Numerical Simulation Research on Multi-field Coupling of Underground Energy Pile

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Abstract. The bearing capacity of the pile foundation determines the safety and stability of the upper structure. However, during the thermal cycling of the energy pile, the stress of the pile will be changed due to temperature changes, which will affect the bearing capacity of the energy pile foundation. In order to analyze the mechanical properties of the energy pile under multi-field coupling, the finite element software COMSOL Multiphysics is used to establish the thermal-mechanical coupling analysis model of the energy pile. We apply thermal load on the pile body and vertical load on the top of the pile. The results show that: Under the multi-field coupling of temperature and mechanical load, the energy pile body expands when heated, and the displacement of the pile top decreases; this will cause uneven settlement between the energy pile foundation laying the heat exchange tube and other pile foundations, which will lead to the tilt and damage of the superstructure; the stress of the pile during the heating of the energy pile will increase.

1. Introduction
With the limitation of national resources and the increasingly prominent environmental problems, the use of non-renewable resources such as coal will cause serious environmental pollution. Using green, renewable and clean energy to replace traditional coal energy has become one of the mainstream topics today. The pile foundation buried source heat pump system, also known as energy pile or energy pile, is based on the heat exchange of the buried heat pipe, and heat exchange pipelines are placed inside the pile foundation to save cost and space[1]. Energy pile is currently the most widely used form of energy underground structure, and it has broad application prospects. There have been precedents for energy pile construction in many countries such as Australia, Austria, Germany, and Switzerland. Our country also follows closely, and has developed the underground energy pile structure vigorously.

However, the temperature change of the energy pile during the thermal cycling will cause additional stress and deformation of the pile foundation. Therefore, the temperature load affects the bearing capacity of the pile foundation and causes uneven settlement of the pile foundation. Numerical simulation has been widely used in ground-source heat pumps. Wang Binbin et al. [2] established a numerical calculation model of energy pile-temperature effect, and obtained the settlement curve of a single energy pile under continuous thermal cycling conditions by numerical simulation. The curve shows that under long-term load, the settlement of the pile top will change periodically and gradually accumulate, which may result in larger settlement or larger uneven settlement. Zhao Haifeng [3] used finite element software to analyze and show that the lateral contraction or expansion of the energy pile
under the action of temperature load changed the contact relationship between the energy pile and the surrounding soil. This will cause irreversible settlement of the energy pile, which will affect the superstructure. With the development of buildings in the future, more heat will inevitably be injected and stored underground, which will cause greater temperature changes in the soil and piles. Therefore, it is necessary to do an in-depth study on the thermal-mechanical coupling of energy piles.

The mechanical properties and deformation of the energy pile under thermo-mechanical coupling are key issues in the study of energy pile bearing capacity changes and safety evaluation. The design of energy piles in our country did not consider the response of temperature and mechanical load, which weakens the safety of energy piles to a certain extent. The mechanical properties of energy piles are related to many factors, such as liquid flow velocity in buried pipes, buried pipe types, temperature, pile top load, pile tip restraint, soil conditions, etc. From the current point of view, the research on the mechanical properties of energy piles under temperature load is still not deep enough, and further research is needed.

This paper used finite element software to systematically study the displacement of the pile top and the change of the pile body stress under the multi-field coupling. In order to evaluate the safety of energy piles, we used numerical simulation to study the changes of the bearing capacity of the energy pile foundation under thermal-mechanical coupling, and judged the safety of the energy pile.

2. Establishment of Thermal-mechanical Coupling Model of Energy Pile

2.1. Overview
In order to analyze the mechanical properties of energy piles under thermal-mechanical coupling, a two-dimensional axisymmetric analysis model was established. A vertical load was applied to the top of the energy piles. The finite element software was used to calculate the displacement of the pile top and the change of the pile body stress with temperature. The calculated area of the established model is 6×6(20D)×32(2L)m in length×width×height, the pile diameter is 0.3m, and the pile length is 16m; the maximum size of the energy pile unit is 0.05m, and the minimum size is 0.03m; the maximum size of the soil around the pile is 0.6m, and the minimum size is 0.4m. The energy pile is buried in homogeneous air-dried sand. The boundary line heat source with a heat source of 27W/m² is used, and the line heat source is buried at a distance of 0.09m from the center of the pile. The upper constraint is not considered when calculating. Unit division adopts free triangular mesh, the maximum element size of the soil is 0.4m, the minimum element size is 0.2m; for pile element encryption, the maximum element size is 0.03m, and the minimum element size is 0.01m. The grid division is shown in Figure 1 and Figure 2.

Figure 1. Model meshing
Figure 2. Mesh division of pile elements
2.2. Choice of Constitutive Model

2.2.1. The constitutive model of pile material. Under the action of the applied pile top load, most of the energy pile strain has not entered the plastic stage, so the linear elastic constitutive model of pile concrete is selected in COMSOL Multiphysics.

2.2.2. Constitutive model of soil material. Since the strain of the soil under the load is small, the soil around the pile adopts Duncan-Zhang’s E-B constitutive model. The expression of the E-B model in the Duncan-Chang model is:

\[ E_1 = K\frac{\sigma_3}{P_a} \left[ \frac{1}{2} R_f \left( \frac{\sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} \right) \left( 1 - \sin \varphi \right) \right]^2 \]  

In the formula: K, n are dimensionless base and dimensionless exponent, which are the intercept and slope of the \( \log \left( \frac{E_1}{P_a} \right) \) and \( \log \left( \frac{\sigma_3}{P_a} \right) \) lines respectively; \( \varphi \) is the strength angle of the soil; \( c \) is the cohesion of the soil; \( R_f \) is the failure ratio, It is obtained by formula (2).

\[ R_f = \frac{(\sigma_1 - \sigma_3)_f}{(\sigma_1 - \sigma_3)_\text{ult}} \]  

\( (\sigma_1 - \sigma_3)_f \) is soil strength; \( (\sigma_1 - \sigma_3)_\text{ult} \) is limit deviation stress of soil.

In the considered project, all material properties are considered independent of temperature[4].

2.3. Boundary Conditions and Initial Conditions

In the solid mechanics module, the pile-soil contact is realized by applying a coupling spring formed by a normal spring and a tangential spring to realize the interaction between the pile element and the soil element, and the spring and the energy pile are in complete contact. The spring stiffness of the tangential spring and the normal spring refer to the research of Gennaro [5] and others using 2×10^6 N/m and 6×10^6 N/m, the top of the soil body and the pile top are free and unconstrained. The bottom of the soil body adopts a fixed constraint. The pile body is surrounded by a roller support boundary, which limits the horizontal displacement and allows vertical displacement. As it is assumed that the soil used is air-dried sand, and the influence of groundwater is not considered, the heat exchange between the energy pile and the soil around the pile is heat conduction. The equation for heat conduction between the pile and the soil is shown in the following equation (3). The surrounding soil adopts solid heat transfer modules to realize heat transfer.

\[ \rho C_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q \]  

Among them, \( \rho \) is the material density; \( C_p \) is the atmospheric heat capacity; \( k \) is the thermal conductivity; Q is the heat source.

2.4. Model Parameter Selection

The currently applied energy piles have a temperature load range of 2-30°C; it will not cause significant changes in the thermal expansion coefficient of the pile concrete and the soil parameters around the pile[6], therefore, in the finite element analysis and calculation, it is assumed that the thermal expansion coefficient of the pile body and the parameters of the soil around the pile are
always constant. The parameters adopted by the Duncan-Chang E-B model of sand are selected in reference[7], and the specific parameters adopted are shown in Tables 1 and Tables 2 below.

| Table 1. Sand Duncan-Chang E-B model parameter values |
|------------------------------------------------------|
| Parameter      | K  | n  | c/kPa | φ  | Rf | Kb    | m    |
| Value          | 215.5 | 0.920 | 6     | 31 | 0.613 | 151.010 | 0.075 |

| Table 2. Parameters of sand and energy piles |
|-----------------------------------------------|
| Material parameters                          | Energy pile concrete | Sand |
| E MPa                                        | 33×103               | 78   |
| λ [W/(mK)]                                   | 1.7                  | 0.25 |
| C_p [J/(kg/K)]                               | 930                  | 930  |
| ρ(kg/m³)                                     | 2200                 | 2650 |
| ν                                            | 0.25                 | 0.3  |
| α                                            | 16×10-6              | 10×10-6 |

3. Displacement and Stress Response of Energy Pile under the Coupling of Vertical Load and Temperature

Figures 3, Figures 4, and Figures 5 show the vertical displacement of the pile top with time when 3000kPa vertical load is applied to the top of the energy pile. At the same time, the displacement of each point along the vertical energy pile at 0d and 20d and the vertical stress of the energy pile along the depth curve can also be obtained. The stress changes along the depth curve. Under the action of a single vertical load, the calculated load on the top of the energy pile is 2.157mm.

In figure 3, we can see that under heating conditions, the vertical displacement of the top of the energy pile changes continuously. It indicated that the energy pile undergoes thermal expansion under the action of thermal load, and the pile top produces upward displacement. The displacement of the pile top continues to decrease and eventually stabilizes. On the 20th day, the displacement of the pile top was reduced to 2.147mm, and the temperature load caused the pile top expansion to rise by 0.01mm. It indicated that the displacement of the energy pile top was caused by thermal-mechanical coupling. The increase in the temperature of the energy pile will cause thermal expansion of the energy pile to reduce the displacement of pile top under the vertical load. This amount of expansion will cause the energy pile foundation with the embedded heat exchange tube to be different from other pile foundations. Uniform deformation results in tilting or destruction of the superstructure.

Figure 3. The displacement curve of the energy pile top under 3000kPa vertical load
Figure 4. The vertical displacement curve of each point of the energy pile top under a vertical load of 3000kPa

Figure 5 shows that the temperature load will generate temperature stress in the energy pile during heating, and the generation of temperature stress will make the pile body concrete bear greater compressive stress.

Figure 5. The vertical stress along the depth of the energy pile top under a vertical load of 3000kPa

4. Conclusion
This paper uses COMSOL Multiphysics establish a two-dimensional axisymmetric energy pile thermal-mechanical coupling model. The energy pile applies vertical load through the top of the pile and is heated by a linear heat source to study the thermo-mechanical characteristics of the energy pile. The following conclusions are obtained:
(1) Under the thermal-mechanical coupling effect of energy piles, when the temperature of the pile body increases, the displacement of the pile top decreases. This will cause uneven settlement between the energy pile foundation with heat exchange pipe and other pile foundations, which will result in tilting and destruction of the superstructure;
(2) Under the thermal-mechanical coupling effect of energy piles, when the temperature of the pile body rises, additional stress will be generated in the pile body, which will cause the pile body concrete to withstand greater compressive stress.

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6. References

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