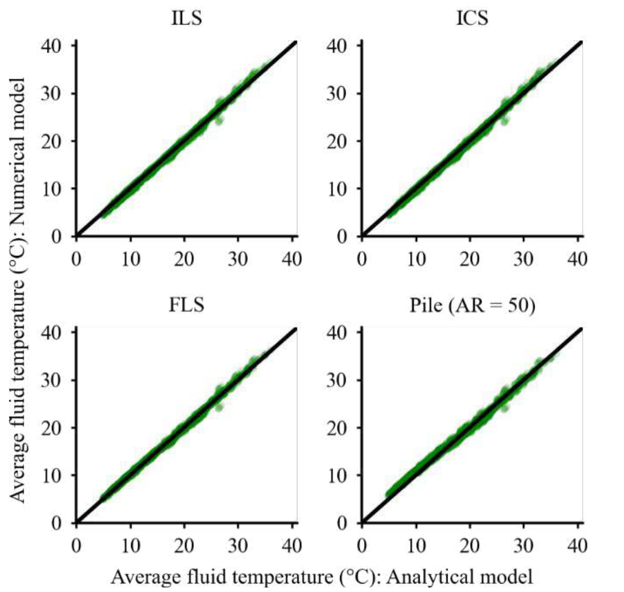

Figure 6. Comparison between average fluid temperature results from the numerical model and analytical simulations. The usage of numerically obtained input parameters (thermal resistance and thermal conductivity) clearly benefit the accuracy of the analytical model adopted.

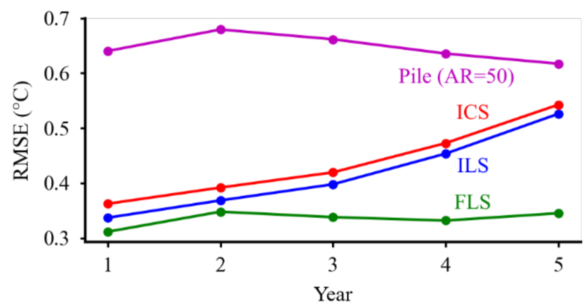

Figure 7. Error values per year of analysis from each analytical model. Note that the AR for the energy piles under study is 114; Specific *G-functions* for energy piles are available for a maximum AR of 50 in the literature to date.

3.3 *Performance assessment*

The thermal load case used favours shallow geothermal systems due to its fairly balanced configuration. However, it still presents an unbalance towards the heating side, resulting in a gradual reduction of the underground temperature with time. A lower underground temperature means a lower performance of the GSHP on cold days and a higher performance on hot days (heating and cooling operations, respectively). The existing thermal interactions in the screw piles group case speed up this soil cooling effect compared to an equivalent BHE, since the temperature changes from Eq. 8 do not exist for the second one. Figure 8 presents the average fluid temperatures per year for the screw pile group in comparison to a BHE with a single U loop with equivalent length and the impact in the GSHP performance considering a hypothetical case where a heat pump performance for both heating and cooling varies linearly and in the same rate accordingly to the variation of the EWT. The virtual COP from the first year of the BHE case operation is a base value (COP_{BASE}) for comparison. The fluid temperature calculations were done using the FLS model as described previously, although for the BHE the results were very similar to the ICS and ILS models.

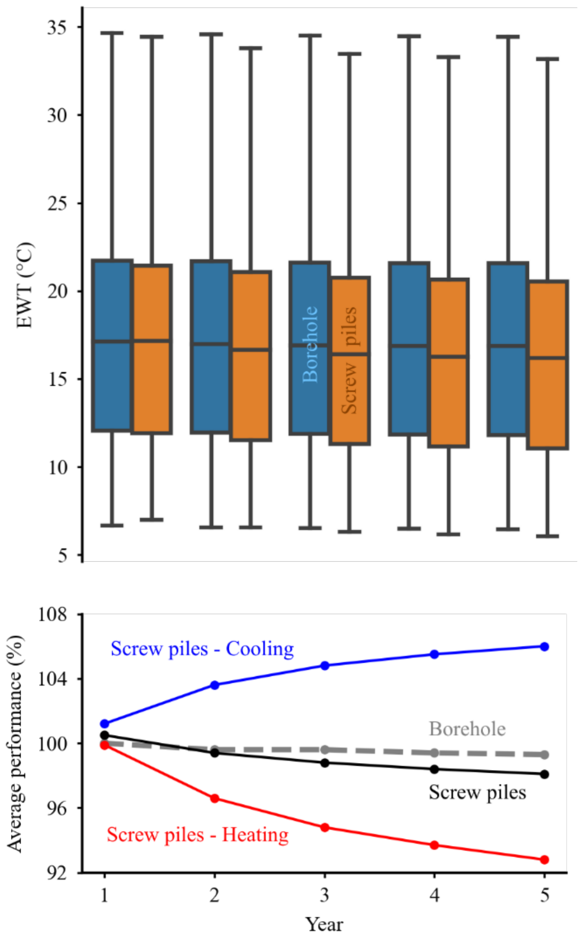

Figure 8. Outlet temperatures distribution and respective performance variation per year from both borehole and screw piles group cases obtained from analytical tools.

The observed performance drop with time is expected since the thermal load case is (slightly) unbalanced. There is no significant variation of the BHE case performance with time, while the thermal interactions from the energy screw pile case causes a more prominent drop in performance for the heating operation. Although, the unbalance benefits its cooling operation due to the lower temperatures, compensating the drop and keeping its performance at 98% of COP_{BASE} while the borehole operates with 99.5% of COP_{BASE} in the fifth year. The graph shows a stabilization trend, indicating that the performance values would not vary much for longer periods.

4 CONCLUSION

The interpretation of the thermal response test (TRT) using traditional analytical methods provided a thermal conductivity value 18% lower than that obtained from more accurate numerical modelling. This conclusion is aligned to Loveridge et al. (2015), confirming that even though the test can be done simultaneously in groups of piles, the interpretation of its results using traditional analytical tools should be done carefully. The lower thermal conductivity from the analytical interpretation may be a result of the non-consideration of thermal interaction between energy piles.

The adopted and further modified methodology presented in work, based on Eq. 6, combined analytical models (for both pile response and thermal interaction) with numerically obtained thermal resistance to evaluate an energy pile group. Four traditional *G-function* models were used to calculate the pile individual ground response, presenting good results when compared to the FEM calculations. The *pile G-functions* errors could be reduced by expanding the work done by Loveridge and Powrie (2013) towards higher AR values, in addition to developing specific thermal interaction functions accordingly to Loveridge and Powrie (2014), which the authors aim to explore in future work. The shortness of the piles favours the application of the finite-source analytical models, especially in the long term. However, the analytical solutions presented in this work still rely on numerical analysis to obtain key input parameters (e.g. thermal resistance, ground thermal conductivity). When given the correct inputs, analytical tools based on traditional models can provide accurate results in a fraction of the time used by FEM models.

The performance analysis indicates that the screw piles group can satisfy the thermal load case evaluated with efficiency equivalent to a vertical BHE. It compensates part of the performance loss on heating operation with gains on cooling. Generally, the performance of shallow geothermal systems worsens the more unbalanced is the load they must attend. This study indicates that this effect is even more significant for multiple short heat exchanger systems.

Additional considerations regarding this work would be to include the presence of the water table as well as different underground heat exchangers interacting. This would take the problem to a scenario where FEM analysis would be expected to outperform analytical methods in accuracy. Groundwater may benefit system performance, due to water properties and energy dissipation due to groundwater flow (if present). Further research is already underway using the numerical and analytical tools presented in this work aiming to answer those questions and potentially others.

5 ACKNOWLEDGEMENTS

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