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A study on heat transfer characteristics and pile group influence of enhanced heat transfer energy piles

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ABSTRACT

Energy pile is a new type of building component which combines ground source heat pump technology with pile foundation. It can be used to heat or cool the buildings by utilizing the stable heat storage characteristics of soil. After 30 years of development, the methods of optimizing buried pipe and other ways to improve the heat transfer efficiency have met bottleneck. The methods of improving the heat transfer efficiency of energy pile need to find a new way. In this study, the graphite powder with high heat transfer characteristics was added into the concrete to prepare enhanced heat transfer concrete. After testing, the heat transfer coefficient of the concrete can be enhanced from 1.71 W/(m·K) to 2.84 W/(m·K). On this basis, the heat transfer models of single pile and pile group in summer working condition are established by using COMSOL Multiphysics software. The simulation results show that the heat transfer capacity of enhanced heat transfer energy pile is obviously higher than that of common energy pile, and the heat transfer capacity is increased by 6.5%. At the same time, the influence scope of soil has increased. Under the condition of pile group condition, the heat transfer enhanced effect of energy piles are affected by the location and the space, the corner pile is the most effective, the edge pile is the second, the center pile is the least; and the larger the space between the pile, the better effect.

1. Introduction

Nowadays, energy development and environmental protection issues are increasingly becoming an important factor for human development. Green, clean and environmentally friendly energy has become the preferential research in many countries. Energy pile system is a new type of building component which combines ground source heat pump with pile foundation. It not only acts as a bearing component to support the building, but also acts as a part of building air conditioning system to exchange heat with surrounding soil. It is due to the own the advantages of energy saving, energy pile has broad prospects for development and popularization. Morino et al. took the lead in burying tubular heat exchangers in steel pipe piles [1]. Pahud et al. buried U-shaped tubular heat exchangers in concrete piles and applied them in more than 500 piles of Munich Airport Building [2]. Laloui et al. designed the ground energy conversion pile, and showed the construction technology, results of field test and numerical model of the pile [3]. Hamada et al. [4] carried out the ground energy conversion test of friction piles in Japan, and recorded the test data and the thermal load of buildings [4]. So, the energy pile was developed gradually.

On the basis of previous studies, many scholars have paid attention on improving the heat transfer capability. Some ideas of optimizing the form of buried pipe and the factors affecting the heat transfer capacity of energy pile have been proposed. Li et al. [5] applied the U-shaped buried pipe to the borehole and pile. The experimental results showed that the heat transfer of the double U− pipes is much larger than that of the single U− pipes [5]. Gao et al. [6] studied Other geometrical arrangements of U shapes (W-shaped and triple U-shaped) and concluded that W-shaped pipes were more efficient than single, double, and triple U-shaped pipes [6,7]. Zarrella et al. [8] analyzed the heat transfer performance of two kinds of buried tube (triple U-tube and spiral pipe) energy pile by numerical simulation and in-situ experiment. The heat exchange of piral pipes was higher than that of triple U-pipes about 23% [8]. Batini et al. [9] studied the effects of different structure of buried tube heat exchanger, fluid velocity and liquid mixture composition on the heat transfer performance of energy pile. The results show that the structure of buried pipe has a very strong influence on the heat transfer performance of energy pile [9]. Cecinato et al. [10] performed parameter analysis by numerical model and found that increasing the amount of buried pipe and the diameter of the pile within a reasonable range is very beneficial to increase the thermal conductivity of the energy pile. At the same time, the length of the pile and the thickness of the protective layer of the concrete also have a significant effect on the heat transfer efficiency [10].

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Meanwhile, some scholars have also carried out research on group pile heat transfer [11–14]. The research shows that, due to the low thermal conductivity of concrete and soil, its process of heat transfer is slow. In the summer, with the continuous operation of the energy pile, the large amount of heat released can not be quickly transmitted through the soil. Therefore, the heat will continuously converge around the buried pipe, and finally a very high temperature region is formed around the buried pipe, which makes the amount of cold that the energy pile can extract continuously decreases. As the range of affected soils continues to increase, the heat-affected areas around adjacent energy piles begin to overlap and interact. The result is that the heat exchange capacity of each single pile in the pile group is much less than that when the single energy pile is working.

At present, the traditional methods such as optimizing buried pipe to improve the heat transfer efficiency have been developed more perfectly, which is difficult to be greatly improved. And there will be the obvious heat accumulation phenomenon due to the lower thermal conductivity of concrete [15–17]. Hence, the main way to improve the heat transfer efficiency and to reduce the heat accumulation is the increase the heat transfer coefficient of the concrete of the energy pile. For this purpose, by adding some extra admixture with higher heat conductivity coefficient into the concrete, the heat transfer performance of the concrete is enhanced while ensuring the stability of the mechanical properties, which will also be a new and effective method. In this study, the graphite powder with high heat transfer characteristics was added into the concrete to make the enhanced heat transfer energy pile. And to analyze the group pile effect, the heat transfer models of group pile are established by using COMSOL Multiphysics software, and the difference of heat transfer effect between enhanced heat transfer energy pile and common energy pile were carried out contrastively.

1.1. Mechanism of heat transfer enhancement

The concrete energy pile system consists of circulating liquid, heat exchange pipes, concrete and soil. The structural diagram is shown in Fig. 1. There is a certain difference between the temperature of the circulating liquid and the temperature of the soil during the heat exchange process in the energy system, and the medium that affects the heat exchange between the circulating liquid and the soil is the pipes and the concrete.

Therefore, to strengthen the heat transfer performance of concrete, and to change temperature relationship from the red line to the green line in Fig. 1 will effectively improve the heat exchange capacity of the entire energy pile system.

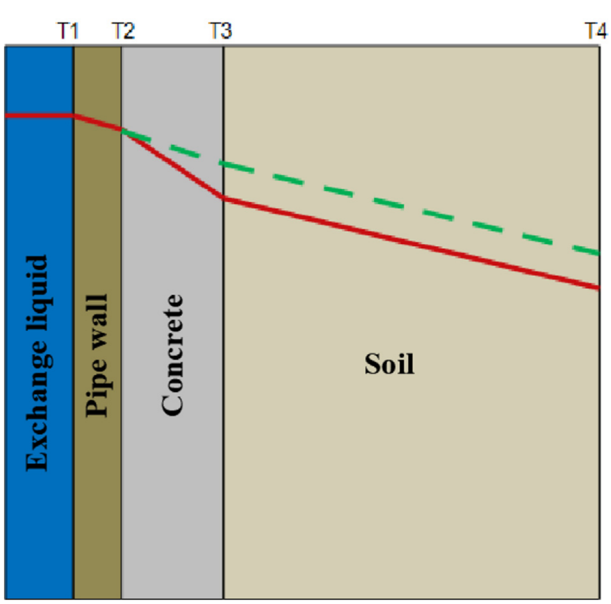


Fig. 1. Schematic diagram of heat transfer enhancement mechanism.

Table 1
The composition of graphite concrete.

	Cement	sand	water	water reducing agent	graphite powder
CG5%	197	799	185	8.56	30
CG10%	197	799	199	8.56	60
CG15%	197	799	212	8.56	90
CG25%	197	799	240	8.56	150

2. Realization of enhanced heat transfer concrete

2.1. Preparation of graphite concrete

Graphite has better heat transfer capacity and thermal conductivity more than some metal materials, such as iron, lead etc. And graphite has good chemical stability at normal temperature and is resistant to acid, alkali and organic solvents. Therefore, the graphite powder with high heat transfer characteristics was selected to add into the concrete to enhance the thermal conductivity.

The enhanced heat transfer concrete is prepared by adding a certain volume of graphite to the mixture of common concrete, and to make sure the slump of the mixture can reach 160–200 mm. The detail stirring process is as follows: firstly, stone, sand, graphite, cement and mineral admixture are put into the mixer, and after dry mixing, water and water reducing agent are added, and finally stirred for 2 min. The matching material ratio is shown in Table 1. The graphite concrete with different graphite contents prepared is shown in Fig. 2.

2.2. The statistics of thermal conductivity

The thermal conductivity was measured by every four samples of the same graphite content at 10 °C, 20 °C, 30 °C and 40 °C environmental temperature (Fig. 3). The average value of the measurement results is shown in Table 2.

According to the testing results of the thermal conductivity of graphite concrete, the thermal conductivity of concrete materials under different graphite contents is fitted, as shown in Fig. 4

The results of thermal conductivity of concrete with different graphite contents show that at the same environmental temperature, with the increase of graphite content, the increase of thermal conductivity is not obvious under the graphite content of 0%–10%. After the graphite content increased to 15%, the thermal conductivity increased significantly. When the graphite content reached 25%, the thermal conductivity increased nearly 2 times compared with pure concrete, which shows that the addition of graphite to concrete can play the important role in heat transfer enhancement.

The fitting formula of the thermal conductivity with different graphite content can be expressed as:

$$\begin{cases} k_{c10^\circ C} = 1.342 - 0.0076C + 0.00148C^2 \\ k_{c20^\circ C} = 1.424 - 0.00534C + 0.00133C^2 \\ k_{c30^\circ C} = 1.594 - 0.0288C + 0.00243C^2 \\ k_{c40^\circ C} = 1.709 - 0.0288C + 0.00295C^2 \end{cases} \quad (1)$$

By replacing the pile material from common concrete to graphite concrete with 25% volume ratio graphite, the thermal conductivity of the energy pile in the summer condition has reached 2.4 W/(m·K) (at 30 °C), The thermal conductivity is significantly higher than that of common concrete.

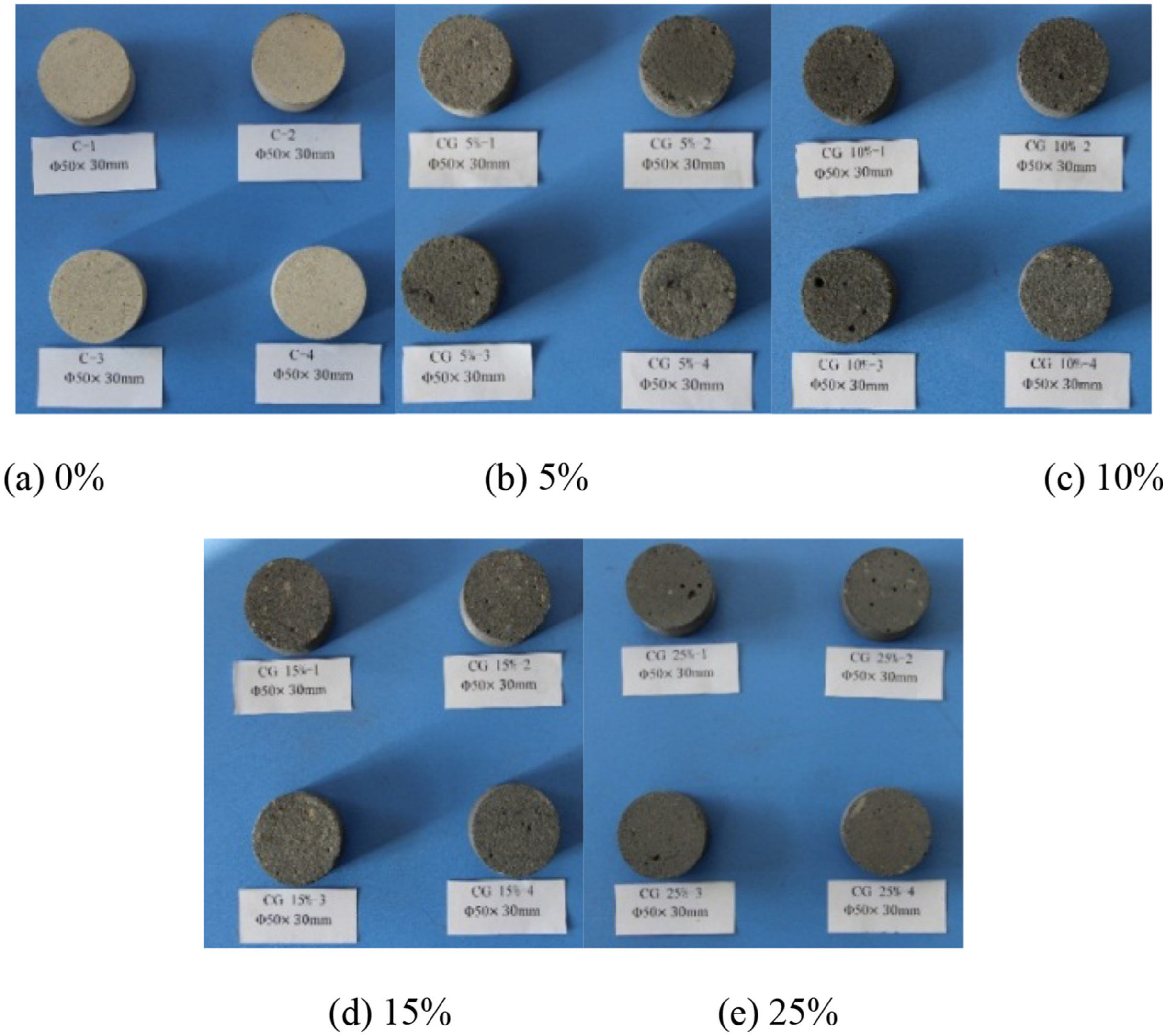


Fig. 2. Concrete specimens with different graphite content.

3. Analysis of heat transfer law of single energy pile

3.1. Establishment of heat transfer model

The simulation of heat transfer is carried out by software COMSOL Multiphysics. The model is composed of pile body, soil and buried pipes. The diameter of pile body is 0.8 m, and the height is 15 m. Considering the need to simulate the long-term operation of the energy pile and eliminate the influence of boundary conditions, the size of the soil should be large enough, the 3D dimension is $20 \times 20 \times 21$ m. The buried pipe has a spiral shape with the 0.3 m radius, 0.3 m space, 0.02 m pipe inner diameter, 0.0025 m pipe wall thickness. The inlet is placed at the top of the pile. After the water enters from the entrance, it firstly reaches the bottom along the spiral tube, and then rises from the straight tube to the top of the pile (see Fig. 5).

The type of soil is silty clay. At the same time, the parameters of enhanced heat transfer concrete with 25% graphite and pure concrete are used for comparative analysis. And the thermal property parameters of the materials are considered as the constant value with changes of temperature in the simulation, and the parameters are shown in Table 3.

The long running condition of the energy pile in the summer would be analyzed, the running time was set as 60 days. The circulating liquid is water, the circulating flow rate is 0.8 m/s, and the inlet temperature is kept at 32 °C. The initial temperature of the soil is 17 °C, and with considering the stable boundary, to keep the temperature of outer boundary of soil at 17 °C invariably during whole simulation process. The heat transfer law of the single energy pile when the pile body material is common concrete and enhanced heat transfer concrete is analyzed and compared.

3.2. Heat exchange capacity analysis

The heat exchange capacity of common energy piles is shown in Fig. 6. It can be observed that the heat exchange capacity of the energy pile on the first day is 172.64 W/m, and then decreases rapidly. On the seventh day it was reduced to 94.76 W/m. Although the rate of decrease in heat exchange is significantly slowed with time, but it is still decreasing, and the heat exchange capacity by day 60 has dropped to 60.57 W/m. This is because the initial soil temperature is very low, and the temperature difference between the soil and the buried pipe is large, so the heat transfer rate is fast, and the heat exchange capacity of the energy pile is high. However, as the temperature of the pile and the soil around the pile rising, the heat exchange capacity of the energy pile decreases rapidly. When the whole system forms a relatively stable temperature gradient, the change rate of heat exchange of energy pile has also slowed down.

The heat transfer curve of enhanced heat transfer energy pile

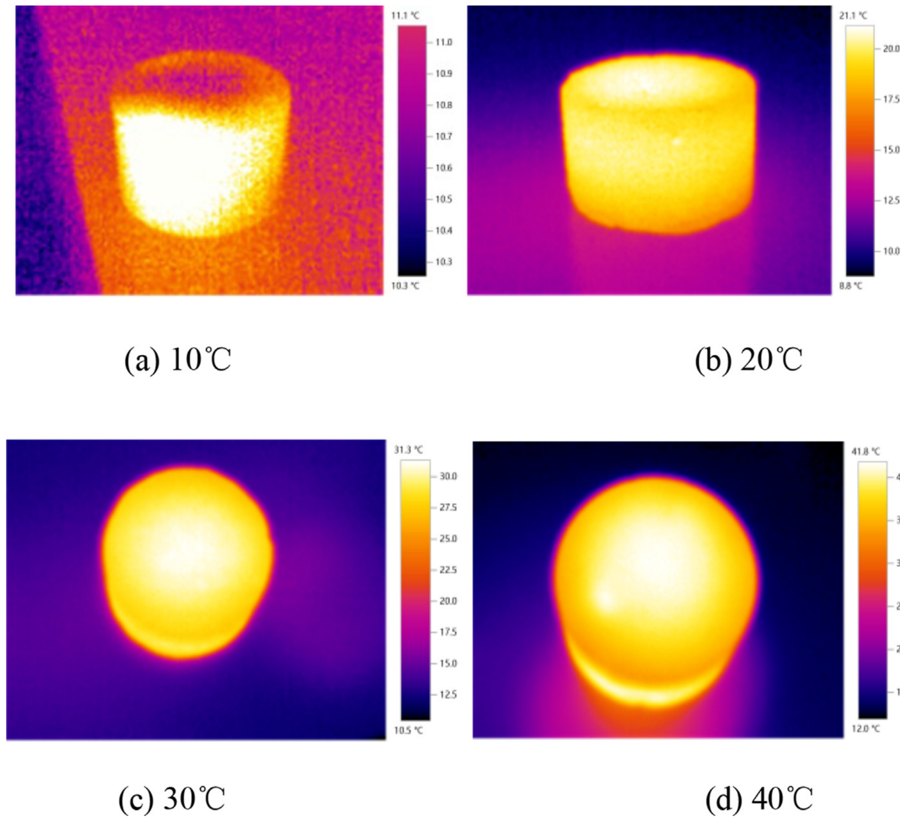


Fig. 3. Infrared pictures of graphite concrete under different environment temperature.

Table 2
Heat conductivity coefficient testing results (W (m·°C)$^{-1}$).

	0%	5%	10%	15%	25%
10 °C	1.38	1.30	1.33	1.67	2.05
20 °C	1.43	1.43	1.48	1.67	2.12
30 °C	1.60	1.51	1.52	1.74	2.39
40 °C	1.71	1.62	1.76	1.91	2.84

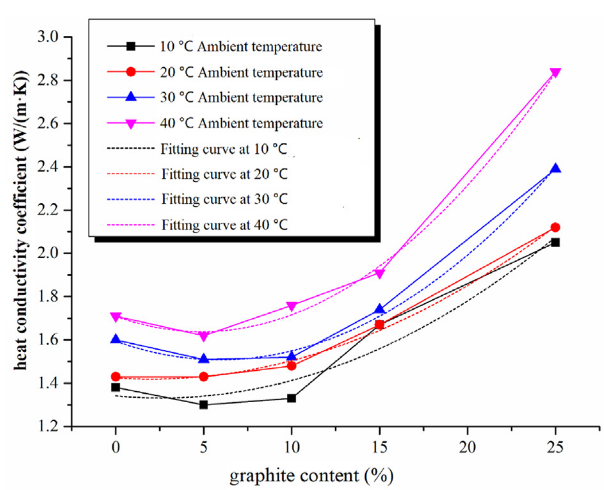


Fig. 4. Heat conductivity coefficients of concrete with different graphite contents.

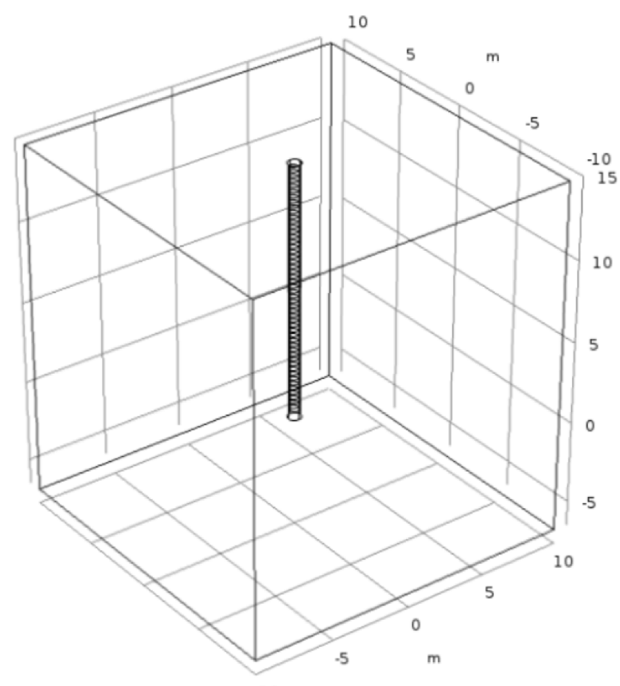


Fig. 5. Heat transfer model of energy pile.

(Fig. 6) has the similar rule with common energy pile, but the heat exchange capacity of enhanced heat transfer energy piles is obviously improved. The heat exchange capacity of enhanced heat transfer energy pile on the first day is 188.07 W/m, which is 5.42 W/m higher than that of common energy pile. When it reaches 60 days, the heat exchange capacity is 63.90 W/m, which is 3.33 W/m higher than that of common energy pile.

Fig. 7 shows the relative improvement effect of heat exchange capacity of enhanced heat transfer energy pile compared to common energy pile. It can be seen from the figure that the percentage of relative

Table 3
Thermo physical parameters of model.

parameter	density (kg/m3)	Thermal conductivity (W/(m·K))	Specific heat (J/(kg·K))
Soil	1900	1.8	1200
Common concrete	2300	1.6	880
Heat transfer enhanced concrete	2200	2.4	850
Pipe (PE)		0.45	

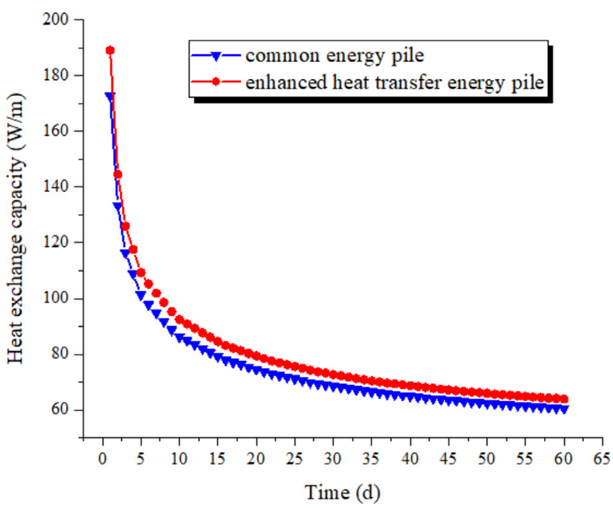


Fig. 6. Heat exchange capacity of common energy pile and enhanced heat transfer energy pile.

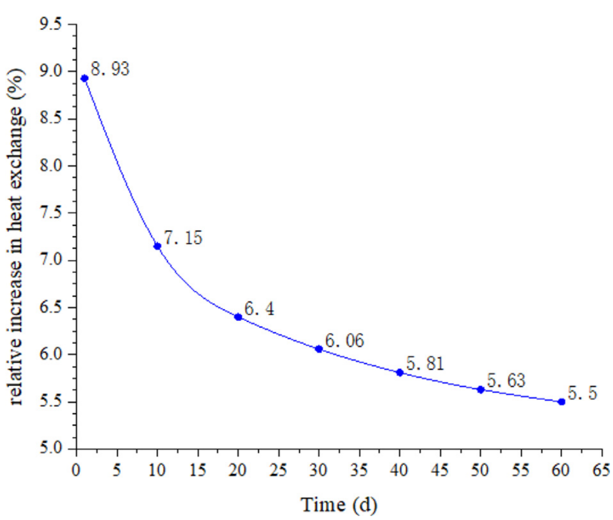


Fig. 7. Enhanced heat transfer energy pile compared with common energy pile.

increase in heat exchange decreases with time, from 8.93% to 5.5%. The simulation results show that the average increase effect of the enhanced heat transfer concrete on the energy pile (continuous running for 60 days) is about 6.5%, which shown that the heat transfer enhanced concrete have the positive effect on the heat-transfer characteristic of energy pile system.

3.3. Thermal effect on soil

The temperature curves of the pile and the soil around the pile were plotted in 20 days, 40 days, and 60 days (Fig. 8). Taking the day 60 temperature curve as an example, the image is basically axisymmetric, the center temperature is the highest (30.16 °C), and the soil

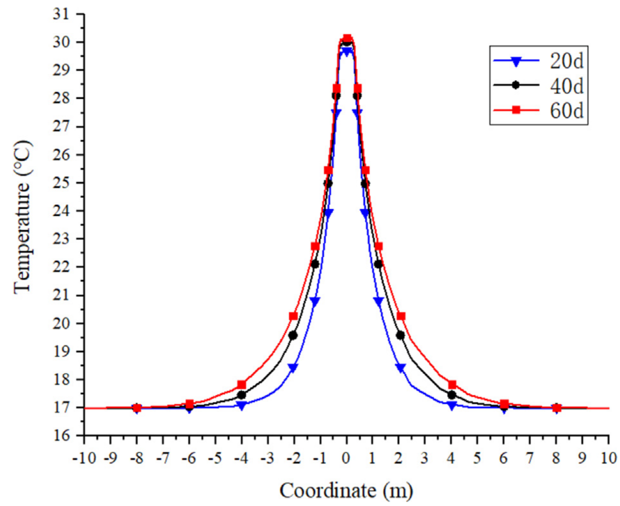


Fig. 8. Temperature curves of pile and soil under common energy pile condition.

temperature drops rapidly with radius expanding. When it reaches 2 *m* from the center of the pile, the temperature is 20.38 °C, and the descending speed is obviously slowed down. When it reached the position of about 5 *m*, the temperature of the soil changed very little, and the temperature was 17.41 °C, which only rose about 0.41 °C.

It can be also seen that as time increases, the overall temperature of the model increases, and the range of soil affected by pile is increasing. The radius of soil affected by the energy pile running for 20 days, 40 days, and 60 days was 5.49 *m*, 7.39 *m*, and 8.61 *m*, respectively.

Similarly, the soil temperature curve (Fig. 9) of the enhanced heat transfer energy pile is basically the same as that of the common energy pile, but the model overall temperature has increased. Taking the 60-day curve as an example, the temperature at the center of the pile, 2 *m* from the center and 5 *m* are 30.31 °C, 20.60 °C, and 17.44 °C, respectively, which is 0.15 °C, 0.22 °C and 0.03 °C higher than that of common energy pile. This shows that the existence of heat transfer concrete does allow more heat to pass through the energy pile material, resulting in an overall increase in temperature throughout the region and an increase in heat exchange.

At the same time, the radius of soil affectd by enhanced heat transfer energy pile has been increased. The radius of soil affectd by pile of 20 days, 40 days and 60 days are 5.52 *m*, 7.45 *m* and 8.66 *m* respectively, which are different from the radius of the common concrete system.

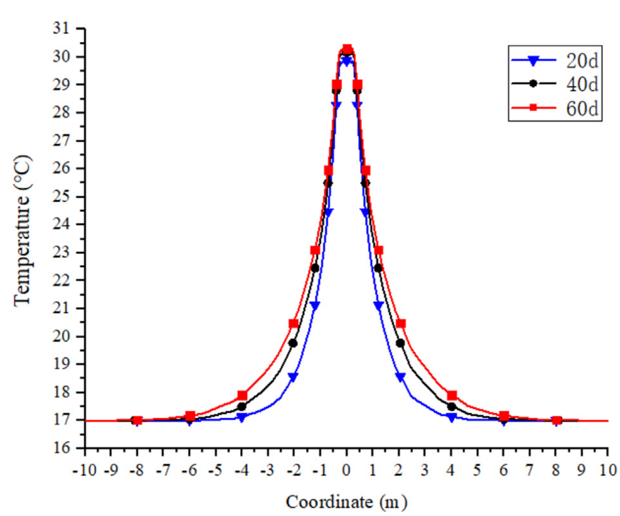


Fig. 9. Temperature of pile and soil under the condition of enhanced heat transfer energy pile.

Only 0.03 *m*, 0.06 *m* and 0.05 *m* have been added. This shows that the increase of the influence of the enhanced heat transfer energy pile on the soil is very small, so it can be treated as a common energy pile when considering the pile spacing in the pile group design.

4. Heat transfer model considering seepage

4.1. Establishment of the model

In the process of heat transfer between energy pile and surrounding soil, the existence of seepage may change the heat transfer process of energy pile and change the heat exchange capacity of energy pile. Therefore, groundwater flow module is added to the model, which combines seepage with heat transfer physical field to analyze the effect of seepage on heat transfer. The simulation assumes that the groundwater flow satisfies Darcy's law and the soil type is consistent with the foregoing, and it is still silty clay. The porosity is 0.4, and the permeability coefficient is $2 \times 10^{\wedge}(-5)$ cm/s. The energy pile is impermeable concrete, which means the water flow can not pass through the energy pile. The simulation assumes that the seepage flows unilaterally along the x-axis, and the temperature of the flow is the same as the initial temperature of the soil, both of which are 17° Celsius. The hydraulic gradient of seepage in the soil is 1.

It should be noted that the permeability coefficient of silty clay used in the simulation is relatively large, and the hydraulic gradient is also large, and may have approached or exceeded the critical hydraulic gradient of the site. This is to simulate the strong seepage effect in silty clay and analyze the change of heat exchange capacity of energy pile under the strong seepage effect.

4.2. Influence of seepage on energy pile

Fig. 10 shows the soil temperature contours under the effect of seepage flow. It can be seen from the figure that the temperature field of soil presents a significant asymmetry. The range of soil affected of the negative half axis of X is obviously smaller than that of positive half axis of X. It can be seen that the existence of seepage changes the distribution of soil temperature field, which indicates that the heat exchange between seepage and soil makes the heat of soil be carried away by seepage, so the affected area of soil is also reduced.

Fig. 11 shows the heat exchange capacity of common energy pile and enhanced heat transfer energy pile under non-seepage and seepage conditions, respectively. The results show that the heat exchange capacity of the energy pile is not significantly increased even under the strong seepage, and the heat exchange curve under the seepage effect is basically the same as that under the non-seepage effect. By calculating the average heat exchange capacity for 60 days, it is found that the heat exchange capacity of the common energy pile under seepage is only 1.73% higher than that under non-seepage. The heat exchange capacity of enhanced heat transfer energy pile under seepage is only 1.86% higher than that of enhanced heat transfer energy pile without seepage. This shows that seepage has little effect on heat transfer of energy pile in soil with low seepage coefficient, such as clay and silty clay. Therefore, seepage factor is not considered in the discussion of pile group simulation.

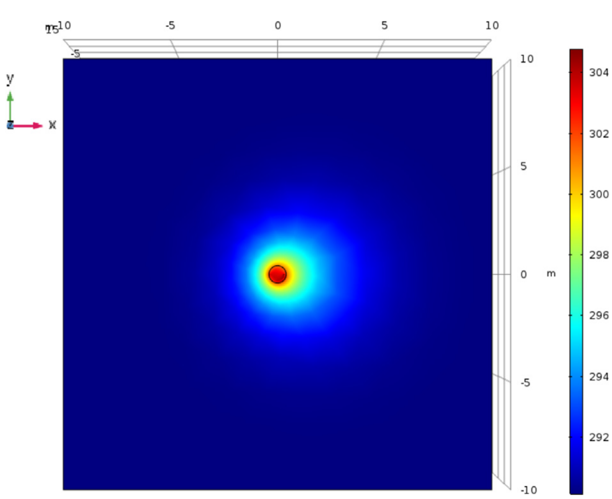
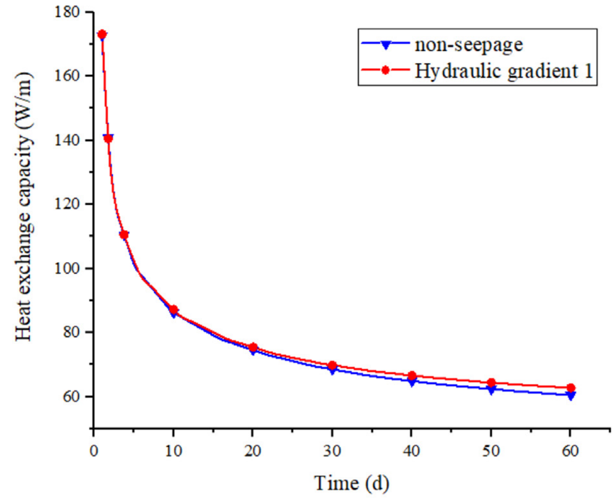
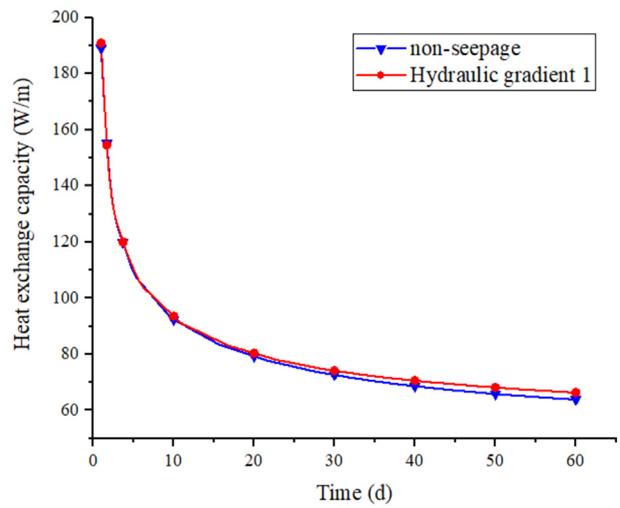


Fig. 10. Soil temperature contours under the effect of seepage flow.



(a) Common energy pile



(b) Enhanced heat transfer energy pile

Fig. 11. Heat exchange capacity under non-seepage and seepage effects.

5. Effect on pile group

5.1. Establishment of group pile heat transfer model

The model is composed of energy pile group, soil and buried pipe group. In order to accurately simulate the working conditions of the energy pile group, the model uses a 3 × 3 pile group combination. At the same time, the pile spacing is set to 3D, 4D, 5D (D is the diameter of the pile) to analyze the influence of pile spacing on the operation of the

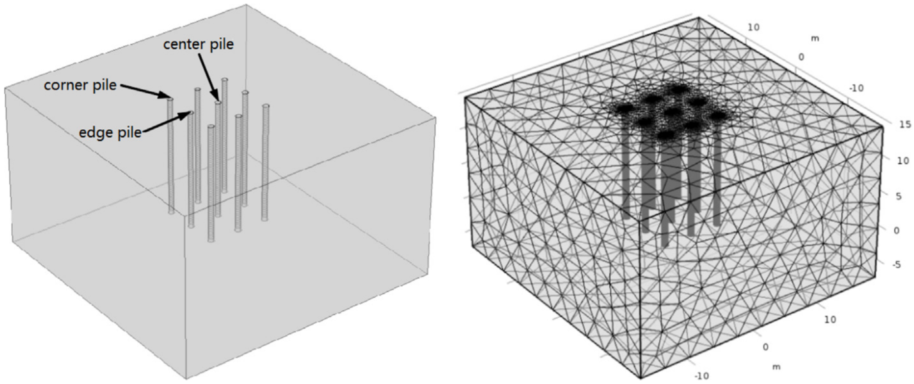


Fig. 12. Heat transfer model of energy pile groups.

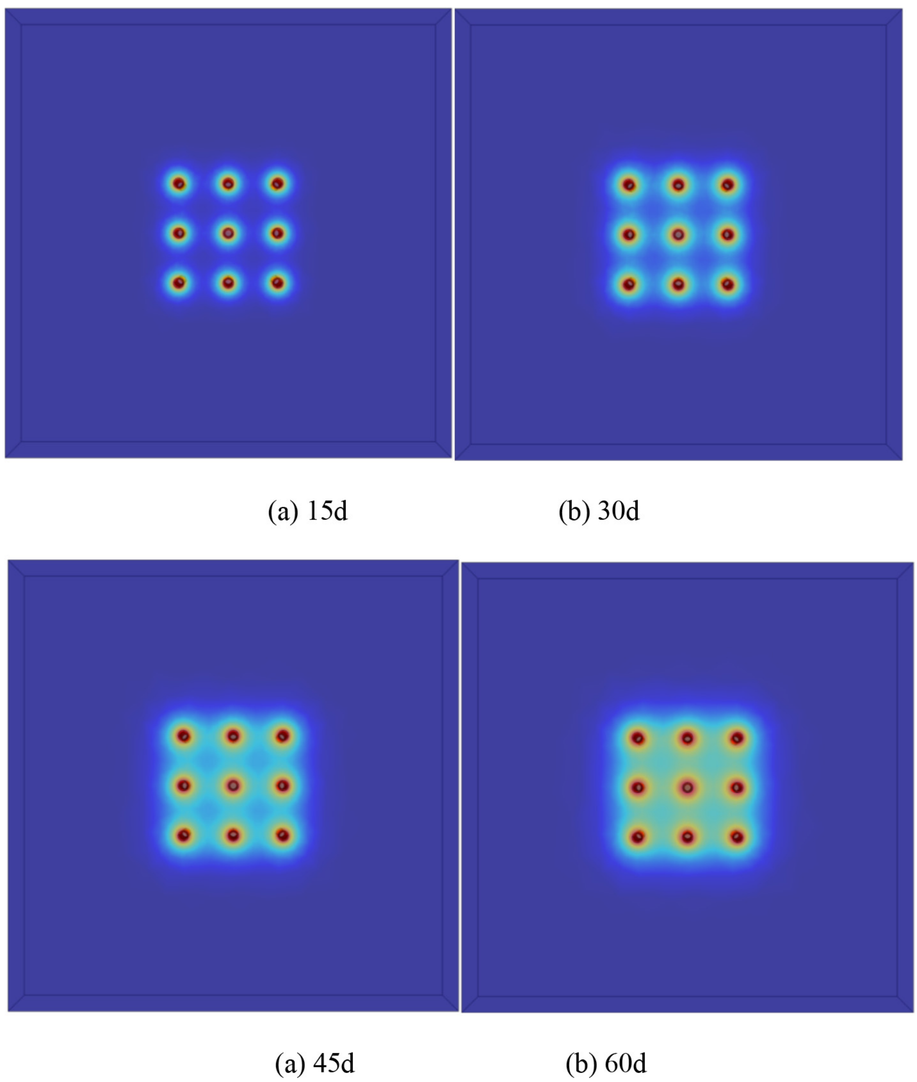


Fig. 13. Distribution of soil temperature at different time points.

pile group. The soil is set to a larger size (36 × 36 × 21) to eliminate the effects of boundary conditions. In the analysis of pile groups, the influence of pile spacing and pile material on pile group work is mainly considered. Therefore, other conditions such as pile size and buried pipe size, initial and boundary conditions setting, and simulation running time are exactly the same as single pile model. Through the obtained results, the heat transfer law of enhanced heat transfer energy pile group and common energy pile group is analyzed. The model is shown in Fig. 12.

6. Analysis of simulation results

6.1. Effect on soil

Whether it is a common energy pile group or an enhanced heat transfer energy pile group, its influence on the soil (Fig. 13) has a

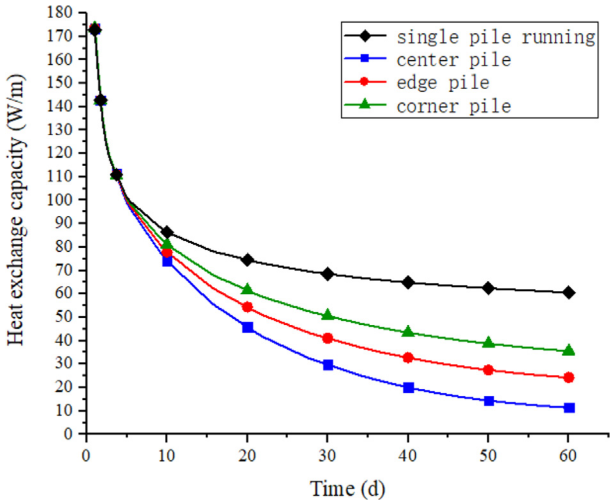


Fig. 14. Heat exchange capacity of common energy pile group.

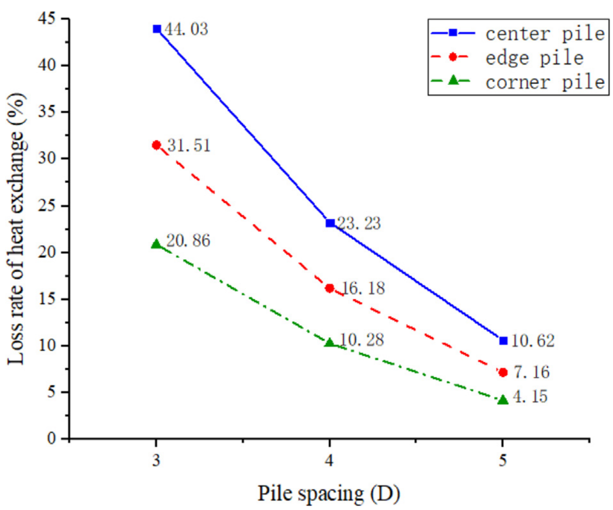


Fig. 15. Loss rate of heat exchange of each single pile in common energy pile group.

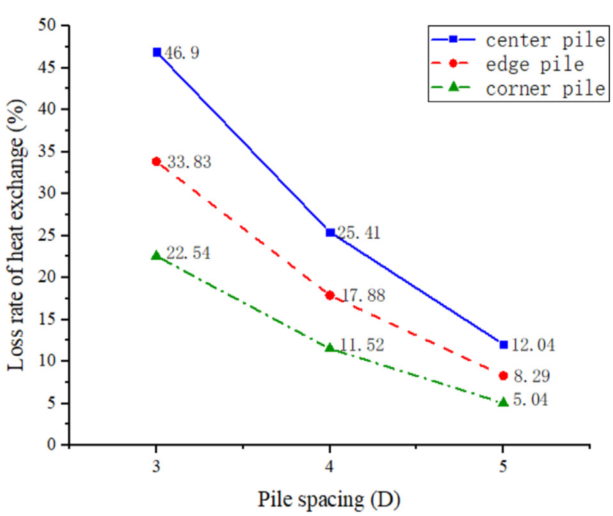


Fig. 16. Loss rate of heat exchange of each single pile in enhanced heat transfer energy pile group.

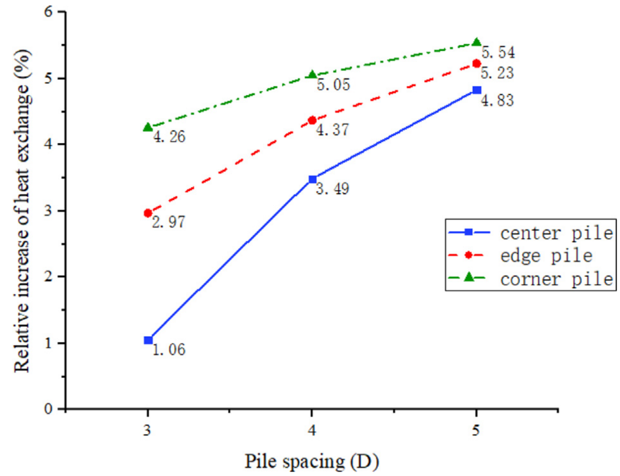


Fig. 17. Increase percentage between enhanced heat transfer and common energy pile group.

common law: through the temperature contours of the model surface, the radius of influence of the energy pile over time growing. The area of the initial relatively high temperature range is small, and the soil temperature of a large part of the space between the pile and the pile is not significantly disturbed. But over time, the soil is affected more and more widely. The high temperature areas begin to intersect or overlap. By 60 days, the area between the pile and the pile has completely changed to a high temperature area. This means that the mutual thermal interference of the energy piles gradually increases with the increase of time.

6.2. Heat exchange

The continuous increase of thermal interference has caused a significant gap in heat exchange between the every single energy pile in the pile group and the single energy pile running alone, which means heat exchange capacity has been lost. Taking the common energy pile group at 3D spacing as an example (Fig. 14), the heat exchange capacity of the energy pile at each position in pile group is close to that of the single pile running alone five days ago, and the curves are basically coincident. However, after 5 days, heat exchange capacity of the energy pile at each position was significantly reduced compared to the single pile, and the gap became larger with time.

The data were further processed to calculate the average heat exchange capacity of energy piles with different materials, different pile spacing and different positions, and compared with the average heat exchange capacity of single pile running alone. The percentage of heat exchange loss is calculated and the curve is drawn (Fig. 15, Fig. 16). The following laws can be obtained:

(1) In a pile group, the center pile suffers the strongest thermal interference, and the heat exchange loss is the largest, followed by the edge pile, and the corner pile loses the least heat exchange capacity.
(2) With the increase of pile spacing, the loss of heat exchange of center pile, edge pile and corner pile decreases. For a large energy pile group, the center pile will be a major component of its pile group. Under the 3D pile spacing, the loss of heat exchange of the common center energy pile and the enhanced heat transfer center energy pile are more than 40%. However, for every 1D increase in pile spacing, the heat exchange loss of the center energy pile can be greatly reduced.
(3) In the case of the same pile spacing, the loss rate of heat exchange of the enhanced heat transfer energy pile is slightly higher than that of the common energy pile.

Although the enhanced heat transfer energy piles have increased heat exchange loss at the same spacing, their heat exchange capacity is improved compared with common energy piles. Fig. 17 shows that the heat exchange capacity of the enhanced heat transfer energy piles at each location is improved compared with the common energy piles, wherein the corner pile has the greatest improvement effect and the center pile has the least improvement effect. However, the improvement effect of enhanced heat transfer energy pile is also affected by the pile spacing. With the increase of pile spacing, the improvement effect is also strengthened, and approaches the percentage of increase when single pile runs alone (6.5%). Under the 5 D spacing, the percentage of increase in heat exchange of each energy pile is stable at about 5%. Therefore, in practical engineering, the better graphite ratio and the reasonable pile spacing can play an effective role in strengthening heat transfer.

7. Conclusion

In this paper, the enhanced heat transfer concrete is prepared by adding graphite into concrete, and the difference between common energy pile and enhanced heat transfer energy pile (25% graphite content) in soil effect and heat exchange capacity is compared. The following conclusions are obtained:

(1) According to the characteristics of high thermal conductivity and chemical stability of graphite, it is used to make enhanced heat transfer concrete, and graphite concrete samples with different volume contents (0%, 5%, 10%, 15% and 25%) are prepared. Through the thermal conductivity measurement test at different environmental temperatures (10 °C, 20 °C, 30 °C, 40 °C), the heat transfer coefficient of concrete has been significantly improved, the maximum thermal conductivity increased to 2.84 W/(m ° C) (40 °C)).
(2) Under the condition of single energy pile running for 60 days, the heat exchange capacity of two kinds of energy piles decreases with the passage of time, and the influence range of the two kinds of energy piles on soil increases continuously. The heat exchange capacity of the enhanced heat transfer energy pile (25% graphite content) is about 6.5% higher than that of the common energy pile, and the influence on soil is slightly increased.
(3) Under the condition of pile group running for 60 days, the thermal interference between piles increases with time. Affected by this, the heat exchange capacity of each pile in the energy pile group is less than that of the single pile running alone. The center pile suffers the strongest heat disturbance, the loss of heat exchange is the largest, followed by the edge pile, and the corner pile loses the least heat exchange. At the same time, with the increase of pile spacing, the loss of heat exchange of center pile, edge pile and corner pile decreases. However, under the same pile spacing, the loss rate of heat exchange of enhanced heat transfer energy pile is slightly higher than that of common energy pile.
(4) Under the condition of pile group, the heat exchange capacity of enhanced heat transfer energy piles is still significantly improved compared with common energy piles. The corner pile has the greatest improvement effect, and the edge pile is second, and the center pile has the least effect. At the same time, the improvement effect of the enhanced heat transfer energy pile is also affected by the pile spacing. With the increase of pile spacing, the improvement effect is also strengthened, and approaches the percentage of increase when single pile runs alone (6.5%).

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