## Finite element analyses of bearing performance of energy pile based on TTS model

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**Abstract.** Energy pile is an emerging geo-structure with heat transfer and bearing performances. Its bearing performance of energy pile could be significantly weakened due to temperature variations when transferring heat to the upper buildings. In this study, an advanced soil model named Tsinghua Thermodynamics Soil (TTS) model was integrated within a finite element (FE) program at plane-strain space to simulate the thermal-mechanical response of energy pile in saturated clays. The bearing performance of energy pile with different friction coefficients was firstly analysed. Then, the influences of drain/undrain conditions and heating-cooling cycles on the evolution of load-displacement curve were emphatically discussed. Finally, by analysing the evolutions of normal and shear stresses at pile-soil interface with temperature, an insight into the bearing performance of energy pile with consideration of thermal effect was provided.

## 1. Introduction

Energy geo-structure is an emerging underground structure for heat exchanging with the surrounding rock and soil. Such structures mainly include pile, wall and tunnels, etc. Among which, the energy pile with a novel heat exchanger configuration, is most widely used since it facilitates efficient utilization of shallow geothermal energy and contributes to underground space savings [1]. The pile is developed to make use of the high thermal storage capacity of concrete and heat exchange area of soils by installing heat exchange tubes into pile instead of drilling hole, making it more cost-effective than conventional systems. The application of energy pile has spread throughout the world. For example, the new terminal of Zurich airport utilizes 300 energy piles to meet the buildings’ 65% heating and 70% cooling needs; Landsea International Block in Nanjing uses 1200 energy piles to save 40% energy consumption; Hamburg Pavilion at Shanghai World Expo and Xuri Building at Tongji University also use energy pile for energy supply.

During the operation of energy pile, temperature variations and heating-cooling cycles will inevitably induce changes in the thermal field around piles and their surrounding soils, which would cause changes in the properties of pile-soil interface and further influence the bearing performance of the pile. A series of in-situ tests were conducted to investigate the thermal-mechanical responses of the energy piles [2-4]. Huang et al. [5] measured load-displacement curves at different temperatures and observed irreversible settlement occurring at pile head after heating-cooling cycle. Liu et al. [6] reported that the ultimate bearing performance of the pile reduced slightly after one heating–cooling cycle. Ng et al. [7]...
carried out in-flight pile load tests under three different temperatures (22, 37, and 52 °C) and different loading sequences. The results showed that the shaft resistance increased at a reducing rate with an increasing temperature; at a higher elevated temperature, toe resistance increased more rapidly than shaft resistance due to a larger downward expansion of the pile.

In the numerical studies conducted by Dupray et al. [8] and Di Donna et al. [9], the thermal-mechanical responses of energy piles were simulated based on the assumption that soils are thermal elastic or thermal elastic-prefect plastic materials. However, results obtained by a large number of elementary laboratory tests show that different types of soils (kaolin clay, soft clay, mud stone and soft rock) present irreversible deformation at elevating temperature, exhibiting obvious thermoelastic and thermoplastic behaviors [10-13]. The volumetric change of soils presents expansive or contractive behavior depending on the stress history. In this regard, the behavior of energy pile foundations during heating–cooling cycles were investigated by using thermoelastic-thermoplastic constitutive models [14, 15].

The TTS model is developed based on the framework of Granular Solid Hydrodynamics [16], aiming to provide more fundamental physical mechanisms for characterizing the complex thermal-mechanical coupling behavior of geomaterials with considerations of the critical state, time-dependent, anisotropic and hysteretic properties [17-19]. Based on the TTS model, Wang et al. [20] numerically investigated the thermal consolidation and creep of foundation soils; Zymnis & Whittle [21] revealed that significant settlements can be induced during the long-term operation of BHEs (i.e., over periods from 10–50 years). These achievements demonstrate incomparable advantages of the TTS model in investigating the thermal effects on foundation and structure.

In this study, after a brief review of TTS model framework and parameters, a fully coupled thermo-hydro-mechanical (THM) finite element (FE) program developed by Zhang et al. [22] was employed to simulate the thermal-mechanical response of pile in saturated clay. The influences of temperature and heating-cooling cycle on the load-displacement curve under drained/undrained conditions were analyzed. The evolutions of normal and shear stress at the pile-soil interface with elevating temperature were discussed. Finally, an insight into bearing performance of the energy pile with consideration of thermal effect was provided.

2. TTS model: A brief review

2.1. Thermoelastic behavior

The TTS model was proposed to describe the nonlinear thermoelastic coupling behavior of geomaterials based on the hyper-elastic theory. The stress-strain relationship of a material is obtained through a free energy function (elastic potential energy function), which is in accordance with the basic laws of thermodynamics. In the TTS model, a thermo-elastic coupling term defined as the elastic potential energy density, \( \omega_e \) (see Eq. 1) is introduced into the elastic potential energy function to describe the elastic thermal expansion of the soil skeleton with consideration of thermal influence (Zheng and Cheng 2017a).

\[
\omega_e = \frac{2}{5} B \left( \varepsilon_r^e + c \right)^2 \left( \varepsilon_r^e \right)^2 + B \zeta \left( \varepsilon_r^e \right)^2 \left( \varepsilon_r^e + c \right)^{1.5} + \int 3K_c \beta_T \Delta T d\varepsilon_r^e
\]

where, \( B = B_0 \exp(B_1 \rho_d) \); \( B_0, B_1, c \) and \( \zeta \) are material parameters; \( \Delta T = T - T_0 \) is the temperature increment; \( T_0 \) is the reference temperature; \( K_c \beta_T \Delta T \) is the additional isotropic thermal loading to restrain the thermo-elastic expansion induced by the temperature increment; and \( \beta_T \) is the thermo-elastic expansion coefficient. The mean effective stress and deviatoric stress for saturated soils can then be expressed as:

\[
\begin{align*}
p' &= K_c \left( \varepsilon_r^e + 3 \beta_T \Delta T \right) \\
q &= \sqrt{6}B\zeta\varepsilon_r^e \left( \varepsilon_r^e + c \right)^{1.5}
\end{align*}
\]
where \( k_e \) is the secant elastic bulk modulus of the solid skeleton:

\[
K_e = 0.6B\varepsilon^e (\varepsilon^e + c)^{0.5} + 0.8B\varepsilon^e (\varepsilon^e + c)^{1.5} + 1.5B\varepsilon^e (\varepsilon^e + c)^{0.5} / \varepsilon^e.
\]

2.2. Thermoplastic behavior

The soil tends to deviate from its elastic contact state due to the collision, slippage and rolling between particles under the mechanical and/or thermal loadings, resulting in inelastic strain. With the continuous interaction between soil particles, the elastic energy decreases and the inelastic strain increases. In the TTS model, the plastic strain rate is determined by the dissipative flows, \( Y_{ij} \), which consists of transient elasticity and granular fluctuation. Zhang and Cheng [19] proposed the following expression of the dissipative flow:

\[
Y_{ij} = \lambda_{ij}T_{ij}^g \varepsilon^e_{ij} + \lambda_{ij}T_{ij}^s \varepsilon^s_{ij} \delta_{ij} \quad (3)
\]

where \( \varepsilon^e_{ij}, \varepsilon^b_{ij} \) are the tensors of elastic and hysteretic strains; \( \varepsilon_{ij} \) is the deviatoric strains; the constant coefficient, \( a \), controls rate-dependence in material behavior; \( T_g \) is granular entropy, a new state variable in the TTS model.

2.3. Granular entropy

When geo-materials are disturbed by external factors (stress, temperature), in addition to the elastic deformation of the soil skeleton, a single particle will undergo random fluctuations as results of the collision, slip, rolling and other inelastic interactions between soil particles. The extent of the fluctuation movement, which reflects the magnitude of the inelastic interaction between soil particles, is the main physical mechanism that causes the irreversible deformation and energy dissipation of the granular solids. Granular entropy is used to describe the fluctuation and movement of particles at the microscopic level.

\[
\dot{T}_g = \frac{m_2 \dot{\varepsilon}^2 + m_3 \dot{\varepsilon}^3 - m_4 T_g}{\rho_d} + m_5 \pi_{kk} \alpha_{bf} \phi_b \dot{T} \quad (4)
\]

where, \( \rho_s \) and \( \rho_d \) are grain density and dry density of soil; \( m_2, m_3, m_4 \) and \( m_5 \) are constant; \( \phi_s, \phi_b \) are the porosity of soil and bound water; \( \pi_{kk} \) is hydrostatic stress; \( \alpha_{bf} \) describes the conversion of bound water to free water.

2.4. Model parameters

There are 12 parameters (material constants) in the TTS model including 4 hyper-elastic parameters, 4 energy dissipation parameters or migration coefficients and 4 temperature-related parameters (Table 1). \( B_0 \) and \( B_1 \) are related to the location and slope of the virgin consolidation line, respectively; \( c \) is linked to cohesion of soils; \( \xi \) affects the in-situ coefficient of earth pressure at rest \( K_0 \). Parameter \( a \) controls rate effects; \( m_2 \) controls elastic strain evolution and location of reload curve. \( \alpha_{bf} \) affects conversion of bound water to free water during heating; \( m_5 \) controls the thermal volumetric strains due to heating-cooling cycles. \( \beta_T \) represents the volumetric thermal expansion of solid particles. \( m_4 \) is the rate of granular temperature production. The values of all the parameters are listed in Table.1. Details about the calibrations of the constitutive parameters can be referred to Zymnis et al. [23].

| Table.1 Model parameters |
|--------------------------|
| symbol | value |
| \( B_0 \) | 10000 Pa |
| \( B_1 \) | 0.0074 m³/kg |
| \( \xi \) | 0.3 |
| \( \beta \) | 1.5 |
3. FEM analysis and discussion

In this section, the FE proposed by Zhang and Cheng [22] is employed to investigate the thermal-mechanical behavior of energy pile in saturated clay. The FEM model are shown in Figure 1, where the pile radius is 0.6 m, the pile length is 10 m. Note that two kinds of pile are considered, namely friction pile and bearing pile. The top of the pile is located at the same height as the soil surface. For the bearing pile, binding constraints are used between the nodes at the bottom of pile and soil; while for the friction one, no constrains are set between the corresponding nodes. For both piles, the pile-soil interface friction coefficient is assumed as 0.2, 0.3 and 0.4, respectively. The initial dry density of foundation soil is 1550 kg/m$^3$. The total number of element is 520.

![Fig.1 FEM model for energy pile](image)

After the gravity loading, thermal loading was applied on the center line of pile. Two thermal loading paths were applied. One is heated from 22 °C to 52 °C, the other involves 22 °C - 52 °C - 22 °C. Once the thermal loading was completed, the constant displacement rate loading was applied at the pile head.

3.1. Bearing performance of energy pile

The load-displacement curve of energy pile under drained condition at 22 °C is shown in Fig.2. It is observed that as the pile-soil interface friction coefficient increases, the bearing performance of the pile increases, while the settlement of pile head gradually decreases. Small increment in the bearing capacity was observed when the friction coefficient $\mu$ increases from 0.2 to 0.3, while significant enhancement in the bearing capacity was obtained as the coefficient further increases to 0.4.
### 3.2. Influence of temperature

Fig. 3 shows the temperature distribution in the foundation during the heating of energy pile. A uniform distribution along the pile body is observed (Fig. 3a). Whereas the temperature in foundation decreases with the distance from the pile (Fig. 3b).

(a) Temperature distributions of energy pile and surrounding soils

(b) Temperature distribution of soils
3.3. The influence mechanism of heating on the bearing performance

3.3.1. Pile-soil interfacial shear stress. The bearing performance of energy piles is closely related to the restraint between pile and soil, which is mainly provided by the pile-soil interfacial normal and shear stresses. Based on the FE analyses in this work, upon heating, the thermal expansion difference between the pile and the foundation soil inevitably leads to changes in the restraint stresses (i.e., pile-soil interfacial normal and shear stresses). Since the thermal expansion of the pile is greater than that of the soil, when the upper pile body is heated, it will produce an upward elongation trend of the upper pile relative to its adjacent soil, resulting in negative interfacial friction (when the interface shear stress is positive, the corresponding lateral resistance is negative). However, for the pile body below the neutral point, a downward elongation trend is produced, resulting in positive lateral friction. In other words, the distribution of lateral friction along the pile body is that the maximum negative friction (interfacial positive shear stress) is generated at the top of the pile, with the increasing depth the negative friction decreases; when the depth is greater than the neutral point, the friction becomes positive and continues to increase with the depth. It is worth noting that if the pile-soil interface slips during heating, the side friction resistance will decrease sharply. A detailed analyses for shear stress at pile and soil interface can be found by Bourne Webb et al. [2] and Amatya et al. [3].

3.3.2. Pile-soil interfacial normal stress. The influence of heating on the pile-soil interfacial normal stress is depth-independent. Figure 4 shows the distribution of interfacial normal stress along the depth $h$. It is observed that at $h = 0.5$ m, the interfacial normal stress attenuates during heating due to the small confining pressure, inducing pile-soil interface slips and decrease in pile-soil interfacial shear stress. For depth below $h = 0.5$ m, the variation of the interfacial normal stress becomes insignificant. The evolution of the interfacial normal stress is related to the interaction between the pile and surrounding soils. The pile body undergoes thermal expansion and contraction upon heating and cooling, while the thermal volumetric change of the soil is complicated. For the normally consolidated soil and lightly over-consolidated soil, volumetric contraction occurs upon heating, resulting in a decrease in the interfacial normal stress and thus, the reduction of the bearing capacity of energy pile. For the heavily over-consolidated soil (OCR > 2), though net volumetric expansion occurs upon heating, in the cases with small lateral earth pressure coefficient $K_0$, contraction would happen in the lateral direction, resulting in a reduction of the bearing capacity of the pile foundation.

3.3.3. Temperature cycling effect. The load-displacement curves of energy pile under constant temperature of 22°C, heating and heating-cooling cycle are shown in Figure 5. It is found that when the pile body is cooled from 52°C to 22°C, the load-displacement curve and bearing performance of pile hardly recover to those in the case without heating ($T = 22°C$). These phenomena could be attributed to
the irreversibility of the thermal deformation and shear strength of the surrounding soil, excess pore pressure and the mechanical behavior of the pile-soil interface.

![Graph](image)

**Fig.5** The capacity performances of friction energy pile

In the case where the surrounding soil is with low compactness, the load-displacement curve tends to move downwards and the bearing capacity will further decrease. The lower the compactness, the greater the unrecoverable thermal deformation of the soil, the stronger dependence of the shear strength on temperature and the greater the excess pore pressure generated during the heating process. During the cooling process of the pile, the thermal deformation of the surrounding soil is irreversible. While the thermal expansion and deformation of the pile body can be completely restored, so that the contact between the pile and soil is further weakened, energy pile and soils would separate in the worse cases, thus reducing the bearing capacity of the pile.

4. **Conclusion**

In this study, Tsinghua Thermodynamics Soil (TTS) model was integrated within a finite element (FE) program to simulate the thermal-mechanical response of energy pile in saturated clays. The influence of thermal loading on the load-displacement curve and bearing performance of energy pile were emphatically analysed. The following conclusions can be drawn from the numerical results.

1. When the energy pile is heated under drained/undrained conditions, the settlement of the energy pile under vertical load increases and the bearing capacity decreases.
2. The bearing performance of energy pile is closely related to the pile-soil interfacial stress. Heating might result in the decrease of interfacial normal and shear stresses.
3. After experiencing heating-cooling cycle, the unrecoverable bearing capacity of energy pile is attributed to the irreversibility of the foundation deformation upon heating.

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