A comparison study on the long-term thermomechanical performance of energy piles under three climatic conditions

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Abstract. Energy piles provide a profitable solution for both structural support and space cooling and heating of residential and commercial buildings. Nevertheless, very few details have been reported on the long-term thermomechanical performance of energy piles concerning the influence of climatic conditions. In this paper, a numerical study is performed to elucidate the long-term thermomechanical behaviour of energy piles under three typical climatic conditions by considering thermal demands of a reference office building. Pile and soil temperature fluctuations, thermal pile axial force, and thermally induced pile head displacement are determined and compared. The results show that the surrounding soil thermal imbalance under climatic conditions with nonsymmetrical thermal demands is more significant than that under climatic conditions with balanced thermal demands. Moreover, notably lower thermal axial forces are induced at the end of thermal cycles under climatic conditions with nonsymmetrical thermal demands. However, the thermally induced pile head displacements are much larger under such climatic conditions, and longer thermal operations are needed to reach the steady state. The study suggests that the use of the unified design method of energy piles subjected to different climatic conditions may adversely affect the design effect. Besides, compared with the thermal forces, energy pile design should pay more attention to the adverse effects of thermally-induced pile head displacement on normal service.

1. Introduction
In recent years, with the increasing expansion of global warming and urbanization, comprehensive worldwide policies for building green multi-energy supply systems have extensively promoted renewable energy sources, such as geothermal energy. Against this background, the energy pile has received increasing attention due to its high efficiency in utilizing shallow geothermal energy. The energy pile is regarded as a profitable solution for space cooling and heating in commercial and residential buildings [1–3]. In this technology, ground source heat pumps (GSHPs) are integrated into piles that are already required for structural support [4,5]. The hybrid system has widely promoted the application of shallow geothermal energy by reducing drilling costs and underground spaces in the past two decades [6–8].
Given the great prospect of utilizing shallow geothermal energy, numerous field tests [10-11, 13-17] have been conducted to investigate the thermomechanical performance of energy piles to endorse their further application. The test results showed that the thermal operations influenced the mechanical performance of the energy pile by (i) increasing the additional thermal compressive stresses and (ii) inducing shaft friction increments due to the temperature increase. According to the test results, other general thermomechanical performances of energy piles have also been obtained.

In addition, numerical simulations[9–26] coupled with various complex tools, as well as laboratory model experiments[27–35], including various centrifuge model tests[32–35], have been conducted to study the mechanism governing the short- and long-term thermomechanical behaviour of energy piles. Although the studies mentioned above have established a basic framework to explain the fundamental mechanism governing the performance of energy piles, few investigations[9] are found, which provide a comprehensive comparison of the long-term behaviour of energy piles under various climatic conditions, especially in terms of the long-term mechanical performance variations induced by thermal operations.

Therefore, this paper investigates the impact of climatic conditions on energy pile design by analysing the long-term thermomechanical performance. First, the obtained mechanical and thermal loads that are imposed on the pile during the thermomechanical process are studied. Second, the numerical model and method are described in detail. Model piles are employed in three representative cities (i.e., Charlotte, Austin, and Chicago) corresponding to the three considered climatic conditions. Preselected thermal loads are imposed on the model piles for ten years. Finally, the results in terms of the pile and surrounding soil, thermal pile axial force, and thermally induced pile head displacement are presented and examined for comparison purposes.

2. Long-term thermomechanical analyses under different climatic conditions

2.1. Determination of the thermal load for thermomechanical coupling analysis
Energy pile operation and performance, especially the long-term thermomechanical performance, are dominated by the thermal demands of buildings, which vary quite differently under different climatic conditions. Thus, it can be reasonably predicted that the thermomechanical performance of energy piles under different climatic conditions is also significantly different. Considering the design requirement of the energy pile and related thermal design standards, such as the Standard of Climatic Regionalization for Architecture[36] and the Thermal Design Code for Civil Building[37], the climatic conditions for energy pile design could be classified into three types; namely, heating demand-dominated, cooling demand-dominated, and balanced heating and cooling demand-dominated climatic conditions. The classification in this study is similar to that of Sutman et al.[19], who considered the climatic conditions to be warm, cold, and mild, respectively. In this study, three typical cities are selected to represent the different climatic conditions: (i) Charlotte, corresponding to the balanced heating and cooling demand-dominated climatic condition; (ii) Austin, corresponding to the heating demand-dominated climatic condition; (iii) Chicago, corresponding to the cooling demand-dominated climatic condition. Design weather and more information could be found in Ref. [38].

2.2. Development of the numerical model

2.2.1 Mathematical formulation. In the heat transfer analysis, this study employs heat transfer in porous materials theory. The heat transfer mode is conduction. The energy conservation equation is

\[ \rho c_p \left( \frac{\partial T}{\partial t} - \nabla \cdot \left( \lambda \nabla T \right) \right) = 0 \]  (1)
where \( \rho \) represents the density; \( c_p \) is the specific heat; \( t \) is heat transfer time; \( \lambda \) is thermal conductivity; \( \nabla \) is the gradient. It is worth noting that the thermal properties of the surrounding soil and piles are assumed to be temperature independent.

The energy conservation equation of the heat carrier fluid during operation can be written as

\[
\rho_f c_{pf} \frac{\partial T_f}{\partial t} + \rho_f c_{pf} u_f \nabla T_f = \nabla \left( \lambda_f \nabla T_f \right) + Q_{\text{wall}}
\]

(2)

where \( \rho_f \) is the density of the heat carrier fluid; \( c_{pf} \) is the constant pressure specific heat capacity of the fluid; \( T_f \) is the temperature field of the fluid; \( u_f \) is the tangential velocity of the fluid; \( \lambda_f \) is the thermal conductivity of the fluid; \( Q_{\text{wall}} \) is the external heat exchanged through the pipe wall.

In the thermomechanical coupling analysis, the equilibrium equation can be expressed as

\[
\nabla \cdot \sigma_{ij} + \rho g_i = 0
\]

(3)

where \( g_i \) represents the gravity vector; \( \nabla \) denotes the divergence; \( \sigma_{ij} \) is the total stress tensor, and it can be written as

\[
\sigma_{ij} = C_{ijkl} (\epsilon_{ij} + \alpha \delta_{ii} \Delta T)
\]

(4)

where \( C_{ijkl} \) is elastic stiffness tensor; \( \epsilon_{ij} \) denotes the total strain tensor; \( \alpha \) is the linear thermal expansion coefficient; \( \delta_{ii} \) represents the identity matrix; \( \Delta T \) is the temperature variation.

2.2.2 Simplified thermomechanical coupling numerical method. Due to the complexity of the heat exchange process of the energy pile and the constitutive equation of the soil, numerical simulation is usually used to solve the above mathematical formula. In this study, the finite element software ABAQUS[39] is employed to realize this simplified thermomechanical coupling method. Firstly, a numerical model is built separately for the pile and surrounding soil's heat transfer analysis. The heat transfer analysis results are regarded as the initial thermal conditions to be imported into the mechanical analysis model to solve the thermomechanical problems. In Section 2.3, the accuracy of this simplified method will be verified through a laboratory model test.

2.2.3 Material models. In the following thermomechanical analyses, the stress-strain relationships of the pile and soil are considered by perfect thermo-elasticity and Mohr-Coulomb failure criterion constitutive laws, respectively, as adopted by Rammal et al. [20] and other studies[11,14,40,41]. The yield surface of the Mohr-Coulomb constitutive model is given by

\[
F = R_{nc} q - p \tan \varphi - c = 0
\]

(5)

where \( p \) is the mean stress; \( \varphi \) and \( c \) is the friction angle and cohesion of the soil, respectively; \( R_{nc} \) controls the shape of the yield surface in the deviatoric plane, and it can be written as

\[
R_{nc} = \frac{1}{\sqrt{3} \cos \varphi} \sin \left( \Theta + \frac{\pi}{3} \right) + \frac{1}{3} \cos \left( \Theta + \frac{\pi}{3} \right) \tan \varphi
\]

(6)

where \( \Theta \) is the polar declination. The model considers the non-associated flow rule by defining the plastic potential surface different from the yield surface. The shape of the plastic potential surface is governed by

\[
G = \sqrt{(c_n \tan \psi)^2 + (R_{nc} q)^2} - p \tan \psi
\]

(7)

where \( \epsilon \) is the meridional eccentricity; \( c_n \) is the initial cohesion; \( \psi \) is the dilation angle; \( R_{nc} \) defines the shape of the plastic potential surface in the deviatoric plane, and it can be calculated by

\[
R_{nc} = \frac{4 \left( 1 - e^2 \right) \cos \Theta + (2e - 1)^2}{2 \left( 1-e^2 \right) \cos \Theta + (2e - 1) \sqrt{4 \left( 1-e^2 \right) (\cos \Theta)^2 + 5e^2 - 4e}} R_{nc} \left( \frac{\pi}{3}, \varphi \right)
\]

(8)

where \( e \) is the eccentricity.
2.2.4 Numerical model and boundary conditions. In this paper, the pile and soil's material properties, as shown in Table 1, are the same as those in the study of in situ experiments [20,42] conducted in Dunkirk, northern France. The numerical model with a 3D domain is solved via the finite element code Abaqus[39]. Hexahedron-dominated grids are utilized to mesh the numerical model to reduce the total mesh number. The soil domain has a square section with a width of 16.4 m and a length of 24 m. The pile also has a square section with a width of 0.52 m and a length of 12 m. It is worth noting that heat exchanger pipes are not modelled separately. Besides, to reduce computing resources, only one-quarter of the numerical domain is modelled because of symmetry. The pile is assumed to be in place. The initial stress and displacement states are obtained by imposing the gravity force on the model domain. The vertical and horizontal displacements of the horizontal and vertical soil boundaries are restrained by pinned, and roller supports. To simulate the interaction between the pile and soil, this study adopts frictional and hard contacts in the tangential and vertical directions, respectively, of the interface. These assumptions are sufficient to capture the main features of the mechanical behaviour of the pile.

Table 1. Mechanical parameters of the pile and surrounding soil[30].

|                  | Soil       | Pile       |
|------------------|------------|------------|
| Elastic modulus (MPa) | 73         | 30000      |
| Density (kg/m$^3$)     | 1910       | 2500       |
| Poisson’s ratio       | 0.3        | 0.2        |
| Cohesion (kPa)        | 3          | ---        |
| Friction angle        | 31°        | ---        |
| Linear thermal expansion coefficient | 12×10^{-6} | 5×10^{-6} |
| Conductivity (W/m K)  | 2.00       | 1.80       |
| Specific heat (J/kg K)| 1500       | 880        |

Pile-soil interaction

|                  | Tangential direction | Normal direction |
|------------------|----------------------|------------------|
| $\mu = \tan(\phi) = 0.6$ | Hard contact |

The initial temperature of the model domain is 15 ℃. The surface thermal boundary conditions are set to external air temperature. The equation adopted for the surface boundary condition is written as

$$ T(t) = T_{ave} + A_0 \sin(\omega t) \quad (9) $$

where $T_{ave}$ denotes the average soil temperature; $A_0$ is the annual amplitude of the surrounding soil temperature; $\omega$ represents the annual frequency. In the lateral and bottom boundaries, adiabatic conditions are considered in this study. It is noted that these thermal boundaries conditions are in accordance with Ref. [20].

In the heat transfer model, ten years of equivalent thermal loads mentioned in Section 2.1 are imposed on the pile to study the long-term behaviour of energy piles under different climatic conditions. The thermal load, as the heat source, is uniformly distributed across the pile domain, as depicted in Eq. (9). This practice is reasonable and feasible and is widely adopted to study energy piles[43,44] because of the small temperature difference between the inlet and outlet heat exchanger pipes.

2.3. Validation of the numerical model

This section verifies the feasibility of the simplified thermomechanical coupling method by model test. Song et al.[59] performed a laboratory model test to investigate the thermomechanical behaviour of the energy pile under multiple thermal cycles. A corresponding numerical model was established to compare the experimental and analytical values gap using the experimental model's geometry and relevant physical properties. The relevant parameters of the model experiment are as follows: effective pile length 0.7m, pile diameter 36 mm; pile body concrete elastic modulus is 6.7Gpa, thermal expansion coefficient is 18×10^{-6} m/^\circ C, weight is 24 kN/m$^3$; the soil around the pile is Fujian standard sand, the internal friction angle is 31 °, the unit volume weight is 17 kN/m$^3$. The pile top has only a loading device
with a deadweight of 60 N, and the pile top displacement is not limited. Three thermal cooling cycles with a target temperature of 10 °C are applied to the pile.

Figure 1 shows the variation curve of the test and simulated pile head displacement versus time. It can be seen from the figure that the simulated value of the displacement and settlement of the pile top is higher than the test value during multiple cooling cycles. As the thermal cycle increases, the irreversible settlement gradually accumulates, but the accumulation rate decreases. After the experiment, an irreversible settlement of 0.144% D (i.e., pile diameter) is generated on the pile head, which is close to the test value of 0.14% D. Therefore, given the comparison between simulation and experiment, the sequential thermomechanical coupling method can be confidently utilized to investigate the long-term performance (i.e., subjected to multiple thermal cycles) of energy piles.

![Figure 1. Results in comparison of pile head displacement](image)

3. Results of the three climatic conditions
A finite element model is employed to study the long-term thermomechanical behaviour of the energy piles installed in the three representative cities, which correspond to the three different climatic conditions. This section provides the results in terms of (i) pile and soil temperature fluctuations, (ii) pile axial thermal force distribution, and (iii) thermally induced pile head displacement.

3.1. Temperature fluctuations of the pile and surrounding soil
Figure 2 shows the temperature fluctuations at the midpoint of the pile versus the elapsed time. As shown in Figure 5, we can observe two types of thermal responses during the various thermal operations in the different cities: (i) in Charlotte, the maximum temperature variation of the pile induced by thermal injection and extraction during thermal operation has a small change magnitude compared with the two other cities, i.e., the pile exhibits the thermal balance phenomenon during thermal operations under balanced heating and cooling demand-dominated climatic conditions; (ii) the long-term temperature of the pile decreases and increases in Austin and Chicago, respectively, i.e., the thermal imbalance phenomenon of the pile is observed during operations under climatic conditions dominated by heating or cooling demands. The residual temperature variation of the pile installed in Charlotte is -2.3°C after ten years of thermal operation. The residual temperature observed in a city like Charlotte under balanced heating and cooling demand-dominated climatic conditions may account for the non-perfectly balanced heating and cooling thermal loads. In Austin and Chicago, the residual temperature variations are -6.7 and 10.2°C, respectively, within the typical temperature range (±15~20°C) of energy piles in the practical operation of energy piles[45].
3.2. Thermal axial force distribution of the pile

Figure 3(a), (b), and (c) show the thermally induced axial force at a pile depth of 6.5 m with the thermal cycle. The differences are considerable among the three cases; both the compressive and tensile strengths decrease in Austin and Chicago, while the compressive and tensile strengths increase in Charlotte. In addition, in Charlotte, the thermal cycles generate a larger thermally induced force than the cooling cycles. In Austin and Chicago, the maximum thermal forces during the tenth thermal cycle are 4.6% and 13.7%, respectively, of the imposed mechanical load, which are relatively smaller than those during Charlotte's tenth thermal cycle. Interestingly, as shown in Figure 8, it seems that the longer the energy pile system is operated, the greater the influence of the auxiliary thermal load on the residual thermally induced axial force is. Nevertheless, from the perspective of the axial forces induced by thermal operation, the conventional design method adopted under balanced heating and cooling demand-dominated climatic conditions may be very conservative when implemented under climatic conditions such as those of Austin and Chicago.
Normalized thermal axial force, $N_{th}/N_{mech}(\%)$

(a) Compressive

(b) Compressive

Time (year)

Normalized thermal axial force, $N_{th}/N_{mech}(\%)$

Tensile
3.3. Thermally-induced pile head displacement

Figure 4 depicts the thermally induced pile head displacement along with the elapsed time for the three climatic conditions. As shown in Figure 4, the pile head heave in Charlotte is observed during the first half of the year because of the thermal expansion of the pile. The thermally induced displacement reaches 15% of the mechanically induced settlement. It then decreases during the following cooling phase, in which thermally induced settlement of the pile head occurs. The maximum thermally induced settlement increases with the elapsed time during the subsequent thermal cycles but gradually declining growth rate. At the end of the tenth thermal cycle (i.e., the tenth year), the maximum thermally induced pile settlement reaches 21% of the mechanically induced settlement. The maximum thermally induced settlement has still not stabilized after ten years of thermal operation. The settlement growth rate gradually decreases without completely dissipating. In Austin (i.e., heating demand-dominated climatic conditions), the pile head is uplifted due to the thermal expansion of the pile. At the end of the thermal cycles, the pile heave is not recovered due to the residual temperature variations of the pile, resulting in irreversible pile head displacement. The final maximum pile displacement reached 48% of the mechanically induced settlement after ten years of thermal operation. In Chicago (i.e., cooling demand-dominated climatic condition), the pile head displacement induced by thermal shrinkage of the pile accumulates with the thermal cycle but also at a gradually declining cumulative rate without reaching zero.
4. Conclusions

In this paper, a comparative study is performed to elucidate the long-term behaviour of energy piles under different climatic conditions in terms of the temperature fluctuations of the pile and surrounding soil, thermal pile axial force, and thermally induced pile head displacement. The main conclusions are as follows:

(1) Compared to the initial state, the pile and surrounding soil residual temperature changes are significantly larger under the climatic conditions solely dominated by thermal demands, such as the heating or cooling demand, compared to balanced heating and cooling demand-dominated climatic conditions.

(2) The irreversible thermally induced pile head displacements under the climatic conditions of Austin and Chicago are much larger than those under the climatic conditions of Charlotte, and more time is required to reach the steady-state.

(3) The results show that applying the unified design method for energy piles subjected to different climatic conditions may affect the design effect. Furthermore, compared with thermal forces, more attention should be paid to the impact of the additional pile head displacement induced by thermal operation on the safe service of energy piles.

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