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Thermal performance of thermo-active pile groups

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ABSTRACT: The thermal performance of thermo-active pile (TAP) groups, made up of TAPs with 900 mm diameter and 20 m length with double U-loop (2U) pipe arrangement and a pile spacing of four times the pile diameter is investigated using numerical analyses where heat exchanger pipes are modelled explicitly. In this paper, the operation of the TAPs is modelled with a constant heat flux and the thermal performance is quantified by the average change in temperature at the pile wall, which corresponds to the maximum change in temperature within the soil. The thermal performances of an infinitely large TAP group as well as a 3x3 TAP group are compared against that of a single TAP. It is shown that TAPs within a larger pile group are characterised by poorer thermal performance. This is a result of the thermal interference between the TAPs, where TAPs are heated up or cooled down by adjacent TAPs within the group. Such penalty on thermal performance is quantified in this research. Finally, a parametric study on the effects of soil thermal conductivity on the thermal performance of the 3x3 TAP group is presented, quantifying the impact of this property on the modelled thermal interference.

Keywords: thermo-active pile; thermal performance; pile group; numerical analyses; thermal analyses

1 INTRODUCTION

Thermo-active piles are piles with heat exchanger pipes embedded within them that allow a carrier fluid to circulate, enabling heat to be exchanged with the ground and provide low carbon heating and cooling to above-ground buildings. In recent years, there has been a growing popularity of designing piles to be thermo-active in the United Kingdom (Amis & Loveridge, 2014; Sani et al., 2019; Loveridge et al., 2022) in order to fulfil sustainability targets and reduce carbon emissions. For instance, the Merton Rule requires a proportion of the energy demand of the building to be generated on site using renewable sources (Merton Council, 2010; World Wide Fund For Nature, 2019), playing an important role in promoting the deployment of thermo-active piles, as designing geotechnical structures to be thermo-active is perhaps the only feasible and economically viable option in dense urban environments. In order to fulfil relevant legislation or simply to predict the performance and costs of building energy systems, the response of thermo-active piles has to be determined.

In practice, thermo-active piles are often deployed in groups (rather than having a single thermo-active pile amongst conventional piles in a pile group), and it has been reported that when thermo-active piles operate as a group, the thermal interference that occurs between them would deteriorate their thermal performance (compared to that of a single thermo-active pile) (Lyu et al., 2020), as thermo-active piles are heated up or cooled down by adjacent thermo-active piles. As a result, it is necessary to quantify the penalty in thermal performance when thermo-active piles operate as a group.

In this paper, the operation of thermo-active piles is modelled by applying a constant heat flux into the piles, while the thermal performance of thermo-active piles is quantified by the average change in temperature at the pile wall, which corresponds to the maximum change in temperature that the soil experiences. It should be noted that a pile with poorer thermal performance is characterised by a larger change in average temperature at the pile wall for a given heat flux, as this would correspond to a larger change in temperature of the carrier fluid, which reduces the efficiency of the heat pump. Moreover, a larger change in temperature within the soil means that its capacity to exchange heat with the pile is reduced.

The thermal performance of a single thermo-active pile is first compared to that which is placed within an infinitely large thermo-active pile group made up of identical piles. These form the upper and lower limits of thermal performance for this particular pile. Subsequently, a 3-by-3 thermo-active pile group which piles with the same characteristics is considered, and the thermal performance of the piles at the centre, edge and corner of the group are analysed to quantify their performance between the established upper and lower limits.

Lastly, a parametric study on the effects of soil thermal conductivity on the thermal performance of the 3-by-3 thermo-active pile group is conducted. In this parametric study, the soil thermal conductivity is halved and doubled in order to quantify its role on the thermal performance of the thermo-active pile group.

In order to model the thermal performance of the thermo-actives accurately, three-dimensional (3D) thermal numerical analyses are conducted using COSMOL Multiphysics® (COMSOL AB, 2022), where the heat exchanger pipes are explicitly simulated.

2 MODELLING APPROACH

All the thermo-active piles considered throughout the research presented in this paper have the same geometric characteristics: 900 mm in diameter and 20 m in length. For thermo-active pile groups, it is assumed that the piles are spaced apart by four times the pile diameter, which is 3.6 m, measured between pile axes. The piles have a double U-loop (2U) pipe arrangement, where the inner pipe diameter is 26.2 mm and the concrete cover is 70 mm. At the top of the pile, the pipe inlets are connected to the pipe outlets to form closed circuits, with the heat flux being prescribed to the fluid before it is recirculated back into the ground, as illustrated in Figure 1. The carrier fluid is assumed to be water with a flow rate of $1 \times 10^{-4}\ m^3 \cdot s^{-1}$ per U-loop and volumetric heat capacity of $4.18 \times 10^6\ J \cdot m^{-3} \cdot K^{-1}$. All analyses involve heating up the pile(s) with a constant heat flux of 1000 W per pile, which corresponds to 500 W per U-loop or a power per unit pile length of 50 $W \cdot m^{-1}$, for a year.

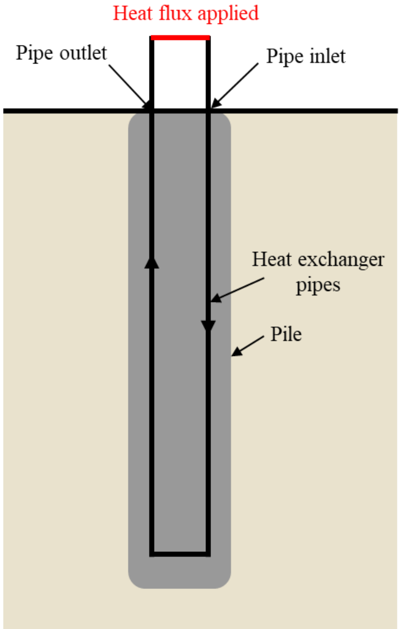

Figure 1 Illustration of how the heat flux is applied to a thermo-active pile

The following three analyses have been conducted in order to quantify the penalty in thermal performance when thermo-active piles operate as a group:

- A single thermo-active pile
- An infinitely large thermo-active pile group
- A 3-by-3 thermo-active pile group

Two different domains have been adopted. For the analyses considering a single thermo-active pile, as well as the 3-by-3 thermo-active pile group, an 80 m by 80 m domain that is 40 m deep is adopted in order to ensure that boundary effects are minimal, and the thermo-active pile(s) is/are located at the centre of the domain. All the domain boundaries are prescribed with a thermal boundary condition where the temperature is not allowed to vary from its initial value.

For the analysis considering an infinitely large thermo-active pile group, the plan view of the adopted domain is illustrated in Figure 2, noting that only the shaded region is modelled. The pile that is investigated is located at the centre of the domain, with the length of the sides being equal to the spacing between the piles, which is 3.6 m, while the depth of the domain is 40 m. The temperature at the top and bottom boundaries is not allowed to vary from its initial value, while the four boundaries on the side are modelled as adiabatic, thus simulating an infinite number of thermo-active piles surrounding the one being investigated.

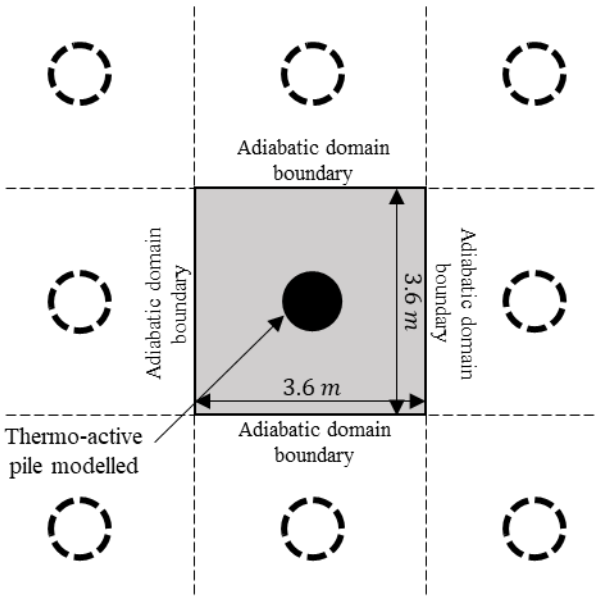

Figure 2 Plan view illustration of the domain used to simulate an infinitely large thermo-active pile group

The initial ground temperature is assumed to be 20°C, and the thermal properties of the pile and soil are given in Table 1.

Table 1. Thermal properties of the pile and soil

Property	Pile	Soil
Thermal conductivity $k\ [W \cdot m^{-1} \cdot K^{-1}]$	2.3	1.8
Volumetric heat capacity $\rho C_p\ [J \cdot m^{-3} \cdot K^{-1}]$	1.9×10^6	1.8×10^6

3 RESULTS

3.1 Single thermo-active pile

A single thermo-active pile is heated with a constant heat flux of $1000\ W$ for a year and the evolution with time of the average change in temperature at the pile wall is presented in Figure 3. On the other hand, Figure 4 plots the same results as those presented in Figure 3, but with the time axis being normalised as Fourier number F_0 (see Equation (1)) using the thermal conductivity of the ground k_{soil} $[W \cdot m^{-1} \cdot K^{-1}]$, volumetric heat capacity of the ground $\rho C_{p,soil}$ $[J \cdot m^{-3} \cdot K^{-1}]$ and the radius of the thermo-active pile r_{pile} $[m]$, and the temperature change axis being normalised as G-function Φ_g (see Equation (2)) using the thermal conductivity of the ground and the applied heat flux per unit pile length P $[W \cdot m^{-1}]$ (same as those presented in Loveridge and Powrie (2013)).

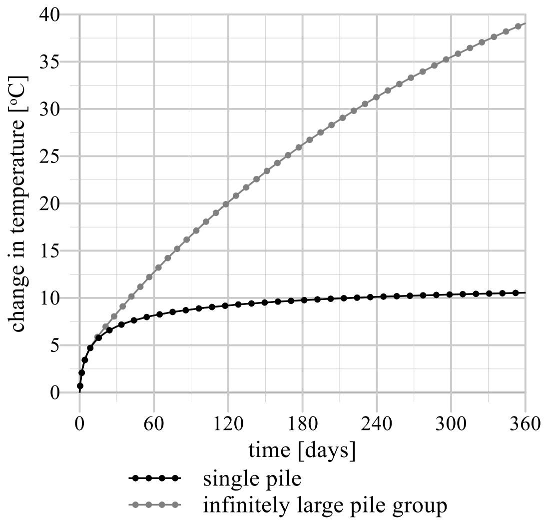

Figure 3 The upper and lower limits of average temperature change at the pile wall

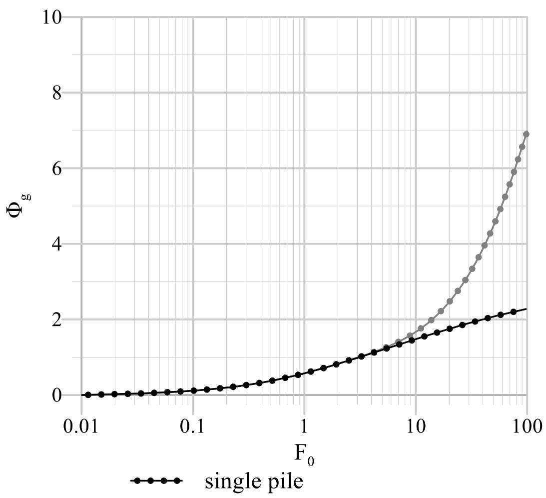

Figure 4 The upper and lower limits of G-function

$$F_0 = \frac{k_{soil} t}{\rho C_{p,soil} r_{pile}^2} \quad (1)$$

$$\Phi_g = \frac{2\pi k_{soil}}{P} \Delta T_{wall} \quad (2)$$

Referring to Figure 3 and Figure 4, the temperature at the pile wall increases monotonically with time, as the heat flux applied to the pile is constant. However, it can be observed that the rate of increase in temperature slows down with time as heat propagates into the surrounding soil. By the end of one year of operation, the average temperature at the pile wall is 10.6°C above the initial ground temperature.

Note that the curves for the single thermo-active pile analysis shown in Figure 3 and Figure 4 represent the lower limit in terms of change in temperature at the pile wall, and hence the upper limit in terms of thermal performance, as there are no adjacent thermo-active piles to contribute to the rise in temperature.

3.2 Infinitely large thermo-active pile group

An infinitely large thermo-active pile group in a rectangular array is considered where identical piles are spaced apart by four times the pile diameter, which equates to $3.6\ m$. Each pile is heated up by a constant heat flux of $1000\ W$ for a year and the evolution with time of the average change in temperature at the pile wall for any pile within the group is plotted in Figure 3, while Figure 4 plots the corresponding normalised quantities.

Referring to Figure 3, it can be observed that for the piles within the infinitely large pile group, as opposed to the case for the single pile, the rate of increase in temperature at the pile wall, given by the slope of the tangent to the curve, remains high throughout the year of operation due to the heat flux from adjacent thermo-active piles. After one year operation, the pile wall of the piles within the infinitely large pile group experiences an increase in temperature of 39.0°C, which is 268% higher than that for the single pile, hence demonstrating the significance of thermal interference effects within pile groups.

On the other hand, an interesting observation from Figure 4 is that the G-functions (which correspond to changes in temperature at the pile wall) for both the single pile and the piles within the infinitely large pile group are identical up to a Fourier number of around 6 (which in the present case corresponds to around 14 days of operation). Beyond this point the G-function for the piles within the infinitely large pile group diverges considerably from that of the single pile. This means that the effects of thermal interference within the infinitely large pile group only affect the response of thermo-active piles after around 14 days of operation. Prior to that, the thermal response of piles within the group is identical to that of single piles, meaning that any group effects can be disregarded in the short term. It is expected that, for a reduced pile spacing, this time threshold will reduce, with the heat flux from one pile reaching adjacent ones sooner.

3.3 3-by-3 thermo-active pile group

A 3-by-3 thermo-active pile group with piles separated by four times the pile diameter is considered. Each of the nine piles within the group is heated up by a constant heat flux of 1000 W for a year and the evolutions with time of the average change in temperature at the pile wall are compared to the upper and lower limits established in Sections 3.1 and 3.2 in Figure 5. Note that this analysis has resulted in three different types of pile response, which correspond to the response of the piles at the centre, edge and corner of the group. All three types of response are therefore plotted on Figure 5, in addition to a curve that plots the average response across all nine piles. On the other hand, Figure 6 plots the corresponding normalised quantities.

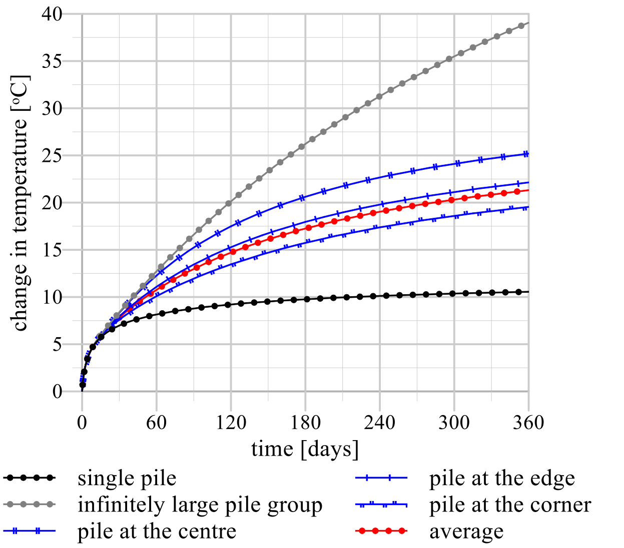

Figure 5 Average temperature change at the pile wall for the 3-by-3 thermo-active pile group

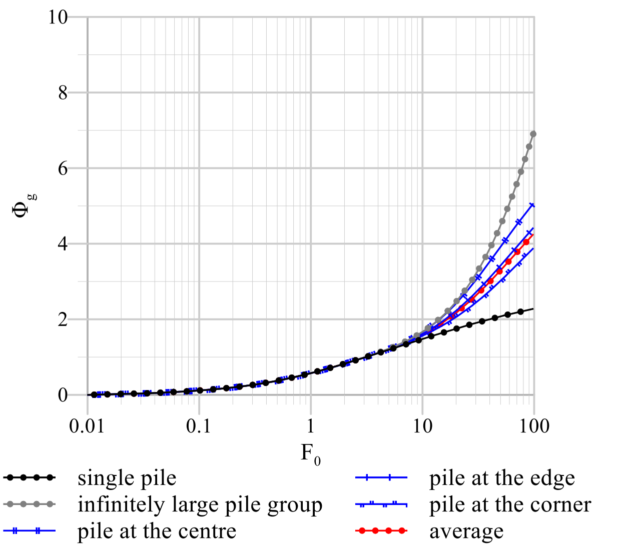

Figure 6 G-functions for the 3-by-3 thermo-active pile group

As expected, the change in temperature at the pile wall for all the piles within the 3-by-3 thermo-active pile group falls within the upper limit defined by the infinitely large pile group (where the effect of thermal interference is maximum) and the lower limit defined by the single pile (where there is no thermal interference). Within the 3-by-3 pile group, the pile wall of the pile at the centre shows the greatest change in temperature, followed by the pile at the edge, then the pile at the corner. These results are anticipated as the effects of thermal interference are the greatest for the pile at the centre of the group, while piles further away from the group centre experience smaller effects from thermal interference.

Another observation from Figure 5 and Figure 6 is that, similar to the case for the infinitely large pile group, the change in temperature at the pile walls of the piles from the 3-by-3 group is identical to that of the single pile up to around 14 days of operation. This can be explained by the fact that the surplus heat which starts to appear at the pile walls within pile groups at around 14 days of operation comes from the heat flux of the immediately adjacent piles. As a result, the time of operation for which the effects of thermal interference begin to show up is independent on the size of the pile group. A temperature change contour graph for pile mid-depth at 14 days of operation is given in Figure 7, which shows the moment when heat fronts from thermo-active piles begin to reach adjacent ones.

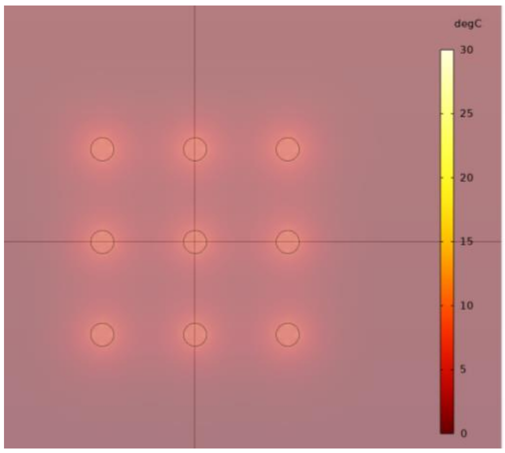

Figure 7 Temperature change contour graph for pile mid-depth at 14 days of operation for the 3-by-3 thermo-active pile group

As shown in Figure 5, after one year of operation, the changes in temperature at the pile wall are 25.2°C, 22.1°C and 19.5°C for the piles at the centre, edge and corner of the pile group, respectively. These correspond to 139%, 110% and 85% above that observed in the single pile, respectively. A temperature change contour graph for pile mid-depth after a year of operation is shown in Figure 8. This shows that the effects of thermal interference can still be significant despite the small number of piles used within the group, and therefore must be accounted for when evaluating the thermal performance of thermo-active pile groups, which involve two or more thermo-active piles.

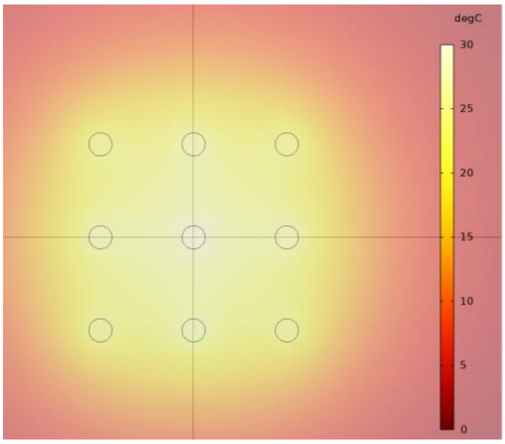

Figure 8 Temperature change contour graph for pile mid-depth after a year of operation for the 3-by-3 thermo-active pile group

4 PARAMETRIC STUDY

In this parametric study, the effects of soil thermal conductivity on the thermal performance (quantified by the average change in temperature at the pile wall) of the 3-by-3 thermo-active pile group are investigated. The analysis described in Section 3.3 is repeated, but with soil thermal conductivities of $0.9\, W \cdot m^{-1} \cdot K^{-1}$ and $3.6\, W \cdot m^{-1} \cdot K^{-1}$ (i.e. half and double of that adopted in Section 3, respectively).

The average temperature change at the pile edge for the piles at the centre, edge and corner of the group, as well as their average, are presented in Figure 9 for each soil thermal conductivity considered. Note that a corresponding figure which plots the normalised time and temperature is not given here as it is identical to that shown in Figure 6. The reason for this is that the soil thermal conductivity appears both in the Fourier number and the G-function (see Equations (1) and (2)).

Referring to Figure 9, it can be observed that, as the soil thermal conductivity increases, the changes in temperature at the pile edges reduce. This is because a soil with higher soil thermal conductivity is able to dissipate the heat injected into the piles more efficiently, resulting in better thermal performance. After one year of operation, the changes in pile edge temperature averaged across all nine piles within the group are 32.7°C, 21.3°C and 13.0°C for soil thermal conductivities of $0.9\, W \cdot m^{-1} \cdot K^{-1}$, $1.8\, W \cdot m^{-1} \cdot K^{-1}$ and $3.6\, W \cdot m^{-1} \cdot K^{-1}$, respectively. In other words, halving the original soil thermal conductivity results in an average of 54% increase in pile edge temperature rise, while doubling it results in a 39% reduction in temperature rise. These substantial differences imply that soil thermal conductivity plays an important role in the thermal performance of thermo-active pile groups, especially when the range of soil thermal conductivity considered in this study ($0.9 - 3.6\, W \cdot m^{-1} \cdot K^{-1}$) lies within a realistic range for soil thermal conductivities (Banks et al., 2013). This study has shown that having a higher soil thermal conductivity can improve the thermal performance of thermo-active pile groups considerably, potentially improving the economic viability of this type of ground-source energy systems.

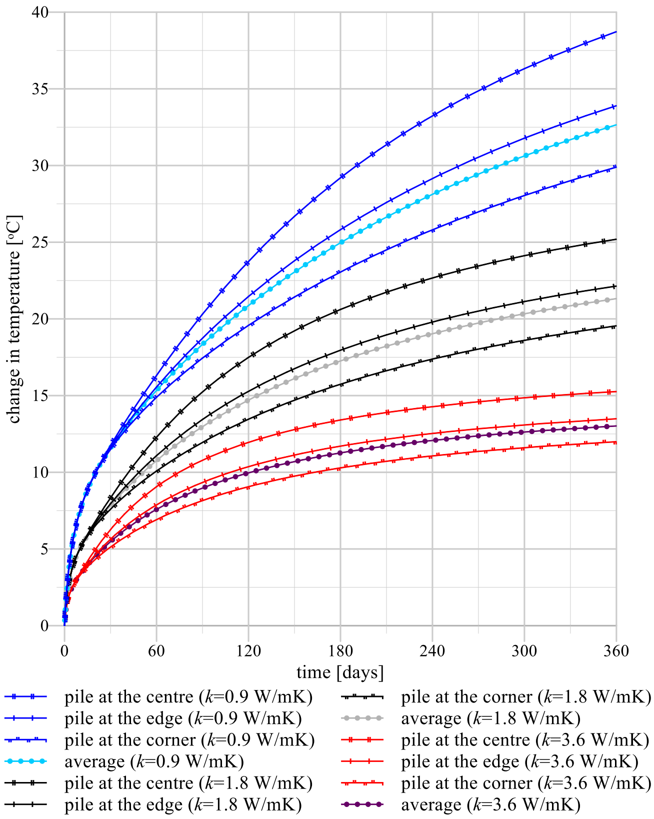

Figure 9 Average temperature change at the pile wall for the 3-by-3 thermo-active pile group when different soil thermal conductivity is adopted

5 CONCLUSIONS

Numerical thermal analyses of thermo-active piles have been presented in this paper with the aim of quantifying the effects of thermal interference on the thermal performance of thermo-active piles. Thermal performance has been quantified by the average change in temperature at the thermo-active pile wall, which is also the maximum change in temperature that the soil surrounding the pile experiences. A larger change in temperature can be interpreted as poorer thermal performance, as this means that the ability to transfer heat to the soil is reduced, with the corresponding larger change in temperature of the carrier fluid also reducing the efficiency of the heat pump.

Three analyses have been conducted to investigate the group effects. First, a single thermo-active pile is considered. The change in temperature obtained at the pile wall for this pile establishes a lower limit for temperature changes (hence an upper limit in terms of thermal performance), as there is no thermal interference for this case. Subsequently, an infinitely large thermo-active pile group is considered, with the change in temperature at the pile wall for this case corresponding to an upper limit of change in temperature (hence lower limit in terms of thermal performance), as the effects of thermal interference are at their maximum for the given pile spacing. The average change in temperature at the pile wall is found to be 268% higher than that of the single pile after one year of operation, showing the potential significance of thermal interference. Lastly, a 3-by-3 thermo-active pile group is considered and, as expected, the changes in temperature observed at the pile edge for the piles at the centre, edge and corner of the group all fall within the lower and upper limits defined by the previous two analyses. Despite the presence of only nine operating thermo-active piles, the effects of thermal interference are still found to be significant, where the average temperature changes are $85 - 139\%$ higher than that of the single pile. This demonstrates that the effects of thermal interference on the thermal performance of thermo-active piles have to be accounted for when designing pile groups. It is found that for both groups (infinitely large and 3-by-3), the effects of thermal interference only start to appear at around a Fourier number of 6, which corresponds to about 14 days of operation, before which the piles behave as a single pile. This means that the time of operation for which the effects of thermal interference begin to appear is independent of the size of the pile group, but more likely on the pile spacing, as this controls how fast the heat flux from one pile can reach adjacent ones.

Finally, a parametric study on the effects of soil thermal conductivity on the thermal performance of the 3-by-3 thermo-active pile group is conducted. In this study, the soil thermal conductivity is halved and doubled. It has been shown that increasing the soil thermal conductivity while remaining within a realistic range results in a significant reduction in temperature changes at the pile edges, and therefore soil thermal conductivity plays an important role in the thermal performance of thermo-active pile groups. This brings up the potential of enhancing the thermal performance of thermo-active piles by improving the soil thermal properties, though this is a subject that requires further investigation.

6 ACKNOWLEDGEMENTS

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