Numerical Modelling of Structural Response Characteristics of Energy Piles under Long-term coupled Thermo-Mechanical Loads

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Abstract. The structural response and bearing capacity of energy piles under heating and cooling conditions are investigated using COMSOL finite element software, and the reasonableness of the numerical simulation results is confirmed using experimental data from TPT tests in Tianjin Binhai Lake; the performance of energy piles under long-term load in winter and summer is also investigated using steady-state simulation. The results show that the cooling pile has a greater influence on the pile's axial load and axial strain, and that the settlement under thermal coupling is less than that of the pile in normal condition; in the steady-state simulation of the friction pile in long-term operation, the overall axial load under thermal condition is increasing compared to the pile subjected to structural load only, and that the settlement under thermal coupling is less than that of the pile in normal condition; the axial load on the upper portion of the pile is partially growing, while the axial load on the bottom part of the pile is greater than the force under structural stress alone, and the energy pile's lateral frictional resistance is increasing. In the case of cooling, the lateral frictional resistance of the pile body shows a pattern of decreasing in the top portion and increasing in the lower part.

1. Introduction

Energy pile [¹] has both heat transfer properties as heat exchangers and mechanical properties as the upper load of the structure, and has two characteristics. The load transfer characteristics and settlement of energy piles have been studied by domestic and foreign scholars using field tests, theoretical formulations and numerical simulations. Amatya [²] achieved fruitful results on pile-soil interaction and load transfer mechanism, summarizing the pile lateral frictional resistance and axial stress law under structural and temperature loads. By testing the strain distribution characteristics of end-bearing energy piles during operation, Cartney [³] pointed out that the degree of pile end restraint determines the form of pile strain distribution. Katsura [⁴] used the linear heat source model to simulate the temperature change of soil around the group pile, and improved the calculation speed by simplifying the algorithm while ensuring the accuracy. By summarizing the previous experiments and conducting field tests, Lu Hongwei [⁵] analyzed the bearing capacity characteristics and transmission law of frictional energy piles under the action of heat-force coupling. Guo Haoran [⁶] found that the change of load transfer law between the pile and soil during the heat transfer process of energy pile would affect the pile bearing capacity through numerical simulation. Liu Ganbin [⁷] used Abaqus software to
analyze the variation of pile bearing capacity with temperature. Laloui [8] used numerical simulation and experimental data to point out the need to consider the influence of hot and cold cycles on the pile body when designing energy piles. Nam [9] creat a three-dimensional numerical model of the U-shaped buried energy pile by the finite element method to consider the energy transfer process of the energy pile under the action of surface-air thermal convection and groundwater seepage. Wu Di [10] conducted model tests and numerical simulations on the load-bearing characteristics of single U-shaped buried energy piles. Suryatriyastut [11], Gashti [12] and Jeong [13] also carried out numerical simulations of the load transfer of energy piles by temperature variations.

A large amount of experimental shows that most of the pile-soil settlement curves is nonlinear[14], which makes the settlement of energy piles under thermal coupling still need to be further studied. In this paper, numerical modeling based on existing experiments is conducted to analyze the settlement and structural response of energy pile under the long-term coupled thermo-mechanical loads, which is used for the design of energy pile foundations.

2. Theory of Energy Piles under Long-term coupled Thermo-Mechanical Loads

2.1. Heat Transfer Theory of Energy pile

Heat transfer between concrete and soil and heat exchanger tube occurs through solid contact (heat conduction), heat transfer between tube wall and fluid occurs by heat conduction, and heat transfer within the fluid occurs through both heat conduction and heat convection.

When both heat conduction and heat convection processes present in the interior of the energy pile, the energy pile heat transfer control equation is:

\[
\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \nabla T + \nabla \cdot (-k \nabla T) = Q + Q_{\text{ted}}
\]

In the above equation, \( \rho \) is the pile density, kg/m\(^3\); \( c_p \) is the heat capacity J/(kg\(\cdot\)K); \( Q \) is the heat source, W/m; \( Q_{\text{ted}} \) is the thermal damping, W/m. The first term is the time accumulation term, which controls the accumulation of heat during the transient process; the second term is the conduction term, which represents the heat transfer process inside the energy pile; and the third term is the fluid convection term, which represents the process of fluid heat transfer inside the pipe.

The energy conservation equation for incompressible circulating fluid in an energy pile heat exchanger is:

\[
\rho A C_p \frac{\partial T}{\partial t} + \rho A C_p u e_T \cdot \nabla, T = \nabla, \cdot (A k \nabla, T) + \frac{1}{2} f_D \rho d_h^1 \rho u^2 + Q + Q_{\text{wall}}
\]

Where, \( u \) is the cross-sectional flow velocity, m/s; \( \rho \) is the density of fluid circulating in the pipe, kg/m\(^3\); \( C_p \) is the constant pressure heat capacity of the fluid, J/(kg\(\cdot\)K); \( T \) is the temperature of the fluid, K; \( k \) is the thermal conductivity of the fluid, W/(m\(\cdot\)K); \( Q \) is the generalized heat source, W/m; \( d_h \) is the hydraulic equivalent diameter, m.

\( f_D \) is the friction coefficient, which is used to calculate the pressure loss due to viscous shear and can be expressed as a function of Reynolds number and relative roughness. For Newtonian fluids, the Churchill formula can be used, as follows:

\[
f_D = 8\left(\frac{8}{\text{Re}}\right)^{1.2} + (A + B)^{-1.5}
\]

Where:

\[
A = [-2.457 \ln\left(\left(\frac{7}{\text{Re}}\right)^{0.5} 0.27\left(\frac{e}{d}\right)\right)]^{16} \quad B = \left(\frac{37350}{\text{Re}}\right)^{16}
\]
Q\text{wall} \text{ is the heat exchange between the circulating fluid inside the heat exchanger through the tube wall and the outside world, W/m, which can be calculated according to the following formula:}

\[ Q_{\text{wall}} = (hZ)_{\text{eff}} (T_{\text{ext}} - T) \] (5)

Where, h is the total heat transfer coefficient, W/(m²·K), consisting of three components including, internal film resistance, tube wall film resistance and external film resistance; Z is the average perimeter considering the heat exchanger wall thickness, m; T\text{ext} is the heat exchanger tube wall external temperature, K; (hZ)\text{eff} is the average effective thermal conductivity.

### 2.2. Principal mechanical model of energy pile

Energy piles using thermoelastic principal structure model\(^{[15]}\):  

\[ \sigma_{p,ij} = \frac{1}{1+\mu_p} (\varepsilon_{p,ij} + \frac{\mu_p}{1-2\mu_p} \varepsilon_{p,v} + \frac{1+\mu_p}{1-2\mu_p} \alpha_p \Delta T_p) \] (6)

In the above equation, \( \sigma_{p,ij} \) is the pile stress; \( \varepsilon_{p,ij} \) is the pile strain; \( E_p \) is the pile modulus of elasticity; \( \mu_p \) is the Poisson's ratio of the pile; \( \varepsilon_{p,v} \) is the pile body strain; \( \alpha_p \) is the pile thermal expansion/shrinkage coefficient.

The equilibrium equation of the pile unit is expressed as:

\[ \sum_{j=1}^{3} \frac{\partial \sigma_{p,ij}}{\partial x_j} + \rho_p g_i = 0 \] (7)

where, \( \rho \) is the density of the pile, kg/m\(^3\).

The relationship between pile displacement and strain is:

\[ \varepsilon_{p,ij} = \frac{1}{2} \left( \frac{\partial u_{p,j}}{\partial x_j} + \frac{\partial u_{p,i}}{\partial x_i} \right) \] \[ \varepsilon_i = \sum_{j=1}^{3} \varepsilon_{i,j} \] (8) (9)

### 3. Structure Response of Energy Pile under Thermo-Mechanical Loads

#### 3.1. Model Validation

To verify the reasonableness and correctness of the numerical simulation results in this paper, the structural response of the energy pile under thermal coupling were analyzed by comparing the literature\(^{[16]}\) about the TPT tests results of the energy pile in Binhai Lake, Tianjin with the calculated results in this paper.

The TPT test simulates the performance of the energy pile under year-round operating conditions, including continuous heating for 24 hours (inlet fluid temperature 35°C), recovery for 24 hours, cooling for 24 hours (inlet fluid temperature 5°C), and recovery for another 24 hours, with a circulating fluid flow rate of 0.8 m\(^3\)/h. As shown in Figure 2:
Figure 1. Schematic diagram of simulated working conditions

Monopile is simulated in this paper. The pile is cylindrical, as shown in Figure 2, with a length of 43 meters and a diameter of 0.7 meters. Due to the need to model long-term load and temperature effects in order to fully meet the criteria of pile body force calculation accuracy, the energy pile buried pipe is of the double U tandem type; the buried pipe diameter is 36mm, and the soil heat transmission range is 14m×14m×55m. The constraint form is that restrict the horizontal displacement of the soil body around the boundary and the bottom boundary.

This paper sets material parameters based on soil samples drilled at the test site. The geotechnical boundary temperature is constant at 14.6°C[16]. The parameters of the pile body and soil are shown in Table 1. Energy pile adopts each homogeneous elastic model, and the soil on the pile side adopts the Drucker-Prager criterion and matches the Mohr—Coulomb criterion.

Table 1. Material parameters of piles and soils.

| Material | P (kg/m³) | k (W/(m ⋅ K)) | Cₚ (J/(kg ⋅ K)) | E (GPa) | μ | α (με/℃) | Cᵤ (kPa) | Φ ° |
|----------|-----------|---------------|------------------|---------|---|---------|---------|-----|
| C40      | 2300      | 2.78          | 880              | 32.5    | 0.25 | 10      | -       | -   |
| Soil     | 1850      | 1.54          | 1340             | -       | -   | -       | 20      | 35  |
Figure 2. Energy pile, pile-side soil and buried pipe grid division

Figure 4 compares the experimental results of temperature, axial force, thermal stress, and axial strain variations along the depth direction of the energy pile in the TPT test to the simulated results when a load of 3000 kN was applied to the pile at the top.

(a) temperature[℃]
(b) axial load[kN]
(c) thermal stress[MPa]
(d) axial strain[με]

Figure 3. TPT 5℃ and 35℃ simulation versus experimental results

The numerical simulation results are consistent with the distribution of axial load, stress, temperature, and thermal stress in the pile body, as shown in the following four figures. Although the numerical simulation results differ from the field test in some ways, the change trend is essentially the
same, and the numerical simulation results are consistent with the distribution of axial load, stress, temperature, and thermal stress in the pile body. The influence of material characteristics and groundwater could be the cause of the discrepancy in results.

The simulated pile depth is 43 meters, the soil layer changes dramatically, the geological circumstances are complex, and the thermal characteristics of the soil are influenced by a variety of elements, therefore there are discrepancies.

In conclusion, the numerical model findings are reasonable and can be used as a reference basis for engineering reality.

3.2. Structure Response under Long-term Temperature Load

Within 24 hours, the non-steady-state pile thermal coupling analysis was completed using the above numerical simulation analysis of energy pile based on experiments. When the experimental data are compared to the numerical simulation results, it is clear that the numerical model results are reasonable and can be utilized as a reference foundation, despite minor deviations.

The Tianjin Binhai area is part of an artificially modified marine sedimentary plain, and lateral friction resistance is important when a pile is loaded. In this paper, a steady-state simulation is performed for a temperature increase of 5°C when the inlet water temperature is increased from 5°C to 35°C, and the penalty function of the pile-soil contact pair is modified to simulate this.

![Figure 4](image_url)

**Figure 4.** Structure response of piles under inlet water temperature increased from 5°C to 35°C

The lateral frictional resistance and axial load of the pile body under long-term loading are shown in Figure 4(a)(b). Figure 4(a) demonstrates that, under the heat condition, the lateral frictional
resistance of the energy pile decreases at the top and increases at the bottom, with the neutral plane as the dividing line, as compared to the pile subjected merely to structural loads. In the case of cooling, however, the lateral frictional resistance of energy heaps increases towards the top and decreases at the bottom. With inlet water temperature, the maximum variation in pile lateral friction resistance is 2 kPa/°C. Under the heat condition, the axial load on the pile body as a whole tends to increase, the axial load on the upper part of the pile body partially increases, and the axial burden on the bottom portion of the pile body is more than the force under the structural load alone, as shown in Figure 4(b). In the case of cooling, the axial load on the top part of the pile continues to rise, but the axial stress in the lower section of the pile is lower than the force acting solely on the structural load. Although cooling lowers the level of the load-bearing pile, there is no tensile stress in the pile, which is consistent with Amatya and Bourne-calculation Webb's model and has some reference importance. The axial load on the pile might vary by up to 100 kN/°C depending on the inflow temperature.

Figure 4(c) shows the temperature and axial displacement of the pile body under long-term loading, respectively. Figure 4(c) shows that the magnitude of heat transfer of the energy pile increases with the increase of the inlet water temperature under the long-term heating condition, in the order of 2°C, 2.5°C, 4°C, and 5°C, and the magnitude of heat transfer of the energy pile increases with the decrease of the inlet water temperature under the long-term cooling condition, in the order of 2°C and 2.5°C. The results show that the magnitude of heat transfer increases with the difference between the inlet water temperature and the initial temperature, and the heat transfer efficiency increases; Figure 4(d) shows that the expansion/contraction of the pile occurs under heating and cooling conditions, and therefore positive/negative axial displacement increments occur, respectively. The results show that the structural load and the surrounding soil severely limit the pile deformation, with the expansion of the pile under heating conditions and the load limitation at the top of the pile, together with the additional thermal stresses on the bottom soil, leading to a decrease in the axial displacement at the top of the pile and an increase in the axial displacement at the bottom of the pile, and the opposite under cooling conditions. The sudden change in axial displacement occurs at 3/4 of the pile body. The displacement increase at the top of the pile is the largest, with displacement increment at 0.2 mm/°C. With the increase of depth, the axial displacement increment gradually decreases, and the displacement increment at the bottom of the pile is only about half of that at the top of the pile.

3.3. Bearing Capacity of Energy Piles

![Figure 5. Q-s curve of energy pile compared with normal state](image-url)
Figure 5 shows the Q-s curves of load versus settlement for the energy pile in the steady state with thermal coupling versus the normal state. The simulation results show that the state is linear from 2000kN to 6000kN, and nonlinearity starts to appear from 6000kN to 8000kN, and the elastic going and plastic zones coexist, i.e., the pro-plastic load appears in this interval, followed by a significant increase in pile settlement. Due to the overall increasing trend of axial pile load under thermal condition, the pile settlement in thermodynamically coupled state is smaller and the critical edge pressure is larger compared to the normal state. Compared with the actual field results, the overall trend of numerical simulation results is consistent and the settlement error is within a reasonable range.

4. Conclusion
To better reflect the bearing characteristics of energy piles under long-term coupled thermo-mechanical loads, this paper compares the results of existing TPT tests and simulates a consistent trend of temperature, axial force, thermal stress, and axial strain changes along the depth direction of the energy pile.

(1) In a non-stationary simulation, the discrepancy between the heating pile and numerical simulation results is minor, and the trend is consistent; the cooling pile and numerical simulation results have some differences, but the trend is consistent. The cooling pile has a bigger effect on the axial load and axial strain of the pile than the heated pile.

(2) In the heated case, the axial load as a whole tends to increase, and the axial load on the upper part of the pile increases partially, while the axial load on the lower part of the pile is more than the force under the action of structural load alone, and the latera tends to increase. In the case of cooling, the converse is true. In contrast to the normal state, the pile settlement in the thermodynamically coupled state is smaller, and the critical edge pressure is higher in the steady-state simulation.

(3) In a long-term steady-state simulation, the highest variation in pile lateral friction resistance with changing water inlet temperature is about 2kPa/°C, while the maximum variation in pile axial load with changing water inlet temperature is around 100kN/°C. When heated, the top axial displacement decreases and the bottom axial displacement increases; when cooled, the sudden change in pile axial displacement appears at 3/4 of the pile; the displacement increase at the top of the pile is the largest, and the displacement increment is 0.2mm/°C; with the increase of depth, the axial displacement increment gradually decreases.

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