Thermo-Hydro-Mechanical Numerical Analysis of Energy Pile in Saturated Clay

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Abstract. In order to study the mechanical properties of energy piles under long-term heat injection-heat extraction cycle loading conditions, the influence of temperature on the mechanical properties of foundation soils needs to be considered. The subroutine of an elastic-plastic constitutive model of soil considering the influence of temperature is developed in Abaqus. Finally, the changes of additional pile top displacement, lateral friction resistance and axial force of energy pile under long-term heat injection-pumping cyclic loading under different loads and different soil parameters under the same load are discussed. The results show that: (1) The soil around the pile is subjected to plastic deformation due to the expansion and contraction of the pile. The higher the load on the pile top is, the greater the additional temperature settlement generated at the pile top is. (2) Under 0.5PU load, the increase of OCR, swelling index or permeability coefficient of foundation soil will cause the decrease of additional settlement of pile top. And the additional side friction and axial force, plastic parameters or soil permeability coefficient increases will produce greater additional side friction and axial force. This study has certain significance for the long-term use of energy piles.

1. Introduction

Energy pile is a new type of pile which is filled with heat exchange tubes in traditional heat pump devices. At the same time, the new pile plays a role of heat exchange and bearing the load of the upper building. Due to its multi-functional advantages and the characteristics of energy conservation and environmental protection, it has attracted wide attention [1-4]. Lu et al.[5] studied the influence of combined action of temperature and load on the mechanical properties of single friction energy pile through the experimental data of pile body temperature, axial force and pile top settlement measured under multi-level load and heat exchange. The test results show that the applied load on the pile top and the constraint on the pile end will affect the additional axial force of the energy pile temperature. Kong et al.[6] carried out the model experiment of energy pile, and carried out the cold and hot temperature cycles of two kinds of piles under working load and without load. The experimental results show that the residual settlement at the top of the pile without load is about 10 % of that under working load after a temperature cycle. After many thermal-cold cycles, the pile settlement will continue to accumulate. Huang et al.[7] proposed a new calculation model for heat transfer of spiral buried pipe rock-socketed energy pile. The calculation results show that the additional temperature of soil changes greatly in the range of double pile diameter at pile top and bottom.

NG et al.[8] used a new heating and cooling system to control the cycle temperature of energy piles in centrifuges. Through the system, the settlement changes of energy piles are studied when the
foundation soil is lightly consolidated kaolin and heavily consolidated soil. Based on the summary of a large number of temperature-controlled triaxial shear tests, it is found that the shear strength of the soil increases (thermal hardening) after heating. And it can also be shown as the weakening of shear strength (thermal softening). Based on the UH model, Yao et al. calculated the critical state parameters of soil at different temperatures by determining the potential strength of overconsolidated soil. Zhou & N.G. improved the complementary unified critical state model, in which the influence of temperature on the parameters of preconsolidation pressure and spacing ratio was considered, and a constitutive model considering the effect of temperature was constructed. Xiong et al. constructed a new constitutive model based on the subloading yield surface modified cam-clay model, which consider the influence of temperature on preconsolidation pressure and critical state parameters. It can uniformly describe the thermal hardening and thermal softening characteristics of soil with different overconsolidation ratios.

In order to deeply understand the influence of mechanical properties of foundation soil on energy pile performance, this paper compiles the soil constitutive theory proposed by Xing et al. based on the secondary development function of UMAT constitutive subprogram of ABAQUS. Finally, the numerical simulation analysis of energy piles with different soil mechanical parameters under different loads and the same load is carried out, which is under the long-term heat injection-extraction cycle load. The numerical analysis results can provide certain reference value for the design of energy piles.

2. Unified elastic-plastic model of thermal hardening and thermal softening

2.1. Model yield surface

In order to consider the influence of temperature on the preconsolidation pressure and critical state parameters of soil, Xiong et al. proposed a new thermoelastic-plastic constitutive model based on the modified Cam-clay model of the lower load surface. The yield surface function is expressed as following:

\[ f_T = \ln \frac{p}{p_0} + \ln \left( \frac{q^2}{M^2 p^2} + 1 \right) - \frac{1}{C_p} \left( \varepsilon_p^p - \rho_T \right) = 0 \]  

\( f_T \) is the load function, \( p \) is the average principal stress, \( p_0 \) is the reference average principal stress, \( q \) is the deviatoric stress, \( C_p = \left( \lambda - \kappa \right) / \left( 1 + e_0 \right) \), \( \lambda \) is the compression index of the soil, \( \varepsilon_p^p \) is the plastic volumetric strain, \( M = M_q + g \left( T - T_0 \right) / T_0 \), \( \rho_T \) is the void ratio difference between the overconsolidation state and the normal consolidation state after heating, and its expression is as follows:

\[ \rho_T = \left( \lambda - \kappa \right) \ln OCR_T \]  

where, \( OCR_T \) is the ratio of \( p_i / p_T = p_{i0} \exp \left( \frac{3\alpha_1 \left( T - T_0 \right) \left( 1 + e_0 \right)}{\kappa} \right) / p_i \), \( p_{i0} \) is the initial average principal stress.

2.2. Plasticity factor and flow rule

The model uses the combined flow rule to calculate the plastic strain:

\[ d\varepsilon^p = A \frac{df_T}{\varepsilon_p^p} \quad d\varepsilon^\varepsilon = A \frac{df_T}{\varepsilon_p^\varepsilon} \]  

where, \( A \) is the plastic factor, which is a positive scalar and can be calculated by the coordination equation:

\[ A = \frac{\frac{\partial f_T}{\partial \varepsilon_p^p} \cdot d\varepsilon_p^p - \frac{\partial f_T}{\partial \varepsilon_p^\varepsilon} \cdot \frac{2q^2}{M_q^2 + M^2 p^2} \cdot dT}{C_p \frac{\partial f_T}{\partial \varepsilon_p^p} \frac{\partial \rho_T}{\partial \rho}} \]  

\( C_p \) is the constrained critical state parameter.
where, \( \tilde{p} = p \exp \left( \frac{3\alpha_T (1 + \epsilon_0) (T - T_0)}{\kappa} \right) \), \( a \) is the development control parameter of over-consolidation ratio to control the development rate of over-consolidation ratio.

2.3. Loading and Unloading Conditions of the Model

The loading and unloading conditions of the model are:

\[
\begin{align*}
\text{Loading:} & \quad \| \partial \varepsilon \| > 0, \\
& \quad A > 0, \frac{\partial f_1}{\partial \sigma_y} d\sigma_y > 0 \quad \text{Hardening} \\
& \quad A > 0, \frac{\partial f_2}{\partial \sigma_y} d\sigma_y < 0 \quad \text{Softening} \\
\text{Unloading:} & \quad \| \partial \varepsilon \| = 0, \quad A \leq 0
\end{align*}
\]

2.4. Summary of model parameters

The subloading yield surface modified cam-clay model parameters are \( \lambda \), \( K \), \( e_0 \), \( M \), \( \nu \) and \( a \). On this basis, the new model adds two temperature-related parameters, namely the critical state development control parameter \( g \) and the soil linear thermal expansion coefficient \( \alpha_T \).

3. Realization of secondary development of model

3.1. UMAT subroutine writing process

The writing process as shown in Figure 1.

![Figure 1 UMAT subroutine procedure](image)

This paper uses the explicit second-order algorithm to carry out the secondary development of the constitutive model. In this method, each step of strain increment is subdivided into many sub-step increments:

\[
\{ \Delta \varepsilon_{str} \} = \Delta T \{ \Delta \varepsilon \} \quad \text{\textcopyright MERGEFORMAT (6)}
\]
where, $\Delta \xi_i$ is the size of the second order, $\Delta \epsilon_i$ is the strain increment of an incremental step. $\Delta T$ to control the size of each order, which is $0 < \Delta T < 1$. Therefore, we only need to control the error of $\Delta T$ to control the error of the whole order. The methods for controlling errors include Euler method, modified Euler method and Runge-Kutta method. The modified Euler method is used here, and the detailed introduction of Potts[18] is shown.

4. Energy pile example analysis

4.1. Overview of calculation examples

The size of the pile-soil model is 40 m×40 m×30 m(L×B×H), the radius of the pile is $R = 0.5$ m, and the length of the pile is $L = 20$ m, which is modeled by 1/4. In order to reflect the actual working conditions, this simulation first considers the superstructure construction, and then starts the heat exchange. The time of a temperature cycle is set as one year, and the change of temperature curve is affected by seasonality, as shown in Figure 2 (a). Since this paper focuses on the influence of temperature cycle on the mechanical properties between piles and soils, the internal part of the pile will no longer be refined, and the temperature boundary is directly set outside the pile. The thermophysical parameters of pile soil are listed in Table 2.

| Table 1 Material parameters of silt |
|-------------------------------------|
| $\nu$ | $M$ | $\lambda$ | $\kappa$ | $\rho_0$ | $g$ | $\alpha/\text{C}^{-1}$ | $a$ |
| 0.30 | 1.2 | 0.09 | 0.006 | 0.68 | 0 | $-6.0 \times 10^{-6}$ | 5000 |

| Table 2 Thermo-physical parameters of piles and soils |
|-----------------------------------------------|
| Thermal conductivity | Density | Heat capacity | Thermal conductivity | Density | Heat capacity |
| W/(mk) | kg/m$^3$ | J/(kgk) | W/(mk) | kg/m$^3$ | J/(kgk) |
| Sand | 1.2 | 2200 | 1500 | Pile | 2.95 | 2500 | 960 |

Figure 2 Temperature condition and Load-displacement curve of pile

The lightweight overconsolidated clay with OCR of 2 was selected for simulation, and the parameters were taken from the model parameters used by Xiong et al. to simulate the shear test of the soil sample at different temperatures. The effective saturated weight of soil is 12 kN/m$^3$, and the permeability coefficient is $5 \times 10^{-8}$ m/s. The pile adopts linear elastic model, its modulus is 20GPa, Poisson's ratio is 0.2. Pile-soil interface adopts penalty function model with friction coefficient of 0.4. And the whole soil is saturated soil, the top of the model drainage. According to the simulation content, the calculation process can be divided into three parts. The first part is the balance of ground stress, the second part is the loading of superstructure load, and the last part is the temperature cycle of ten years. Figure 2 (b) is the load-settlement curve of single pile. It can be seen from the figure that the corresponding load PU at the inflection point is 2200 kN.
4.2. Overview of calculation examples

4.2.1. Temperature response Figures 3 (a) and (b) show the temperature variation over time at each point in the middle and bottom of the pile. From Figure 3 (a), it can be found that the point closer to the pile axis has higher temperature amplitude. And the point far away from the axis, its amplitude is small, and relative to the point near the axis, the maximum amplitude appears at a time lag phenomenon. This is because it takes a certain time for the pile to transmit to the surrounding soil after heating. The temperature variation law of each point at the pile bottom is similar to that of several points at the pile side. It can be seen from Figure 3 that in the range of 5.65 m from the pile side and 4 m from the bottom of the pile, the influence of pile heat transfer is very small.

![Figure 3 Temperature curve of each point of soil around the pile body](image)

4.2.2. Mechanical response of energy pile under different pile top loads In order to study the change of mechanical properties of energy pile after long-term thermal cycle loading under different loads, four different loads of 0.25 PU, 0.5 PU, 0.75 PU and PU were applied to the top of the pile, and then the numerical analysis and comparison of ten temperature cycles were carried out. Figure 4 (a) shows the variation of additional displacement of pile top caused by temperature cycle under four working conditions that after removing the influence of load on pile top. It can be seen from the diagram that when the pile top bears different loads, the displacement changes are obvious. The greater the load on the top, the more obvious the settlement changes of the pile top after multiple temperature cycles. According to《Technical specification for building pile foundation》(JGJ94-2008)[19], the safety factor of vertical bearing capacity of pile foundation is usually taken as 2, so the maximum design load is 0.5PU. At this time, the changes of the lateral friction and axial force of the energy pile in the first and tenth temperature cycles with the pile are shown in Figs. 4 (b) and (c). It can be seen from the figure that due to the load transferred by the superstructure after construction, the lateral friction resistance shows a gradual increase with the increase of the distance to the pile top, and the maximum value is 28.8 kPa. The exertion of side friction resistance in Figure 4 (b) is closely related to the change of axial force. If the side friction increases, the temperature causes the positive friction and the axial force decreases. On the contrary, the axial force increases. When the energy pile is heated for the first time and the tenth time, the lateral friction of the upper part of the pile body decreases, and the change in the latter time is greater. The axial force increases after two heating. In terms of cooling, the axial force becomes smaller after the first cooling. After the tenth cooling, the axial force of the upper part increases due to the change of the relative trend of pile-soil displacement.
4.2.3. Effect of Different Soil Parameters on Mechanical Response of Energy Piles

The changes of pile top settlement, lateral friction and axial force of energy pile are related to the mechanical properties of foundation soil. Due to the limited space, this section will only discuss the influence of the following three parameters (OCR, rebound index and soil permeability coefficient k) on the performance of energy pile. In the numerical simulation, the bearing performance of 0.5PU was analyzed. Figure 5-7 is the comparison of calculation results. The displacement, lateral friction resistance and axial force in the figure are all additional quantities caused by temperature load, which are not repeated later. It can be seen from Figure 5 (a) that there is a significant difference in the settlement between the two after ten temperature cycles. The soil at the pile end is a process of loading and unloading when the pile is subjected to thermal expansion and heat extraction shrinkage. When other parameters remain unchanged, the greater the OCR, the higher the shear strength of the soil, so the settlement change of the pile top under the condition of OCR = 4 is smaller. The additional side friction and axial force have little change.

In the modified Cam-Clay model, the value of $\lambda - \kappa$ determines the plastic strain of soil after being subjected to external load, and a plastic parameter $\zeta = \lambda - \kappa$ is defined here. When the $\lambda$ remains unchanged and the $\kappa$ increases, the plastic deformation of the soil decreases, so the settlement of the pile top of the example affected by temperature is smaller, as shown in Figure 6 (a). When the value of $\kappa$ is smaller, the plastic deformation of soil is relatively small, resulting in the decrease of relative sliding displacement between pile and soil. Therefore, the smaller the value of $\kappa$ is, the larger the pile body friction will be, and thus the magnitude of axial force will change accordingly.

The permeability coefficient of soil is also a factor that cannot be ignored. If the permeability coefficient is small, the excess pore pressure caused by temperature will be difficult to dissipate in time. This will reduce the effective stress of the soil on the pile side, resulting in an increase in the additional displacement of the pile top. At the same time, it will also weaken the lateral friction and reduce the additional axial force, as shown in Figure 7.
The Journal is foundation Chinese) Gang-qiang, Gang, In-situ Towards C, and Zhejiang of thermo-elastic-plastic generated 52(12) T, written Natural the GUNAWAN thermo-mechanical permeability of Province increase soil pile. explicit al. cycles plastic after constitutive LORIA the after is Behaviour Considering (in was and Rock algorithm tests of under stress of 958-964. energy the geothermal research 0.5PU Hong-wei, Mechanical permeability piles[J]. larger friction China -100 is. formula. subjected -10 axial Heat of the of L. of the software the 200 under MIMOUNI load that deformation of Chinese) of a Transfer L. Science thermo-mechanical to additional force side and will the of the OCR, energy the axial Euler and of the heating, the LALOUI in of Wen-hua. by of the OCR, energy the axial Energy index the soil of the heating. LALOUI in of of the LIU al. 78 axial secure secondary top expansion Geotechnical Computers Engineering energy the Chinese) supported of the OCR, HUANG 1102-1107. the of the LIU loads[J]. 2015, group of pile Computers Engineering cycling[J]. and the soil of the OCR, swelling index and coefficient of permeability are compared. The increase of OCR, swelling index or permeability of foundation soil will cause the decrease of additional pile top settlement. And the additional side friction and axial force, plastic parameters or soil permeability increases will produce greater additional side friction and axial force.

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