Investigation of the thermal response of PHC energy pile backfilled with phase change material

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Abstract. The influence of phase change material (PCM) backfill material within precast high-strength concrete (PHC) pile on the thermal behavior of the energy pile is rarely studied. This paper develops a numerical model to investigate the thermal response of the PHC energy pile backfilled with PCM. The results show that the higher latent heat and thermal conductivity of PCM backfill material inside the PHC pile can effectively improve the heat transfer capacity of PHC energy pile. Besides, the intermittent operation mode is beneficial to the enhancement in heat transfer behavior of PCM-backfilled PHC energy pile. For PCM and improved PCM backfill material, the heat exchange rates of PHC energy pile at 6:18 intermittent mode rise by 57.11\% and 64.06\% compared with continuous mode. Finally, because the improved PCM backfill material has higher latent heat and thermal conductivity, the ground temperature around the improved PCM-backfilled PHC energy pile shows a faster growth trend than PCM backfill material. Additionally, the intermittent operation mode produces a slower growth rate of ground temperature around the pile.

1. Introduction

Shallow geothermal energy is a green, environmentally friendly, and renewable energy [1, 2]. At present, the energy pile technology using the shallow geothermal energy has developed quickly, and this technology has been adopted for the underground structures in many countries [3, 4].

The numerous studies concerning the thermal response and heat transfer mechanism of energy piles have been conducted. Hamada et al. [5], Jalaluddin et al [6], and Gao et al. [7] both performed the field tests to compare the influence of different geometric configurations of heat exchange pipes on the heat transfer capacity and efficiency of energy piles, and the better type of heat exchanger was obtained in their experiments. The field experimental results of Laloui et al. [8] indicated that the thermal strain of pile was characterized by the thermo-elastic property, and the larger thermal stress was generated inside the energy pile at condition of temperature loads. Faizal et al. [9] conducted the field experiments to investigate the influence of different operation patterns on the thermal response of energy pile and found that the intermittent operation patterns produced higher heat transfer rate and...
lower thermal loads. The laboratory model results of Yang et al. [10] presented that the higher inlet temperature, intermittent operation mode, and the optimization of spiral pitch of coil pipe both could improve the heat transfer rate of energy pile with coil pipe. The model test results of Ng et al. [11] showed that the ultimate bearing capacity of energy pile enhanced with an increase in pile temperature, and the increase of temperature firstly caused an increase in the pile lateral friction, and then it induced the gradual increase in pile tip resistance. Gashti et al. [12] developed a model to evaluate the thermal performance of steel energy pile, which showed that double U type pipe had the higher heat transfer efficiency. They also found that the temperature varies greatly along the cross section of pile, and the temperature of the pile is also inconsistent along the depth direction. The numerical results of Sani and Singh [13] indicated that the soil saturation condition, operation pattern, and magnitude of heat injection rate could impact the performance of the energy pile system and soil temperature variation trend.

To date, some researchers have devoted themselves to study the thermal response performance of the precast high-strength concrete (PHC) energy pile [14–17]. Park et al. [14] and Go et al. [15] found that the pipe configuration, operation mode, thermal conductivity of grout, and groundwater seepage could affect the heat transfer performance and thermal resistance of PHC energy pile and the variation of ground temperature. Guo et al. [16] analyzed the temperature variation and recovery trend of ground soil around the PHC energy pile and the pile temperature variation characteristic. Zhang et al. [17] combined the field tests and numerical simulations to investigate the long-term thermal response of the PHC energy pile in stratified foundation. In previous studies of the PHC energy pile, the backfill materials inside the PHC pile are ordinary cement grout, backfill soil, and water. However, the research concerning the effect of phase change material (PCM) as backfill material on the thermal performance of PHC energy pile has been rarely reported.

In this study, a 3D numerical model was developed to evaluate the influence of PCM backfill material in PHC pile on the thermal response of PHC energy pile. At first, the effect of thermophysical properties of PCM backfill material on the heat transfer behavior of PHC energy pile was analyzed. Then, the heat transfer performances of PCM-backfilled and improved PCM-backfilled PHC energy pile under different operation modes were assessed. Finally, the ground temperature variation trends around the PCM-backfilled and improved PCM-backfilled PHC energy pile were analyzed. The relevant results can become a basis for the application of PCM backfill material in PHC energy pile.

2. Theoretical analysis of heat transfer

To simplify the conjugate heat transfer mechanisms of the PHC energy pile and ground, some assumptions were applied as follows: (1) the impact of groundwater advection on the heat transfer of numerical model is not considered in this study [16, 17]; (2) the contact boundary between the backfill material and the internal surface of the PHC energy pile meets the continuity condition; (3) the heat transfer of the heat exchange pipe wall is assumed to follow the quasi-steady state property due to the considerably thin pipe wall.

The governing equation of heat conduction of the PHC energy pile and ground can be obtained as:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q,$$  \hspace{1cm} (1)

where $\rho$ is the density of solid, such as pile, soil layer, and solid backfill material (kg/m³); $C_p$ is the specific heat capacity at constant pressure of solid (J/(kg K)); $k$ is the thermal conductivity of solid (W/(m K)); $T$ is the temperature of solid (K); $t$ is the time (s); $Q$ is the general heat source term (W/m³).

For the PHC energy pile backfilled with PCM, the phase transition heat transfer equations are presented in the following part. In Eq. (1), the density and thermal conductivity of PCM are obtained as follows:

$$\rho_{PCM} = \theta(T) \rho_{PCM1} + (1 - \theta(T)) \rho_{PCM2}$$ \hspace{1cm} (2)

$$k_{PCM} = \theta(T) k_{PCM1} + (1 - \theta(T)) k_{PCM2}$$ \hspace{1cm} (3)
where $\theta(T)$ is the phase mass fraction, and it is a function of $T$. The subscripts of $PCM1$ and $PCM2$ are the PCM in solid phase and liquid phase.

The specific heat capacity of PCM is determined to include an additional term of latent heat, which is shown in Eq. (4).

$$C_{p,PCM} = \frac{1}{\rho_{PCM}}[(\theta(T)\rho_{PCM1}C_{p,PCM1} + (1-\theta(T))\rho_{PCM2}C_{p,PCM2}) + L\frac{\partial\alpha_m(T)}{\partial T}]$$

where $L$ is the latent heat of PCM; $\alpha_m$ is the smooth transition function, which has the effect to prevent the numerical instability caused by the rapid change of specific heat capacity. The $\alpha_m$ is determined by the following equation:

$$\alpha_m(T) = \frac{1}{2}\frac{(1-\theta(T))\rho_{PCM2} - \theta(T)\rho_{PCM1}}{\theta(T)\rho_{PCM1} + (1-\theta(T))\rho_{PCM2}}$$

The continuity, momentum, and energy conservation equations of incompressible fluid within the pipe are expressed in Eqs. (6), (7), and (8).

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f u_f) = 0$$

$$\rho_f \frac{\partial u_f}{\partial t} = -\nabla p_f - \frac{1}{2} f_d \rho_f \frac{\partial A}{\partial d_h} [u_f | u_f|] + q_{wall}$$

$$\rho_f A C_{p,t} \frac{\partial T_f}{\partial t} + \rho_f A C_{p,t} u_f \nabla T_f = \nabla \cdot (A k_f \nabla T_f) + \frac{1}{2} f_d \rho_f A \frac{\partial A}{\partial d_h} | u_f | + q_{wall}$$

where $u_f$ is the flow rate of fluid within the pipe (m/s); $p_f$ is the water pressure within the pipe (Pa); $f_d$ is the Darcy friction factor of the fluid; $d_h$ is the mean hydraulic diameter (m); $A$ is the cross section area of the pipe (m²); $q_{wall}$ is the heat source term of the pipe wall (W/m).

The heat exchange through the pipe wall ($q_{wall}$) is represented as follows:

$$q_{wall} = h_e (T_{ext} - T_f)$$

where $h_e$ is the effective heat transfer coefficient (W/(m K)); $T_{ext}$ is the external temperature outside the heat exchange pipe (K).

The effective heat transfer coefficient ($h_e$) can be described as:

$$h_e = \frac{2\pi}{\frac{1}{d_{p,in}} h_{int} + \frac{1}{k_p} \ln \left( \frac{d_{p,ext}}{d_{p,in}} \right)}$$

where $h_{int}$ is the internal film heat transfer coefficient of the pipe (W/(m² K)); $k_p$ is the thermal conductivity of the pipe (W/(m K)); $d_{p,in}$ is the inner diameter of the pipe (m); $d_{p,ext}$ is the outer diameter of the pipe (m).

The equation of internal film heat transfer coefficient ($h_{int}$) is expressed in Eq. (11).

$$h_{int} = N_u k_p \frac{k_f}{d_h}$$

where $N_u$ is a dimensionless number for the intensity of convective heat transfer, which is named as the Nusselt number.

3. Finite element modeling and validation

3.1. Numerical model

In the current study, a 3D geometric model of the ground and PHC energy pile was developed by using COMSOL Multiphysics. The calculation area of the ground is considered to be enlarged as much as possible to minimize the impact of assumed boundary conditions on the numerical results.
According to the results of Sani and Singh [13], Péron et al. [18], and Ma and Wang [19], the ground with the radius of 10 m and the depth of 50 m was set as the calculation area of numerical model, which is shown in Fig. 1. The lateral boundary and bottom boundary of the ground were set as thermal insulation boundary. The upper boundary was set as the convective heat transfer boundary.

\[ T_g(\theta, r, z, t)|_{\theta = 0} = T_0(z, t)|_{\theta = 0} \]  
(12)

The upper boundary condition can be expressed as Eq. (13).

\[ q_{upper}(\theta, r, z, t)|_{\theta = 0} = h(T_g - T_{air}) \]  
(13)

The lateral boundary and bottom boundary conditions are shown in Eq. (14).

\begin{align*}
\frac{\partial T_g(\theta, r, z, t)}{\partial r}|_{r = 0} &= 0 \\
\frac{\partial T_g(\theta, r, z, t)}{\partial z}|_{z = 0} &= 0
\end{align*}

(14)

where \( T_g \) is the temperature at the different depths and time (K); \( T_0 \) is the initial ground temperature (K); \( h \) is the convective heat transfer coefficient (W/(m\(^2\) K)); \( T_{air} \) is the ambient temperature of the ground surface (K).

The meshing of the ground and PHC energy pile are shown in Fig. 1. The geometric dimensioning of the model of PHC energy pile is consistent with the PHC energy pile used at the test site [16, 17]. The energy pile was a pretensioned spun concrete pile, the PHC pile was made of C80 high-strength concrete, and the length of the pile was 24 m. The external diameter of the PHC pile was 0.5 m, the inner diameter was 0.28 m, and the wall thickness was 0.11 m. The U-type pipe was adopted in the PHC energy pile, which was a high density polyethylene (HDPE) pipe. The external diameter, inner diameter, and wall thickness of U-type pipe were 25, 20.4, and 2.3 mm, respectively. The circulating water flowed within the heat exchange pipe. The properties the PHC, HDPE pipe, and circulating water applied in the current numerical simulation are shown in Table 1. The ground properties used in the model were consistent with the measured data at the test site [16, 17], which are shown in Table 2.

The initial ground temperature used in the current model is shown in Fig. 2. The inlet fluid temperature was set as the constant values of 40 ℃, and the flow rate of circulating fluid was set as 0.5 m\(^3\)/h. The basic properties of PCM backfill material are listed in Table 3.
Table 2. Thermophysical indexes of each soil layer.

| Layer name | Scope of depth (m) | Thermal conductivity (W m⁻¹ K⁻¹) | Specific heat capacity (J kg⁻¹ K⁻¹) | Thermal diffusivity (mm²/s) | Density (g/cm³) |
|------------|--------------------|----------------------------------|------------------------------------|-----------------------------|-----------------|
| 1-2        | 1.8-4.3            | 1.37                             | 885                                | 0.84                        | 1.89            |
| 2-2        | 4.3-11.5           | 1.15                             | 877                                | 0.77                        | 1.74            |
| 2-3        | 11.5-13.5          | 1.54                             | 918                                | 0.87                        | 1.97            |
| 2-3        | 13.5-16            | 1.71                             | 934                                | 0.95                        | 1.97            |
| 2-4        | 16-17.4            | 1.35                             | 843                                | 0.84                        | 1.95            |
| 2-5        | 17.4-24            | 1.30                             | 775                                | 0.86                        | 1.99            |

3.2. Validation of numerical model

Li et al. [22] performed the experiments to investigate the effect of PCM grout on the thermal response of borehole heat exchanger. The heat transfer mechanism of PHC energy pile backfilled with PCM is similar to the borehole backfilled with PCM, thus the numerical model of PHC pile backfilled with PCM developed by COMSOL Multiphysics can be verified by the experimental results of Li et al. [22]. The settings of geometrical parameters, condition, and materials properties are consistent with Li et al. [22]. The comparison between experimental results and numerical results are presented in Fig.
3. It is found that the deviation between measured values and numerical values is lower than 3%. Thus, the model established by COMSOL Multiphysics can be used to simulate the heat transfer process of PHC energy pile backfilled with PCM.

![Comparison between experimental data and numerical results of PCM backfilled model.](image)

3.3. Thermal performance analysis method

The heat exchange rate is used in this study for assessing the heat transfer performance of the PHC energy pile. The equation of the heat exchange rate per meter ($q$) of the PHC energy pile is shown in Eq. (15).

$$ q = \frac{m_f c_f (T_{in} - T_{out})}{l} $$

(15)

where $m_f$ denotes the mass flow rate of circulating water (kg/s); $c_f$ denotes the specific heat capacity of the circulating water at constant pressure (J/(kg K)); $T_{in}$ denotes the inlet temperature of the circulating water (K); $T_{out}$ denotes the outlet temperature of the circulating water (K); $l$ denotes the effective length of the PHC pile (m).

4. Results and discussion

4.1. Effect of thermophysical properties of PCM on heat transfer performance

The impact of thermophysical properties of PCM backfill material on the heat transfer performance of PHC energy pile is shown in Fig. 4. When the latent heat of PCM increases by 200 kJ/kg, the heat exchange rate of PHC pile backfilled with PCM has been improved by 19.61% at 2 h. The enhancement effect of the latent heat of PCM backfill material on the heat transfer of energy pile reduces with elapsed time. At 7 days, the heat exchange rate of PHC energy pile backfilled with PCM rises by 7.12% with an increase in latent heat of PCM. Moreover, when the latent heat of PCM is 300 kJ/kg and the thermal conductivity of PCM increases by 0.4 W/(m K), the heat exchange rate of PHC energy pile backfilled with PCM has been improved by 30.75% and 30.43% at 2 h and 7 days, respectively. It is deduced that the higher latent heat and thermal conductivity of PCM backfill material can effectively improve the heat transfer performance of PHC energy pile. Thus, the improved PCM backfill material (latent heat of 300 kJ/kg and thermal conductivity of 1.49 W/(m K)) is used in the following part.
4.2. Effect of different operation modes on heat transfer performance

Fig. 5 shows the thermal performance of PHC energy pile backfilled with PCM and improved PCM under various operation modes. It can be found that the intermittent operation mode has a significant improvement on the heat transfer performance of PHC energy pile backfilled with PCM and improved PCM, which is more than continuous operation mode. The improved PCM backfill material produces higher thermal behavior than PCM backfill material under different operation modes. As shown in Fig. 5, the 6:18 mode represents 6 h operation and 18 h pause. Under 6:18 mode, the PHC energy pile backfilled with PCM and improved PCM both has the highest heat exchange rate. For the PHC energy pile backfilled with PCM, the heat exchange rates of energy pile under 6:18, 8:16, 16:8, 18:6 modes increase by 57.11%, 44.35%, 9.04%, and 4.99% at 7 days compared with the continuous operation mode. Moreover, for the PHC energy pile backfilled with improved PCM, the heat exchange rates under 6:18, 8:16, 16:8, 18:6 modes rise by 64.06%, 47.67%, 10.32%, and 6.30% at 7 days compared with the continuous operation mode. The reason is that the phase change materials (PCMs) can release latent heat during the phase transition process, which can effectively improve the heat transfer capacity of PHC energy pile. The intermittent mode is beneficial to recover PCMs to their original state, then the part of PCMs within the PHC pile can change from solid phase to liquid phase and produce the phase transition process again. Thus, the intermittent operation mode can significantly enhance the thermal performance of PHC energy pile backfilled with PCM and improved PCM.
4.3. Ground temperature variation around the PHC energy pile

Fig. 6 presents the evolutions of ground temperature at the 0.5 m distance from the PCM-backfilled and improved PCM-backfilled PHC energy pile. It is found that the operation mode and PCM backfill material can affect the ground temperature variation trend. For PCM and improved PCM backfill materials in PHC energy pile, the ground temperatures at different depths increase in a fluctuating tendency at 6:18 mode and 8:16 mode, while the ground temperature fluctuations at 16:8 mode and 18:6 mode are not remarkable compared with 6:18 mode and 8:16 mode. The ground temperatures directly increase with time at continuous mode. The shorter operation time (namely 6:18 mode) can result in the smaller increment of ground temperature, which can alleviate the heat accumulation near to the pile. Moreover, because the improved PCM backfill material possess higher thermal conductivity and latent heat, the growth rates of ground temperature at different points around the PHC pile backfilled with improved PCM are relatively large.
5. Conclusions

This study employed the numerical simulation method to evaluate the thermal response of PHC energy pile backfilled with PCM. The main conclusions are drawn:

1) The thermophysical properties of PCM backfill material have a remarkable effect on the thermal behavior of PHC energy pile. The higher latent heat and thermal conductivity of PCM backfill material produce better heat transfer performance of PHC energy pile under various operation modes.

2) The intermittent operation mode can remarkably improve the thermal performance of PCM-backfilled PHC energy pile. At 6:18 intermittent operation mode, the heat exchange rates of PHC energy pile backfilled with PCM and improved PCM respectively increase by 57.11% and 64.06% compared with continuous operation mode.

3) The improved PCM-backfilled PHC energy pile results in the higher increment of ground temperature than PCM backfill material due to the enhancement in thermophysical properties of PCM. The shorter operation time can lead to an obvious recovery in ground temperature, which generates a slower growth rate of ground temperature.

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