Thermal response of energy screw piles connected in series

Author 1 - Luis A. Bandeira Neto, MSc (Geotech), CEng[1]
Author 2 - Guillermo A. Narsilio✉, PhD, MSc (Math), MSc (CE), CEng[2]
Author 3 - Nikolas Makasis, PhD, MSc (CS), ME (CIEV), CEng[3]
Author 4 - Ruchi Choudhary, PhD, Arch[4]
Author 5 - Yale Carden[5]

Abstract:
Energy piles are a consolidated underground heat exchanger alternative to traditional boreholes in ground source heat pump (GSHP) systems. Previous works focused on assessing the differences between piles and boreholes, but few assessed small piles in operational conditions. Moreover, most of these studies centred around cylindrical concrete piles, overlooking short screw piles. Using in-situ testing, established analytical methods and advanced 3D finite element model simulations, this work assesses three thermal response tests (TRT) executed in different energy pile structures, one being a unique group of eight short energy screw piles connected in series, located in the same site in Melbourne, Australia. Detailed numerical analysis provided reliable soil and structure thermal parameter predictions and detailed computations allowed the study of thermal effects for the energy screw piles steel components. The results show limited impact of the steel components on effective thermal conductivity, but a reduction in thermal resistivity which may provide a speedier thermal exchange in short term GSHP operation. In addition, the more traditional TRT rigs and analytical interpretation provided reasonable results for the pile group in series, and show a similar performance to a borehole heat exchanger of similar pipe length, however, the short piles engages only the upper, potentially lower thermal conductivity soil layers. TRT in single short screw piles require careful consideration, noting that common rigs may be unable to cater for the required low fluid flow rates and heating power, thus, for the cases assessed herein the pile group TRT proved to be more reliable than individual pile testing due to their short length.

Keywords
Shallow Geothermal; Thermal response test; Energy Screw Piles; Numerical Analysis;

---

[1] PhD candidate, Dept. of Infrastructure Engineering, Univ. of Melbourne, Parkville, VIC 3010, Australia. ORCID: 0000-0002-4314-2637. Email: bandeiraneto@unimelb.edu.au
[2] Professor and Deputy head of Department (Research), Dept. of Infrastructure Engineering, Univ. of Melbourne, Parkville, VIC 3010, Australia (corresponding author). ORCID: 0000-0003-1219-5661. Email: narsilio@unimelb.edu.au
[3] Research Associate, Engineering Department, University of Cambridge, Cambridge, UK. ORCID: 0000-0002-6678-1239. Email: nm735@eng.cam.ac.uk; also Dept. of Infrastructure Engineering, Univ. of Melbourne, Parkville, VIC 3010, Australia.
[4] Professor, Engineering Department, University of Cambridge, Cambridge, UK. ORCID: 0000-0001-6915-3433. Email: rc488@cam.ac.uk
[5] Managing Director, GeoExchange Australia Pty Ltd, 100 Walker Street, North Sydney, NSW 2060, Australia. Email: ycarden@geoexchange.com.au

Full contact details of corresponding author
Guillermo A. Narsilio, Deputy Head of Department (Research) and Professor
Engineering Block B 205, Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC 3010, Australia
Email: narsilio@unimelb.edu.au, Phone: +61 (3) 8344 4659, Fax: +61 (3) 8344 4616

List of Notations

$C_{p,g}$	specific heat capacity of ground material (J/(kg K))
$C_{p,c}$	specific heat capacity of grout (J/(kg K))
$C_{p,s}$	specific heat capacity of steel (J/(kg K))
$C_{p,f}$	specific heat capacity of carrier fluid (J/(kg K))
Fo	Fourier number (-)
H	heat exchanger length (m)
Q	power rate (W)
q_{rate}	fluid flow rate (L/min)
R_b	thermal resistance ((m K)/W)
r_b	borehole/pile radius (m)
$T_{farfield}$	undisturbed ground temperature (°C)
$T_{i,water}$	starting water temperature (°C)
T_{in}	fluid inlet temperature (°C)
T_{out}	fluid outlet temperature (°C)
$\bar{T}_f$	integral mean fluid temperature (°C)
$\bar{T}_b$	integral mean borehole temperature (°C)
α_g	thermal diffusivity of ground (W/(m K))
λ_g	thermal conductivity of ground (W/(m K))
λ_c	thermal conductivity of grout (W/(m K))
λ_s	thermal conductivity of steel (W/(m K))
λ_f	thermal conductivity of water (W/(m K))
ρ_g	density of ground (kg/m^3)
ρ_c	density of grout (kg/m^3)
ρ_s	density of steel (kg/m^3)
ρ_f	density of water (kg/m^3)

1 Introduction

The need to meet the growing energy demand and reduce greenhouse gas emissions is more critical than ever, resulting to a gradual worldwide energy supply transition to renewable energy sources. Shallow geothermal energy systems for heating and cooling buildings represent a way to contribute to these issues (Johnston et al, 2011). Direct energy extraction coupled with Ground Source Heat Pumps (GSHPs) is among the most popular applications of shallow geothermal energy. These systems comprise of a heat pump connected to a High-Density Polyethylene (HDPE) pipe circuit embodied in underground heat exchangers and to a heating and cooling distribution system in buildings that can take different forms (ducted air, refrigerant fan coil units, etc) (Brandl, 2006). A heat carrier fluid (e.g. water) circulates in the pipes transporting heat from/into the ground, taking advantage of the more constant soil temperature in comparison to the atmosphere air (ARENA, 2014; Arulrajah et al, 2015; Brandl, 2006; Loveridge et al, 2020). If designed correctly, the system extracts at least 75% of the energy used for heating and cooling from the soil, contributing to the operational economics of this renewable energy source (Brandl, 2006). In other words, the system has a coefficient of performance (COP) of 4, providing 4 units of thermal energy per 1 unit of power used to run the GSHP. Higher COPs are common nowadays. Consequently, there is a growing trend in using GSHP systems for buildings' thermal comfort worldwide (Lund & Boyd, 2016), however the installation costs involved restrain the system feasibility in broader conditions (Lu & Narsilio, 2019). An application that can reduce these installation costs is the usage of underground supporting structures as heat exchangers (forming energy structures), which has drawn much attention in recent years (Adam & Markiewicz, 2009; Singh et al, 2019).

Energy piles are the most well-studied energy structure (Brandl, 2006; Loveridge et al, 2020), given their geometrical similarity (and frequency) to traditional borehole heat exchangers. This similarity allowed, in principle, importing methods from established borehole practice to energy pile geothermal design. Nevertheless, thermally activating piles brings new challenges regarding both thermal and geotechnical designs. The geotechnical performance of the pile may be affected by the heating and cooling operation, due to dilation stresses and changes in the soil mechanical properties (Amatya et al, 2012; Laloui & Donna, 2011; Laloui & François, 2009). Pile geometry and distribution are defined primarily by the geotechnical and structural needs, usually distributed irregularly on the terrain. Therefore, energy pile fields are subjected to inconsistent or irregular sequences of heat exchanger placements (and of pipe connections in parallel and series), raising the challenge of obtaining each pile's heat exchanging rate and, consequently, the whole system's thermal capacity (Katsura et al, 2009). In addition, heat exchanger length is restrained for existing piles, demanding a strategy that evaluates the available energy for that geometry instead of defining lengths and geometries of the heat exchangers, as done with boreholes (Makasis et al, 2018a). Moreover, even though piles are typically cylindrical, they can be substantially shorter and eventually larger in diameter than boreholes, which influences their thermal performance as heat exchangers (Jensen-Page et al, 2019; Loveridge & Powrie, 2013). Furthermore, different foundation solutions may involve different geometries and materials, uncommon to the underground heat exchanger practice (Alberdi-Pagola et al, 2018; Huang et al, 2019; Jalaluddin et al, 2011; Makasis et al, 2018b). Despite all those differences, energy pile thermal design still uses tools and methods developed for boreholes in the first place.

Thermal behaviour knowledge of the soil and heat exchangers is essential for GSHP system design. Precise soil thermal conductivity (λ_g), heat exchanger thermal resistance (R_b) and undisturbed ground temperature (T_{g0}) estimations are critical for proper GSHP system sizing (Loveridge et al, 2017). The Thermal Response Test (TRT) is the main in-situ test tool used to estimate these parameters. Conceived (Austin III, 1998; EklÖF & Gehlin, 1996) and standardized (ASHRAE, 2001) for boreholes, TRT has also been applied on energy piles (Brettmann & Amis, 2011; Franco et al, 2016; Jensen-Page et al, 2019). Common TRT execution consists on injecting heat to the ground at a constant power rate by circulating water inside the HDPE pipes of the tested heat exchanger with the help of a circulation pump and a heater. Cooling TRTs are a less common alternative. ASHRAE testing guidelines require the measurement of heating power, inlet and outlet fluid temperatures during the test, while recording the flow rate is suggested. The heating power should be between 50 and 80 W/m length of the borehole, and fluid flow rate should ensure a temperature difference between 3 to 7 °C. These recommendations aim to avoid overheating and to keep the temperature difference reasonably larger than the sensor precision. However, most existing TRT rigs were built for borehole testing, which means their heating elements and circulation pumps are not always suitable for shorter heat exchangers (e.g. short piles) and thus adaptations are required. Instead of building new or modifying existing equipment, TRTs can also be performed in groups of piles (Brettmann & Amis, 2011). However, deeper understanding on how to perform and interpret group TRTs is required.

Traditionally, TRT outputs are interpreted based on heat transfer analytical models (Franco & Conti, 2020; Witte, 2016) with the Infinite Line Source Model (ILSM) (Carslaw & Jaeger, 1959) being the most popular. ILSM has a simple implementation but is bounded to several simplifying assumptions that may hinder both precision and accuracy of the results, depending on the vertical heat exchanger geometry. The commonly larger diameters and shorter length of energy piles swerve from ILSM conventions, which lead to pile specific methods, such as pile G-functions (Loveridge & Powrie, 2013). ILSM assumes the ground is a single homogeneous and isotropic material, which led borehole practice to adopt effective ground thermal conductivity ($\lambda_{g,eff}$) and thermal diffusivity ($\alpha_{g,eff}$) as an equivalent representation of the thermal properties of the whole soil strip tested. Alternatively, finite element (FE) tools can model boreholes and energy structures (Bidarmaghz et al, 2016; Franco et al, 2016; Jensen-Page et al, 2019; Signorelli et al, 2007), that despite requiring more computational resources, allows a broader range of considerations (Jensen-Page et al, 2018; Loveridge & Powrie, 2013), such as multiple heat exchangers (Loveridge & Powrie, 2014). Regarding energy pile groups, Katsura et al (2009) states that several piles connected in series could be considered as a single length-equivalent heat exchanger. However, it is known that thermal interference may happen from one heat exchanger to another depending on the distances between them (Cimmino & Bernier, 2014; Eskilson, 1987; Loveridge & Powrie, 2014). Thermal interference is not accounted for in the typical analytical methods such as the ILSM. Brettmann & Amis (2011) performed a group TRT in three piles connected in series, with different grout properties and diameters. Temperature sensors installed in the soil between the piles confirmed that no thermal interaction occurred during the eight-day testing period. A value of $\lambda_{g,eff}$ = 2.66 W/(m/K) was found using the ILSM model equation and the fluid temperature results, while the analysis of the measurements from the temperature sensors installed inside each pile provided lower values by about 3% to 8%. Loveridge and others performed further analysis in the same pile group, running individual and group TRTs (Loveridge et al, 2015a; Loveridge et al, 2015b). The study concludes that group test can be interpreted using simple analytical methods if no thermal interaction occurs, although the interpretation results point that the pile group did not reach steady state even after eight days of testing. In these studies, no analysis was undertaken regarding the thermal resistance, which is a measure of the pile or borehole geometry influence to heat transfer within the GHE rather than within the soil. Despite these handful notable studies, the lack of published analyses on pile group thermal response testing leaves gaps regarding both execution and interpretation of energy pile group TRTs.

To continue contributing to the energy structure knowledge, this work analyses the results of TRTs performed in a typical borehole and short energy screw piles (individually and as a group) located in a single site in Melbourne – Australia. The usage of screw piles as energy piles has been documented before (Huang et al, 2019; Jalaluddin et al, 2011) but without a closer examination of its particularities. Faizal et al (2016) points that the presence of steel in the pile lowers the thermal resistance due to its higher thermal conductivity. The screw piles and the borehole analysed in this work have similar diameters, which contributes to isolate the effects of the steel components on the thermal performance and evaluate how the thermal performance of a single-long heat exchanger compares to several shorter ones connected in series. Temperature sensors along the borehole and energy screw piles are used to validate detailed 3-D FE models, providing reliable estimations for the thermal parameters, as they prove to be effective on assessing group TRTs. Additionally, the application of the ILSM typically used in borehole practice is assessed by comparing its results with the numerical ones, in order to assess its applicability in short pile groups TRT interpretation, having the borehole in the same site as reference.

2 Methodology

This work presents and analyses the results of three thermal response tests executed in different energy structures (one being a group of eight energy screw piles connected in series) during the construction of a building in Melbourne. The results of the TRT and the underground temperature sensors readings are analysed analytically, considering the group of energy screw piles as an equivalent-long single borehole. After the preliminary test data analysis, 3-D FE models were validated and calibrated and later used for simulating the tests. Analysis of numerical simulation results provided reliable estimations for the effective ground thermal conductivity and the heat exchangers' thermal resistance for each test, as well as further insights regarding each energy structure's performance.

2.1 Experimental site

The Plumbing Industry Climate Action Centre (PICAC) construction site is located in Narre Warren, about 60 km southeast from Melbourne (Australia), where a GSHP system supplies thermal comfort to the $4{,}500\ m^2$ school buildings. The underground heat exchangers comprise of several boreholes and energy screw piles that support the building. The boreholes were dug inside open-end screw piles, reaching 100 metres depth, while the energy screw pile pipes were inserted inside 13-meter deep close-end screw piles. Both were filled with "thermal grout" (i.e., silica bentonite grout) (Figure 1). A single "U-loop" of HDPE PN 12.5 pipes was installed in each energy structure, with 40 mm nominal (outer) diameter in the boreholes, and 32 mm, in the screw piles. Two of the building's energy structures were instrumented: one Borehole (B) and a Group of eight energy screw piles connected in series (G). Within the Borehole B, a Geokon Thermistor String (Model 3810-2) with 9 sensors (± 0.2 °C precision) positioned every 20 meters was attached externally to its HDPE pipes. In the Group G, a single NTC Dixell thermistor was installed in the bottom of each one of the eight screw piles. For temperatures between -10 °C and 40 °C, these sensors have ± 0.5 °C precision. The borehole excavation log reveals a residual clay layer on top of shale rock, and the ground water table was encountered at a depth of 7 m. The Narre Warren area geology has occurrence of granite intrusions on siltstones and sandstones below clayey soil (Peck et al, 1992). The site profile information, from the borehole excavation log, alongside details of both energy structures are presented in Figure 2.

During the building construction phase, three TRTs were performed by The University of Melbourne energy structures research team (Chan & Sait, 2018; Hanson & Robertson, 2018). Both Borehole B and Group G were tested, using the same equipment and heating power. Three heating elements provided a nominal power of 5.5 kW (i.e., 55.0 W/m to 50.9 W/m), and data was recorded for over two days on each test, ensuring that enough of the test occurred within heat transfer steady-state phase. During the test executed on the pile group, the surface pipes that connect the piles were insulated. The third TRT was performed in a single energy screw pile S, more than 15 meters distant from both B and G to avoid thermal interaction. To perform this TRT test, the equipment had to be adapted to avoid overheating. The electric connection of a 1.5 kW element was modified from in series to in parallel to provide half (750 W) nominal power (i.e., 57.7 W/m). During all tests, inlet and outlet temperatures were recorded every minute, as also the equipment power consumption and the temperature in the structure sensors when available. Due to a malfunction in the TRT device, the flow rate q could not be measured.

Therefore, it was back-calculated using Equation 1, considering the heating power recorded during the test. The fairly stable power rate provided by the generator, presented in the results section, ensured minimal variation on the calculated flow rate.

$$q_{rate} = \frac{Q}{\rho_f Cp_f (T_{in} - T_{out})} \quad (1)$$

where q_{rate} is the fluid flow rate, Q is the power rate, ρ_f is the fluid density, Cp_f is the fluid heat capacity and T_{in} and T_{out} are the fluid inlet and outlet recorded temperatures, respectively. Hereafter, TRT-G refers to the test performed on the group of eight energy screw piles, TRT-B to the one undertaken on the borehole and TRT-S to the one done in a single screw pile.

2.2 Analytical analysis

The suitability of simple analytical heat transfer models for interpretation of TRTs is key to engineering practice. Equation 2, derived from the log-linear approximation of the ILSM, is the simplest and most popular method of interpreting λ_g from TRTs, used from its primordial applications (EklÖF & Gehlin, 1996). Beier & Smith (2002) followed the same principle to evaluate R_b when the testing time $t = t_1$, which is the intercept of the log-linear approximation in the ln-space (Equation 3) (i.e. $ln(t_1) = 0$).

$$\lambda_g = \frac{Q}{4\pi m H} \quad (2)$$

$$R_b = \frac{1}{4\pi\lambda_g}\left[\frac{\mathrm{T}(t_{1hr}) - T_0}{m} - \ln\left(\frac{4\alpha_g t_{1hr}}{e^{\gamma} r_b^2}\right)\right] \quad (3)$$

where m is the slope of the line obtained through linear regression of the recorded average fluid temperature plotted against the natural logarithm of time, T_0 is the undisturbed ground temperature, H is the heat exchanger length and R_b is the pile or borehole steady state thermal resistance. The ILSM is not able to consider different soil layer properties, and the λ_g obtained is an 'effective' value for the ground thermal conductivity λ_g. In addition, the simplification is only valid when the time (t) is sufficiently large to ensure steady state conditions, i.e., when the short-term heat transfer that mostly occurs within the heat exchanger itself, is over. Since the magnitude of this time (t) is related to the ground thermal properties themselves (α_g is the ground themal diffusivity) and the heat exchanger geometry (r_b is the borehole diameter), borehole practice uses Fourier number Fo as a nondimensional time ($Fo = (\alpha_g \cdot t)/r_b^2$). This ILSM simplification is valid for Fo ≥ 5 (EklÖF & Gehlin, 1996; Eskilson, 1987), which corresponds to the beginning of the steady state heat transfer phase in the energy structure. However, others pointed that disregarding a larger portion of the beginning of the test and analyse it only when Fo ≥ 20 can reduce λ_g estimation error from 10% to 2.5% (Vieira et al, 2017).

This work evaluates the results from all TRTs using Equations 2 and 3 to obtain estimations of λ_g and R_b. Different test time windows with distinct starting times in terms of Fo (1, 5, 10 and 20) are analysed, to compare the tests in terms of results convergence and accuracy. When analysing TRT-G, the group of energy screw piles in series are considered as a single length-equivalent borehole to check if the model can interpret the group test. In order to support the analytical analysis and support the results, an established numerical model is used to build different geometries and analyse further the energy structures.

2.3 Numerical analysis: Finite Element models

A transient 3-D FE model previously developed and validated within the University of Melbourne is used in this work to undertake the numerical analysis. The model couples the governing equations of fluid flow and heat transfer (continuity, momentum conservation and energy balance equations). Only conductive heat transfer is considered on all materials, except for the circulating water where both conductive and convective processes are accounted for. This means that no groundwater presence was directly considered in this work, however, the parameters obtained from the TRT indirectly account for the groundwater effect (Franco & Conti, 2020). Detailed information of the model can be found in (Bidarmaghz, 2014; Makasis, 2019), as well as applications on several energy structures (Bidarmaghz et al, 2016; Cecinato & Loveridge, 2015; Delerablee et al, 2019; Di Donna & Laloui, 2015; Faizal et al, 2022; Insana & Barla, 2020; Jensen-Page et al, 2019; Makasis & Narsilio, 2020; Makasis et al, 2018b; Rotta Loria et al, 2015; Zhang et al, 2022).

Three different geometries were implemented using the FE package COMSOL Multiphysics, one for each energy structure tested. The first model incorporates a single 13-metre energy screw pile with one HDPE U-loop pipe (32 mm diameter) inside as shown in Figure 3-a. The detail in Figure 3 shows how the 7.1 mm wall and steel screw of the pile were modelled using a simplified geometry of the screw. Simulations with and without the screw piles steel components (hereafter referred as Complete and Simple analyses, respectively) were undertaken on the respective single and group models (Figure 3-a and Figure 3-b) to evaluate their effect on the piles' thermal response. The HDPE pipes that interconnect the piles on the surface (Figure 3-b) were considered perfectly insulated. The third and last model shown in Figure 3-c corresponds to Borehole B, having a 40 mm diameter HDPE pipe U-loop. All model geometries followed the respective heat exchanger design (as per Figure 1 and Figure 2).

All three models considered a centre-to-centre HDPE pipe spacing of 50 mm and an isotropic and homogeneous soil, as to render an (single) effective soil thermal conductivity. For simulating the TRTs, the adopted heat transfer boundary conditions were ambient temperature on the top surface of the geometry and undisturbed ground (farfield) temperature on its sides and bottom. The heat power recorded in each test was used to obtain the inlet fluid temperature using Equation 1, based in the outlet fluid temperature computed on each simulation time step, reproducing water circulation.

Figure 3 presents the models' geometries and respective meshes. During the calibration of the FE model, presented in section 3.3, the experimental tests were simulated for a range of λ_g and λ_c values. The simulated average fluid temperatures were compared with the experimentally measured values (results are relatively insensitive to the variations of specific heat capacity and density, thus the fixed values in all simulations). Table 1 presents the materials and parameters considered. The material parameters were obtained either from COMSOL library or common values for soil materials from Melbourne (Colls, 2013). A mesh sensitivity analysis was conducted to ensure the fluid temperature values were independent on the mesh size (Table 2) and no boundary effects were observed in any of the analyses. The simulations incorporated 15-minute intervals up to 12 hours, to enable better convergence and reduce initialisation errors, followed by hourly time stepping until their respective end time. The predicted versus measured fluid temperature root mean squared error (RMSE) was the gauge metric to assess calibration. The pair $\lambda_{g,eff}$ and λ_c values that resulted in the lowest RMSE was assumed as the interpretation result of each test. The energy structures' transient thermal resistance R_b was calculated using Equation 4 from each model results as well:

$$R_b = \frac{H}{Q}\left(\overline{T_f} - \overline{T_b}\right) \tag{4}$$

where Q is the power rate and T_f and T_b are the integral mean temperature values from the circulating fluid and the pile/borehole wall, respectively.

The comparison between the temperature measurements inside the structures during the tests (sensors shown in Figure 2) with the equivalent values obtained in the numerical simulations ensured the FE models suitability to simulate the energy structures in this work. In addition to $\lambda_{g,eff}$ and R_b estimations, the numerical models provided the opportunity for a more detailed look at the heat exchangers. The model results were analysed, focusing on the energy screw pile response both individually and as a group of heat exchangers, and its comparison to the borehole located in the same site.

3 Results and Discussion

3.1 Experimental results

As per section 2.1, three undertaken TRTs are presented in this study. The measured values for all three tests are presented in Figure 4. All tests presented typical TRT fluid temperature trends, and power supply was stable (less than 1% variation). Nevertheless, each test had its particularities worth mentioning. TRT-G fluid temperatures show to be more influenced from ambient conditions than the other tests. The longer pipe extension exposed in the surface is a possible reason behind it, despite the pipe insulation. Murphy, McCartney, and Henry (2014) studied the effect of the horizontal run-out length of pipe in the TRT results, showing that extensive segments may result in underestimation of λ_g due to heat loss. However, their tests were executed in each pile individually, while here the effect is distributed between the piles connected in series. Moreover, the horizontal pipes on the referred experiment were not insulated, which significantly increase the heat losses. A difference of 0.2 W/(m·K) on λ_g was reported due to 23.6 metres of horizontal piping. The expected impact on TRT-G is lower since the pipes were insulated. TRT-B resulted in lower and more steady fluid temperatures than TRT-G. The power inlet was steady during the test, but a short power outage occurred right before it completed 6 hours, and the effect is shown on the fluid temperature measurement. The temperature difference is lower than TRT-G, which means a higher fluid flow rate; this is attributable to the longer pipe extension and greater number of elbow connections in the pile group G.

TRT-S presented a very low fluid temperature difference, the inlet and outlet values seemingly overlapping on the graph due to the scale. As described in section 2.1, for this test the TRT rig heating elements were adapted, however, the circulation pump operated normally which resulted in a flow rate much higher than recommended (ASHRAE, 2001), hindering the test measurements. To obtain the TRT-S flow rate it was not possible to use Equation 1, therefore the pumping power required to circulate the water on both TRT-B and TRT-G was calculated using the well-known Darcy-Weisbach equation for determination of the power and obtaining the pipe friction factor using Churchill equation (Churchill, 1977), considering the respective pipe configuration of each test. The result value was then used to obtain the flow rate for the shorter (hence less hydraulic resistant) pipe circuit of the single screw pile, calculated as 43.5 L/min (Table 1). The ambient temperature was not recorded during TRT-S hence data from the Moorabbin Airport weather station, located less than 20 kilometres from the site, is included alongside the fluid temperatures in Figure 4. Despite all the problems that raise uncertainty on the results of TRT-S, the fact that it presented a fluid temperature trend and there are other tests undertaken on the same site were considered enough to analyse its results alongside TRT-G and TRT-B. Moreover, the challenges observed in the execution of TRT-S are worth highlighting, as they are in line with the types of issues this work is analysing regarding the execution of TRTs in single piles versus groups of piles, showcasing the unsuitability of TRT on single similarly short piles and the need to measure and adjust flow rates.

The sensors installed within Group G and Borehole B measured the ground temperature prior to starting each test, registering 18.8 °C and 17.5 °C on average, respectively. After starting the circulation pump, the fluid temperature sensors inside the pipes recorded the temperature for a few minutes on each test. Both TRT-G and TRT-B presented temperatures close to 18 °C, matching what the underground sensors were measuring previously, while TRT-S presented a temperature above 19 °C and was the only test where the temperature started to rise before the heaters were turned on. This suggests that the heat energy from the circulation pump was significant enough to heat the short pile, even though the measurement period before turning the heating elements was brief (4 minutes).

Figure 5 presents the temperatures recorded by the sensors installed at the bottom of each pile from Group G during TRT-G. From the 0 hr measurements it is possible to see the temperature recorded by G-3 was higher than the presented by other sensors and kept this way during the execution of the test. Likely, this sensor was damaged during installation or was not properly calibrated. The remaining sensors indicate that the temperature rises faster at the first piles in the series, while towards the end there is a lower pile-to-pile relative temperature difference, sometimes inside the sensors' precision range. It is also worth noting that potential discrepancies on the vertical position of G sensors (due to the nature of their installation) would not be surprising and could justify some of the observed behaviour. Figure 6 presents the temperature measurements of the Borehole B sensors during TRT-B. The more "erratic" measurements may indicate direct influence of the different soil/rock materials present on each sensor depth. Potentially the pipe and the sensors could have their respective position and spacing was affected by the grout pouring.

3.2 Analytical analyses

Given the time constrains involved in performing numerical simulations, it is recommended to undertake analytical analysis first, to provide guidance on the expected results and save time (Signorelli et al, 2007). Therefore, the experimental results presented in section 3.1 were analysed using the ILSM linear regression, as commonly done in practice. Even though the ILSM linear regression is deemed valid only when the testing time is higher than Fo=5, the results were analysed using data when time was higher than Fo=1, Fo=5, Fo=10 and Fo=20 respectively to find the slope *m*. Table 3 presents the time that corresponds to each Fourier number of each TRT. Figure 7 presents the logarithm plot used in the analyses while Table 4 presents the results for the different time windows. It is possible to observe in Figure 7 that analyses starting later in time (higher Fo numbers) are more susceptible to noise in the data due to reduction of the total test time analysed (Jensen-Page et al, 2019). The noise resulting from the ambient temperature influence is more significant on TRT-G and TRT-S. On the other hand, the results of these tests seem to converge faster, as the values of λ_g and R_b starting from Fo=1 are similar to the ones starting from Fo=5 and Fo=10. The steel in the screw piles seems to hasten the short-term heat transfer, therefore the interpretation using early stages of the test provides better results than for the pure-grout borehole. Regarding TRT-B, the results start to converge only after Fo=5. However, since only the analyses after Fo=10 and Fo=20 do not include the power outage event, the time window starting at Fo=10 analysis results were selected as preliminary values to perform the simulations.

Equation 2 was also applied to the Group G and Borehole B temperature sensors to estimate the λ_g for Fo=10 with results shown in Figure 8 for each sensor, according to their position in each structure. The λ_g values for G are considerably steadier than the B ones, due to them being in the same material, while B sensors are spread between different material layers, therefore they respond directly to them. The coefficient of variation of the G sensors λ_g results is only 3% and drops to 1% when sensor G-3 is excluded, while for B sensors it sits at 8%. The fact that the B sensors installed at the same depth had similar λ_g results strengthens this hypothesis. B-1 and B-9 are the only borehole ones inside the clay layer, while all others are in contact with the blue shale; a division also visually observed in the results. The computed λ_g for Sensor B-5 is considerably higher than others. Similarly, all G sensor results are higher than the λ_g obtained from the TRT-G fluid temperature. One possible explanation for this is the fact that these sensors are installed below the pipe U-loop curve, meaning that the heat energy reaching them is lower than the one being radially transmitted. Another key point is that the effective thermal conductivity of soil and rock materials tends to rise with depth due to reduced porosity (Fei, Narsilio, & Disfani, 2021; Schjønning, 2021). Figure 8b) presents a growing λ_g trend with depth, and the distributed λ_g estimated for each pile toe in the group correspond to material actually tested at the maximum depth (~13 metres), which may also explain why the average values of the G sensors are higher than the TRT-G.

3.3 FEM calibration and further validations

As described in section 2.3, each one of the numerical models was calibrated by fixing all parameter values presented in the table except for the effective ground thermal conductivity (λ_g) and grout thermal conductivity (λ_c). The first guest value of λ_c was based in the literature while for λ_g, from the analytical analysis undertaken in the previous section for Fo = 10. The outputs were compared using RMSE to decide the most suitable values.

Figure 9 presents the calibration results for the single screw pile models. To study the effect of the steel components on its thermal operation, the calibration was done both by considering the steel wall and screw in the model (Complete model) as well as, alternatively, excluding the screw and modelling all pile as grout material (Simple model). The lowest RMSE value was found for λ_g = 1.1 W/(m·K) and λ_c = 1.6 W/(m·K) for the Complete model, a 0.2 W/(m·K) difference on λ_g from the analytical analysis result. The results obtained using the Simple model were slightly lower for higher thermal conductivity values on both materials. Table 1 shows how the steel thermal conductivity is significantly higher than grout, accelerating the heat transport. Therefore, the best fit on the Simple model happens at higher thermal conductivity values to compensate the absence of the steel components. However, the lowest RMSE value of the Simple model was found for λ_g = 1.3 W/(m·K) and λ_c = 1.6 W/(m·K), showing there is a small impact of considering the steel components on the model.

The Group models' calibration was again done using both Complete and Simple model configurations to observe the effects of the screw piles steel components. Figure 10 presents the calibration results for both. This time the Complete model lowest RMSE value was found for λ_g = 1.5 W/(m·K) and λ_c = 1.6 W/(m·K). The λ_g result match the one obtained from TRT-G results using analytical means, while the λ_c value matches what is observed in the single pile model and resembles what is reported in the literature. The lowest RMSE values on the Simple model was obtained for λ_g = 1.5 W/(m·K) and λ_c =

1.8 W/(m·K), resulting in a difference in the grout thermal conductivity of 0.2 W(m·K) between the Simple and Complete models. The resulting λ_g is 0.4 W/(m·K) (36%) higher in the Group model in comparison to the Single pile model (1.5 compared to 1.1 W/(m·K)), which can be presumably credited to the problems with the execution of TRT-S. In addition, the piles placement of further than 15 metres apart could be a contributing factor to the difference, as similar thermal conductivity heterogeneity was observed in smaller distances between energy piles in previous studies (Loveridge et al, 2017).

The Borehole model calibration presented a lower sensitivity to the variation of both λ_g and λ_c. Given the RMSE results presented in Figure 11, the λ_g values may be ranging between 3.1 and 3.7 W/(m·K) and λ_c between 2.0 and 2.2 W/(m·K). The λ_g values are in line with the one obtained analytically in the previous section (3.1 W/(m·K)) however λ_c is significantly larger than the previous screw pile models' results (1.6 W/(m·K)) and values reported in the literature (Faizal et al, 2016). It is likely that there is more than one reason to this significant increase in the λ_c value. First, as observed in Figure 1, the Borehole B was built inside an open-end screw pile, meaning the grout is in direct contact with the groundwater encountered seven metres below the surface, while the energy screw piles are closed steel shells where the grout and the water are kept separated. Kim and Oh (2019) studied the saturation effect on the thermal conductivity of grout mixtures commonly used in boreholes finding it can increase λ_c up to 40% approximately, while Asadi et al (2018) shows this difference can go up to 58% considering a more extensive range of works with grout and concrete. Another potential reason is the variable pipe spacing resulting from the construction process, observed when analysing the results of the sensors installed along the pipe in Figure 6. Makasis et al. (2018b) show that the consideration of variable pipe spacing can produce a fluid temperature difference of nearly 1 °C for boreholes with λ_c = 1.4 W/(m·K).

In addition to the model calibration using fluid temperature data, the models were then validated using the other underground sensor measurements. Both Borehole B and Group G temperatures recorded within the energy structures during the respective tests were compared against the values predicted by the calibrated models where the sensors are expected to be placed. In the Group G, the sensors were attached to the U loop bottom curb, later positioned inside the steel case and filled with grout (Figure 2). It is likely that grout pouring might have filled the space between the sensors and the pipes, potentially dislocating it a few millimetres. Therefore, two measurement points were placed in the model: one exactly at the bottom pipe wall and another 10 mm below. The experimental and predicted temperature values, as well as the detail on the model measurement points, are presented in Figure 12. The agreement was fairly good for all instruments except for G-3, for which results were identified as uncertain in section 3.1.

The thermistor string attached to Borehole B is 32 mm diameter, so the measurement points in the model were positioned 16 mm away from the pipes, as presented in the Figure 13 alongside the experimental versus simulated temperature plots for each sensor. The comparison model results in

Figure 13 is the one where λ_g = 3.1 and λ_c = 2.2 W/(m·K), however there is no significant difference from other models with similar RMSE values (Figure 11). The agreement is very good for the majority of the sensors. Given the higher precision of the sensors installed within Borehole B, it is worth attempting to identify the reason for the discrepancies. As stated in sections 3.1 and 3.2, the measurements obtained from the sensors were significantly more erratic than the ones from the screw piles group likely due to contact with different soil layers and variable pipe spacing. Therefore, incorporating different material layers and convective heat transfer within the soil (even though beyond the scope of this work) would likely result in better agreement in the results, similar to that for G.

Overall the agreement in Figure 13 is deemed satisfactory and considered appropriate for comparing its results to the analytical methods, especially considering that this model performance has been validated in previous studies as well (Makasis et al, 2018b; Jensen-Page et al, 2019). Even thought the numerical results backed the ILSM analysis on both borehole B and group G, both numerical and analytical results prove that soil layering impacts both structures differently, which should be accounted for in the design. It is beyond the scope of this work to analyse soil layering effects in the thermal conductivity (Lee, 2011; Raymond & Lamarche, 2013; Signorelli et al, 2007); these will be further explored in future studies.

3.4 Energy screw piles FE models analysis

The flexibility of the numerical models permits the undertaking of more detailed analyses. One of such analysis entails calculating the integral mean temperature within the pipes and heat exchanger walls and inserting it in Equation 4 to obtain each heat exchanger transient thermal resistance R_b. However, as noted in section 3.2, the heat energy absorbed by each pile from Group G is not the same for a parallel configuration (as the ΔT between fluid and ground is higher for the first pile than the last), therefore the correct value per pile had to be obained from Equation 1, using each pile's inlet and outlet temperature difference, evaluated from the validated model.

Figure 14 presents the average heating power absobed per pile during the test, as well as the respective steady state R_b (for Fo $\geq$ 10). The heating power absorbed per each pile drops linearlly as the pile's distance from the inlet increases, which is reaosnable for the configuration. Pile 1 exchanges 13.1% of the total heat power injected, while Pile 8 exchanges 10.8 %. The difference in R_b values is small enough to be the result of numerical errors. The model results show that no thermal interaction happens between the piles during the test (i.e. the heat rejected by one pile does not reach others until the end of the test), as observed in the video supplementary file attached to this paper.

Table 5 presents the thermal resistance values at different times of the simulated TRT (indicated by Fo) for λ_c = 1.6 W/(m·K) for the screw pile models and λ_c = 2.2 W/(m·K) for the borehole case. The thermal resistance of the Complete models is lower than when there are no steel components; the difference of approximately 0.016 (m·K)/W means the energy screw piles fluid temperature has a difference of 0.8 °C for every 50 W/m heating injected, against its equivalent pure grout pile. Moreover, the short-term heat transfer duration seems to be shorter on the energy screw piles when steel is considered, as the values from Fo=1 and Fo=5 are closer to Fo=20 in the Complete models. This is in line with the faster value convergence observed in the analytical analysis of the TRTs executed in the screw piles (Table 4). The thermal resistances predicted in the analytical analyses are slightly overestimated for the Borehole B and slightly underestimated for the Group G (considering the results of the Complete model). This indicates that Equation 3 accounts for the effect of the steel components to some extent. Figure 15 presents thermal plots of both Complete and Simple screw pile models at the end of TRT-S simulation. The cross-section plots show lower pile temperatures when steel is considered, and the temperature within the steel wall is uniform. As for the pile tip, the screw does not seem to have significant thermal influence, as the axial heat transfer remains similar. Likely, screws positioned within the pipes depth range would have more impact on the heat transfer.

4 Summary and Conclusions

Interest in energy structures continues to grow, with energy piles leading the path. Using a real energy pile implementation case in Melbourne – Australia, this work investigated the response of TRTs in groups of energy piles. Experimental results provided insights and a solid base to further validate a numerical approach (already established for other structures) to a group of energy screw piles connected in series. The results looked on both group effects and screw piles particularities and traditional analytical methods used in the borehole practice had their accuracy evaluated for the group case. This work's key findings are summarised below:

- In the studied case, the TRT could be executed in the energy screw piles group following the same guidelines from borehole practice (ASHRAE, 2001). However, given the short length of the screw pile, testing a single element requires low heating energy and a small circulation pump, not commonly available in practice. Moreover, external effects (e.g. heat from the circulation pump) become more important and harder to control. Testing several piles in series can be undertaken with the same TRT equipment used for traditional boreholes. In this work, the test executed in the single energy screw pile had to be executed with a flow rate higher than recommended which hindered its results, a problem avoided in the pile group test. Therefore, the group test proved to be a better alternative than to test the short screw piles individually in this case.
- The pile horizontal pipe length exposed can potentially impact the test results. Proper thermal insulation becomes even more important to avoid underestimation as reported by Murphy et al. (2015). To reduce the impact of increased exposure to ambient conditions, an alternative would be to counterbalance the ambient temperature effects from the test (Abdelaziz et al, 2015). The

analyses in this work indicated that no important thermal interaction occurred between the piles during the test, however, these piles are placed relatively 'far' from each other and the tests are reasonably short in duration.

- The analytical tools used for TRT interpretation in borehole practice provided overall satisfactory λ_g results for the energy screw pile group. Unlike the results for Borehole B, the least accurate results for the screw pile group were obtained using the later test intervals (starting from Fo = 20 until the end of the test – as recommended by Vieira et al. (2017)), due to the higher noise from ambient temperature influence in the energy screw piles and relative minor dataset size. However, analytical methods considering earlier test intervals provide better results for the energy screw piles compared to the borehole, likely because the steel speeds up the start of the steady state heat transfer phase. This indicates that the TRT duration in energy screw piles could have been lowered in terms of Fourier number.
- The screw pile steel components do have an influence on their thermal performance, however, these are seemingly minor. The higher thermal conductivity of the steel lowers the pile thermal resistance, similar to when steel circulation pipes are used (Faizal et al, 2016). In the case studied, the 7.1 mm steel wall from the pile lowered the thermal resistance by 0.016 (m·K)/W according to the numerical model simulation, while the screw presence was not significant, likely due to its location on the pile toe. The analytical interpretation of the TRT-G captured this effect, since the results were closer to the numerically obtained values from the Group Complete model (that considered the steel components).
- TRT-B analysis presented several layering effect indications. These were expected given the site condition and soil profile (Figure 2, Figure 6 and Figure 8). However, the model calibration process revealed that the grout may also have been affected by the ground water presence, increasing its thermal conductivity by around 55%, which is in line with previous laboratory observations. This effect on the grout was not observed in the screw piles, since their steel cases were closed therefore the grout was not in direct contact with the groundwater.
- Both Group G and Borehole B have very similar total length and diameter, and the validation of the analytical methods for both confirm their thermal behaviour is also similar. However, the fact that no thermal interaction occurred between Group G piles is key for these statements. The analytical methods applied here do not account for thermal interactions between heat exchangers, which are expected to occur in the long-term (e.g. years) (Bandeira Neto et al., 2022). Models that correctly model the axial heat transfer, such as the Finite line source model (Zeng et al., 2002; Lamarche & Beauchamp, 2007) and thermal interactions should be considered to capture the differences on the thermal behaviour of the Borehole B and Group G that are not presented within the TRT time frame.
- TRT-B results in a higher effective ground thermal conductivity, as the borehole reaches deeper soil and rock formations and a higher portion is located below the water table, compared to the

piles. The steel of the screw pile benefits its thermal performance, however, so does the groundwater in the borehole concrete. This means that the borehole is expected to perform better thermally than the screw pile group, although energy screw piles are more cost effective to build. In addition, even though the TRT timeframe did not allow for thermal interference to occur, this will likely happen during the normal operation of the energy screw piles, depending always on the thermal load.

- Given that borehole TRTs are typically executed for site characterization, the results presented here highlight the importance of confirming the thermal performance of the energy structures after the structural design is done. Even when their thermal behaviour is similar to the borehole, as is the case of the tested group of eight energy screw piles.

In fairness, the cost involved in drilling and installing the 100 m length of borehole as the extra pipe fittings required to build the energy screw pile group should be considered when comparing both structures energy output. Even though the performance of both Borehole B and Group G can be estimated using the ILSM, the particularities of each energy structure must be considered to ensure optimal design.

5 Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

6 Acknowledgments

The Authors Acknowledge the contribution from GeoExchange Australia, Hutchison builders and PICAC leadership for providing access to the energy structures, and funding from the Australian Research Council (project number LP160101486) and the University of Melbourne is much appreciated. Assistance from Lawrence Hanson, Benjamin Robertson, Wayne Chan, Kieran Joseph Sait, Dr Gregorius Riyan Aditya and Dr Linden Jensen-Page in the fieldwork is acknowledged and appreciated.

7 Supplemental Materials

Video S1 is available online in the ASCE Library (ascelibrary.org)

8 References

Abdelaziz, S. L., Olgun, C. G. & Martin, J. R. (2015) Counterbalancing ambient interference on thermal conductivity tests for energy piles. *Geothermics*, 56, 45-59.

Adam, D. & Markiewicz, R. (2009) Energy from earth-coupled structures, foundations, tunnels and sewers. *Géotechnique*, 59(3), 229-236.

Alberdi-Pagola, M., Poulsen, S. E., Loveridge, F., Madsen, S. & Jensen, R. L. (2018) Comparing heat flow models for interpretation of precast quadratic pile heat exchanger thermal response tests. *Energy*, 145, 721-733.

Amatya, B. L., Soga, K., Bourne-Webb, P. J., Amis, T. & Laloui, L. (2012) Thermo-mechanical behaviour of energy piles. *Géotechnique*, 62(6), 503-519.

ARENA (Australian Renewable Energy Agency) (2014) *Looking foward: barriers, risks and rewards of the australian geothermal sector to 2020 and 2030.* Canberra: Australian Renewable Energy Agency.

Arulrajah, A., Narsilio, G., Kodikara, J. & Orense, R. P. (2015) Key issues in environmental geotechnics: Australia–New Zealand. *Environmental Geotechnics*, 2(6), 326-330.

Asadi, I., Shafigh, P., Abu Hassan, Z. F. B. & Mahyuddin, N. B. (2018) Thermal conductivity of concrete – A review. *Journal of Building Engineering*, 20, 81-93.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) (2001) 1118-TRP: *Methods for Determining Soil and Rock Formation Thermal Properties from Field Tests.*

Austin III, W. A. (1998) *Development of an in situ system for measuring ground thermal properties* Oklahoma State University.

Bandeira Neto, L., Narsilio, G., Makasis, N., Hanson, L., Benjamin, R., & Carden, Y. (2022). Evaluation of analytical design methods for energy pile groups using a screw-pile case study in Australia. In 20th International Conference on Soil Mechanics and Geotechnical Engineering Proceedings, Sydney, Australia (pp. 4989-4994).

Beier, R. A. & Smith, M. D. (2002) Borehole thermal resistance from line-source model of in-situ tests. *ASHRAE Transactions*, 108, 212.

Bidarmaghz, A. (2014) *3D numerical modelling of vertical ground heat exchangers*. Thesis (PhD) The University of Melbourne, Melbourne, Australia.

Bidarmaghz, A., Makasis, N., Narsilio, G. A., Francisca, F. M. & Carro, P. M. E. (2016) Geothermal energy in loess. *Environmental Geotechnics*, 3(4), 225-236.

Brandl, H. (2006) Energy foundations and other thermo-active ground structures. *Géotechnique*, 56(2), 81-122.

Brettmann, T. & Amis, T. (2011) *Thermal Conductivity Evaluation of a Pile Group Using Geothermal Energy Piles*.

Carslaw, H. & Jaeger, J. (1959) Conduction of Heat in Solids (Clarendon, Oxford).

Cecinato, F. & Loveridge, F. A. (2015) Influences on the thermal efficiency of energy piles. *Energy*, 82, 1021-1033.

Chan, W. & Sait, K. J. (2018) *Performance and Cost Comparison of a Single Borehole and Series-Connected Screw-Pile Ground Heat Exchangers - a Case Study in Melbourne*. MEng The University of Melbourne.

Churchill, S. W. (1977) Friction-factor equation spans all fluid flow regimes. Chem. Eng. 84 (24), 91-92.

Cimmino, M. & Bernier, M. (2014) A semi-analytical method to generate g-functions for geothermal bore fields. *International Journal of Heat and Mass Transfer*, 70, 641-650.

Colls, S. (2013). Ground heat exchanger design for direct geothermal energy systems. Thesis (PhD) The University of Melbourne, Melbourne, Australia.

Delerablee, Y., Burlon, S. & Reiffsteck, P. (2019) Long Term Assessment of Thermal Sustainability of Thermoactive Geostructures. *Environmental Geotechnics*, 7, 1-62.

Di Donna, A. & Laloui, L. (2015) Numerical analysis of the geotechnical behaviour of energy piles. *International Journal for Numerical and Analytical Methods in Geomechanics*, 39(8), 861-888.

EklÖF, C. & Gehlin, S. (1996) A Mobile Equipment for Thermal Response Test.

Eskilson, P. (1987) Thermal analysis of heat extraction boreholes.

Faizal, M., Bouazza, A. & Singh, R. M. (2016) Heat transfer enhancement of geothermal energy piles. *Renewable and Sustainable Energy Reviews*, 57, 16-33.

Faizal, M., Moradshahi, A., Bouazza, A. & McCartney, J. S. (2022) Soil Thermal Response to Temperature Cycles and End Boundary Conditions of Energy Piles. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(5), 04022027.

Fei, W., Narsilio, G. A., & Disfani, M. M. (2021). Predicting effective thermal conductivity in sands using an artificial neural network with multiscale microstructural parameters. International Journal of Heat and Mass Transfer, 170, 120997.

Franco, A. & Conti, P. (2020) Clearing a Path for Ground Heat Exchange Systems: A Review on Thermal Response Test (TRT) Methods and a Geotechnical Routine Test for Estimating Soil Thermal Properties. *Energies*, 13(11), 2965.

Franco, A., Moffat, R., Toledo, M. & Herrera, P. (2016) Numerical sensitivity analysis of thermal response tests (TRT) in energy piles. *Renewable Energy*, 86, 985-992.

Hanson, L. & Robertson, B. (2018) *Thermal performance of energy screw piles in series*. MEng The University of Melbourne.

Huang, J., McCartney, J. S., Perko, H., Johnson, D., Zheng, C. & Yang, Q. (2019) A novel energy pile: The thermo-syphon helical pile. *Applied Thermal Engineering*, 159, 113882.

Insana, A. & Barla, M. (2020) Experimental and numerical investigations on the energy performance of a thermo-active tunnel. *Renewable Energy*, 152, 781-792.

Jalaluddin, Miyara, A., Tsubaki, K., Inoue, S. & Yoshida, K. (2011) Experimental study of several types of ground heat exchanger using a steel pile foundation. *Renewable Energy*, 36(2), 764-771.

Jensen-Page, L., Loveridge, F. & Narsilio, G. A. (2019) Thermal Response Testing of Large Diameter Energy Piles. *Energies*, 12(14), 2700.

Jensen-Page, L., Narsilio, G. A., Bidarmaghz, A. & Johnston, I. W. (2018) Investigation of the effect of seasonal variation in ground temperature on thermal response tests. *Renewable Energy*, 125, 609-619.

Johnston, I. W., Narsilio, G. A. & Colls, S. (2011) Emerging geothermal energy technologies. *KSCE Journal of Civil Engineering*, 15(4), 643-653.

Katsura, T., Nagano, K., Narita, S., Takeda, S., Nakamura, Y. & Okamoto, A. (2009) Calculation algorithm of the temperatures for pipe arrangement of multiple ground heat exchangers. *Applied Thermal Engineering*, 29(5), 906-919.

Kim, D., & Oh, S. (2019). Relationship between the thermal properties and degree of saturation of cementitious grouts used in vertical borehole heat exchangers. Energy and Buildings, 201, 1-9.

Laloui, L. & Donna, A. D. (2011) Understanding the behaviour of energy geo-structures. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, 164(4), 184-191.

Laloui, L. & François, B. (2009) ACMEG-T: Soil Thermoplasticity Model. *Journal of Engineering Mechanics*, 135(9), 932-944.

Lamarche, L. & Beauchamp, B. (2007) A new contribution to the finite line-source model for geothermal boreholes. *Energy and Buildings*, 39(2), 188-198.

Lee, C. K. (2011) Effects of multiple ground layers on thermal response test analysis and ground-source heat pump simulation. *Applied Energy*, 88(12), 4405-4410.

Loveridge, F., Low, J. & Powrie, W. (2017) Site investigation for energy geostructures. *Quarterly Journal of Engineering Geology and Hydrogeology*, 50(2), 158-168.

Loveridge, F., McCartney, J. S., Narsilio, G. A. & Sanchez, M. (2020) Energy geostructures: A review of analysis approaches, in situ testing and model scale experiments. *Geomechanics for Energy and the Environment*, 22, 100173.

Loveridge, F., Olgun, C. G., Brettmann, T. & Powrie, W. (2015a) The thermal behaviour of three different auger pressure grouted piles used as heat exchangers. *Geotechnical and Geological Engineering*, 33(2), 273-289.

Loveridge, F. & Powrie, W. (2013) Temperature response functions (G-functions) for single pile heat exchangers. *Energy*, 57, 554-564.

Loveridge, F. & Powrie, W. (2014) G-Functions for multiple interacting pile heat exchangers. *Energy*, 64, 747-757.

Loveridge, F. A., Olgun, C. G., Brettmann, T. & Powrie, W. (2015b) Group thermal response testing for energy piles, *Geotechnical Engineering for Infrastructure and Development*, 2595-2600.

Lu, Q. & Narsilio, G. A. (2019) Cost effectiveness of energy piles in residential dwellings in Australia.

Lund, J. & Boyd, T. (2016) Direct Utilization of Geothermal Energy 2015 Worldwide Review. *Geothermics*, 60, 66-93.

Makasis, N. (2019) *Further understanding ground source heat pump system design using finite element methods and machine learning techniques*. Thesis (PhD) The University of Melbourne, Melbourne, Australia.

Makasis, N. & Narsilio, G. A. (2020) Energy diaphragm wall thermal design: The effects of pipe configuration and spacing. *Renewable Energy*, 154, 476-487.

Makasis, N., Narsilio, G. A. & Bidarmaghz, A. (2018a) A robust prediction model approach to energy geo-structure design. *Computers and Geotechnics*, 104, 140-151.

Makasis, N., Narsilio, G. A., Bidarmaghz, A. & Johnston, I. W. (2018b) Ground-source heat pump systems: The effect of variable pipe separation in ground heat exchangers. *Computers and Geotechnics*, 100, 97-109.

Murphy, K. D., McCartney, J. S., & Henry, K. S. (2014). Impact of Horizontal Run-Out Length on the Thermal Response of Full-Scale Energy Foundations. In Geo-Congress 2014 Technical Papers (pp. 2715-2724).

Peck, W., Neilson, J., Olds, R. & Seddon, K. (1992) *Engineering geology of Melbourne*CRC Press.

Raymond, J. & Lamarche, L. (2013) Simulation of thermal response tests in a layered subsurface. *Applied Energy*, 109, 293-301.

Rotta Loria, A. F., Gunawan, A., Shi, C., Laloui, L. & Ng, C. W. W. (2015) Numerical modelling of energy piles in saturated sand subjected to thermo-mechanical loads. *Geomechanics for Energy and the Environment*, 1, 1-15.

Schjønning, P. (2021). Thermal conductivity of undisturbed soil – Measurements and predictions. Geoderma, 402, 115188.

Signorelli, S., Bassetti, S., Pahud, D. & Kohl, T. (2007) Numerical evaluation of thermal response tests. *Geothermics*, 36(2), 141-166.

Singh, R. M., Sani, A. K. & Amis, T. (2019) 15 - An overview of ground-source heat pump technology, in Letcher, T. M. (ed), *Managing Global Warming* Academic Press, 455-485.

Vieira, A., Alberdi-Pagola, M., Christodoulides, P., Javed, S., Loveridge, F., Nguyen, F., Cecinato, F., Maranha, J., Florides, G., Prodan, I., Van Lysebetten, G., Ramalho, E., Salciarini, D., Georgiev, A., Rosin-Paumier, S., Popov, R., Lenart, S., Erbs Poulsen, S. & Radioti, G. (2017) Characterisation of Ground Thermal and Thermo-Mechanical Behaviour for Shallow Geothermal Energy Applications. *Energies*, 10(12), 2044.

Witte, H. J. L. (2016) 4 - In situ estimation of ground thermal properties, in Rees, S. J. (ed), *Advances in Ground-Source Heat Pump Systems* Woodhead Publishing, 97-116.

Zeng, H. Y., Diao, N. R. & Fang, Z. H. (2002) A finite line-source model for boreholes in geothermal heat exchangers. *Heat Transfer—Asian Research*, 31(7), 558-567.

Zhang, J., Dias, D., Pan, Q., Ma, C. & Tsuha, C. d. H. C. (2022) Long-Term Thermo-Hydraulic Numerical Assessment of Thermo-Active Piles - A Case of Tropical Soils. *Applied Sciences*, 12(15), 7653.

List of Figures

List of Tables