




Thermo-energy performance of neighbouring energy piles

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Article

Keywords

Energy piles
Operating modes
Thermal interaction
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Abstract

Energy piles are often closely spaced such that the thermal response of one pile might affect the response of neighbouring piles through heat transfer in the soil. This paper examines the changes in extracted energy and ground temperature of two cast-in-place bored energy piles installed below a six-storey building, with a diameter of 0.6 m, length of 10 m and 3.5 m centre-to-centre distance. Field experiments were conducted on singular and dual piles for cooling and cyclic temperatures, continuous daily operation of the ground source heat pump (GSHP) and intermittent cyclic operations with stoppage-to-operating ratios of 2:1 and 1:2. Compared to single pile operations, greater energy was extracted from dual piles for all operating modes despite thermal interaction through the soil volume between the dual piles. The larger stoppage-to-operating ratio of the GSHP induced lower pile and ground temperature changes and higher energy extraction than continuous operation for single and dual pile operations. The larger stoppage-to-operating ratio of the GSHP reduced the thermal interaction between the dual piles by imposing lower ground temperature changes compared to continuous operation. The results demonstrate the practical significance of managing the GSHPs operating modes for optimal thermal performance of multiple closely spaced energy piles.

1. Introduction

Improving energy performances of buildings is critical in the efforts to transit to a low carbon future. A significant portion of building energy is taken up by indoor heating/cooling. For new buildings that require foundation piles for structural support, ground source heat pumps (GSHP) are increasingly used for indoor heating/cooling by utilizing on-site shallow geothermal energy by converting the piles to underground heat exchangers, known as energy piles. Multiple piles are constructed as energy piles in a building footprint, depending on the heating/cooling requirements of the structure. The neighbouring energy piles would be expected to interact thermally due to the presence of multiple heat sources in the soil, which will enhance heat transfer in the soil, and could affect the thermal performance of the piles. The thermo-energy performance of neighbouring energy piles has received little attention under field conditions and currently remains largely hypothetical.

Current literature on the energy and ground temperature variations at a field scale is mostly related to isolated energy piles behaviour under monotonic temperatures (e.g. Li et al., 2006; Gao et al., 2008; Bourne-Webb et al., 2009; Jalaluddin et al., 2011; Singh et al., 2015; Wang et al., 2015; Faizal et al., 2016; Chen et al., 2017; Faizal & Bouazza, 2018; Guo et al., 2018) and daily cyclic temperatures from intermittent operations of the GSHP (You et al., 2014;

Park et al., 2015, 2019; Faizal et al., 2016; Faizal & Bouazza, 2018). The above studies showed that cyclic temperature operations of isolated energy piles impose lower ground temperature changes and higher geothermal energy extraction/rejection than the monotonic temperature operation of the piles. Furthermore, these field studies led to the hypothesis that cyclic temperature operations of multiple energy piles would improve the geothermal energy utilization of the piles and reduce the ground temperature changes between the piles, hence decreasing the thermal interaction between neighbouring piles. Further field tests on the influence of temperature cycles are required to validate this hypothesis.

Even though several field studies have been conducted on the thermo-mechanical behaviour of energy piles in groups (Wood et al., 2009; You et al., 2014; Jeong et al., 2014; Mimouni & Laloui, 2015; Murphy et al., 2015; Rotta Loria & Laloui, 2017; You et al., 2018; Kong et al., 2019; Fang et al., 2020; Moradshahi et al., 2021a, b), these studies did not provide comprehensive insights into the energy, ground temperature responses and thermal interaction between neighbouring energy piles under temperature cycles. The energy utilization of multiple energy piles would be expected to be larger than isolated energy piles due to the increased surface area for heat transfer between the piles and the soil, as has been shown in field studies based on monotonic temperatures of energy piles by You et al. (2014). However, the assumption of obtaining higher geothermal energy with a higher number of energy

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piles cannot be put into practice without understanding the ground temperature variations due to thermal interaction between the piles. Also, extrapolating the energy obtained from isolated energy pile field tests to represent multiple energy piles could be inaccurate due to the lack of understanding of thermal interaction between neighbouring piles through the soil. Greater ground temperature changes and increased thermal interaction between the piles due to multiple heat sources in the soil may reduce the geothermal energy utilization and degrade the performance of the GSHP. Therefore, field investigations on neighbouring energy piles are critical to understand the piles' energy and ground thermal responses.

This paper explores the influence of temperature cycles on the energy and ground temperature changes between two neighbouring cast-in-place bored energy piles installed under a six-storey residential building. Field investigations were conducted for singular and dual pile operations.

2. Field setup and experiments

The experiments were conducted on two energy piles installed below a six-storey student residential building at Monash University, Melbourne, Australia. The building is founded on the Brighton Group of materials consisting of mostly dense sand (Barry-Macaulay et al., 2013; Singh et al., 2015). A summary of the site's ground conditions is given in Table 1. The soil is inferred to be unsaturated since no groundwater was encountered up to the piles' drill depth during installation. The piles had a diameter of 0.6 m and length of 10 m and were spaced at a centre-to-centre distance of 3.5 m. A schematic of the field setup is shown in Figure 1. Four high-density polyethylene (HDPE) pipe U-loops were installed in each pile with an inner diameter of 20 mm and an outer diameter of 25 mm.

The ground temperatures were monitored using Type T thermocouples installed at depths of 1 m, 3.05 m, 5 m, 7.28 m, 9.5 m and 12 m in two boreholes, BH1 and BH2, located at 0.63 m and 1.95 m radial distances, respectively, from the edge of pile 1 (referred to herein as EP1). The inlet and outlet water temperatures were monitored using Type T thermocouples installed in the plumbing manifold. A WaterFurnace commercial 2-5 kW Envision GSHP was used to circulate water in the piles. Pico Technology's USB-TC08 data loggers recorded temperatures from the

thermocouples. The water flowrates were recorded using Flomec TM series digital water flowmeters. The pile temperatures were obtained from Geokon 4200 vibrating wire strain gauges installed at five depths in EP1 using Campbell Scientific CR1000 data loggers. A detailed description of the instrumentation and installation of the energy piles is given in Faizal et al. (2019a, b).

A total of five experiments were conducted, two on a single energy pile (EP1) and three on the dual piles operating together and connected in series (EP1 + EP2). The five tests were as follows: (1) single pile cooled daily for 24 hours (referred to as 1P-24C), (2) single pile cooled daily for 8 hours with 16 hours of natural ground thermal recovery (referred to as 1P-8C16N), (3) dual piles cooled daily for 24 hours (referred to as 2P-24C), (4) dual piles cooled daily for 16 hours with 8 hours of natural ground thermal recovery (referred to as 2P-16C8N), and (5) dual piles cooled daily for 8 hours with 16 hours of natural ground thermal recovery (referred to as 2P-8C16N). The 8C16N and 16C8N operating modes represented the stoppage to operating time intermittent ratios of 2:1 and 1:2, respectively. The details of all experiments are summarised in Table 2. Water was used as the heat exchange fluid flowing in the HDPE pipes. The water flowrates were higher for the single pile experiments and were approximately 15 litres per minute (LPM); they were 11.5 LPM for the dual piles experiments. An evaluation of the temperatures of EP1, ground temperatures between the two piles and energy extracted for single and dual piles were conducted based on the experimental results obtained in the current investigation.

The inlet, outlet, and change in water temperatures between inlet and outlet for all the experiments are shown in Figure 2. Only 12 days of results are presented for all experiments for the sake of clarity on the comparative analysis. The water temperatures for the 24C mode are shown in Figures 2a-c. The lowest inlet water temperature was close to 0 °C for the single pile test (Figure 2a) and 5 °C for the dual piles test (Figure 2b). The fluctuation in inlet and outlet water temperatures on day 9 of the 1P-24C test was due to heat pump performance issues encountered on the day. The change in water temperature was approximately 2 °C for single pile and 3 °C for dual piles (Figure 2c). There were some limitations in controlling the inlet water temperatures in the 24C mode, which led to differences in the pile and ground temperatures (discussed later in the paper). The water temperatures for the 8C16N mode are shown in Figures 2d-f. During cooling, the inlet water temperatures were between 8 - 16 °C for the single pile (Figure 2d) and 8-14 °C for the dual piles (Figure 2e). The change in water temperatures was between 2-3 °C for the single pile and 3-4 °C for the dual piles (Figure 2f). The water temperatures for 16C8N mode are shown in Figures 2g-h. The only test for this mode was conducted on the dual piles, with an inlet temperature of 6-13 °C (Figure 2g) and a change in water temperature of 3-4 °C (Figure 2h).

Table 1. Summary of ground conditions (modified from Faizal et al. 2019a, b).

Depth (m)	Soil type	Soil description
0-0.4	Fill material	Crushed rock silt, sand, moist, medium dense
0.4-3.5	Sandy clay	Silt, sand (sand lenses) moist, stiff - very stiff
3.5-12.5	Sand	Sand, clay lenses, silt, cemented lenses, moist, dense

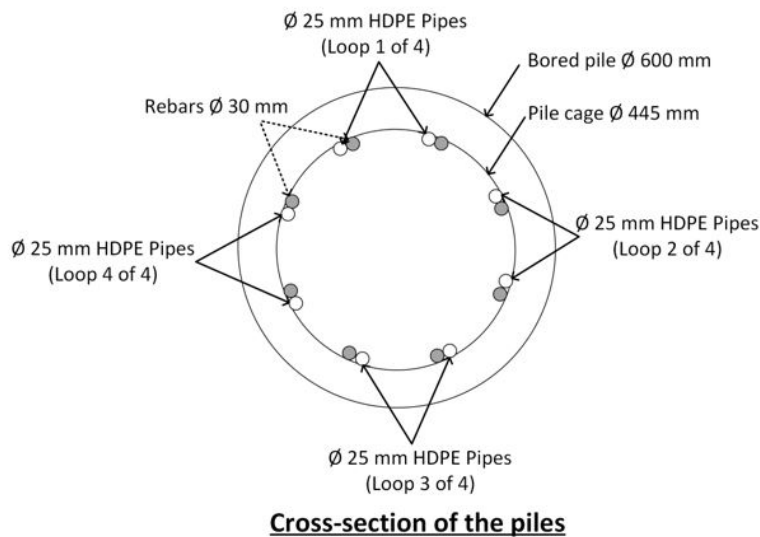
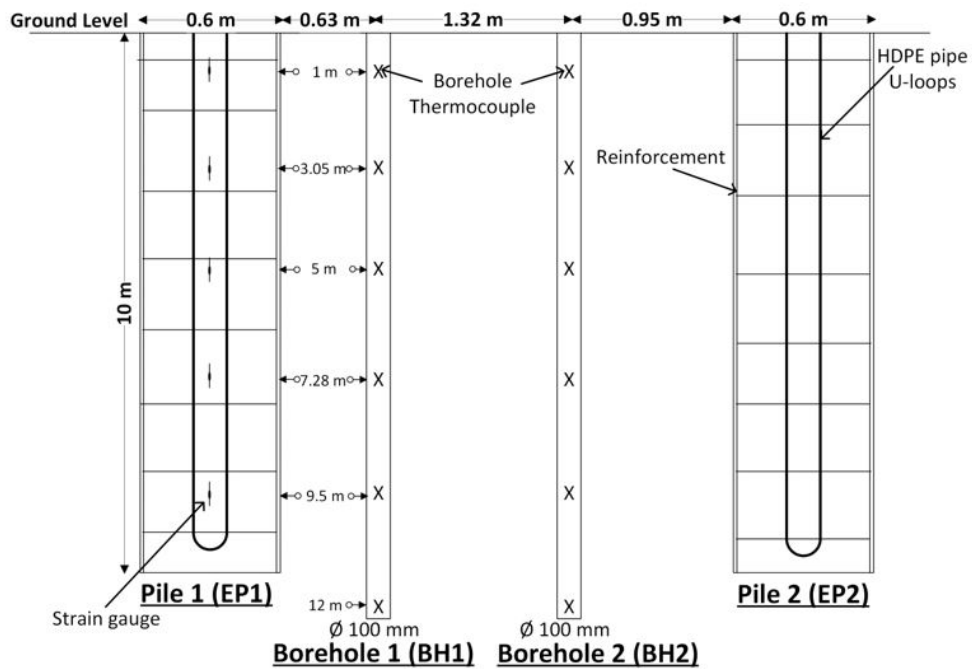


Figure 1. Schematics of the two energy piles installed under the six-storey residential building at Monash University, Australia (modified from Faizal et al., 2019a, b).

Table 2. Summary of experiments.

Operating mode	Description	Start date	End date
1) 1P-24C	Single energy pile cooled daily for 24 hours	2 September 2019	23 September 2019
2) 1P-8C16N	Single energy pile cooled daily for 8 hours with 16 hours of natural ground thermal recovery	12 April 2019	7 May 2019
3) 2P-24C	Dual-energy piles cooled daily for 24 hours	10 June 2019	24 June 2019
4) 2P-16C8N	Dual-energy piles cooled daily for 16 hours with 8 hours of natural ground thermal recovery	5 June 2020	19 June 2020
5) 2P-8C16N	Dual-energy piles cooled daily for 8 hours with 16 hours of natural ground thermal recovery	10 July 2020	24 July 2020

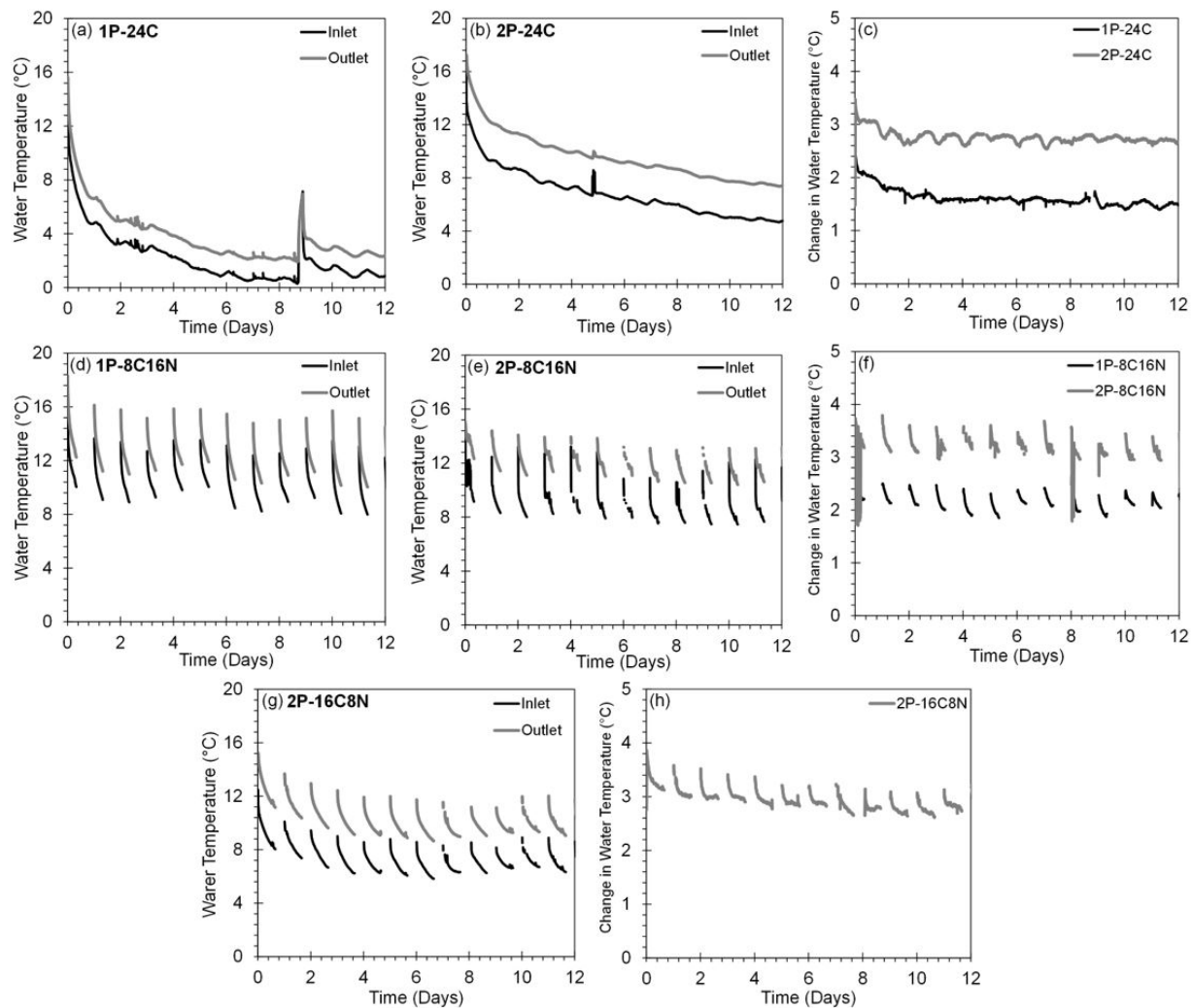


Figure 2. Water temperatures: (a) inlet and outlet (1P-24C); (b) inlet and outlet (2P-24C); (c) change in fluid temperature (24C); (d) inlet and outlet (1P-8C16N); (e) inlet and outlet (2P-8C16N); (f) change in fluid temperature (8C16N); (g) inlet and outlet (2P-16C8N); and (h) change in fluid temperature (16C8N).

3. Results and discussions

3.1 Pile temperatures

The change in temperatures of EP1 at a middle depth of 5 m for all experiments are shown in Figure 3 and Figure 4 (note that only EP1 was instrumented to obtain pile temperatures). The pile temperatures closely followed the trends of the inlet water temperatures shown in Figure 2. A comparison of the influence of different operating modes on the temperatures of EP1 for single and dual piles is shown in Figure 3. The temperature changes of EP1 in the 1P-24C and 1P-8C16N modes were approximately 14 °C and between 2-8 °C, respectively (Figure 3a). The fluctuation in pile temperature on Day 9 for the 1P-24C test was caused by water

temperature fluctuation due to heat pump performance issues. The maximum pile temperature reduction in the 1P-8C16N mode was approximately 43% lower than 1P-24C mode.

The temperature changes of EP1 in the 2P-24C, 2P-16C8N and 2P-8C16N modes were approximately 12 °C, between 1-7 °C, and between 2-6 °C, respectively (Figure 3b). The maximum temperatures reductions in the 2P-16C8N and 2P-8C16N modes were approximately 42% and 50% lower than the 2P-24C mode. The largest change in pile temperatures is in the 24C mode due to the continuous operation of the GSHP. The temperatures of EP1 remained closer to initial undisturbed conditions in the cyclic operating modes for both single and dual piles due to frequent ground temperature recoveries during non-operating times of the GSHP, particularly for the 8C16N mode with greater natural ground thermal recovery time. Cyclic operating modes of the

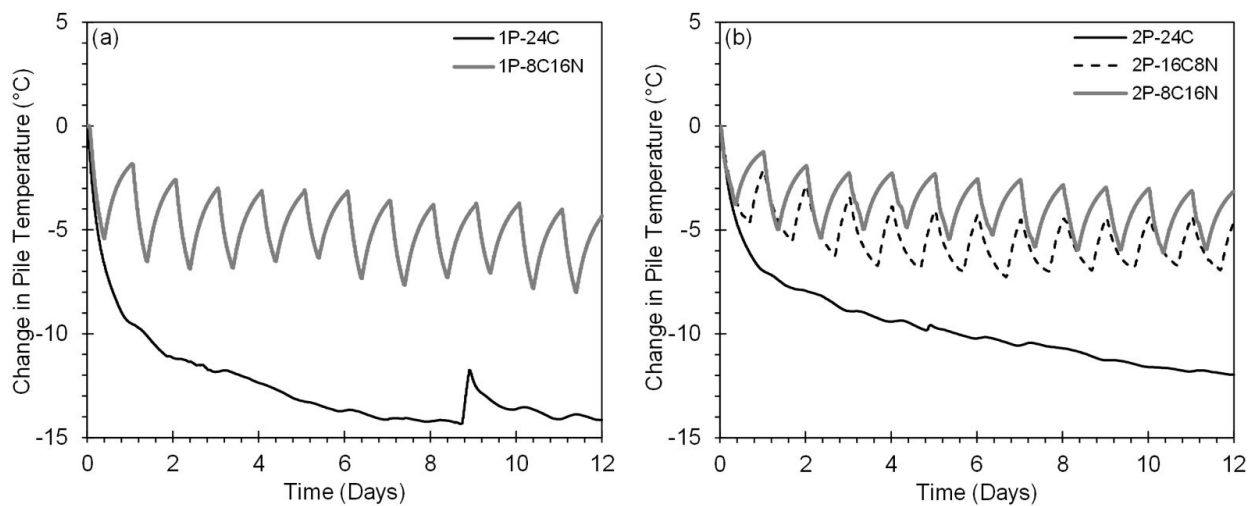


Figure 3. Comparison of change in pile temperatures of EP1 between different operation modes of the GSHP for: (a) single pile; and (b) dual piles.

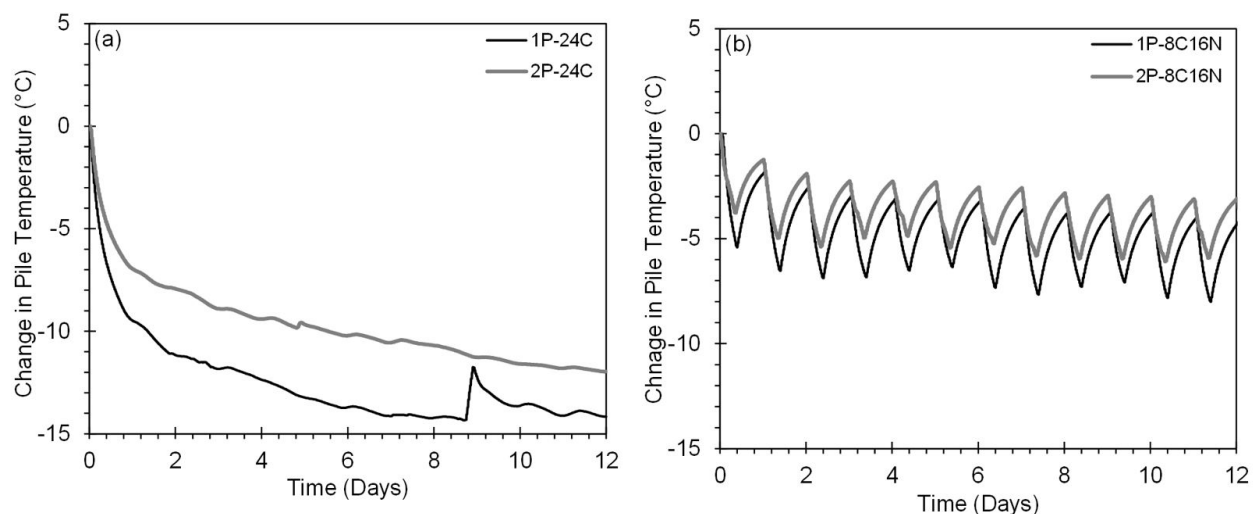


Figure 4. Comparison of change in pile temperatures of EP1 between single and dual piles experiments for: (a) 24C mode; and (b) 8C16N mode.

GSHP with greater stoppage to operating time intermittent ratios (2:1 in the present case) will therefore develop lower pile temperatures, and hence likely lower thermal stresses in the piles, for long term operations. Similar observations were also reported by Faizal et al. (2016) for a single field-scale energy pile.

A comparison of EP1 temperature changes for a single pile against dual piles experiments for a given operating mode is shown in Figure 4. Due to issues in controlling the inlet water temperatures in the 24C modes, the pile temperatures are different for single and dual piles experiments (Figure 4a). However, the pile temperatures are similar in the 8C16N modes (Figure 4b), indicating that the influence of operation

of the second pile (i.e. EP2) in dual piles experiments is not significant on the temperature variations of EP1, for the given pile spacing. The temperatures of EP1 would also have been similar for the 24C modes for single and dual piles experiments (Figure 4a) if the inlet water temperatures were similar (Figure 2a, b).

3.2 Ground temperatures

The change in ground temperatures in BH1 and BH2, with respect to the initial undisturbed conditions, at a depth of 5 m is shown in Figures 5 and 6 for all experiments. The radial distance, R , of BH1 is 0.63 m from the edge of

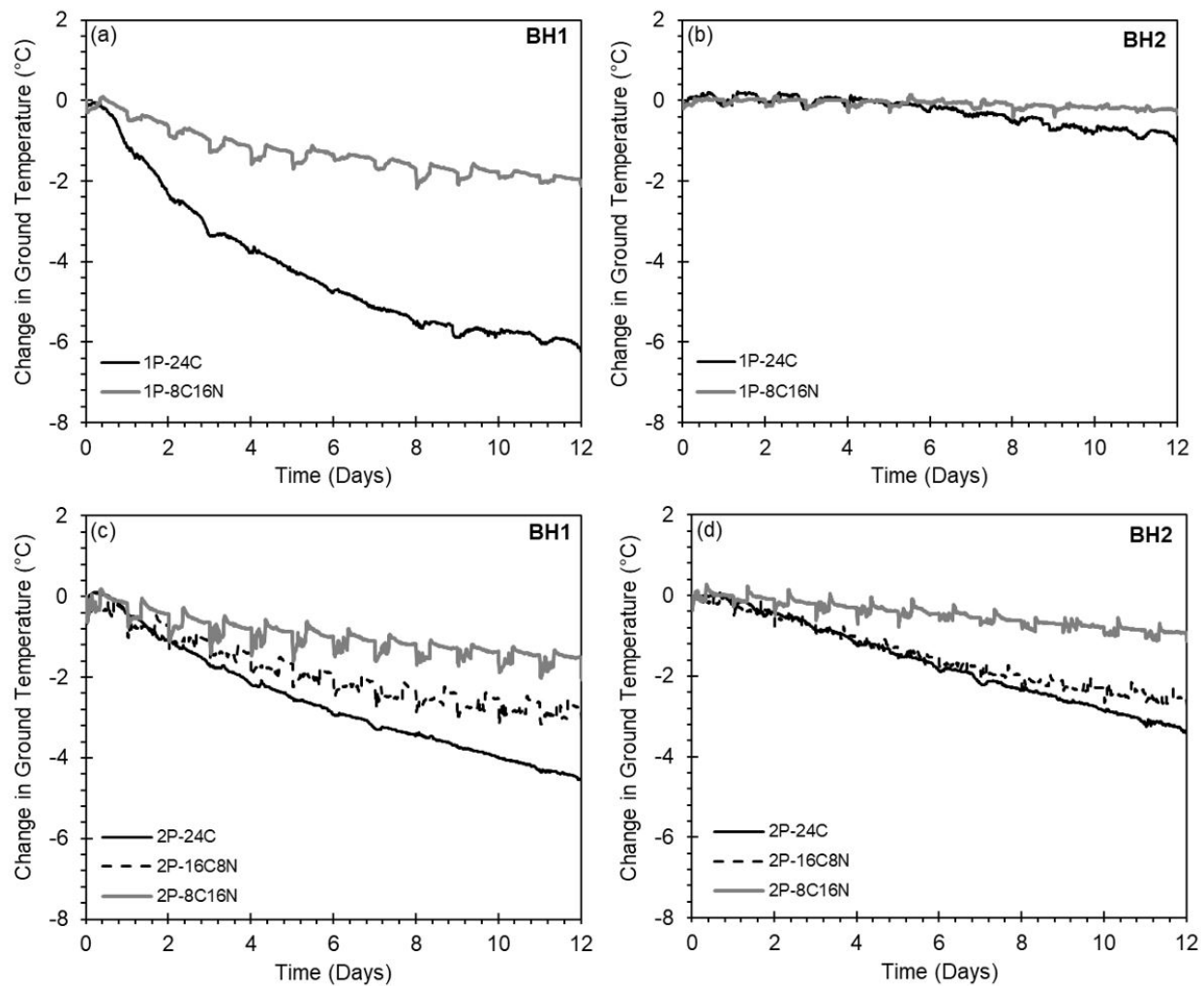


Figure 5. Comparison of change in ground temperatures between different operation modes of the GSHP for: (a) single pile at BH1; (b) single pile at BH2; (c) dual piles at BH2; and (d) dual piles at BH2.

EP1 and 2.27 m from the edge of EP2, whereas BH2 is at $R = 1.95$ m from the edge of EP1 and at $R = 0.95$ m from the edge of EP2 (Figure 1). The undisturbed ground temperature at the test site was between $17\text{ }^{\circ}\text{C}$ and $19\text{ }^{\circ}\text{C}$.

A comparison of the influence of different operating modes on the ground temperature changes for single and dual piles is shown in Figures 5a, b and 5c, d, respectively. For the single pile 1P-24C and 1P-8C16N modes, the ground temperatures at BH1 (Figure 5a) decreased by $5.6\text{ }^{\circ}\text{C}$ and $2.1\text{ }^{\circ}\text{C}$, respectively, and by $1\text{ }^{\circ}\text{C}$ and $0.3\text{ }^{\circ}\text{C}$, respectively, at BH2 (Figure 5b). The 1P-8C16N mode had approximately 63% and 70% smaller temperature changes at BH1 and BH2, respectively, than the 1P-24C mode. A smaller change in ground temperatures in the 1P-8C16N mode is due to the presence of 16 hours of natural ground recovery time daily, which alleviates the ground temperature changes. The temperature changes at BH1 were greater than BH2 for the single pile operating modes as the thermal influence of energy piles

on the ground reduced in the radial direction. Field studies conducted on isolated energy piles have also shown that ground temperature changes are largest closest to the energy pile and diminish with increasing radial distance from the edge of the pile (Amis et al., 2008; Bourne-Webb et al., 2009; Chen et al., 2017; Faizal & Bouazza, 2018; Faizal et al., 2016; Guo et al., 2018; Murphy et al., 2015; Singh et al., 2015).

For the dual piles 2P-24C, 2P-16C8N and 2P-8C16N modes, the ground temperatures at BH1 (Figure 5c) decreased by $4.6\text{ }^{\circ}\text{C}$, $2.7\text{ }^{\circ}\text{C}$ and $1.5\text{ }^{\circ}\text{C}$, respectively, and by $3.4\text{ }^{\circ}\text{C}$, $2.5\text{ }^{\circ}\text{C}$ and $0.9\text{ }^{\circ}\text{C}$, respectively, at BH2 (Figure 5d). Compared to the 2P-24C mode, the 2P-16C8N and 2P-8C16N modes had approximately 41% and 67% smaller temperature changes at BH1, respectively, and about 26% and 74% smaller temperature change at BH2, respectively. Similar to the single pile test results shown in Figures 5a and 5b, the ground temperature changes were highest in the 24C mode. However, due to the presence of dual heat sources in

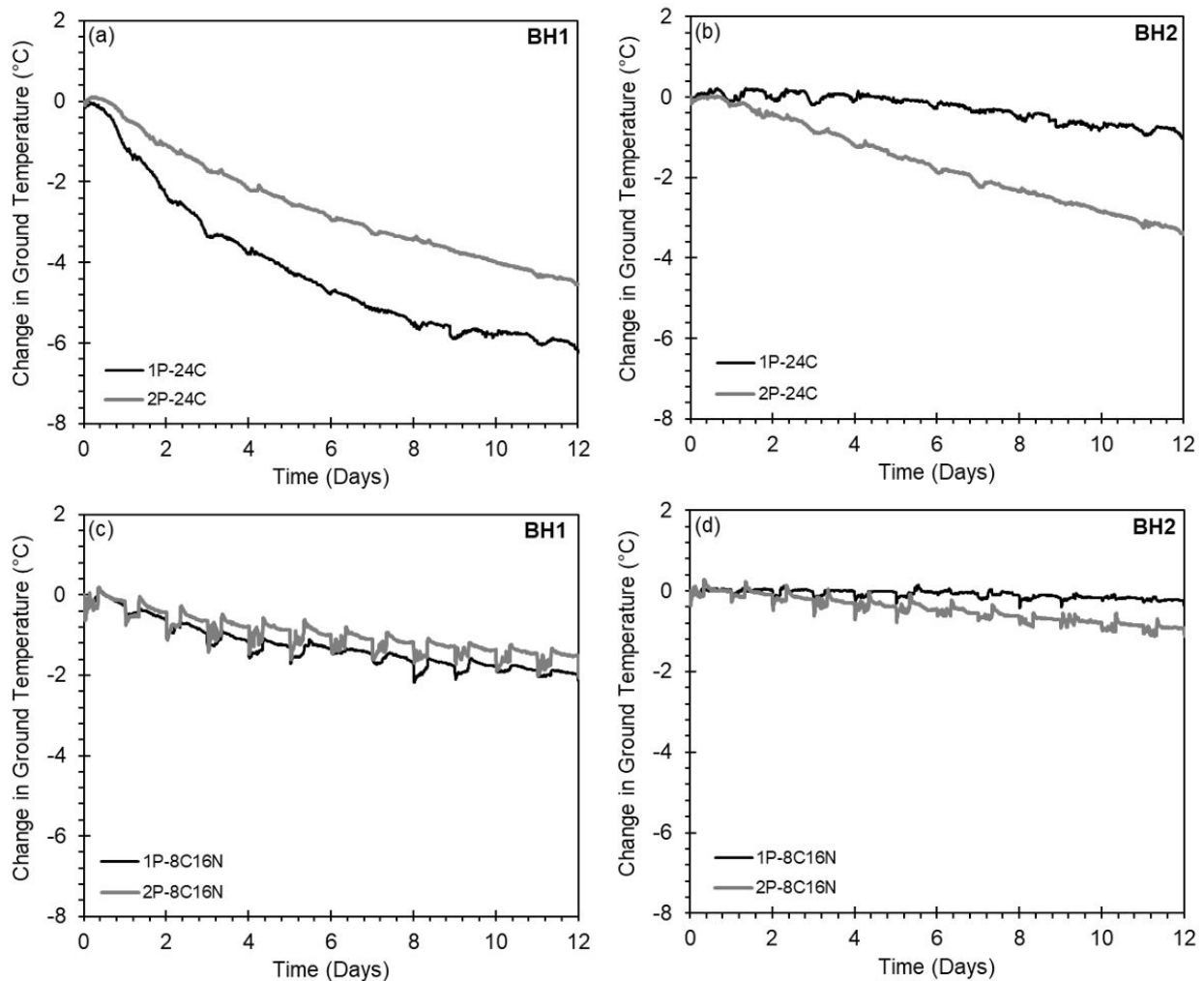


Figure 6. Comparison of change in ground temperatures between single and dual piles experiments for (a) 24C mode at BH1; (b) 24C mode at BH2; (c) 8C16N mode at BH1; and (d) 8C16N mode at BH2.

the ground, the ground temperature changes at BH2 were more significant in the dual piles experiments than that of single pile experiments, indicating the presence of thermal interaction between the two piles through the ground.

A comparison of ground temperature changes for a single pile against dual piles experiments for a given operating mode is shown in Figure 6. The ground temperatures for the 24C mode at BH1, shown in Figure 6a, are different due to the differences in the inlet water and EP1 temperatures, as discussed in relation to Figures 2-4. The ground temperatures for the 8C16N mode at BH1, shown in Figure 6c, are similar for both single and dual piles experiments, indicating a negligible influence of EP2 on ground temperatures at BH1 which is at $R = 2.27$ m from the edge of EP2 during dual piles experiments. The influence of the 1P-24C mode on the ground temperatures at BH2 is lower than that of the 2P-24C mode because BH2 is at $R = 1.95$ m from the edge of EP1 and at $R = 0.95$ m from the edge of EP2 (Figure 6b). Similarly, the 2P-8C16N mode

had a bigger influence on the ground temperatures at BH2 than the 1P-8C16N mode (Figure 6d).

The ground temperature results shown in Figures 5 and 6 indicate that thermal interaction exists between the piles during dual piles experiments due to increased ground temperature changes. The lower temperature changes at BH2 for dual piles experiments for the intermittent operating modes, particularly for higher recovery times in the 8C16N mode, compared to continuous operating mode indicates that intermittent operation of the GSHP will be beneficial in reducing the thermal interaction between multiple energy piles and hence improve the energy extracted/rejected by the piles for long-term operations.

3.3 Energy

The average daily energy extracted for all the experiments is shown in Figures 7 and 8. The energy extracted, \dot{Q} , was calculated as follows:

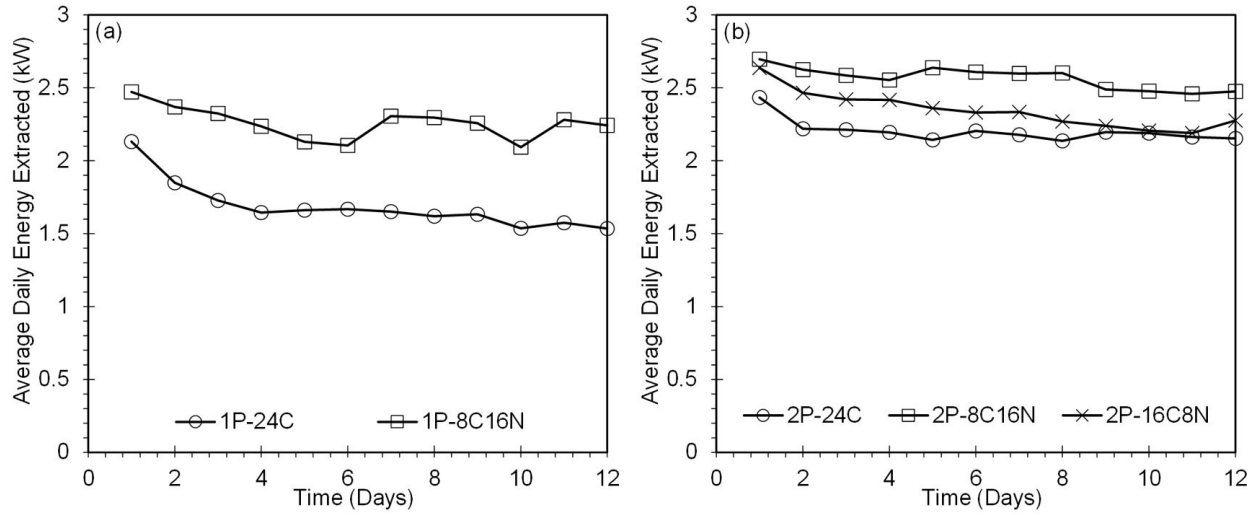


Figure 7. Comparison of average daily energy between different operation modes of the GSHP for: (a) single pile; and (b) dual piles.

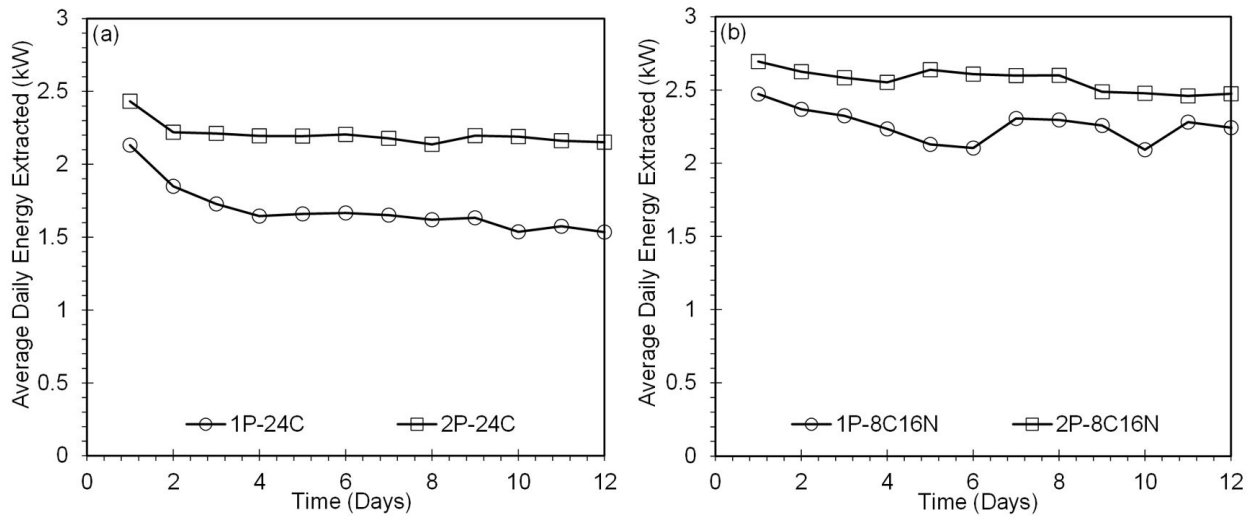


Figure 8. Comparison of average daily energy between single and dual piles experiments for (a) 24C mode; and (b) 8C16N.

$$\dot{Q} = \rho \dot{V} C_p (T_{outlet} - T_{inlet}) \quad (1)$$

where ρ is the density of the water, \dot{V} is the water flow rate, C_p is the specific heat capacity of the water, and T_{outlet} and T_{inlet} are the outlet and inlet water temperatures, respectively.

A comparison of the influence of different operating modes on the energy extracted for single and dual piles is shown in Figures 7a and 7b, respectively. The average energy extracted for single pile 1P-24C and 1P-8C16N modes, shown in Figure 7a, was 1.69 kW and 2.26 kW, respectively. The 1P-24C mode had a 25% lower average energy extracted than the 1P-8C16N mode. The average energy extracted for the 2P-24C, 2P-16C8N and the 2P-8C16N modes, shown in Figure 7b, was 2.21 kW, 2.35 kW and 2.57 kW, respectively. The 2P-24C

mode had 6% and 14% lower average energy extracted than the 2P-16C8N and 2P-8C16N modes, respectively, because of continuous reduction in pile and ground temperatures in the 24C mode, hence decreasing the energy efficiency of the system. The results shown in Figures 7a and 7b indicate that intermittent operating modes of the GSHP, particularly with higher ground thermal recovery times, lead to higher energy extracted than the continuous operation of the GSHP and would be beneficial for long-term operations of the pile. A higher energy extraction rate for intermittent operation of the GSHP compared to the continuous operation was also reported by Ren et al. (2020) for dual field micro-steel-pipe piles and by Faizal et al. (2016) and Faizal & Bouazza (2018) for a single field energy piles.

A comparison of the average daily energy extracted for single pile against dual piles experiments for a given operating mode is presented in Figures 8a and 8b. Compared to the single pile, the average energy extracted by dual piles was 31% greater for the 24C mode (Figure 8a) and 14% greater for the 8C16N mode (Figure 8b). The average energy extracted is larger during dual piles operation due to the greater length of the heat exchanger pipes, which increases the heat transfer between the water and the ground. These results indicate that a higher number of energy piles with the intermittent operation of the GSHP would provide higher thermal loads to the building with reduced thermal interaction between the piles. The reduction in thermal interaction between the piles during intermittent operation results in alleviation of ground temperature changes (as discussed for Figures 5 and 6), leading to an increased temperature difference between the pile and the ground, and hence increase in heat transfer and energy efficiency of the dual piles.

4. Conclusions

This paper investigated the impact of different operating modes of the GSHP on the energy extracted from the ground and temperature changes around single and closely spaced dual-energy piles and the effect of single and dual-energy piles operation on the energy and ground temperature responses. Monotonic and cyclic cooling experiments, resulting from continuous and intermittent operations of the GSHP, respectively, were conducted on the two piles spaced at a centre-to-centre distance of 3.5 m. The cyclic operation of the GSHP induced lower pile and ground temperature changes than continuous operation for both single and dual piles experiments. The ground temperature changes indicated thermal interaction took place between the piles during the dual pile operation. However, the cyclic operation of the GSHP was found to be beneficial in reducing the ground temperature changes and reducing the thermal interaction between the two energy piles when operated together. The intermittent operation of the GSHP, particularly with higher rest times of the GSHP, also showed larger geothermal energy extracted than the continuous operating modes for both single and dual piles experiments. The higher energy extracted during dual piles experiments indicated that a higher number of energy piles would provide higher thermal loads to the building despite the thermal interaction between the piles through the ground.

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Declaration of interest

The authors have no conflicts of interests.

Authors' contributions

Hassam Ayaz: Conceptualization; Formal analysis; Investigation; Data Curation; Writing - Original Draft; Visualization. Mohammed Faizal: Conceptualization; Methodology; Writing - Review & Editing; Supervision. Abdelmalek Bouazza: Methodology; Resources; Writing - Review & Editing; Supervision; Project administration; Funding acquisition.

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