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Thermal resistance analysis of an energy pile and adjacent soil using radial temperature gradients

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1 **Abstract**

2 This paper examines the thermal resistances of energy piles and surrounding soils. A field-
3 scale bored energy pile was installed through stiff sandy clay and dense sand and instrumented
4 to measure temperatures on the external walls of the heat exchanger pipes, at the pile-soil
5 interface, and in the soil. The radial temperature gradients between the pipes and the pile-soil
6 interface, and the pile-soil interface and the soil, were used to evaluate the pile and soil thermal
7 resistances, respectively. The thermal resistances were on the same order of magnitude with
8 values of 0.053 mK/W, 0.072 mK/W, and 0.066 mK/W for the pile, stiff sandy clay, and dense
9 sand due to similarities in their thermal properties. The analysis suggests that pile and soil
10 thermal resistances are influenced by the pile dimensions, number of pipes, concrete cover, soil
11 type and duration of heating. Hence, meticulous interpretation of thermal resistances
12 considering these parameters should be conducted to understand heat transfer processes in
13 energy piles and surrounding soils accurately. Estimates of the pile thermal resistance from the
14 equivalent diameter and thermal response test methods were found to be inconsistent with each
15 other, highlighting the significance of considering in-situ radial temperature gradients in
16 designing energy pile systems.

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18 **Keywords:** *Energy pile; field tests; pile thermal resistance; soil thermal resistance;*
19 *temperature gradients.*

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25 **Nomenclature**

26	D	diameter of the energy pile (m)
27	L	U-loop; thermo-active length of the pile (m)
28	L/D	aspect ratio of the energy pile
29	Q/L	heat injected per unit length of the pile (W/m)
30	n	number of pipes in the pile
31	ρ	density of water (kg/m ³)
32	V	volume flow rate of water (L/min, m ³ /s)
33	C_p	specific heat capacity of water (J/kgK)
34	f_{in}	fluid temperatures at inlet of the U-loops (°C)
35	f_{out}	fluid temperatures at outlet of the U-loops (°C)
36	k_c	concrete thermal conductivity (W/mK)
37	P_{in}	pipe temperatures at inlet of the U-loops (°C)
38	P_{out}	pipe temperatures at outlet of the U-loops (°C)
39	Q_p	heat source per pipe (W/m)
40	R_c	concrete thermal resistance (mK/W)
41	R_p	total thermal resistance of the pile (mK/W)
42	R_{pb}	thermal resistance between pipe and pile-soil interface (mK/W)
43	R_{soil}	soil thermal resistance (mK/W)
44	r_b	pile radius (m)
45	r_{eff}	effective radius of the pile (m)
46	r_o	outer radius of the pipes (m)
47	T_b	pile-soil interface temperatures (°C)
48	T_p	pipe temperatures (°C)
49	T_{∞}	undisturbed ground temperature (°C)
50	ΔT_f	change in water temperatures between inlet and outlet of U-loops (°C)

51

52 **Introduction**

53 Energy piles are constructed by installing closed-loop heat exchanger pipes within the
54 reinforced concrete piles and operate by circulating a heat exchanger fluid from a ground source
55 heat pump (GSHP) through the pipes. Heat exchanger pipes are commonly formed into U-
56 loops and attached to the reinforcement cages of the piles, although spiral configurations have
57 also been used (Brandl 2006; Zarrella et al. 2013; Go et al. 2014; Wu et al. 2021). During
58 GSHP operation, transient thermal gradients develop in the pile cross-section and the
59 surrounding soil due to the thermal resistances of the pile material (often concrete) and the soil,
60 respectively (Bourne-Webb et al. 2016; Faizal et al. 2016a; Abdelaziz and Ozudogru 2016a,
61 2016b; Caulk et al. 2016; Han and Yu 2020; Moradshahi et al. 2021a). The thermal resistances
62 of energy piles and the surrounding soils are necessary parameters required in the thermal
63 design and analysis of energy pile systems. Currently, the interpretation of thermal resistances
64 of field scale energy piles and surrounding soils using radial temperature gradients in the pile
65 cross-section and the soil remain to be satisfactorily addressed. This is due to the lack of
66 embedded instruments in existing field-scale energy piles to measure temperatures on the heat
67 exchanger pipes in a pile and at the pile-soil interface.

68 The thermal resistance of energy piles is commonly defined using methods developed
69 for borehole heat exchangers. The widely known thermal response test (TRT) is an in-situ test
70 where a heat pulse is applied to a heat exchanger by circulating fluid at a constant heat transfer
71 rate for a given period (e.g., Gao et al. 2008; Park et al. 2013; Loveridge et al. 2014; Mimouni
72 and Laloui 2015; Luo et al. 2018; Jensen-Page et al. 2018). The thermal resistance can be
73 interpreted from TRT using the infinite or finite line source or cylinder source analyses. The
74 equivalent diameter (or equivalent pipe) method is an alternative approach to estimate the
75 thermal resistance of the energy pile by combining all the heat exchanger pipes in the pile's

76 cross-section into a single equivalent pipe (Loveridge and Powrie 2014; Song et al. 2021).
77 Finally, the conduction shape factor method considers the arrangement and number of pipes in
78 the pile's cross-section to estimate the pile's thermal resistance (Loveridge and Powrie 2014).
79 These methods provide reasonable estimates of thermal resistance of energy piles but do not
80 consider the influences of temperature gradients within the pile cross-section.

81 The primary goal of GSHP systems is to efficiently exchange heat between the
82 circulating fluid and the soil in the underground thermal network. Therefore, it is a common
83 perception that the thermal resistance of an energy pile or borehole heat exchanger is the
84 thermal resistance between the fluid in the pipes and the perimeter of the heat exchanger in
85 contact with the soil (e.g., De Carli et al. 2010; Bozis et al. 2011; Park et al. 2013, 2018;
86 Loveridge and Powrie 2013, 2014; Alberdi-Pagola et al. 2018). Hence, the interpretation of the
87 thermal resistance of energy piles would improve by investigating temperature gradients
88 between the pipes and the pile-soil interface. Characterising the thermal resistance of energy
89 piles from the pile internal thermal gradients remains a challenge due to the lack of temperature
90 measurements of the pipes and the pile-soil interface at a field scale. Preliminary field tests
91 conducted by Jalaluddin et al. (2011) and Loveridge et al. (2016) monitored temperatures of
92 the heat exchanger pipes in the piles. Loveridge et al. (2016) further investigated the pile's
93 apparent thermal resistance by evaluating temperatures monitored at the pile cage and on the
94 pipes of a single U-loop installed at the centre of the pile.

95 Further field studies, considering the heat injection rates in the pipes and temperature
96 measurements of the pipes and the pile-soil interface, are needed to provide more insight into
97 the pile's internal heat transfer and the value of thermal resistance used in design. Due to their
98 larger diameters than borehole heat exchangers, there are often multiple U-loops in energy
99 piles, which means there are multiple heat sources in an energy pile. Hence, a more complex
100 thermal resistance circuit analysis may be necessary between the pipes and the interface.

Furthermore, pile thermal resistance analyses from radial temperature gradients can be applied to piles with any length-to-diameter aspect ratios, compared to TRT tests which only work well with large length-to-diameter ratios (Loveridge et al. 2014).

Several analytical and numerical modelling studies have characterized the internal heat transfer and thermal resistance of energy piles (e.g., Bozis et al. 2011; Li and Lai 2012; Loveridge and Powrie 2013, 2014; Lee and Lam 2013; Zarrella et al. 2013, 2017; Hu et al. 2014; Abdelaziz and Ozudogru 2016a, 2016b; Caulk et al. 2016; Park et al. 2018; Maragna et al. 2019; Han and Yu 2020; Moradshahi et al. 2021a) but omitted transient internal temperature gradient measurements between the heat exchanger pipes and pile-soil interface typical of in-situ conditions. The internal thermal resistances of borehole heat exchangers have been thoroughly studied (e.g., De Carli et al. 2010; Lamarche et al. 2010; Bauer et al. 2011; Koenig 2015; Javed and Spitler 2017; Cui et al. 2018) but the lessons learned cannot be applied to energy piles as different thermal behaviour of piles is expected due to differences in dimensions and number of heat exchanger pipes.

The thermal resistances of individual soil layers around field-scale energy piles have also received limited attention, even though the temperature gradients in the soil have been extensively studied (e.g. Li et al. 2006; Bourne-Webb et al. 2009; Murphy et al. 2015; Singh et al. 2015; Yu et al. 2015; Faizal et al. 2016b; Chen et al. 2017; Guo et al. 2018). Park et al. (2018) developed numerical models using fluid temperature measurements in energy pile field tests to investigate the ground thermal resistances around energy piles. Still, they did not include any sensors to measure temperature variations at the pile-soil interface. Further field studies on evaluating soil thermal resistances from measurements of thermal gradients between the pile-soil interface and the soil will provide valuable insights into soil thermal resistances under actual boundary conditions. Soil thermal resistances are also beneficial for designing many underground structures that experience temperature changes, such as energy

geostructures (tunnels, walls, and basement slabs), buried pipes transporting sewerage/water/gas, buried high-voltage electric cables, and underground nuclear storage facilities.

This paper evaluates the thermal resistances of a cast-in-place energy pile and the soil from the heat injection rates in the heat exchanger pipes and temperatures measured at the external walls of the pipes, at the pile-soil interface, and in the soil. An improved understanding of the thermal resistances of the energy pile and the surrounding soil obtained from in-situ measurements is valuable in accurately predicting the thermal performances of GSHPs coupled with energy piles and other energy geostructures. A comparison with available measurements of heating tests on energy piles in different soil deposits from the literature is also used to help understand the ranges in thermal resistances for different energy pile geometries in different soil layers.

Experimental Setup and Procedure

The energy pile was installed below a six-storey student residential building. The site soil profile is a dense sandy soil referred to as the Brighton group (Barry-Macaulay et al. 2013, Faizal et al., 2018, 2019a,b). The instrumentation of the energy pile, relevant to the current study, is shown in Figure 1. No groundwater was encountered up to the depth of the pile. The energy pile had a diameter of 0.6 m and a length of 10 m. The concrete used had a water to cement ratio of 0.42 and consisted of 7 mm aggregated cement, slag, fly ash and water. The thermal conductivity of the concrete was numerically back-analysed in previous studies conducted on this site and had a value of 1.5 W/mK (Moradshahi et al. 2021a; 2021b). The thermal conductivities of the soil from numerical back-analysis were 1.1, 1.7, 2, and 2.3 W/mK for depths of 0 – 0.5 m, 0.5 – 3.5 m, 3.5 – 6 m, and 6 – 12.5 m, respectively (Moradshahi et al. 2021a; 2021b). The setup was heavily instrumented with vibrating wire strain gauges and

thermocouples described in detail in Faizal et al. (2019 a, b). The soil profile and the locations of sensors in the pile and surrounding soil are shown in Figure 2.

There were four high-density polyethylene (HDPE) pipe U-loop heat exchangers with outer and inner diameters of 25 mm and 20 mm, respectively, attached symmetrically to the inside of the reinforcement cage of the pile (Figure 1a and b). The nominal concrete cover between the edge of the pipes and the pile-soil interface was 95 mm. The horizontal spacing between the pipes in a given U-loop was approximately 200 mm. The pipes and sensors were installed before lowering the reinforcement cage in the drilled hole. Concrete was then slowly poured using 100 mm diameter removable polyvinyl chloride (PVC) tremie pipes housed in steel guides welded onto the reinforcement cage (Figure 1b). The individual pipes of all the loops were connected to a plumbing manifold placed in a pump room 15 m away from the energy pile. Each U-loop's inlet and outlet fluid temperatures were recorded using Type T thermocouples installed in the manifold. Type T thermocouples were also installed on the external walls of the pipes, in the soil and at the pile-soil interface (Figure 2).

The thermocouples on the pipe walls were attached using cable ties (Figure 1b) at depths of 1.3 m, 5 m, and 9.8 m in the first U-loop and at depths of 1.3 m and 9.8 m in the other U-loops (Figure 2). The interface thermocouples were installed by tying them to a steel cable with a deadweight attached to its end and lowered along the side of the borehole wall after the pile cage was installed in the borehole and before pouring concrete (Figure 1c and d). These interface thermocouples were placed at depths of 1.1 m, 3.6 m, and 6.6 m (Figure 2). The thermocouples in the soil were installed at radial distances of 0.63 m and 1.95 m from the edge of the pile and at approximately every 2 m depth up to a depth of 12 m. These thermocouples were attached to a 20 mm diameter PVC pipe and inserted into a 100 mm diameter borehole backfilled with a cementitious grout. The data from all the thermocouples were recorded using Pico Technology's USB-TC08 data loggers.

A heating test was conducted on the energy pile using an inlet water temperature and flow rate of approximately 48°C and 11 L/min, respectively. The heating unit was placed near the plumbing manifold in the pump room. All the four U-loops were connected in series. The pile was heated for 18 days, followed by 50 days of natural temperature recovery. The fluid and soil temperatures in this heating test were reported in previous studies conducted at the site (Faizal et al. 2019a; Moradshahi et al. 2021a). However, the pipe and interface temperatures and the thermal resistance of the pile and the soil were not reported in any of the previous studies conducted at this site.

Results and Discussions

Fluid Temperatures and Heat Injection Rates

The fluid temperatures and heat injection rates into the pile are shown in Figure 3. The fluid temperatures in the heating unit were not regulated by a thermostat so the inlet fluid temperatures were not constant with time. The fluid temperatures at the inlet and outlet of successive individual pipes, according to Figure 2, can be hypothetically represented by the following relation for a heating case:

$$L_1 f_{in} > L_1 f_{out} \geq L_2 f_{in} > L_2 f_{out} \geq L_3 f_{in} > L_3 f_{out} \geq L_4 f_{in} > L_4 f_{out} \quad (1)$$

where L is the loop number, f_{in} and f_{out} are fluid temperatures at the inlet and outlet of the U-loops, respectively, and 1 – 4 are loop numbers. Given that the U-loops were connected in series, the fluid temperature at the outlet of each loop is expected to be similar to the fluid temperature at the inlet of the consecutive loop if there were no heat losses.

The fluid temperature results shown in Figure 3a agree well with relation 1. At the end of the experiment, the fluid temperature reduced from approximately 48°C at the inlet of loop

1 to 44°C at the outlet of loop 4. The fluid temperature at the outlet of each loop is also similar to the fluid temperature at the inlet of the consecutive loop, confirming that there were negligible heat losses between consecutive loops for the series arrangement of the loops in the energy pile.

The heat injected by each U-loop per unit length of the pile Q/L (W/m), was calculated using the following equation:

$$Q/L = \rho V C_p \Delta T_f / L \quad (2)$$

where ρ is density of the heat exchange fluid (water) (1000 kg/m³), V is the volume flow rate of the heat exchange fluid (11 L/min or 0.00018 m³/s), C_p is the specific heat capacity of the heat exchange fluid (4200 J/kgK), L is the thermo-active length of the pile (10 m) and ΔT_f is the change in the heat exchange fluid temperatures between the inlet and outlet of each U-loop.

The changes in fluid temperatures per U-loop shown in Figure 3b were between 0.7 – 1.3°C. Unlike the consistent drop in fluid temperatures in successive pipes (Figure 3a), the changes in fluid temperatures in individual loops were inconsistent with the largest change observed in loop 1 and the lowest in loop 3 (Figure 3b), signifying that the heat injection rates per U-loop were inconsistent as well, as shown in Figure 3c. The low temperature difference in loop 3 could be due to differences in water flowrates between the loops. However, this could not be verified because the water flow rates in the individual loops could not be measured in the field test. The total change in fluid temperature and heat injection rate between the inlet of loop 1 and exit of loop 4 was approximately 4°C and 315 W/m, respectively. The heat injection rates in the U-loops were between 50 – 100 W/m, with the highest in loop 1 and lowest in loop 3. Thus, the heat injection rates from the U-loops were not symmetrical in the pile cross-section, even though the loops were arranged symmetrically in the pile.

226

227 ***Pile Thermal Resistance***

228 The thermal resistance of the pile was evaluated from the temperature differences
229 between the pipes and the pile-soil interface between 1.1 to 1.3 m depth below the ground
230 surface. Each pipe in a given U-loop acts as a heat source in the pile. Thus, there were eight
231 heat sources in the cross-section of the pile at a given depth. Given that it was practically
232 impossible to measure the fluid temperatures inside the pipes at a given location, the pipe
233 temperatures were considered the temperatures of the heat sources. The pipe temperatures were
234 evaluated at a depth of 1.3 m only since the thermocouples on both the inlet and outlet pipes of
235 all the U-loops were only installed at this depth (Figure 2). Hence, to investigate the
236 temperature change between the pipes and the interface at a similar depth, only the interface
237 temperatures measured at a depth of 1.1 m were used in this study (Figure 2). These depths
238 were close enough to have minimal variations in temperatures with depth. At this depth, the
239 initial fluid, pipe, and interface temperatures were approximately 20°C.

240 The thermal resistance circuit adopted to investigate the thermal resistance of the pile
241 is shown in Figure 4. A number of assumptions were made in analyzing the circuit:

- 242 1. The thermal resistance analysis was based on the steady state radial heat transfer between
243 the pipes and the pile-soil interface at the considered depth, while vertical heat transfer
244 in the pile was ignored.
- 245 2. Since the pile-soil interface temperatures, T_b , were measured at a single location at the
246 considered depth, the interface temperatures were assumed to be the same over the
247 circumference of the pile-soil interface at that depth.
- 248 3. The concrete was assumed to be a homogenous solid; hence, the heat transfer mechanism
249 between the pipes and the interface was assumed to be conduction only.

4. The heat injection rate from a given U-loop shown in Figure 3c was equally divided between the two pipes in that loop; hence, there were eight heat sources in the pile.
5. The heat injection perimeter of the pile was assumed to be the circumference of the reinforcement cage where the heat exchanger pipes are installed. There were eight symmetrical pipes on the heat injection perimeter in the present paper, but they can be any number depending on the specific case studied.
6. The region enclosed within the heat injection perimeter is referred to as the inner shell. The region between the heat injection perimeter and the interface is referred to as the outer shell. The outer shell is the focus of the analysis since heat transfer between the heat exchange fluid and the soil occur in this region, as will be discussed later.
7. The thermal properties and resistances of the fluid and the pipe were ignored since the pipe wall temperatures were considered as the heat source temperatures. Hence, the pile thermal resistance is the thermal resistance of the concrete in the outer shell.
8. The analysis is based on transient field results. Therefore, any effects due to internal building activities, thermal capacity of the concrete and fluid, thermal interaction between the pipes, dimensions of the pipes and the pile, and location of the pipes in the pile were already accounted for in the temperature measurements and are not considered separately in the analysis.

The thermal resistance between a pipe in the heat injection perimeter and the pile-soil interface, R_{pb} (mK/W), was obtained using the following equation:

$$R_{pb} = \frac{T_p - T_b}{Q_p} \quad (3)$$

where T_p and T_b are the pipe and pile-soil interface temperatures ($^{\circ}\text{C}$ or K), respectively, and Q_p is the value of the heat source from the pipe (W/m).

The pipe temperatures at the inlet and exit of each U-loop and the pile-soil interface temperature are shown in Figure 5. Similar to the fluid temperatures, the individual pipe temperatures during heating, according to Figure 2, can be hypothetically represented by the following relation:

$$L_1P_{in} > L_1P_{out} \geq L_2P_{in} > L_2P_{out} \geq L_3P_{in} > L_3P_{out} \geq L_4P_{in} > L_4P_{out} > T_b \quad (4)$$

where L is the loop number, P_{in} and P_{out} are the pipe temperatures at inlet and outlet legs of the U-loops, respectively, T_b is the pile-soil interface temperature, and 1 – 4 are loop numbers. Similar to the fluid temperatures, assuming there were no heat losses, the pipe temperature at the outlet of each U-loop is expected to be similar to the pipe temperature at the inlet of the consecutive U-loop at a given depth.

The results shown in Figure 5 generally agree well with relation 4, i.e. the maximum temperature is the pipe wall temperature at the inlet of the first U-loop and decreases to the lowest temperature magnitude at the pile-soil interface. The pipe temperatures decreased with the increasing number of pipes and dropped from 46°C from the inlet of loop 1 to 43°C at the exit of loop 4. However, the fourth U-loop does not satisfy relation 4 since the outlet pipe temperature was higher than the inlet pipe temperature. There were also slight differences between pipe temperatures at the outlet and inlet of successive U-loops (between loops 2 – 4). These variances were likely due to the differences in the heat injection rates from the U-loops into the pile (Figure 3c). The different pipe temperatures indicate that there was no thermal symmetry in the pile cross-section at any given time.

The thermal resistance of the pile (i.e., the outer shell thermal resistance shown in Figure 4) was evaluated using the pipe and pile-soil interface temperatures shown in Figure 5 and equation 3. As indicated earlier, the thermal resistance of pile or borehole heat exchangers is the thermal resistance between the fluid in the pipes and the interface of the heat exchanger and the soil (De Carli et al. 2010; Bozis et al. 2011; Loveridge and Powrie 2013, 2014; Park et al. 2013, 2018). This hypothesis is valid since heat transfer occurs radially from the pipes to the ground. Hence, even if the inner shell was a thermal insulator or was utterly hollow, there will still be heat transfer between the pipes and the pile-soil interface. Also, the results are consistent with the analysis of Loveridge and Powrie (2014) that indicated that the concrete cover thickness over the pipes played a significant role in affecting the thermal resistance of the pile, where a higher concrete cover led to higher thermal resistance.

The temperature differences between the pipes and the pile-soil interface are shown in Figure 6a. The values ranged between 0.9 – 3.4°C at the end of the experiment. The temperature difference between the first pipe and the pile-soil interface was the largest since the fluid and pipe temperatures were largest in the first pipe as shown in Figures 3a and 5. It is to be noted that the temperature measured at the pile-soil interface was considered constant over the circumference of the pile edge. In reality, this may not be the case, as the heat injected into the pile from the pipes was not symmetrical, as shown in Figure 3c.

The individual pipe-interface thermal resistances are shown in Figure 6b and were calculated using equation 3. The values ranged between 0.02 to 0.07 mK/W towards the end of the experiment, with the largest value for the first pipe, which had the largest pipe-interface temperature difference. The individual thermal resistances vary with time due to variations in temperature differences between the pipes and the pile-soil interface shown in Figure 6a.

The total thermal resistance of the pile, R_p , was obtained by averaging the eight individual pipe-interface thermal resistances in the outer shell (Figure 6b). The R_p value varied

with time and had a value of approximately 0.053 mK/W at the end of the experiment, shown in Figure 6c. This value is for the setting investigated in the current study (i.e. pile diameter 0.6 m, a concrete cover of 95 mm, pile thermal conductivity of 1.5 W/mK, and eight symmetrical pipes in the cross-section). It can be applied to similar pile dimensions, number of pipes and their location in the pile cross-section. Loveridge and Powrie (2014) evaluated pile thermal resistances using the conduction shape factor analysis and reported similar R_p of approximately 0.056 mK/W for a pile diameter of 0.6 m, concrete cover of approximately 95 mm, pile thermal conductivity of 1.5 W/mK, and eight symmetrical pipes in the cross-section.

The R_p value in the present study was compared against the concrete thermal resistance, R_c , estimated using the commonly used equivalent diameter approach (Loveridge and Powrie 2014) where all the pipes are lumped together, using the following equation:

$$R_c = \frac{\ln\left(\frac{r_b}{r_{eff}}\right)}{2\pi k_c} \quad (5)$$

where r_b is the pile radius, k_c is the concrete thermal conductivity, and r_{eff} is the effective radius given as:

$$r_{eff} = r_o \sqrt{n} \quad (6)$$

where r_o is the outer radius of the pipes, and n is the number of pipes in the pile. The thermal resistance using the equivalent diameter approach was 0.2269 mK/W (Figure 6c) and was almost four times larger than the R_p obtained using the radial thermal gradients. The equivalent diameter approach has limits since it relies on the dimensions of the pipes and the pile and the

thermal conductivity of the concrete and does not consider the heat injection rates and radial temperature gradients within the pile.

Some of the effective thermal resistances of field-scale energy piles using thermal response tests (TRT) from previous studies are summarized in Table 1. Thermal response tests, even though widely used, have some limitations such as assumption of homogenous soil medium with a uniform initial temperature, application of steady-state heat flux, discarding part of the dataset, and only applicable for piles with large length-to-diameter aspect ratios (Loveridge et al. 2014; 2017). Also, TRT results do not monitor the transient and spatial pipe, interface and soil temperatures. Still, the TRT results shown in Table 1 provide valuable insights into the influence of different pile configurations on the pile thermal resistance between the heat exchanger pipes and the pile-soil interface.

As seen in Table 1, for a given pile diameter-to-length aspect ratio and concrete cover, the effective thermal resistance of the pile reduces with the increasing number of U-loops due to an increase in heat sources in the pile cross-section. Therefore, a higher number of U-loops would be expected to reduce the pile thermal resistance in the outer shell of the pile cross-section. For a given number of U-loops, the effective thermal resistance reduces with increasing pile aspect ratio due to an increase in the heat transfer area over the pile length. This, in turn, could also influence the temperature difference between the heat injection perimeter and the pile-soil interface, and thus the thermal resistance. The influence of concrete cover is not evident in Table 1. However, as reported by Loveridge and Powrie (2014), a reduction in concrete cover will reduce the thermal resistance in the outer shell of the pile. The comparative analysis further suggests that estimating thermal resistances using existing methods (i.e. thermal response tests and equivalent diameter method) might result in design inconsistencies since they overlook the thermal gradients between the pipes and the pile-soil interface.

Soil Thermal Resistance

The thermal resistances of three soil layers were evaluated at depths of 1.1 m, 3.6 m, and 6.6 m, corresponding to the locations of the pile-soil interface temperatures. A schematic of the thermal resistance circuit of the soil is shown in Figure 7. The analysis was based on heat conduction in a composite or multi-layered cylinder (Çengel and Ghajar 2011). The energy pile transfers heat into the soil, leading to temperature differences in the soil between the pile-soil interface, T_b , and the undisturbed ground temperature, T_∞ , at a given radial distance where soil temperatures are not affected by the operation of the energy pile (e.g. Singh et al. 2015; Faizal and Bouazza 2018; Guo et al. 2018). The soil temperatures in the two boreholes are represented by T_1 and T_2 . The heat input, Q , is the total heat injection rate calculated using the fluid temperature difference between the inlet of loop 1 and exit of loop 4, shown in Figure 3c. The heat input remains constant throughout the radial resistance network. The thermal resistance between two temperature points is calculated using equation 3. Since the thermal resistances are in series between T_b and T_∞ , the total thermal resistance of the soil, R_{Soil} , at a given depth is the sum of the individual resistances.

The soil thermal resistance circuit was analysed based on the following assumptions:

1. The heat transfer between T_b and T_∞ at the depth of interest was considered to be in the radial direction only, while vertical heat transfer in the soil was ignored.
2. Since the analysis is based on temperature differences between different points in the soil, the soil was assumed to be a thermally homogenous solid medium with conduction as the heat transfer mechanism.
3. The pile and the soil were assumed to be in perfect contact, and thus the presence of any thermal contact resistances at the pile-soil interface is ignored at such a large scale.
4. The analysis is based on direct temperature measurements in the field. Therefore, any effects due to internal building activities, thermal capacity of the soil, and variations of

thermo-hydro-mechanical properties of the soil were already accounted for in the temperature measurements and are not considered in the analysis.

The pile-soil interface temperatures at the three depths, d , are shown in Figure 8a. The initial temperatures were approximately 18°C at $d = 3.6$ m and $d = 6.6$ m, and 20°C at $d = 1.1$ m. The pile-soil interface temperatures ranged between 38°C to 43°C, with the highest at $d = 1.1$ m. Being closer to the surface, the interface at $d = 1.1$ m would experience higher heat energy from the inlet fluid than the other depths.

The soil temperatures, shown in Figure 8b, were not measured at the exact depths of the pile-soil interface temperature measurements. They were assessed at depths of 1 m, 3.05 m and average values were taken between 5 m and 7.28 m to obtain radial thermal gradients between the pile-soil interface and the soil at depths of 1.1 m, 3.6 m, and 6.6 m, respectively. The average of initial soil temperatures measured at the two boreholes before the heating experiment was considered as the undisturbed ground temperatures in the far-field, T_{∞} . The temperatures in borehole 1 (BH1) were much larger than the temperatures in borehole 2 (BH2), which recorded very low changes for the duration of the experiment. It is commonly known that soil temperature changes are largest near energy piles, reduce with increasing radial distance, and become negligible at a given radial distance from the pile (e.g. Singh et al. 2015; Faizal and Bouazza 2018; Guo et al. 2018; Bergström et al. 2020). The soil temperatures were between 28°C – 29°C at BH1 and approximately 20°C at BH2 at the end of the experiment.

The temperature differences between the temperature points are shown in Figure 8c (and evaluated with respect to the schematic shown in Figure 7). The temperature differences were the largest closest to the pile between T_b and T_1 , and have very low magnitudes between T_2 and T_{∞} . At borehole 2, the soil temperatures at $d = 1$ m went slightly below the initial soil temperature, possibly due to some thermal effects from internal building activities, as shown

in Figure 8b. This resulted in negative temperature differences between T_2 and T_∞ , but with very low magnitudes (Figure 8c). The individual thermal resistances are shown in Figure 8d. Similar to the temperature difference trends, the largest were R_1 closest to the pile and lowest were R_3 the furthest from the pile. Due to negative temperature differences between T_2 and T_∞ , R_3 also had some negative values, although these values were close to zero and can be considered negligible compared to the other two resistances.

The soil thermal resistances increase with the heating time due to a continuous increase in soil temperatures, with a lower rate of change in thermal resistance towards the end of the test. This analysis suggests that a longer heating duration of the piles is preferred to estimate soil thermal resistances after soil temperatures have reached a certain level of thermal equilibrium. The total soil thermal resistances, R_{Soil} , shown in Figure 8e, were 0.072 mK/W at $d = 1.1$ m and 0.066 mK/W at $d = 3.6$ m and 6.6 m at the end of the experiment. These were obtained by summing the individual thermal resistances per depth, shown in Figure 8d. The R_{Soil} values have slight differences, possibly due to different soil profiles and densities. As shown in Figure 2, the soil profile at $d = 1.1$ m was stiff to very stiff sandy clay, and dense sand at $d = 3.6$ m and 6.6 m. Soils with higher densities would be expected to have lower thermal resistances due to more efficient heat transfer from increased interparticle contacts and less air-filled voids (Bourne Webb et al. 2020). There are insignificant differences between R_{Soil} values and pile thermal resistance, R_p , shown in Figure 6c. The R_p values can be higher or lower than the R_{Soil} values, depending on the concrete cover between the heat exchanger pipes and the pile-soil interface. Decreasing the concrete cover will reduce R_p (Loveridge and Powrie 2014), and it should be noted that R_{Soil} could be different for different soil types, saturation levels, thermal properties, densities and groundwater flow. The thermal properties of the pile and the soil will also influence the pile and soil thermal resistances (Loveridge et al. 2012). In any case, the thermal resistance of the soil should be lower than the thermal resistance of the pile for

efficient heat transfer between the heat exchanger fluid and the soil, and hence, efficient thermal performance of the GSHP.

The temperature changes and thermal resistances of some other types of soils around field energy piles are presented in Figure 9 and Table 2. Only selected studies with sufficient data were used to estimate the soil thermal resistances. The thermal resistances were estimated according to the schematic shown in Figure 7. The pile temperatures monitored in these field tests are assumed to be the pile-soil interface temperatures due to a lack of instrumentation at the interface. As a result, the soil thermal resistances shown in Figure 9 were larger than the soil thermal resistance values obtained in the current study (Figure 8e). It is known that temperature gradients exist across the cross-section of energy piles. For example, numerical studies showed that the temperature difference between the centre and edge of the pile could be up to 4°C (Moradshahi et al. 2021b).

The thermal resistances shown in Figure 9 increase with heating time and have slight differences due to the differences in soil types, heat injection rates, and the duration of thermal response tests. The temperature changes of soil also cause moisture movement in the soil, which gives rise to the soil's coupled convective and conductive heat transfer processes (e.g. Faizal et al. 2021); this coupled heat and mass transfer analysis was, however, not possible to conduct with the available field data. The thermal resistances of unsaturated dense sands reported by Singh et al. (2015) and unsaturated dense sand-sandstone reported by Murphy et al. (2015) had slight differences, with values of 0.128 mK/W (Figure 9a) and 0.159 mK/W (Figure 9b) at the end of the heating tests, respectively. The energy piles used in these two tests had similar diameters, thermo-active pile lengths, and hence similar aspect ratios (Table 2). However, the heat injection rates were different. Also, the in-situ conditions, such as soil initial water contents and densities and pile installation effects on the soils, would not have been the same. The thermal resistances of saturated stiff clay reported by Guo et al. (2018) (Figure 9c)

and saturated clayey sand with groundwater flow at a hydraulic conductivity of 1×10^{-5} m/s reported by Lines and Williams (2019) (Figure 9d) were 0.112 mK/W and 0.169 mK/W, respectively, at the end of the tests. The duration of these tests was low compared to the tests conducted by Singh et al. (2015) and Murphy et al. (2015), and ground temperature changes likely did not stabilize. Also, the presence of groundwater flow reported in the study by Lines and Williams (2019) is a slow process and probably did not significantly affect the soil temperatures in the short test duration (Figure 9d). Nevertheless, the results shown in Figure 9 and Table 2 give an upper range of thermal resistances of different soils that could be used as a first approximation for designing energy pile systems and other energy geostructures.

Conclusions

This study investigated the thermal resistances of a field-scale energy pile and the surrounding dense sand using radial thermal gradients in the underground thermal network. The thermal resistance of the energy pile was evaluated using the temperature gradients between the heat exchanger pipes and the pile-soil interface and had a value of 0.053 mK/W at the end of the heating test. Comparing the analysis presented in the current study with the common equivalent diameter method and thermal response tests from other studies indicated that quantifying radial thermal gradients between the pipes and the pile-soil interface at a field scale is essential for assessing thermal resistances of energy piles for design purposes. These existing methods do not monitor the in-situ transient and spatial pipe, interface and soil temperatures. They might result in design inconsistencies if radial thermal gradients are not accounted for when estimating the thermal resistances. The current analysis suggests that pile thermal resistance is low for lower concrete cover, larger aspect ratios and a larger number of U-loops in the pile. Therefore, these parameters (i.e. concrete cover, pile dimensions, and

number of U-loops) should be carefully accounted for when estimating pile thermal resistances to avoid design errors.

The soil thermal resistance was evaluated using the temperature gradients between the pile-soil interface and the soil. The thermal resistance of stiff sandy clay (0.072 mK/W) clay and dense sand (0.066 mK/W) had similar values, likely due to similar densities and thermal properties. There were slight differences between the pile and soil thermal resistances, likely due to the concrete cover of the pipes in the pile. Installing the heat exchanger pipes closer to the pile-soil interface would be expected to reduce the pile thermal resistance. The current analysis suggested that the soil thermal resistances could be influenced by the soil types, the in-situ thermo-hydro-mechanical conditions of the soil, and duration of tests; hence, a careful interpretation process should be adapted for different sites. The range of soil thermal resistances reported in this paper can be used as a reference in the preliminary design stages of energy piles installed in different soil types.

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List of Figures

Figure 1. Instrumentation of the energy pile: (a) HDPE pipe U-loops attached to the pile cage, (b) thermocouple attached to the pipe wall, (c) interface thermocouples attached to a steel cable and dead weight, and (d) installing the interface thermocouples.

Figure 2. Schematic of the energy pile showing the locations of thermocouples across the cross-section and with depth (L, loop; P, pipe; f, fluid).

Figure 3. Fluid temperatures and heat injection rates: (a) fluid temperatures at inlet and outlet of each U-loop (modified from Faizal et al. 2019a), (b) difference between inlet and outlet fluid temperatures in each U-loop, and (c) heat injected by each U-loop into the pile.

Figure 4. Thermal resistance circuit of the pile cross-section.

Figure 5. Pipe temperatures at the inlet and outlet of each U-loop at a depth of 1.3 m and pile-soil interface temperatures at a depth of 1.1 m.

Figure 6. Pile thermal resistances and temperature differences between pipes and interface: a) temperature differences between pipes and pile-soil interface, b) individual pipe-interface thermal resistances, and c) comparison of the total pile thermal resistances.

Figure 7. Schematic of the thermal resistance network of the soil around the energy pile.

Figure 8. Soil temperatures and thermal resistances: a) pile-soil interface temperatures, b) soil temperatures, and c) soil temperature differences, d) individual soil thermal resistances, and e) total soil thermal resistances (d = depth).

Figure 9. Temperatures and thermal resistances of various soils around energy piles: a) unsaturated dense sand, b) unsaturated dense sand-sandstone, c) saturated stiff clay, and d) saturated clayey sand with groundwater flow (R = radial distance from the edge of the pile).

Table 1. Pile thermal resistances using thermal response tests (TRT) from other field tests (D = pile diameter; L = thermo-active length of the pile; L/D = aspect ratio of energy pile; R_b = pile thermal resistance; * minimum concrete cover is back-analysed from the available details).

Source	D (m)	L (m)	L/D	U-loops	Concrete cover* (mm)	R_b (mK/W)
This paper	0.6	10	16.7	4	95	0.053 (Radial temperature gradient)
Mimouni and Laloui 2015	0.9	24	26.7	4	70	0.048
Loveridge et al. (2014)	0.3	26	86.7	1	67	0.125
Loveridge et al. (2015), Brettman and Amis (2011)	0.305	18.3	60	1	64	0.1006
				2	64	0.0631
	0.457	18.3	40	1	140	0.1269
				2	140	0.0973
Park et al. (2013) [PHC]	0.4	13.25	33.1	2	90	0.131
	0.4	13.75	34.4	3	80	0.098
Luo et al. (2018)	0.6	18.5	30.8	2	50	0.11
	0.8	18.5	23.1	4	50	0.16
Abdelaziz et al. (2015)	0.25	30.5	122	1	75	0.6

Table 2. Soil thermal resistances around energy piles estimated from other field tests (D = pile diameter; L = thermo-active length of the pile; L/D = aspect ratio of energy pile; R_{Soil} = soil thermal resistance; Q/L = heat injection rate per unit thermo-active length of the pile).

Source	D (m)	L (m)	L/D	U-loops	Q/L (W/m)	Duration (Days)	R_{Soil} (mK/W)
This paper	0.6	10	16.7	4	315	18	Unsat. stiff sandy clay = 0.072 Unsat. dense sand = 0.066
Bouazza et al. (2013), Singh et al. (2015)	0.6	14.2	23.7	3	171	52	Unsat. dense sand = 0.128
Murphy et al. (2015)	0.61	15.2	24.9	2	137	21	Unsat. dense sand-sandstone = 0.159
Guo et al. (2018) [PHC]	0.5	24	48	1	171	8	Sat stiff clay = 0.112
Lines and Williams (2019) [Square]	0.4 x 0.4	13.5	33.8	3	102	5	Sat. clayey sand with groundwater flow = 0.169

List of Figures

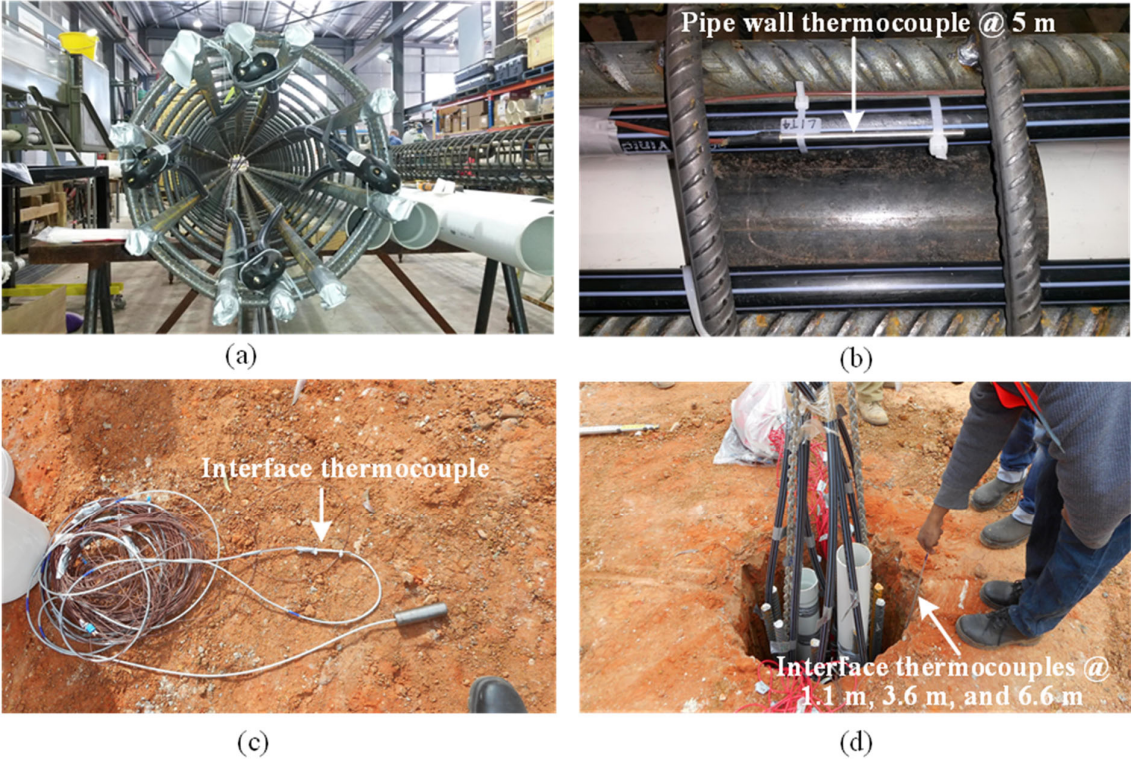


Figure 1. Instrumentation of the energy pile: (a) HDPE pipe U-loops attached to the pile cage, (b) thermocouple attached to the pipe wall, (c) interface thermocouples attached to a steel cable and dead weight, and (d) installing the interface thermocouples.

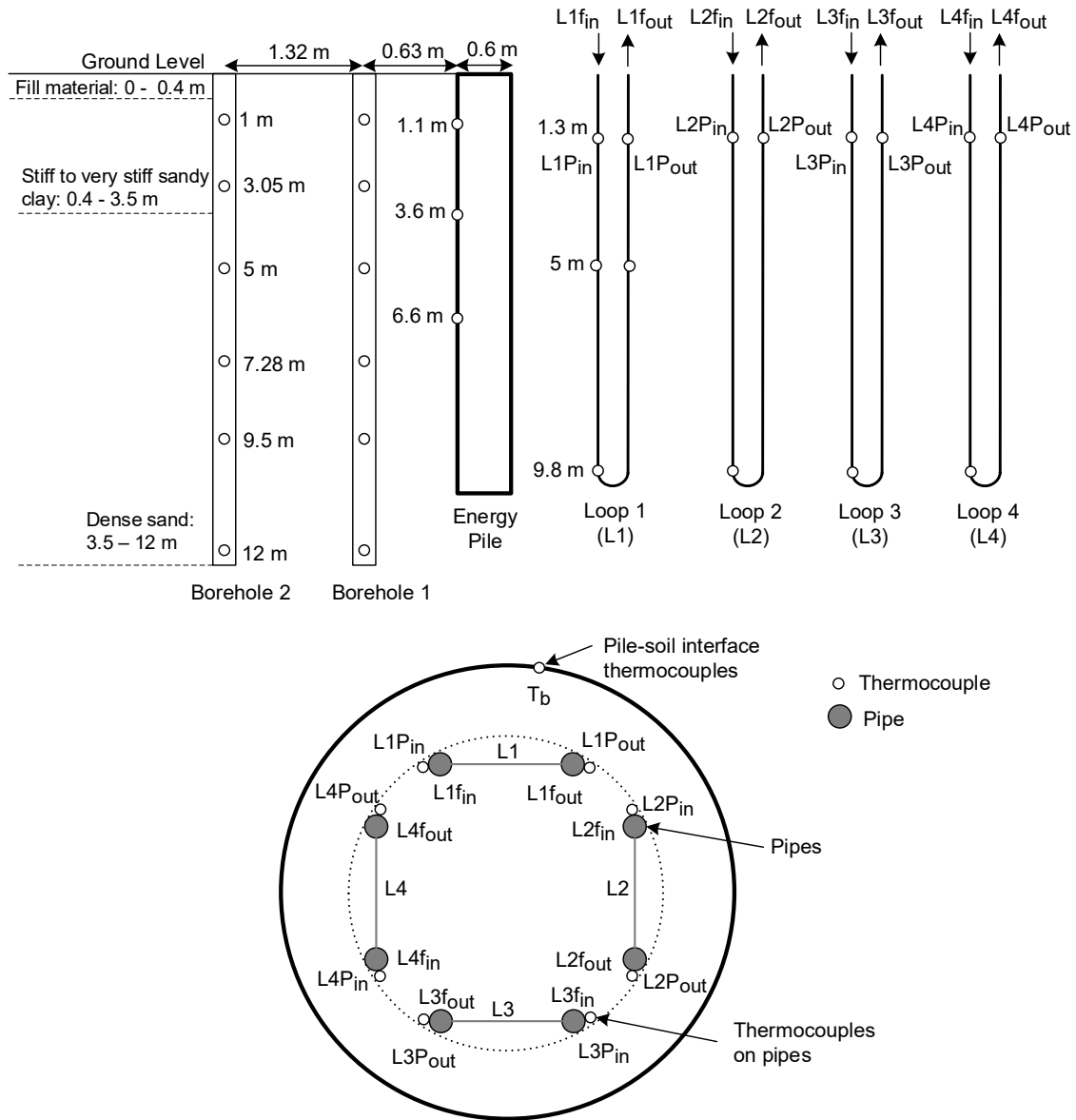


Figure 2. Schematic of the energy pile showing the locations of thermocouples across the cross-section and with depth (L, loop; P, pipe; f, fluid).

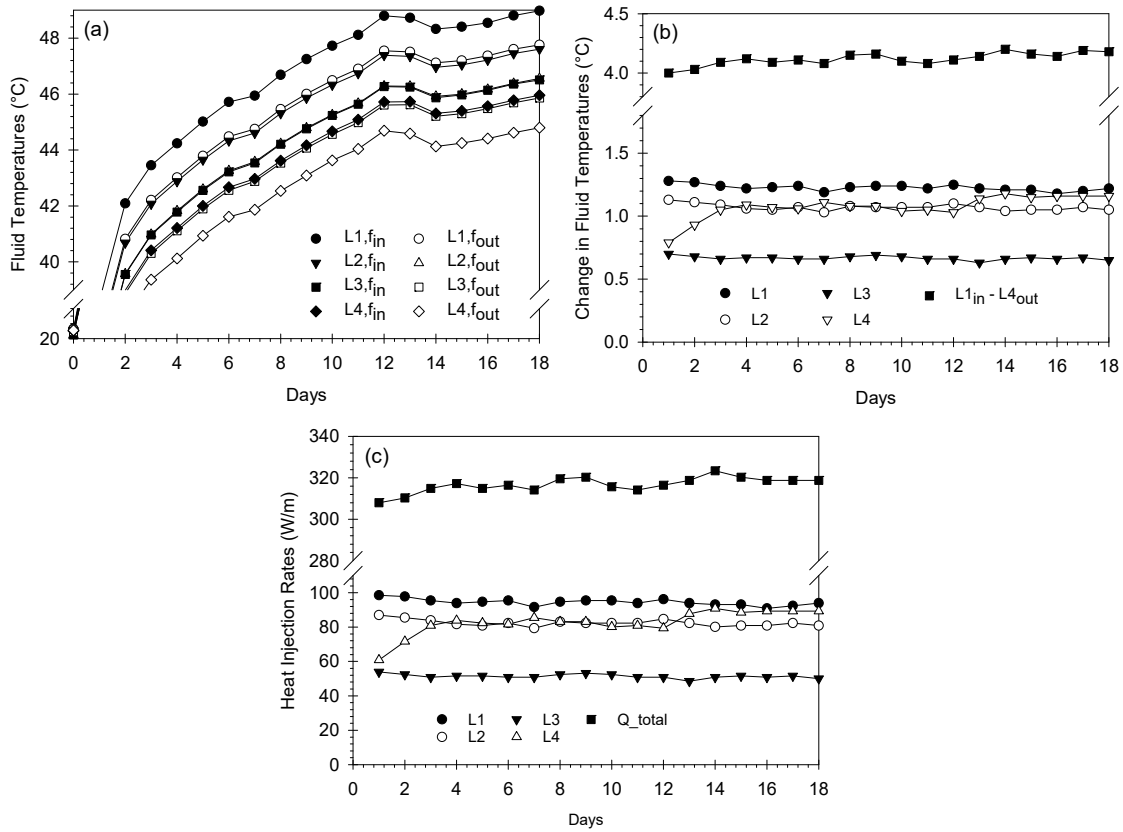


Figure 3. Fluid temperatures and heat injection rates: (a) fluid temperatures at inlet and outlet of each U-loop (modified from Faizal et al. 2019a), (b) difference between inlet and outlet fluid temperatures in each U-loop, and (c) heat injected by each U-loop into the pile.

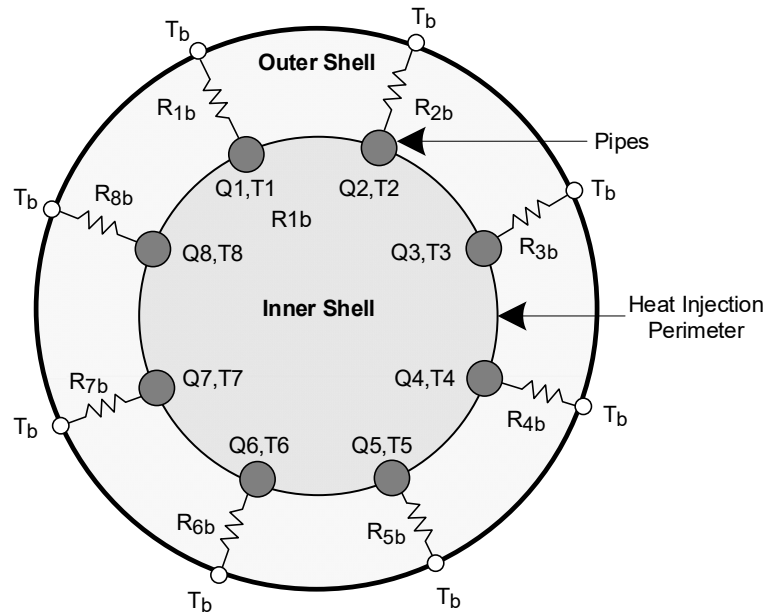


Figure 4. Thermal resistance circuit of the pile cross-section.

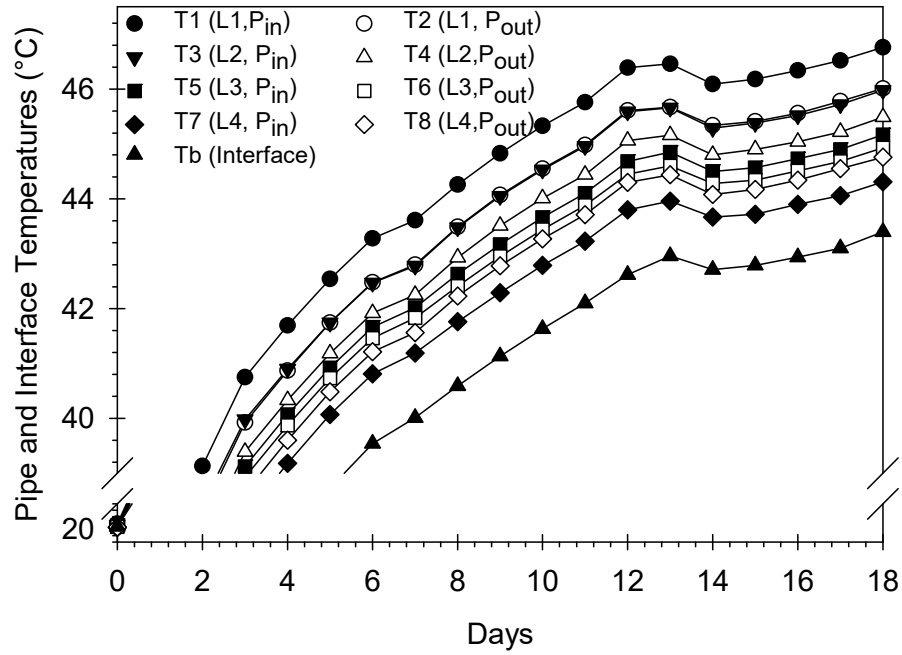


Figure 5. Pipe temperatures at the inlet and outlet of each U-loop at a depth of 1.3 m and pile-soil interface temperatures at a depth of 1.1 m.

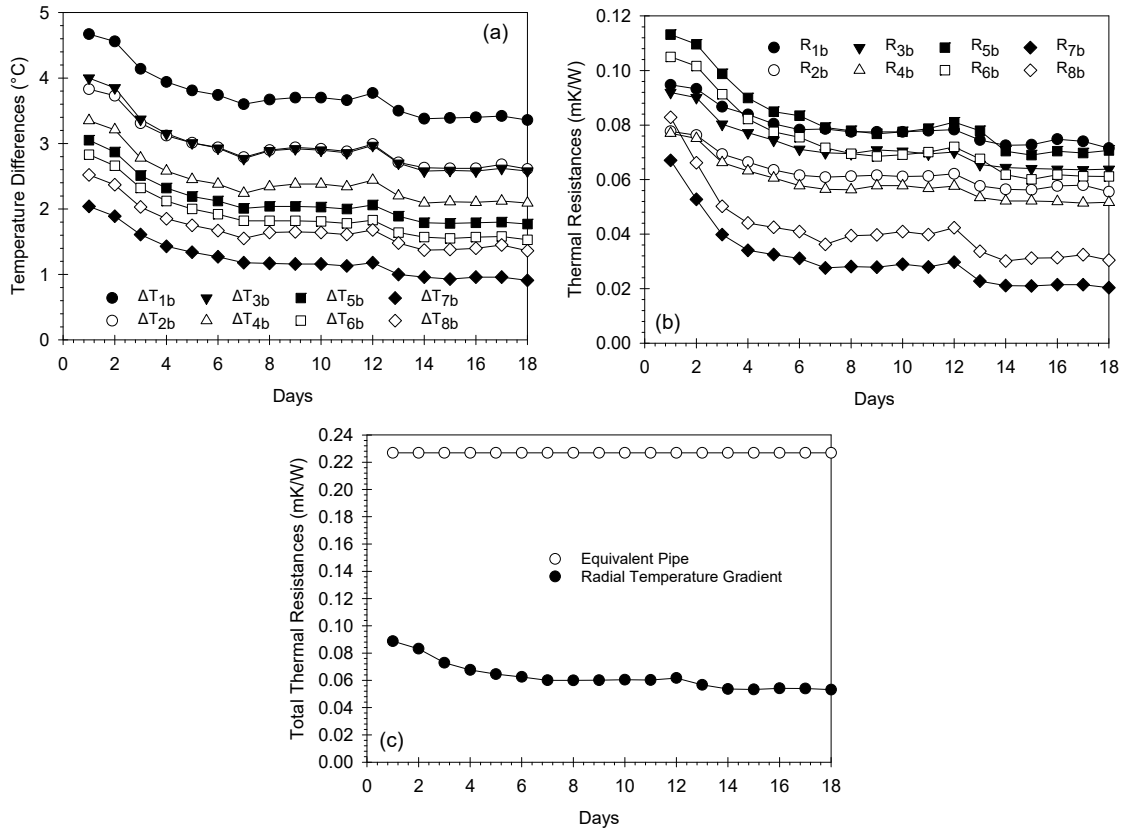
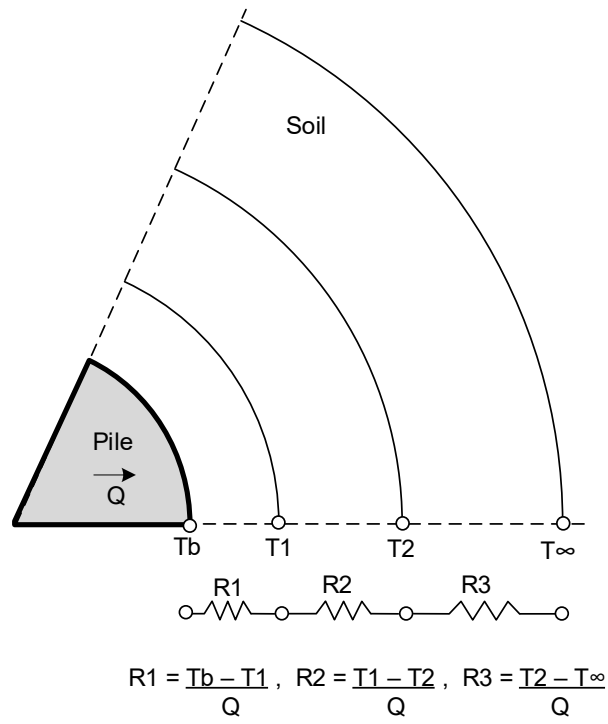


Figure 6. Pile thermal resistances and temperature differences between pipes and interface: a) temperature differences between pipes and pile-soil interface, b) individual pipe-interface thermal resistances, and c) comparison of the total pile thermal resistances.



$$R_{\text{Soil}} = R1 + R2 + R3$$

Figure 7. Schematic of the thermal resistance network of the soil around the energy pile.

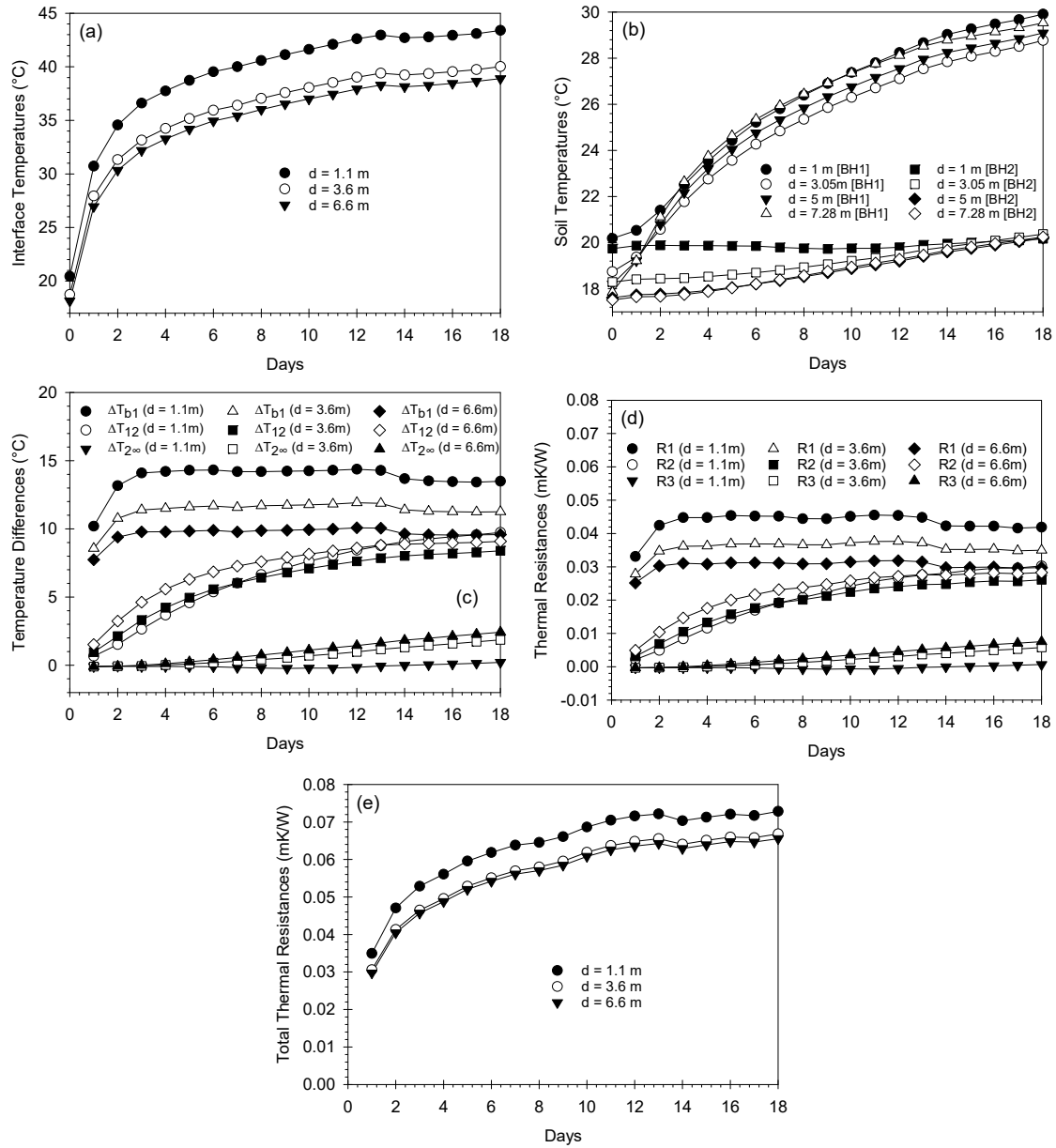


Figure 8. Soil temperatures and thermal resistances: a) pile-soil interface temperatures, b) soil temperatures, and c) soil temperature differences, d) individual soil thermal resistances, and e) total soil thermal resistances (d = depth).

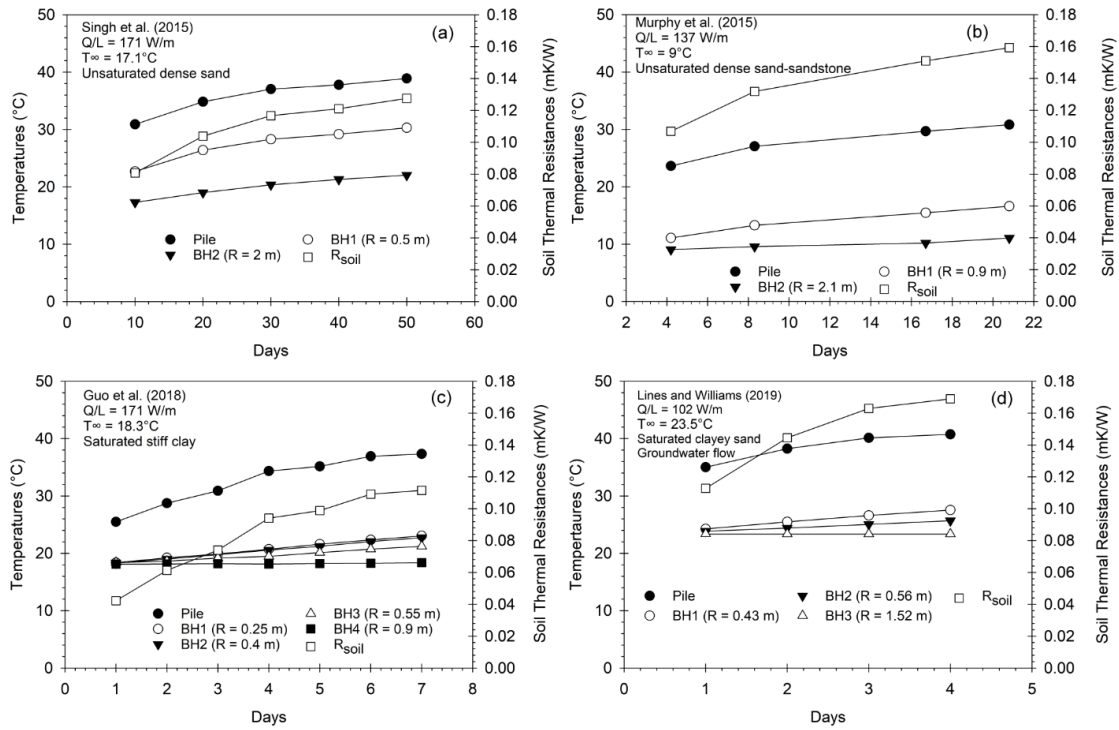


Figure 9. Temperatures and thermal resistances of various soils around energy piles: a) unsaturated dense sand, b) unsaturated dense sand-sandstone, c) saturated stiff clay, and d) saturated clayey sand with groundwater flow (R = radial distance from the edge of the pile).