Open Access Journal

Journal of Power Technologies 98 (4) (2018) 345–351

journal homepage:papers.itc.pw.edu.pl

Heat Transfer Enhancement of Graphite–modified Concrete Energy Piles

Haoran Guo[a], Lan Qiao[a,*], Yunyang Xiao[a], Xiangyu Ren[b]

[a] *School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China;*
[b] *School of Electrical Computer and Telecommunications Engineering, University of Wollongong, Gwynneville NSW 2500, Australia*

Abstract

Designed for utilizing the ground-source systems for heating and cooling, the use of energy piles in commercial and residential buildings has increased exponentially especially in Europe. The heat transfer efficiency of energy piles may directly influence the energy-saving effect on buildings. Apart from the optimization of pipe laying, many other factors can also influence the heat transfer efficiency of energy piles. In this study, a new method that can increase the heat transfer efficiency of energy piles was proposed to explore the influences of adding graphite powder with high thermal conductivity to pile concrete on the heat transfer efficiency of energy piles. The thermal resistance models of energy piles in three different pipe-burying modes were constructed by combining the 2D plane method and the heat transfer mechanism of energy piles. The internal heat transfer characteristics of energy piles at different temperatures, graphite contents, and pipe-burying modes were discussed by combining the indoor thermal conductivity test of graphite-modified concrete. The external heat transfer characteristics of graphite-modified concrete energy piles were analyzed through numerical simulation analysis. Results demonstrate that the increase in graphite contents is beneficial to heat transfer in energy piles. In particular, thermal conductivity significantly increases when the graphite content exceeds 5%. The high temperature in the pipe is also conducive to the thermal conductivity of the energy pile. The thermal conductivity of the concrete samples with 8% graphite content in an environment at 40 ℃ is 1.35 times that at 20 ℃. The heat transfer efficiency of the spiral coil-type energy pile is higher than those of single-U and double-U tube energy piles. The proposed method provides a certain reference for improving the heat transfer efficiency of energy piles and constructing the internal and external heat transfer models in energy piles.

Keywords: energy piles; graphite-modified concrete; thermal conductivity; numerical simulation; thermal resistance

1. Introduction

With the development of sustainable energy worldwide, energy consumption problems can be encountered in various industries. Among these problems, a building's energy consumption accounts for a large proportion of the total energy consumption by the whole society [1].

The energy pile system, which offers additional cooling and warming to buildings based on geothermal resources, has been rapidly developed because of its innate advantages. This system has been extensively used in green energy-saving buildings in many countries [2, 3, 4]. Unlike traditional ground source heat pumps of drilling pipes, energy piles bury heat exchange pipes directly into concrete piles. They not only save land occupation and initial investment cost of buried pipes but also increase the heat exchange area between a heat exchanger and soil mass, which is conducive to an increase in heat transfer efficiency. With research progress, technologies that increase the heat transfer efficiency of energy piles have been developed through the optimization of pipe burying. A systemic study has been performed to further improve the heat exchange efficiency of energy piles. The coupling effect of hydro-transport-thermal energy piles and surrounding soil mass has been investigated to simulate the actual heat transfer of energy piles and provide a basis for their practical applications [5, 6]. Systematic studies on heat transfer theory [7, 8] and thermal response test [9, 10] have been conducted to optimize these systems.

According to the latest international research, the heat transfer enhancement of concrete in energy piles is challenging, and it involves multiple basic subjects. Pile material is essential for the heat transfer efficiency of energy piles. If a highly heat-conductive admixture can be added to the concrete material of energy piles while guaranteeing its mechanical properties, then it may be a new method to improve the heat transfer efficiency of energy piles.

This study investigated the feasibility of graphite-modified

---

[*] Corresponding author
Email address: `lanqiao_ustb@126.com` (Lan Qiao)

concrete materials on the basis of the aforementioned analysis to enhance the heat transfer properties of energy piles. This study also considered the effects of ambient temperature and different pipe-burying modes on the heat transfer efficiency of graphite-modified concrete energy piles.

2. State of the art

Studies on the heat transfer characteristics of energy piles have been performed. Morino et al. [11] proposed the concept of burying a pipe heat exchanger in the pile foundation for the first time in 1994 and numerically analyzed the heat transfer characteristics of double U-tube pipe heat exchangers by using the finite difference method. However, Morino did not implement experimental and quantitative studies on the heat transfer performance of energy piles. In 1996, Pahud et al. [12] developed simulation software for the numerical analysis of a U-tube pipe heat exchanger and applied it to the practical engineering of Munich Airport. Nevertheless, the software was inapplicable for simulating the heat transfer of energy piles under other burying modes. In 2007, Hamada et al. [13] from Hokkaido University performed an experiment on heat transfer between a friction-type energy pile and the surrounding soil mass and implemented a long-term monitoring on the cooling/heating loads of buildings. They provided data supporting the heat exchange efficiency of energy piles. In 2013, through numerical simulations, Zarrella et al. [14] compared the heat-transfer efficiency of Helical pipe and triple U-tube energy piles, results from which indicate that the former is more efficient. In 2014, Dupray et al. [15] numerically analyzed the running effect of a seasonal storage system of energy piles from the perspectives of thermodynamics and mechanics. They found that the heat accumulation efficiency of soil mass surrounding the energy pile remains basically the same as the increase in the annual average temperature. Go et al. [16] proposed the multiple regression equation of effective borehole thermal resistance for energy piles with spiral coils. They compared the adjustment coefficient of the regression equation with the thermal response experimental results of energy piles and analyzed the heat transfer performance of energy piles by performing a thermal response test. However, the specific expression of the thermal resistance of energy piles with spiral pipe burying has yet to be provided. In 2015, Park et al. [17] studied the heat transfer performance of two large spiral coil-type energy piles through multiple heat exchange in situ tests and found a positive relationship between the length of a heat exchanger and the heat transfer efficiency. The heat exchange rate is not directly proportional to the length of the buried pipe, and a small coil pitch may cause thermal interference in the coil circuit. In 2017, Carotenuto et al. [18] proposed a high-efficiency 3D numerical model to simulate heat transfer between energy piles and surrounding soil masses, thereby reducing the calculation time of a fully 3D model. However, Carotenuto's method currently lacked specific test verification.

In China, Li et al. [19] from Tongji University carried out experimental and numerical simulation comparisons among energy piles with different pipe-burying modes and concluded that double U- and W-shaped burying modes achieve high heat transfer efficiency. However, Li et al. [19] did not compare them with a heat exchanger with spiral burying pipes. Zhang et al. [20] from the Shandong University of Architecture and Engineering proposed a heat transfer model applicable to spiral burying pipe and compared the laboratory test results with the calculated results of analytical solutions. They confirmed that the proposed model can reflect the actual heat transfer of energy piles well, but it is applicable for investigating the external heat transfer characteristics of energy piles, and the heat transfer in piles is disregarded. Li et al. [21] from Tianjin University discovered the influences of backfill materials in pile and drilling pipes and found that the former is superior to the latter in terms of heat transfer and stability. Zhao et al. [22] constructed a steady-state heat transfer model for energy piles with U-tube pipes by using the energy equilibrium method and simulated and calculated the influences of soil thermal conductivity on the heat transfer characteristics of energy piles. Chen et al. [23] established a theoretical heat transfer model of energy piles with double U-tube pipes in parallel connection. They compared their theoretical model results with numerical simulation results and verified the reliability of the proposed model. Li et al. [24] numerically simulated the temperature distribution of energy piles through finite element numerical analysis and confirmed the accuracy of simulation results by in situ test data. Zhao et al. [25] examined the heat transfer characteristics of energy piles by in situ tests and explored the applicability of different heat transfer models to energy piles with spiral pipes. Liu et al. [26] tested the variation law of temperature in energy piles with preburied single-steel U-tube pipes and the surrounding soil mass under different temperature cyclic loads by using a model. They concluded that the heat transfer efficiency of energy piles with preburied steel pipes is lower than that of energy piles with binding pipes.

The heat transfer between energy piles and the surrounding soil masses has been investigated. However, most of these studies have optimized the pipe-burying modes of concrete piles, analyzed heat transfer theory, and examined the optimal matching parameters of a heat pump device to increase heat transfer efficiency. Only a few studies have discussed the influences of pile materials. Graphite with high thermal conductivity and chemical stability is added to pile concrete to address this problem. The thermal conductivity of graphite-modified concrete piles is analyzed on the basis of the heat transfer mechanism of thermal resistance method and finite element numerical simulation to provide a new method to increase the heat transfer efficiency of energy piles.

The remainder of this study is organized as follows. Section 3 describes the heat transfer mechanism in energy piles, constructs the thermal resistance of energy piles with different pipe-burying modes, and carries out a laboratory test on the thermal conductivity of pile materials under different graphite contents and temperatures. Section 4 analyzes the thermal conductivity of the graphite-modified concrete material by considering the laboratory physical performance test results. The heat transfer performance in and outside graphite-modified concrete energy piles is investigated through thermal resistance method and numerical simulation. Section 5 summarizes the conclusions.

3. Methodology

3.1. Heat transfer mechanism of energy piles

The energy pile exchanges heat with the surrounding soil mass based on the stable heat storage performance of soil mass by using the earth as a heat source or a heat sink and the pile body as a heat exchanger. Such heat exchange is the heat transfer between the fluid in the buried pipes and the concrete pile and between the pile body and the surrounding soil but not the heat convection between two fluids applied to traditional heat exchangers.

Linear, cylindrical surface and coil heat source models are major heat transfer models between energy piles and surrounding soil masses worldwide. All of these models can be used to calculate the problems of the surrounding soil mass of the energy piles by using their surface temperature as the initial temperature. The relationship between the fluid temperature T_f and the surface temperature T_{bw} of the energy piles can be expressed as follows:

$$T_f = T_{\mathrm{bw}} + \frac{q}{H} R_b \tag{1}$$

where, q is the heat exchange capacity, H is the heat-exchange time.

Therefore, reducing the thermal resistance of the energy pile by changing the thermal conductivity of materials and reducing the heat loss of concrete piles are new methods to increase the heat transfer efficiency between the energy pile and the surrounding soil.

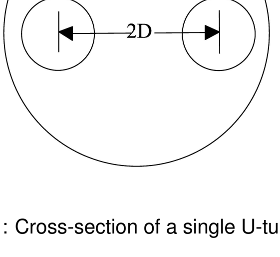


Figure 1: Cross-section of a single U-tube pipe

Inside the energy piles, heat flux must overcome three heat resistance of the fluid in the tubes transmitting to the outer wall of the pile without considering contact thermal resistance. These resistances are the convective heat transfer resistance of fluid in pipes (R_f), wall resistance (R_{pe}), and thermal resistance from the outer pipe wall to the outer wall of concrete piles (R_{be}). In existing energy piles, single U-tube, double U-tube, and spiral coil-type pipes are common pipe-burying modes. The thermal resistance of U-tube burying pipes has been investigated, but few studies have discussed the heat resistance of spiral coil-type pipes. The thermal resistances of energy piles with U-tube and spiral coil-type pipes are calculated because the former can be simplified as the series connection of multiple vertical heat exchange pipes and the latter has relatively complicated shapes. r_{pe} is set as the equivalent radius of the U-tube pipe, and its value is generally $r_{pe} = r_p \sqrt{n}$, where n is the number of vertical heat exchange pipes. r_i, r_p and r_b are the inner and outer radii of the pipe and the radius of the energy piles, respectively. k_p, k_b and k_s are the thermal conductivities of the pipe wall, the concrete pile, and the surrounding soil mass, respectively. 2D is the central distance of the buried pipe (Fig. 1 and Fig. 2).

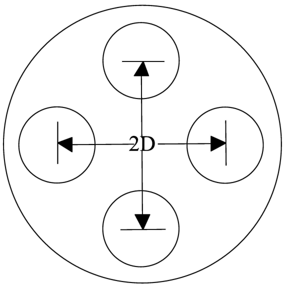


Figure 2: Cross-section of a double U-tube pipe

1) The thermal resistance of energy pile with single U-tube pipe (R_{eU1}) is written as follows:

$$\begin{aligned} R_{eU1} &= R_{f1} + R_{pe1} + R_{be1} \\ &= \tfrac{1}{4\pi r_i h} + \tfrac{1}{2\pi k_p} \ln\left(\tfrac{r_p \sqrt{2}}{r_p \sqrt{2} - (r_p - r_i)}\right) \\ &+ \tfrac{2}{4\pi k_b}\left[\ln\left(\tfrac{r_b}{r_p}\right) + \ln\left(\tfrac{r_b}{2D}\right) + \tfrac{k_b - k_s}{k_b + k_s} \ln\left(\tfrac{r_b^4}{r_b^4 - D^4}\right)\right] \end{aligned} \tag{2}$$

2) The thermal resistance of energy pile with double U-tube pipes (R_{eU2}) is expressed as follows:

$$\begin{aligned} R_{\mathrm{eU2}} &= D_{f2} + R_{pe2} + R_{be2} \\ &= \tfrac{1}{8\pi r_i h} + \tfrac{1}{2\pi k_p} \ln\left(\tfrac{r_p \sqrt{4}}{r_p \sqrt{4} - (r_p - r_i)}\right) + R_{be2} \end{aligned} \tag{3}$$

Where

$$R_{be2} = (R_{11} + R_{13} + 2R_{12})/4 \tag{4}$$

$$R_{11} = \frac{1}{2\pi k_b}\left[\ln\left(\frac{r_b}{r_p}\right) - \frac{k_b - k_s}{k_b + k_s} \ln\left(\frac{r_b^2 - D^2}{r_b^2}\right)\right] \tag{5}$$

$$R_{12} = \frac{1}{2\pi k_b}\left[\ln\left(\frac{r_b}{\sqrt{2}D}\right) - \frac{k_b - k_s}{2(k_b + k_s)} \ln\left(\frac{r_b^4 + D^4}{r_b^4}\right)\right] \tag{6}$$

$$R_{13} = \frac{1}{2\pi k_b}\left[\ln\left(\frac{r_b}{\sqrt{2}D}\right) - \frac{k_b - k_s}{k_b + k_s} \ln\left(\frac{r_b^2 + D^2}{r_b^2}\right)\right] \tag{7}$$

3) Thermal resistance of energy piles with spiral coil-type pipes (R_{eS})

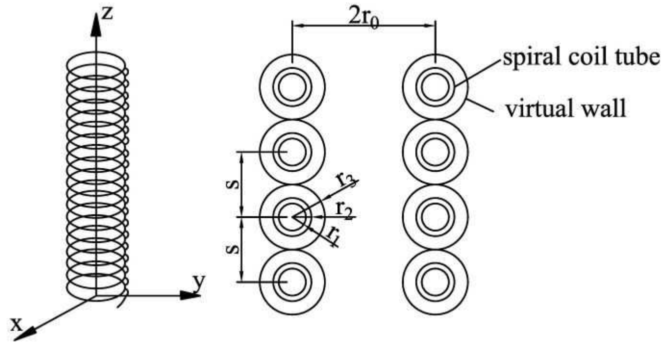


Figure 3: Profile map of spiral coil-type pipe

R_{be} varies in different cross sections because of the complicated geometrical shape of spiral coil-type pipes. Therefore, a virtual spiral pipe and a virtual U-tube pipe are assumed to surround the spiral pipe (Fig. 3). The radii of the virtual spiral pipe and the outer radius of the virtual U-tube pipe are the same as the thread pitch of the actual spiral pipe. If the thermal resistance between the virtual spiral pipe wall and the virtual U-tube pipe wall is neglected, then R_{be} can be expressed as $R_{be} = R_{beS} + R_{beU}$, where where R_{beS} and R_{beU} are the thermal resistance from the outer wall of the actual spiral pipe to the virtual spiral pipe and the thermal resistance from the virtual U-tube pipe wall to the outer wall of concrete piles, respectively.

Our analysis suggests that the thermal resistance of the energy piles with the spiral coil-type pipe (R_{eS}) can be calculated as follows:

$$R_{es} = R_f + R_{pe} + R_{be} = R_f + R_{pe} + R_{beS} + R_{beU} \tag{8}$$

$$R_f + R_{pe} = \frac{1}{\pi d_i h} + \frac{1}{2\pi k_p} \ln\left[\frac{r_p}{r_i}\right] \tag{9}$$

$$R_{beS} = \frac{1}{2\pi k_b} \ln\left[\frac{s/2}{r_p}\right] \tag{10}$$

$$R_{beU} = \frac{1}{2\pi k_b}\left[\ln\left(\frac{r_b}{s/2}\right) - \frac{k_b - k_s}{k_b + k_s}\ln\left(\frac{r_b^2 - D^2}{r_b^2}\right)\right] \tag{11}$$

where r_i, r_p, s and r_b are the inner and outer radii of the actual spiral coil-type pipe, thread pitch, and radius of energy piles, respectively. k_p and k_b are the thermal conductivities of the actual spiral coil-type pipe wall and the concrete pile, respectively.

3.2. Experiment on the heat transfer performance of the graphite-modified concrete material

Graphite material is divided into natural flaky and late processing powder graphite. This material is discovered from a laboratory test in which the specific surface area of powder graphite particles is high due to the small grain size. It has strong water absorption in the stirring of concrete, thereby influencing the workability of concrete materials. Hence, natural flake graphite is used as the additive of the concrete material in the following tests.

Four groups are set in the proposed experiment. Natural flake graphite is used to replace fine aggregate sands in concrete. The volume ratios of graphite in four groups are 0%, 2%, 5%, and 8%. Different doses of high-performance polycarboxylic acid powder-like water-reducing agent are added to all of the groups to assure the workability of graphite and concrete mixture because of the strong water absorption of the graphite surface. In the experiment, the water reducing agent and water are fully mixed into the solution. Later, the graphite-modified concrete samples are prepared in accordance with the regulations in GB/T 17671-1999 [27]. The collapsibility of the graphite-modified concrete mortar is tested in accordance with the regulations in GB/T 2419-2005[28]. Table 1 shows the test results of the mixture ratio and the collapsibility. All of the prepared samples are cured in a box at approximately 20 ℃ and humidity higher than 90%.

Figure 4: DRE-III multi-functional fast heat conductivity tester

A DRE-III multi-functional fast heat conductivity tester was employed to test the thermal conductivity of the graphite-modified concrete material. The samples were prepared in accordance with the mixting ratios in Table 1 (i.e., four samples for each group). Each sample size was $\phi 50\,\mathrm{mm}\times 30\,\mathrm{mm}$, the tester and the testing process are shown in Fig. 4. The thermal conductivities of the graphite-modified concrete material with different graphite contents and at various temperatures were tested. The samples that were heated in a constant-temperature box were used to examine the thermal conductivity at different environmental temperatures.

4. Result Analysis and Discussion

4.1. Analysis of test results on heat transfer performance of graphite-modified concrete materials

Eight groups of concrete samples with different graphite contents were prepared (Table 1). The thermal conductivities of each group were tested at 10°C, 20°C, 30°C, and 40°C. The means of the test results are shown in Table 2.

Table 1: Test results of graphite-modified concrete mortar ratio and fluidity

Volume ratio of graphite,	Single material consumption, kg/m^3						Collapsibility, mm
%	Graphite	Water-reducing agent	Cement	Water	Sands	Gravels	
0	0	0	524	215	548	1113	86
2	45	1.5	524	215	503	1113	79
5	112.5	3.75	524	215	435.5	1113	68
8	180	9	524	215	368	1113	55

Table 2: Test results of the thermal conductivity of graphite-modified concrete samples

Test No.	Graphite content, %	Thermal conductivity, W(m°C)$^{-1}$			
		10°C	20°C	30°C	40°C
A1	0	0.95	1.04	1.25	1.41
A2	2	1.01	1.15	1.38	1.55
A3	5	1.12	1.24	1.46	1.63
A4	8	1.25	1.33	1.57	1.79

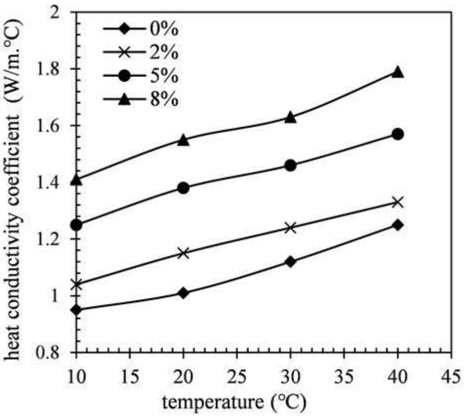


Figure 5: Relation curve between the thermal conductivity of the graphite-modified concrete samples and temperature at different graphite contents

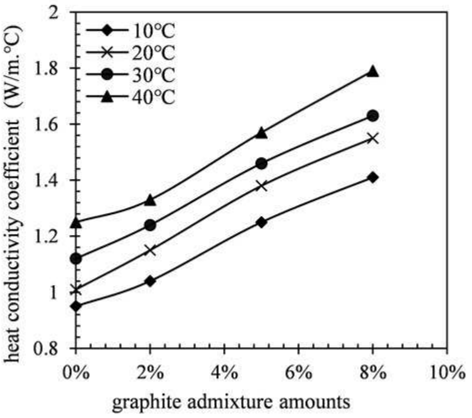


Figure 6: Relation curve between the thermal conductivity of the graphite-modified concrete samples and the graphite content at different environmental temperatures

The relation curves of the thermal conductivities with temperature and graphite content were drawn on the basis of the test results (Fig. 5 and Fig. 6).

Fig. 5 shows the relation curve between the thermal conductivity of the graphite-modified concrete material and temperature. Given the same graphite content, thermal conductivity is positively related to environmental temperature. The graphite-modified concrete material shows high thermal conductivity at a high temperature, indicating that the working efficiency of the energy piles made of the graphite-modified concrete material is higher in summer than in winter.

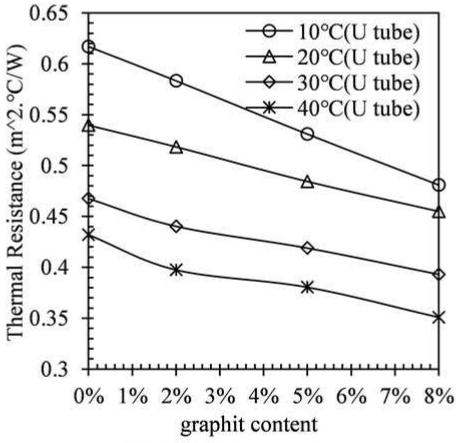
Fig. 6 shows the relationship between the thermal conductivity of the graphite-modified concrete samples and the graphite content. Given the same temperature, the thermal conductivity increases slightly when the graphite content increases from 0% to 2%. After the graphite content exceeds 5%, the thermal conductivity increases significantly as a response to the continuous thermal conduction channel of graphite in the samples. The results indicate that the addition of graphite to concrete materials can enhance heat transfer.

4.2. Analysis of heat transfer performance in graphite-modified concrete energy piles

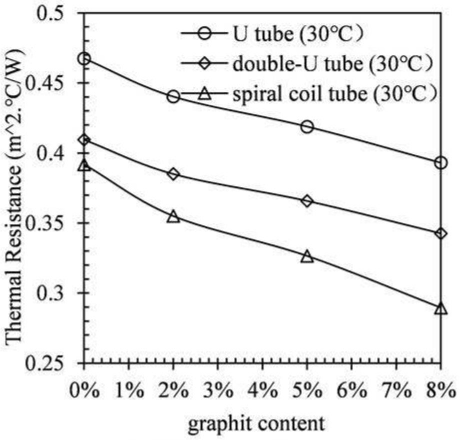
In the follow-up model analysis, the concrete materials with 0, 2, 5, and 8% of the graphite contents were compared. To quantize the heat transfer enhancement of the graphite-modified concrete energy piles, we set the following basic parameters in this model: inner radius of pipe $r_i = 0.01$ m, outer radius of pipe $r_p = 0.012$ m , and diameter of energy pile $r_b = 0.5$ m, and convective heat transfer coefficient of fluid in pipe $h = 100\ \mathrm{W/m^2{}^\circ C}$, and thermal conductivity of pipe wall $k_p = 0.4\ \mathrm{W/m^\circ C}$.

The different thermal conductivities of the graphite-modified concrete materials are obtained from Table 2. The variation curves of the thermal resistance of the energy piles with temperature and graphite contents are shown in Fig. 7a. The variation curves of the thermal resistance of the energy piles with different graphite contents and pipe-burying modes are shown in Fig. 7b.

Fig. 7a shows that the total thermal resistance of the energy pile system decreases continuously as the graphite content continuously increases at the same environmental temperature. In Fig. 7b, given the same graphite content, the highest total thermal resistance is observed in the U-tube energy pile system followed by the double U-tube energy pile system and the spiral coil-type energy pile system. In other words, the spiral coil-type pipe achieves the best heat transfer effect, whereas the U-tube pipe shows the poorest heat transfer effect.



(a) different temperatures



(b) different graphite contents

Figure 7: Variation curves of the thermal resistance of energy piles under different (a) temperatures and (b) graphite contents

4.3. Analysis of the heat transfer performance outside the graphite-modified concrete energy pile

The transient heat transfer of the energy pile system with the spiral coil-type pipes with different graphite contents in summer was analyzed through numerical simulation to verify the heat transfer enhancement between the graphite-modified concrete material and the soil mass. Fig. 8 shows the analysis results.

The numerical analysis reveals that the heat transfer effect of the energy pile system is continuously enhanced with the constant increase in the graphite content. Considering that the thermal conductivity of concrete with 8% graphite is higher than that of concrete with 2% graphite, the heat transfer efficiency of the former system is significantly higher than that of the latter in numerical analysis. Moreover, the numerical analysis indicates that concrete materials with a high graphite content are conducive to the full-process heat transfer of the exchange fluid. In the heat exchange process, the temperature gradient difference between the exchange fluid and the soil mass affects the heat transfer efficiency lesser than that of the pure concrete.

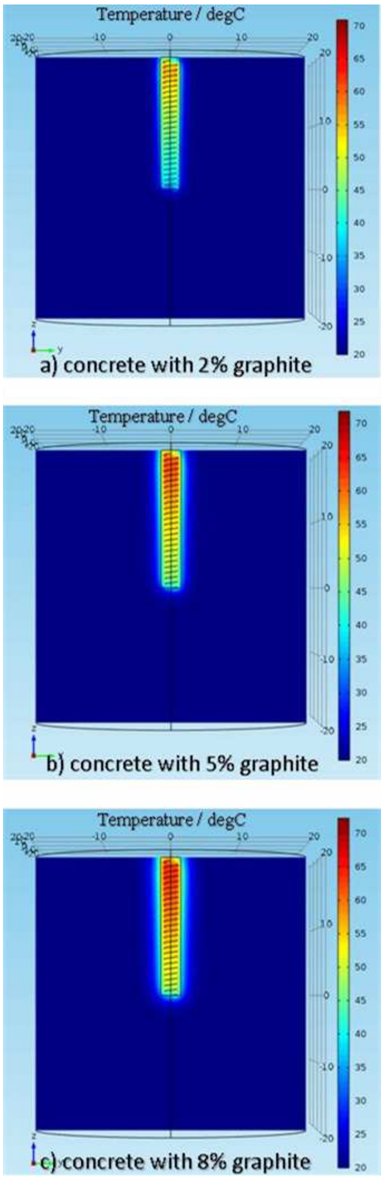


Figure 8: Relation curve between the thermal conductivity of the graphite-modified concrete samples and the graphite content at different environmental temperatures

5. Conclusions

Thermal conduction performances in and outside the graphite-modified concrete energy piles were analyzed by combining numerical simulation and experimental studies based on the 2D plane thermal resistance model with different pipe-burying modes to further explore the optimization method of the heat transfer efficiency of the energy piles and disclose the influences of the thermal conductivity of the pile material on the heat transfer enhancement of the energy pile. The following conclusions could be drawn:

(1) At the same environmental temperature, the thermal conductivity of graphite-modified concrete materials is significantly increased, and the heat transfer efficiency is greatly enhanced after the graphite content exceeds 5%. The in-

crease in the graphite content is beneficial to the heat transfer of energy piles.

(2) The working efficiency of the graphite-modified concrete energy pile is slightly higher in summer than in winter. The high temperature in the pipe is conducive to the improvement of the heat transfer performance of energy piles.

(3) Unlike single and double U-tube pipes, a spiral pipe helps enhance the heat transfer efficiency of energy piles. The heat transfer efficiency between the energy pile and the surrounding soil mass is the highest.

Thus, the influences of graphite powder on the heat transfer performance of the concrete energy piles are investigated by combining laboratory tests and theoretical studies. The constructed internal and external heat transfer models of energy piles with different pipe-burying modes can intuitively exhibit the influences of the temperature and graphite contents on the heat transfer performance of the energy piles. These findings can provide references for exploring the heat transfer enhancement of energy piles. However, the transfer performance of energy piles is influenced by many factors, and the proposed method is limited to considering the effect of the material of the pile body. Other influencing factors should be considered in future studies.

Acknowledgments

This study was supported by Joint Research Program between University of Science and Technology Beijing and National Taipei University of Technology (TW201703) and the Opening Funds of State Key Laboratory of Building Safety and Built Environment (BSBE2015-06).

References

[1] Z. Zhou, Solar-technologies in german architecture, World Architecture 1 (12) (2002) 54–55.

[2] N. Yavari, A. M. Tang, J.-M. Pereira, G. Hassen, Mechanical behaviour of a small-scale energy pile in saturated clay, Géotechnique 66 (11) (2016) 878–887.

[3] C. K. Lee, H. N. Lam, A simplified model of energy pile for ground-source heat pump systems, Energy 55 (1) (2013) 838–845.

[4] A. A. Mehrizi, S. Porkhial, B. Bezyan, H. Lotfizadeh, Energy pile foundation simulation for different configurations of ground source heat exchanger, International Communications in Heat & Mass Transfer 70 (2016) 105–114.

[5] D. Rammal, H. Mroueh, S. Burlon, Impact of thermal solicitations on the design of energy piles, Renewable and Sustainable Energy Reviews 92 (2018) 111–120.

[6] G. H. Go, S. Yoon, D. W. Park, S. R. Lee, Thermal behavior of energy pile considering ground thermal conductivity and thermal interference between piles, Journal of the Korean Society of Civil Engineers 33 (6) (2013) 19–28.

[7] R. Caulk, E. Ghazanfari, J. S. McCartney, Parameterization of a calibrated geothermal energy pile model, Geomechanics for Energy & the Environment 5 (2016) 1–15.

[8] P. Cui, X. Li, Y. Man, Z. Fang, Heat transfer analysis of pile geothermal heat exchangers with spiral coils, Applied Energy 88 (11) (2011) 4113–4119.

[9] H. Park, S. R. Lee, S. Yoon, J. C. Choi, Evaluation of thermal response and performance of phc energy pile: Field experiments and numerical simulation, Applied Energy 103 (1) (2013) 12–24.

[10] F. A, M. R, T. M, H. P. A, Numerical modeling of thermal response tests in energy piles, Journal of Natural Medicines 68 (3) (2014) 505–512.

[11] K. Morino, T. Oka, Study on heat exchanged in soil by circulating water in a steel pile, Energy & Buildings 21 (1) (1994) 65–78.

[12] D. Pahud, A. Fromentin, M. Hubbuch, Heat exchanger pile system for heating and cooling at zu rich airport, IEA Heat Pump 17 (1) (1999) 15–16.

[13] Y. Hamada, H. Saitoh, M. Nakamura, H. Kubota, K. Ochifuji, Field performance of an energy pile system for space heating, Energy & Buildings 39 (5) (2007) 517–524.

[14] A. Zarrella, M. D. Carli, A. Galgaro, Thermal performance of two types of energy foundation pile: Helical pipe and triple u-tube, Applied Thermal Engineering 61 (2) (2013) 301–310.

[15] F. Dupray, L. Laloui, A. Kazangba, Numerical analysis of seasonal heat storage in an energy pile foundation, Computers & Geotechnics 55 (1) (2014) 67–77.

[16] G. H. Go, S. R. Lee, S. Yoon, H. B. Kang, Design of spiral coil phc energy pile considering effective borehole thermal resistance and groundwater advection effects, Applied Energy 125 (2) (2014) 165–178.

[17] S. Park, D. Lee, H. J. Choi, K. Jung, H. Choi, Relative constructability and thermal performance of cast-in-place concrete energy pile: Coil-type ghex (ground heat exchanger), Energy 81 (2015) 56–66.

[18] A. Carotenuto, P. Marotta, N. Massarotti, A. Mauro, G. Normino, Energy piles for ground source heat pump applications: comparison of heat transfer performance for different design and operating parameters, Applied Thermal Engineering 124 (2017) 1492–1504.

[19] K. Li, X. Zhang, J. Gao, J. Liu, Research of heat transfer performance of pile-foundation ground-coupled heat pump and soil temperature rise, 2008, pp. 54–59.

[20] W. Zhang, J. Liu, T. Huang, D. Wu, B. H. Fang, Heat transfer analysis of the ground heat exchanger inside foundation piles, Refrigeration & Air Conditioning: Sichuan 23 (4) (2009) 105–108.

[21] X. Li, Z. Chen, J. Zhao, L. Li, Y. Ma, Experiment and numerical simulation on u-vertical ground coupled heat exchanger with sandstone and cement backfills, Journal of Tianjin University 38 (8) (2005) 679–683.

[22] J. Zhao, T. Wu, Q. Zhu, Y. Gong, Thermal simulation on the steady heat transfer of the u-tube energy piles heat exchanger, Acta Energiae Solaris Sinica 26 (1) (2005) 59–62.

[23] Z. Chen, S. Zhao, Z. Zhang, Heat transfer analysis of energy piles with parallel connected u-tubes, Engineering Mechanics 30 (5) (2013) 238–243.

[24] X. Li, H. Guo, X. Cheng, Experimental and numerical study on temperature distribution in energy piles, China Civil Engineering Journal 49 (4) (2016) 102–110.

[25] H. Zhao, S. Gui, R. Tang, J. Du, Applicability of heat transfer model of energy pile with buried spiral pipe and its experimental verification, Journal of Yangtze River Scientific Research Institute 34 (4) (2017) 111–116.

[26] H. Liu, D. Wu, G. Kong, H. Wu, D. Wu, Thermal response of energy piles with embedded tube and tied tube, Rock and Soil Mechanics 38 (2) (2017) 333–340.

[27] C. B. M. Academy, Gb/t 17671-1999 method of testing cement–determination of strength (1999).

[28] C. B. M. Academy, Gb/t 2419-2005 test method for the fluidity of cement mortar (2005).