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## Thermal response of energy screw piles connected in series

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### **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;

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### ***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)
$\alpha_g$	thermal diffusivity of ground (W/(m K))
$\lambda_g$	thermal conductivity of ground (W/(m K))
$\lambda_c$	thermal conductivity of grout (W/(m K))
$\lambda_s$	thermal conductivity of steel (W/(m K))
$\lambda_f$	thermal conductivity of water (W/(m K))
$\rho_g$	density of ground (kg/m <sup>3</sup> )
$\rho_c$	density of grout (kg/m <sup>3</sup> )
$\rho_s$	density of steel (kg/m <sup>3</sup> )
$\rho_f$	density of water (kg/m <sup>3</sup> )

# 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

36 their thermal performance as heat exchangers (Jensen-Page et al, 2019; Loveridge & Powrie, 2013).  
37 Furthermore, different foundation solutions may involve different geometries and materials, uncommon  
38 to the underground heat exchanger practice (Alberdi-Pagola et al, 2018; Huang et al, 2019; Jalaluddin  
39 et al, 2011; Makasis et al, 2018b). Despite all those differences, energy pile thermal design still uses  
40 tools and methods developed for boreholes in the first place.

41 Thermal behaviour knowledge of the soil and heat exchangers is essential for GSHP system design.  
42 Precise soil thermal conductivity ( $\lambda_g$ ), heat exchanger thermal resistance ( $R_b$ ) and undisturbed ground  
43 temperature ( $T_{g0}$ ) estimations are critical for proper GSHP system sizing (Loveridge et al, 2017). The  
44 Thermal Response Test (TRT) is the main in-situ test tool used to estimate these parameters. Conceived  
45 (Austin III, 1998; Eklöf & Gehlin, 1996) and standardized (ASHRAE, 2001) for boreholes, TRT has  
46 also been applied on energy piles (Brettmann & Amis, 2011; Franco et al, 2016; Jensen-Page et al,  
47 2019). Common TRT execution consists on injecting heat to the ground at a constant power rate by  
48 circulating water inside the HDPE pipes of the tested heat exchanger with the help of a circulation pump  
49 and a heater. Cooling TRTs are a less common alternative. ASHRAE testing guidelines require the  
50 measurement of heating power, inlet and outlet fluid temperatures during the test, while recording the  
51 flow rate is suggested. The heating power should be between 50 and 80 W/m length of the borehole,  
52 and fluid flow rate should ensure a temperature difference between 3 to 7 °C. These recommendations  
53 aim to avoid overheating and to keep the temperature difference reasonably larger than the sensor  
54 precision. However, most existing TRT rigs were built for borehole testing, which means their heating  
55 elements and circulation pumps are not always suitable for shorter heat exchangers (e.g. short piles)  
56 and thus adaptations are required. Instead of building new or modifying existing equipment, TRTs can  
57 also be performed in groups of piles (Brettmann & Amis, 2011). However, deeper understanding on  
58 how to perform and interpret group TRTs is required.

59 Traditionally, TRT outputs are interpreted based on heat transfer analytical models (Franco & Conti,  
60 2020; Witte, 2016) with the Infinite Line Source Model (ILSM) (Carslaw & Jaeger, 1959) being the  
61 most popular. ILSM has a simple implementation but is bounded to several simplifying assumptions  
62 that may hinder both precision and accuracy of the results, depending on the vertical heat exchanger  
63 geometry. The commonly larger diameters and shorter length of energy piles swerve from ILSM  
64 conventions, which lead to pile specific methods, such as pile G-functions (Loveridge & Powrie, 2013).  
65 ILSM assumes the ground is a single homogeneous and isotropic material, which led borehole practice  
66 to adopt effective ground thermal conductivity ( $\lambda_{g,eff}$ ) and thermal diffusivity ( $\alpha_{g,eff}$ ) as an equivalent  
67 representation of the thermal properties of the whole soil strip tested. Alternatively, finite element (FE)  
68 tools can model boreholes and energy structures (Bidarmaghz et al, 2016; Franco et al, 2016; Jensen-  
69 Page et al, 2019; Signorelli et al, 2007), that despite requiring more computational resources, allows a  
70 broader range of considerations (Jensen-Page et al, 2018; Loveridge & Powrie, 2013), such as multiple  
71 heat exchangers (Loveridge & Powrie, 2014). Regarding energy pile groups, Katsura et al (2009) states

72 that several piles connected in series could be considered as a single length-equivalent heat exchanger.  
73 However, it is known that thermal interference may happen from one heat exchanger to another  
74 depending on the distances between them (Cimmino & Bernier, 2014; Eskilson, 1987; Loveridge &  
75 Powrie, 2014). Thermal interference is not accounted for in the typical analytical methods such as the  
76 ILSM. Brettmann & Amis (2011) performed a group TRT in three piles connected in series, with  
77 different grout properties and diameters. Temperature sensors installed in the soil between the piles  
78 confirmed that no thermal interaction occurred during the eight-day testing period. A value of  $\lambda_{g,eff} =$   
79  $2.66 \text{ W/(m/K)}$  was found using the ILSM model equation and the fluid temperature results, while the  
80 analysis of the measurements from the temperature sensors installed inside each pile provided lower  
81 values by about 3% to 8%. Loveridge and others performed further analysis in the same pile group,  
82 running individual and group TRTs (Loveridge et al, 2015a; Loveridge et al, 2015b). The study  
83 concludes that group test can be interpreted using simple analytical methods if no thermal interaction  
84 occurs, although the interpretation results point that the pile group did not reach steady state even after  
85 eight days of testing. In these studies, no analysis was undertaken regarding the thermal resistance,  
86 which is a measure of the pile or borehole geometry influence to heat transfer within the GHE rather  
87 than within the soil. Despite these handful notable studies, the lack of published analyses on pile group  
88 thermal response testing leaves gaps regarding both execution and interpretation of energy pile group  
89 TRTs.

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

## 103 2 Methodology

104 This work presents and analyses the results of three thermal response tests executed in different energy  
105 structures (one being a group of eight energy screw piles connected in series) during the construction  
106 of a building in Melbourne. The results of the TRT and the underground temperature sensors readings

107 are analysed analytically, considering the group of energy screw piles as an equivalent-long single  
108 borehole. After the preliminary test data analysis, 3-D FE models were validated and calibrated and  
109 later used for simulating the tests. Analysis of numerical simulation results provided reliable estimations  
110 for the effective ground thermal conductivity and the heat exchangers' thermal resistance for each test,  
111 as well as further insights regarding each energy structure's performance.

## 112 2.1 Experimental site

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

130 During the building construction phase, three TRTs were performed by The University of Melbourne  
131 energy structures research team (Chan & Sait, 2018; Hanson & Robertson, 2018). Both Borehole B and  
132 Group G were tested, using the same equipment and heating power. Three heating elements provided a  
133 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  
134 each test, ensuring that enough of the test occurred within heat transfer steady-state phase. During the  
135 test executed on the pile group, the surface pipes that connect the piles were insulated. The third TRT  
136 was performed in a single energy screw pile S, more than 15 meters distant from both B and G to avoid  
137 thermal interaction. To perform this TRT test, the equipment had to be adapted to avoid overheating.  
138 The electric connection of a 1.5 kW element was modified from in series to in parallel to provide half  
139 (750 W) nominal power (i.e., 57.7 W/m). During all tests, inlet and outlet temperatures were recorded  
140 every minute, as also the equipment power consumption and the temperature in the structure sensors  
141 when available. Due to a malfunction in the TRT device, the flow rate  $q$  could not be measured.

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

$$145 \quad q_{rate} = \frac{Q}{\rho_f C p_f (T_{in} - T_{out})} \quad (1)$$

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

## 150 2.2 Analytical analysis

151 The suitability of simple analytical heat transfer models for interpretation of TRTs is key to engineering  
 152 practice. Equation 2, derived from the log-linear approximation of the ILSM, is the simplest and most  
 153 popular method of interpreting  $\lambda_g$  from TRTs, used from its primordial applications (EklÖF & Gehlin,  
 154 1996). Beier & Smith (2002) followed the same principle to evaluate  $R_b$  when the testing time  $t = t_l$ ,  
 155 which is the intercept of the log-linear approximation in the ln-space (Equation 3) (i.e.  $\ln(t_l) = 0$ ).

$$156 \quad \lambda_g = \frac{Q}{4\pi m H} \quad (2)$$

$$157 \quad R_b = \frac{1}{4\pi \lambda_g} \left[ \frac{T(t_{1hr}) - T_0}{m} - \ln \left( \frac{4\alpha_g t_{1hr}}{e^\gamma r_b^2} \right) \right] \quad (3)$$

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

171 This work evaluates the results from all TRTs using Equations 2 and 3 to obtain estimations of  $\lambda_g$  and  
 172  $R_b$ . Different test time windows with distinct starting times in terms of  $Fo$  (1, 5, 10 and 20) are analysed,

173 to compare the tests in terms of results convergence and accuracy. When analysing TRT-G, the group  
174 of energy screw piles in series are considered as a single length-equivalent borehole to check if the  
175 model can interpret the group test. In order to support the analytical analysis and support the results, an  
176 established numerical model is used to build different geometries and analyse further the energy  
177 structures.

### 178 2.3 Numerical analysis: Finite Element models

179 A transient 3-D FE model previously developed and validated within the University of Melbourne is  
180 used in this work to undertake the numerical analysis. The model couples the governing equations of  
181 fluid flow and heat transfer (continuity, momentum conservation and energy balance equations). Only  
182 conductive heat transfer is considered on all materials, except for the circulating water where both  
183 conductive and convective processes are accounted for. This means that no groundwater presence was  
184 directly considered in this work, however, the parameters obtained from the TRT indirectly account for  
185 the groundwater effect (Franco & Conti, 2020). Detailed information of the model can be found in  
186 (Bidarmaghz, 2014; Makasis, 2019), as well as applications on several energy structures (Bidarmaghz  
187 et al, 2016; Cecinato & Loveridge, 2015; Delerablee et al, 2019; Di Donna & Laloui, 2015; Faizal et  
188 al, 2022; Insana & Barla, 2020; Jensen-Page et al, 2019; Makasis & Narsilio, 2020; Makasis et al,  
189 2018b; Rotta Loria et al, 2015; Zhang et al, 2022).

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

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

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

$$220 \quad R_b = \frac{H}{Q} (\bar{T}_f - \bar{T}_b) \quad (4)$$

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

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

## 229 3 Results and Discussion

### 230 3.1 Experimental results

231 As per section 2.1, three undertaken TRTs are presented in this study. The measured values for all three  
 232 tests are presented in Figure 4. All tests presented typical TRT fluid temperature trends, and power  
 233 supply was stable (less than 1% variation). Nevertheless, each test had its particularities worth  
 234 mentioning. TRT-G fluid temperatures show to be more influenced from ambient conditions than the  
 235 other tests. The longer pipe extension exposed in the surface is a possible reason behind it, despite the  
 236 pipe insulation. Murphy, McCartney, and Henry (2014) studied the effect of the horizontal run-out  
 237 length of pipe in the TRT results, showing that extensive segments may result in underestimation of  $\lambda_g$   
 238 due to heat loss. However, their tests were executed in each pile individually, while here the effect is

239 distributed between the piles connected in series. Moreover, the horizontal pipes on the referred  
240 experiment were not insulated, which significantly increase the heat losses. A difference of  $0.2 \text{ W}/(\text{m}\cdot\text{K})$   
241 on  $\lambda_g$  was reported due to 23.6 metres of horizontal piping. The expected impact on TRT-G is lower  
242 since the pipes were insulated. TRT-B resulted in lower and more steady fluid temperatures than TRT-  
243 G. The power inlet was steady during the test, but a short power outage occurred right before it  
244 completed 6 hours, and the effect is shown on the fluid temperature measurement. The temperature  
245 difference is lower than TRT-G, which means a higher fluid flow rate; this is attributable to the longer  
246 pipe extension and greater number of elbow connections in the pile group G.

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

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

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

### 285 3.2 Analytical analyses

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

303 Equation 2 was also applied to the Group G and Borehole B temperature sensors to estimate the  $\lambda_g$  for  
304  $Fo=10$  with results shown in Figure 8 for each sensor, according to their position in each structure. The  
305  $\lambda_g$  values for G are considerably steadier than the B ones, due to them being in the same material, while  
306 B sensors are spread between different material layers, therefore they respond directly to them. The  
307 coefficient of variation of the G sensors  $\lambda_g$  results is only 3% and drops to 1% when sensor G-3 is

308 excluded, while for B sensors it sits at 8%. The fact that the B sensors installed at the same depth had  
309 similar  $\lambda_g$  results strengthens this hypothesis. B-1 and B-9 are the only borehole ones inside the clay  
310 layer, while all others are in contact with the blue shale; a division also visually observed in the results.  
311 The computed  $\lambda_g$  for Sensor B-5 is considerably higher than others. Similarly, all G sensor results are  
312 higher than the  $\lambda_g$  obtained from the TRT-G fluid temperature. One possible explanation for this is the  
313 fact that these sensors are installed below the pipe U-loop curve, meaning that the heat energy reaching  
314 them is lower than the one being radially transmitted. Another key point is that the effective thermal  
315 conductivity of soil and rock materials tends to rise with depth due to reduced porosity (Fei, Narsilio,  
316 & Disfani, 2021; Schjøning, 2021). Figure 8b) presents a growing  $\lambda_g$  trend with depth, and the  
317 distributed  $\lambda_g$  estimated for each pile toe in the group correspond to material actually tested at the  
318 maximum depth (~13 metres), which may also explain why the average values of the G sensors are  
319 higher than the TRT-G.

### 320 3.3 FEM calibration and further validations

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

326 Figure 9 presents the calibration results for the single screw pile models. To study the effect of the steel  
327 components on its thermal operation, the calibration was done both by considering the steel wall and  
328 screw in the model (Complete model) as well as, alternatively, excluding the screw and modelling all  
329 pile as grout material (Simple model). The lowest RMSE value was found for  $\lambda_g = 1.1 \text{ W/(m}\cdot\text{K)}$  and  $\lambda_c$   
330  $= 1.6 \text{ W/(m}\cdot\text{K)}$  for the Complete model, a  $0.2 \text{ W/(m}\cdot\text{K)}$  difference on  $\lambda_g$  from the analytical analysis  
331 result. The results obtained using the Simple model were slightly lower for higher thermal conductivity  
332 values on both materials. Table 1 shows how the steel thermal conductivity is significantly higher than  
333 grout, accelerating the heat transport. Therefore, the best fit on the Simple model happens at higher  
334 thermal conductivity values to compensate the absence of the steel components. However, the lowest  
335 RMSE value of the Simple model was found for  $\lambda_g = 1.3 \text{ W/(m}\cdot\text{K)}$  and  $\lambda_c = 1.6 \text{ W/(m}\cdot\text{K)}$ , showing there  
336 is a small impact of considering the steel components on the model.

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

343 1.8 W/(m·K), resulting in a difference in the grout thermal conductivity of 0.2 W/(m·K) between the  
344 Simple and Complete models. The resulting  $\lambda_g$  is 0.4 W/(m·K) (36%) higher in the Group model in  
345 comparison to the Single pile model (1.5 compared to 1.1 W/(m·K)), which can be presumably credited  
346 to the problems with the execution of TRT-S. In addition, the piles placement of further than 15 metres  
347 apart could be a contributing factor to the difference, as similar thermal conductivity heterogeneity was  
348 observed in smaller distances between energy piles in previous studies (Loveridge et al, 2017).

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

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

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

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

386 Overall the agreement in Figure 13 is deemed satisfactory and considered appropriate for comparing its  
387 results to the analytical methods, especially considering that this model performance has been validated  
388 in previous studies as well (Makasis et al, 2018b; Jensen-Page et al, 2019). Even though the numerical  
389 results backed the ILSM analysis on both borehole B and group G, both numerical and analytical results  
390 prove that soil layering impacts both structures differently, which should be accounted for in the design.  
391 It is beyond the scope of this work to analyse soil layering effects in the thermal conductivity (Lee,  
392 2011; Raymond & Lamarche, 2013; Signorelli et al, 2007); these will be further explored in future  
393 studies.

### 394 3.4 Energy screw piles FE models analysis

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

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

409 Table 5 presents the thermal resistance values at different times of the simulated TRT (indicated by  $Fo$ )  
410 for  $\lambda_c = 1.6$  W/(m·K) for the screw pile models and  $\lambda_c = 2.2$  W/(m·K) for the borehole case. The thermal  
411 resistance of the Complete models is lower than when there are no steel components; the difference of

412 approximately 0.016 (m·K)/W means the energy screw piles fluid temperature has a difference of 0.8  
413 °C for every 50 W/m heating injected, against its equivalent pure grout pile. Moreover, the short-term  
414 heat transfer duration seems to be shorter on the energy screw piles when steel is considered, as the  
415 values from Fo=1 and Fo=5 are closer to Fo=20 in the Complete models. This is in line with the faster  
416 value convergence observed in the analytical analysis of the TRTs executed in the screw piles (Table  
417 4). The thermal resistances predicted in the analytical analyses are slightly overestimated for the  
418 Borehole B and slightly underestimated for the Group G (considering the results of the Complete  
419 model). This indicates that Equation 3 accounts for the effect of the steel components to some extent.  
420 Figure 15 presents thermal plots of both Complete and Simple screw pile models at the end of TRT-S  
421 simulation. The cross-section plots show lower pile temperatures when steel is considered, and the  
422 temperature within the steel wall is uniform. As for the pile tip, the screw does not seem to have  
423 significant thermal influence, as the axial heat transfer remains similar. Likely, screws positioned within  
424 the pipes depth range would have more impact on the heat transfer.

## 425 4 Summary and Conclusions

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

- 433 - In the studied case, the TRT could be executed in the energy screw piles group following the  
434 same guidelines from borehole practice (ASHRAE, 2001). However, given the short length of  
435 the screw pile, testing a single element requires low heating energy and a small circulation  
436 pump, not commonly available in practice. Moreover, external effects (e.g. heat from the  
437 circulation pump) become more important and harder to control. Testing several piles in series  
438 can be undertaken with the same TRT equipment used for traditional boreholes. In this work,  
439 the test executed in the single energy screw pile had to be executed with a flow rate higher than  
440 recommended which hindered its results, a problem avoided in the pile group test. Therefore,  
441 the group test proved to be a better alternative than to test the short screw piles individually in  
442 this case.
- 443 - The pile horizontal pipe length exposed can potentially impact the test results. Proper thermal  
444 insulation becomes even more important to avoid underestimation as reported by Murphy et al.  
445 (2015). To reduce the impact of increased exposure to ambient conditions, an alternative would  
446 be to counterbalance the ambient temperature effects from the test (Abdelaziz et al, 2015). The

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

450 - The analytical tools used for TRT interpretation in borehole practice provided overall  
451 satisfactory  $\lambda_g$  results for the energy screw pile group. Unlike the results for Borehole B, the  
452 least accurate results for the screw pile group were obtained using the later test intervals  
453 (starting from  $Fo = 20$  until the end of the test – as recommended by Vieira et al. (2017)), due  
454 to the higher noise from ambient temperature influence in the energy screw piles and relative  
455 minor dataset size. However, analytical methods considering earlier test intervals provide better  
456 results for the energy screw piles compared to the borehole, likely because the steel speeds up  
457 the start of the steady state heat transfer phase. This indicates that the TRT duration in energy  
458 screw piles could have been lowered in terms of Fourier number.

459 - The screw pile steel components do have an influence on their thermal performance, however,  
460 these are seemingly minor. The higher thermal conductivity of the steel lowers the pile thermal  
461 resistance, similar to when steel circulation pipes are used (Faizal et al, 2016). In the case  
462 studied, the 7.1 mm steel wall from the pile lowered the thermal resistance by 0.016 (m·K)/W  
463 according to the numerical model simulation, while the screw presence was not significant,  
464 likely due to its location on the pile toe. The analytical interpretation of the TRT-G captured  
465 this effect, since the results were closer to the numerically obtained values from the Group  
466 Complete model (that considered the steel components).

467 - TRT-B analysis presented several layering effect indications. These were expected given the  
468 site condition and soil profile (Figure 2, Figure 6 and Figure 8). However, the model calibration  
469 process revealed that the grout may also have been affected by the ground water presence,  
470 increasing its thermal conductivity by around 55%, which is in line with previous laboratory  
471 observations. This effect on the grout was not observed in the screw piles, since their steel cases  
472 were closed therefore the grout was not in direct contact with the groundwater.

473 - Both Group G and Borehole B have very similar total length and diameter, and the validation  
474 of the analytical methods for both confirm their thermal behaviour is also similar. However, the  
475 fact that no thermal interaction occurred between Group G piles is key for these statements.  
476 The analytical methods applied here do not account for thermal interactions between heat  
477 exchangers, which are expected to occur in the long-term (e.g. years) (Bandeira Neto et al.,  
478 2022). Models that correctly model the axial heat transfer, such as the Finite line source model  
479 (Zeng et al., 2002; Lamarche & Beauchamp, 2007) and thermal interactions should be  
480 considered to capture the differences on the thermal behaviour of the Borehole B and Group G  
481 that are not presented within the TRT time frame.

482 - TRT-B results in a higher effective ground thermal conductivity, as the borehole reaches deeper  
483 soil and rock formations and a higher portion is located below the water table, compared to the

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

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

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

## 499 5 Data Availability

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

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## 509 7 Supplemental Materials

510 Video S1 is available online in the ASCE Library ([ascelibrary.org](http://ascelibrary.org))

## 511 8 References

512

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