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Procedia Engineering 205 (2017) 3199–3205

Procedia Engineering

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10th International Symposium on Heating, Ventilation and Air Conditioning, ISHVAC2017, 19-22 October 2017, Jinan, China

Investigating the Impact of Thermo-physical Property Difference between Soil and Pile on the Thermal Performance of Energy Piles

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Abstract

As the combination of foundation pile and geothermal heat exchanger, the energy pile has been attracting its industry application and research interests. For the heat transfer model, different analytical models have been established to describe the heat transfer process of the energy pile, e.g. the solid-cylindrical source model, the ring-coil source model, and the spiral heat source model. Most of these analytical models assumed that the pile and the ground soil share the same thermos-physical properties. However, the thermos-physical properties vary with the types of soil, and large property difference may exist between piles and soil. Ignoring this difference, severe calculation error may occur in the heat transfer estimation. Therefore, this paper will establish a numerical model to investigate and examine the impact of thermo-physical properties on the heat transfer performance of energy piles. Different types of soil materials are simulated, and the simulation results show that the assumption of a homogenous domain (in most of the available analytical models) may lead to an incorrect estimation, especially in short-term of operation. Assuming the heat capacity increasing from 1600 to 4800 kJ/K, a temperature difference of 7.16 K with an error of 46.5% can be obvious after 10 days of operation. Also, the inaccuracy would be larger when the pile is larger in radius. So, it can be concluded that differentiating the thermo-physical properties of the pile and soil in calculating the short time temperature response of an energy pile is necessary, especially when the radius ratio of the heat exchanger to the pile is small.

Keywords: Heat transfer; Energy pile, Ground source heat pump, Thermo-physical Property

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Peer-review under responsibility of the scientific committee of the 10th International Symposium on Heating, Ventilation and Air Conditioning.
10.1016/j.proeng.2017.10.269

1. Introduction

As an environmental friendly and sustainable technology utilizing the ground as a heat source or sink for building heat or cooling, Ground coupled heat pump (GSHP) technology has been advancing in recent years. According to Lund and Boyd, the worldwide installed direct-use geothermal capacity soared to from 8664Mwt in 1995 to over 70,000Mwt in 2015 and continue to increase rapidly [1].

Geothermal heat exchangers (GHEs), as a key component of GSHP, always drew considerable interest in researches [2-3]. Pile GHE is an alternative solution for improving the efficiency of the initial cost of GSHP. PGHEs are also known as energy piles that the foundation piles not only carry the mechanical loading of the building but also function as GHEs. As the heat transfer characteristics of energy pile are quite different with the traditional borehole GHE [4], many different types of research have been conducted, especially in molding its heat transfer performance. Man [5] have proposed a ‘‘solid” cylindrical heat source which takes the radius of heat source into consideration. In the later time, a ring-coil source model has been established by Cui [6]. In this model, the spiral heat exchanger was simplified as separated ring-coils:

$$T_{ring,c} = \frac{q_l b}{8\rho c}\int_0^{\tau} \frac{1}{\left[\sqrt{\pi\alpha(\tau-\tau')}\right]^3}\cdot I_0\left[\frac{rr_0}{2\alpha(\tau-\tau')}\right]\cdot \exp\left[-\frac{r^2+r_0^2}{4\alpha(\tau-\tau')}\right]$$
$$\cdot\sum_{n=0}^{m-1}\left\{\exp\left[-\frac{(z-h_1-nb-0.5b)^2}{4\alpha(\tau-\tau')}\right]-\exp\left[-\frac{(z+h_1+nb+0.5b)^2}{4\alpha(\tau-\tau')}\right]\right\}d\tau' \tag{1}$$

It is the first analytical model considering the discontinuity of heat source in its modeling process. But theses analytical models assume that the heat transfer occurs in a homogenous medium in which thermo-physical properties of pile and soil are the same. Generally, the thermo-physical property of soil is considered as the computation basis. Although some researchers [7] differentiated the thermophysical properties of concrete and soil in the model for energy piles, how would the difference affect the temperature response of energy piles was not studied.

Managing to fulfill this gap, in this paper, a finite element model has been established to investigate the influence of thermo-physical properties difference between the pile and soil on the heart transfer performance of energy pile. Different heat conductivity and heat capacity of the pile and soil are employed in the simulation model and the temperature response in each case are discussed in detail. Also, the effects of pile radius the performance of the energy pile are also discussed.

2. Research methods

2.1. Numerical model

A 2-D model is established for the simulation of the heat transfer process of an energy pile with cast-in spiral coils which is 25 in depth. Similar to the ring-coil source model, the spiral heat pipe is simplified as a series of ring-coils. The radius of ring-coil (Heat Source-R) and the pitch are assumed as 0.4m, as shown in Figure 1. The radius of the pile is considered as 0.8 in the investigation the influence of heat conductivity and heat capacity. The finite element simulation software COMSOL Multi-physics is employed for the simulation. In the simulation, the thermo-physical properties of pile and soil are seen as the same in a homogeneous model or treated as different in a composite model. The simulation cases which conducted in this paper is summarized in Table 1.

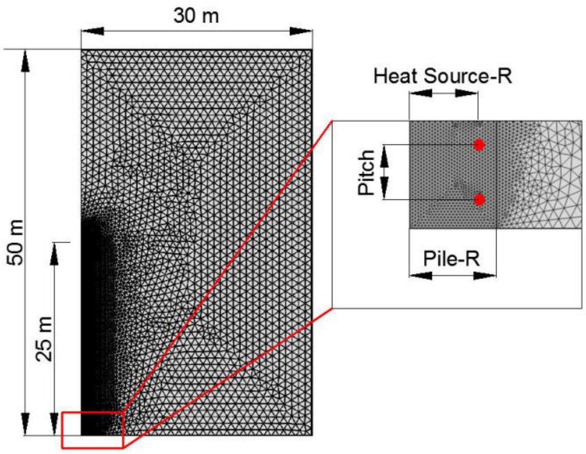

Fig 1 Geometry and mesh of simulation model.

Table 1 Summary of simulation cases.

Case	Heat conductivity [W/mK]		Heat capacity [kJ/K]		Geometrical radius [m]	
	Pile	Soil	Pile	Soil	Pile	Soil
K0，Hom	1	1	1600	1600	0.4	0.8
KP5，Com	5	1				
KP9, Com	9	1				
KS5，Hom	5	5				
KS9，Hom	9	9				
KS5，Com	1	5				
KS9，Com	1	9				
PPC-0.5-1.0, Com	1	1	800	1600	0.4	0.8
PPC-3.0-1.0, Com			4800	1600		
SPC-0.5-0.5, Hom			800	800		
SPC-1.0-0.5, Com			1600	800		
SPC-3.0-3.0, Hom			4800	4800		
SPC-1.0-3.0, Com			1600	4800		
PR-0405-H	1.4	1.4	3003	3003	0.4	0.5
PR-0405-C	1.8	1.4	1600	3003		0.5
PR-0407-H	1.4	1.4	3003	3003		0.7
PR-0407-C	1.8	1.4	1600	3003		0.7
PR-0409-H	1.4	1.4	3003	3003		0.9
PR-0409-C	1.8	1.4	1600	3003		0.9

2.2. Comparison and validation

The accuracy of the simulation model (S) was firstly validated with the analytical model (A), ring-coil source model, by setting the thermo-physical properties of pile and soil as the same. As shown in Fig 2, the simulation results agree perfectly with the analytical solution.

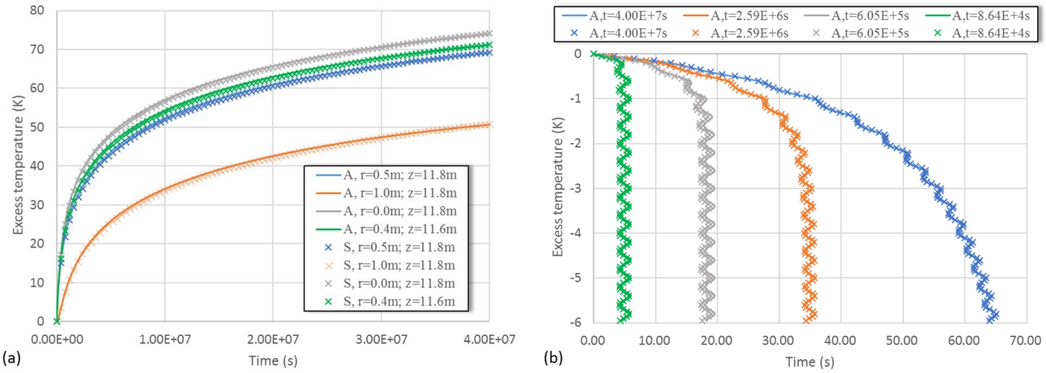

Fig 2 The comparison between analytical model and simulation model in (a) time and (b) depth.

3. Results and discussion

3.1. Influence of heat conductivity

To investigate the effects of the different heat conductivity in soil and pile, two groups of simulations are conducted. In the first group, the heat conductivity of pile varies from 1W/mK to 9W/mK (K0, KP5, KP9), but the heat conductivity of soil remains unchanged as 1W/mK. In the second group, the change in of soil is also considered (KS5-Com and KS9-Com), and to compare the results with the homogenous assumption, two homogenous cases are also simulated (KS5-Hom and KS9-Hom). The temperature response at the pile wall is generally considered as the reference data in calculating the inlet and the outlet temperature of GHEs, thus, the simulation data at the pile wall is collected and analysis. As given in Figure 3, no matter whether the heat conductivity of soil is 5 times and 9 times larger than the pile or the other way round, the effect of the difference in heat conductivity on the long-time running of the energy pile is not obvious, but with a trend of expansion occurs with time increase. The relative error is less than 10% after two weeks (1.2E6s). Additionally, it is not surprised that when the soil heat conductivity is larger, the temperature rise would be much lower than that when the heat conductivity of pile is small. However, in short-term operation, the temperature difference induced by the difference in thermo-physical properties is significant.

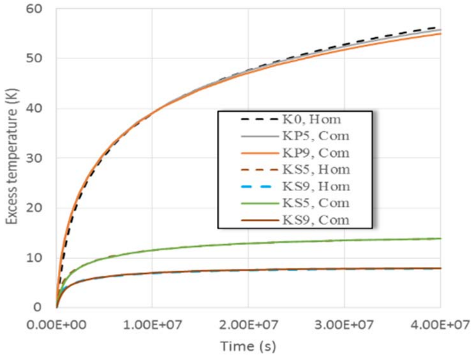

Fig 3 The temperature response in long-term operation in different cases with different heat conductivity.

As shown in Figure 4, although the difference between the homogeneous model and composite model is smaller compared with that when pile heat conductivity is larger, the affecting time tends to be longer. The error ratio is more than 100% in the first 30 hours, when the heat conductivity of pile changes from 1W/mK to 5W/mK.

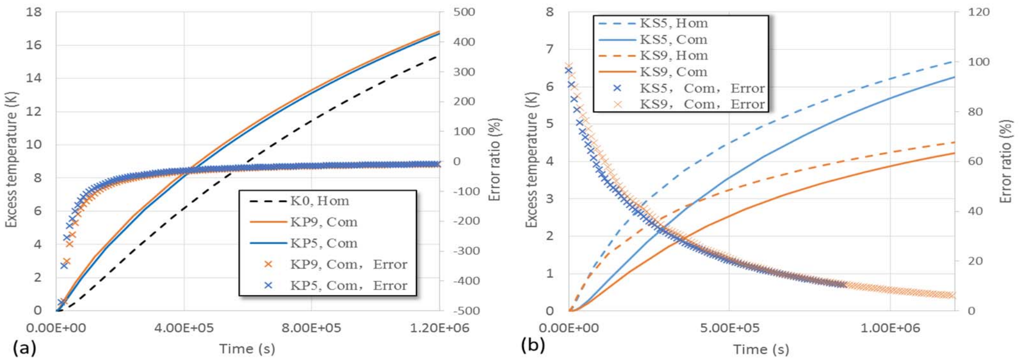

Fig 4 The temperature response in short-term operation in changing of (a) pile and (b) soil with different heat conductivity.

3.2. Influence of heat capacity

In all the cases studying the effects of the heat capacity, the heat conductivities of the pile and soil are the same whereas the heat capacity of both the pile and soil vary from 800 to 4800 kJ/K. The effect of different heat capacities between soil and pile on long-term running is first analyzed (Figure 5). Similar to the first section, a large temperature difference existing between the case of composite model and homogenous model can be obvious at the beginning, and gradually decrease with time. The temperature difference between the case of SPC-1.0-3.0 and SPC-3.0-3.0 is still quite obvious even after one year of operation (3.15e7s).

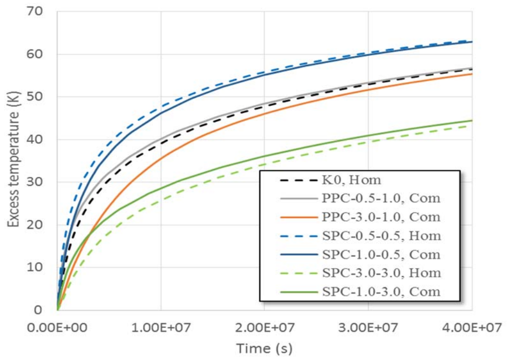

Fig 5 The temperature response in long-term operation in different cases with different heat capacity.

The temperature response in the short time, about 10days running, is illustrated in Fig 6. The change of heat capacity has a more remarkable influence on the temperature response than that of heat conductivity. The temperature rise will be underestimated when the pile has a small heat capacity, on the contrary, it will be overestimated when the pile heat capacity is large. Assuming the heat capacity enlarge from 1600 to 4800 kJ/K, a temperature difference of 7.16K with an error of 46.5% can be obvious after 10days of operation. Also, there are considerable discrepancies in the temperature profile when the change occurs in soil in the short time running.

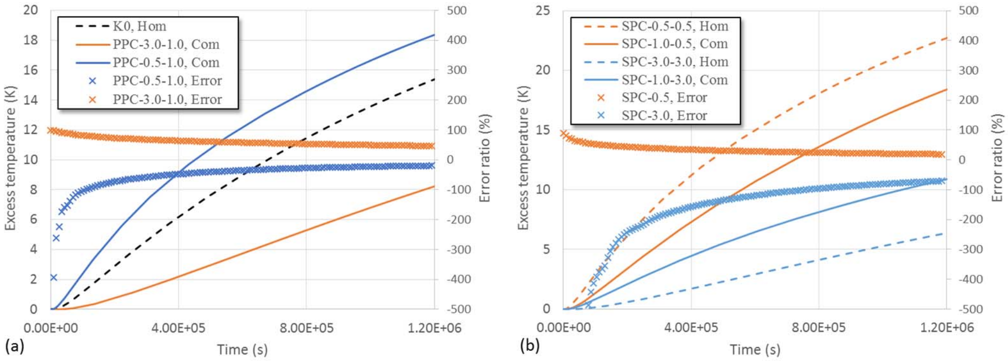

Fig 6 The temperature response in short-term operation in changing of (a) pile and (b) soil with different heat capacity.

3.3. Influence of geometry of pile

As the temperature of pile wall is generally considered as the reference point in a thermal de-sign, the geometry dimension of the pile and the heat exchange pipe is also an influencing factor on the estimation of heat transfer performance of energy pile. In this section, the setting of thermo-physical properties of the pile and the soil domain is according to a real engineering case, when considering the thermo-physical properties difference. Figure 7 (a) and (b) shows the temperature response in a long time running and short time running, respectively. It can also be noted that in the long time running, there is nearly no difference in the temperature response. But, similar to above section, big difference of temperature occurs in the short time running. As a higher heat conductivity but lower heat capacity of the pile, the simulated temperature is always higher in the composite models than that in the homogeneous models. It not surprised that the influence of the difference of thermo-physical properties is more obvious, when the heat exchange pipe is not near the pile wall. With larger pile radius (0.9/0.4), the temperature difference between the homogeneous model and composite model is 2.45K after 10days of operation, but only 1.4K in the case of small pile radius (0.5/0.4).

In addition, temperature profiles in the radical direction are given in Figure 7. The difference of thermo-physical properties has a greater influence on the temperature response with in the pile than the soil, especially in the axial of the pile. A clear peak value can be observed at the point (0.4m) of the heat source in each temperature curve. Although the temperature at the point of heat source tends to be the same, the temperature decreases faster radically outside the spiral coil in the homogeneous model than in the composite.

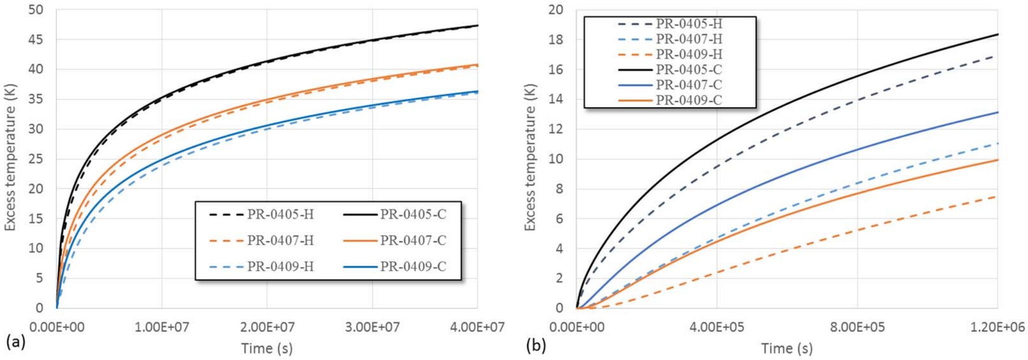

Fig 7 The temperature response in (a) long-term operation and (b) short-term operation with different geometry dimension.

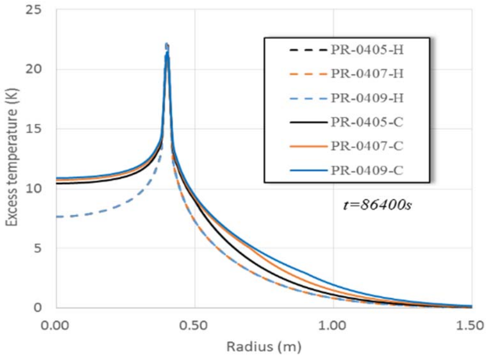

Fig 8 The temperature response along the pile radius with different geometry dimension.

4. Conclusions

This paper analyzed the effects of the thermo-physical properties and geometry of the pile on the heat transfer estimation of a pile GHE through a finite simulation model. The simulation model is first compared with an analytical model to validate its reliability. The simulation results show that the assumption of a homogenous domain (in most of the available analytical models) may lead to an inaccurate estimation, especially in short-term of operation. Assuming the heat capacity increasing from 1600 to 4800 kJ/K, a temperature difference of 7.16 K with an error of 46.5% can be obvious after 10 days of operation. Also, the inaccuracy would be larger if the pile is larger in radius. So, it can be concluded that, differentiating the thermo-physical properties of the pile and soil in calculating the short time temperature response of an energy pile is necessary, especially when the radius ratio of the heat exchanger and the pile is small.

Acknowledgements

The work described in this paper is supported by a grant from The Hong Kong RGC General Research Fund (RGC No: Polyu 5176/13E) and partially supported a Grant from Hong Kong Research Grant Council (RGC) through Grand Research Fund B-Q37H.

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