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Interactions between energy piles caused by temperature

Zhong-jin Wang PhD

Lecturer, School of Civil Engineering and Architecture, Ningbo Institute of Technology, Zhejiang University, Ningbo, China; Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou, China; Zcone High-tech Pile Industry Holdings Co., Ltd, Ningbo, China (corresponding author: zhongjin_wang@zju.edu.cn)
(Orcid:0000-0001-6765-3098)

Peng-fei Fang PhD

Associate Professor, Ningbo Institute of Technology, Zhejiang University, Ningbo, China

Kui-hua Wang PhD

Professor, Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou, China

Ri-hong Zhang PhD

Professorate Senior Engineer, Zcone High-tech Pile Industry Holdings Co., Ltd, Ningbo, China

Fu-yuan Li BEng

Graduate student, Research Center of Coastal and Urban Geotechnical Engineering, Zhejiang University, Hangzhou, China

A new simplified method is proposed to estimate the zero point of displacement variation, assuming that the pile shaft and end resistance are in the elastic stage. The additional pile axial force was calculated by using the proposed method. The temperature distribution among surrounding soils was estimated by using the finite-line-source model. The temperature distribution obtained by the proposed method was compared with that obtained by the finite-element model, and a good agreement was obtained. A method for estimating the interaction caused by heating between energy piles is proposed, and a comparison between the calculated results obtained by the proposed method and those obtained using Abaqus software on energy piles was done to verify the accuracy of the proposed method. It is shown that reasonable predictions about interaction between energy piles can be made without expensive and time-consuming analyses by means of the method proposed in this paper.

Notation

A_r^T	calculation parameter of temperature diffusion
C_{pile}	specific heat of the pile
C_{soil}	specific heat of the soil
c	specific heat capacity
c_{soil}	soil cohesion
E_{pile}	elastic modulus of the pile
E_{soil}	elastic modulus of the soil
G_{bs}	shear modulus of the soil at the pile end
H_{pile}	pile length
k	thermal conductivity
k_b	stiffness of the pile-end soil
k_s	initial stiffness of the shaft stress–relative displacement relationship at the pile–soil interface
L	pile length
l_1	zero point of displacement change
n	pile number of a pile group
r_m	pile limit radius
r_{pile}, r_0	pile radius
T_r^T	temperature at the pile shaft at the middle point of the pile length
U_{it}	total additional displacement of pile i
$u_{ij}^{\Delta T}$	displacement of pile i due to the increase in temperature at pile j
z	vertical position of the calculation point
α	thermal diffusivity
α_{pile}	pile conductivity
α_{soil}	soil conductivity
γ_{pile}	pile density

γ_{soil}	soil density
Δl	length of the computing unit
$\Delta s_{b\Delta T}$	pile base settlement by heating
Δs_m	changes in displacements for the m th computational unit of pile i
Δs_n	change in displacements for the n th computing unit
ΔT	temperature increase of the pile
Δt	increase in temperature at pile j
Δt_n	change in temperature at the top of the n th computing unit
Δt_{n+1}	change in temperature at the end of the n th computing unit
$\Delta u_{ii}^{\Delta T}$	increase in displacement of pile i due to its own heating
λ_p	pile line expansion coefficient
λ_s	soil line expansion coefficient
ν_{bs}	Poisson's ratio of the soil at the pile end
ν_{pile}	pile Poisson's ratio
ν_{soil}	soil Poisson's ratio
ρ	density
$\sum_{j=1}^n u_{ij}^{\Delta T}$	increased displacement of pile i caused by other piles due to heating
τ	time computing heat transfer
$\tau(z)$	shaft shear stress at a given depth z
Φ_{soil}	friction angle of soil

Introduction

In recent years, energy piles have been used increasingly due to their economic benefit and environment-friendly advantage. Energy piles,

utilising shallow energy to transfer heat between the building foundations and the structure, couple the role of heat exchangers to that of structural foundations for buildings (Brandl, 2006; Laloui and Di Donna, 2013; Mimouni and Laloui, 2015). The advantage of energy pile application is that concrete as a heat-transfer medium has a higher thermal capacity. Therefore, as well as reducing land use and installation cost significantly, energy piles are able to increase thermal productivity while preserving environmental sustainability.

There are relatively few studies about pile bearing and deformation characteristics with thermo-mechanical coupling compared to studies about thermal performance (Bourne-Webb, 2013). Despite the widespread use of energy piles, many mechanistic questions need to be studied, such as additional settlements and pile axial force along pile depth during the heating and cooling cycle. Existing studies show that the heating and cooling cycle can change the adhesion forces at the pile–soil interface and produce additional stresses in the pile body (Murphy *et al.*, 2014; Stewart and McCartney, 2014; Yavari *et al.*, 2014).

Field measurements were carried out to investigate the changes in pile bearing characteristics due to temperature, such as the axial forces along pile depth, the displacements at pile head and the pile-side frictional resistance (Akrouch *et al.*, 2014; Amatya *et al.*, 2012; Hemmingway and Long, 2013; Laloui *et al.*, 2006; Suryatriyastuti *et al.*, 2012). The measured results showed that the temperature applied at the pile could lead to additional thermal stresses and displacements and even cause significant thermal deformation and stress in the pile. The test results also showed that additional thermal stresses mobilised in the pile during the heating and cooling processes had been subjected to restraint conditions (Batini *et al.*, 2015; Murphy and McCartney, 2014; Nguyen *et al.*, 2017; Rotta Loria and Laloui, 2016; Saggi and Chakraborty, 2015). While field measurements provide significant understanding of energy piles, such tests are site specific and it is difficult to analyse comprehensively the bearing characteristics of the energy pile due to many uncertainties in site conditions. In contrast, a laboratory experiment is able to isolate and study important variables while minimising uncertainties. Laboratory tests were carried out to examine the heat-transfer performance and bearing characteristics of energy piles (Kong *et al.*, 2017; Wang *et al.*, 2016), and the conclusion was that the heating–cooling cycle could lead to thermal strain and that stress in the pile shaft could occur. The finite-element method and numerical method were also used to simulate energy piles subjected to superstructure loads and seasonally cyclic thermal loads over several years (Di Donna and Laloui, 2015; Wang *et al.*, 2019; Zarrella *et al.*, 2017; Zhang *et al.*, 2017). Besides field measurements and laboratory tests, the thermal behaviour of energy piles can be simulated using analytical models. Among various simulation tools for the heat transfer of energy piles, the finite-line-heat-source model, an analytical model derived by the Green function, has been widely used in commercial design programs. The finite-line-heat-source model is available to simulate the thermal behaviour of soils surrounding the energy pile by neglecting the radial dimension of

the heat source and vertical heat flow (Li *et al.*, 2014; Park *et al.*, 2017).

Studies have shown that temperature would lead to additional pile displacements and axial forces along pile depth and there is a point at which the temperature-induced displacement is zero (Wang *et al.*, 2019). In practical engineering, it is very important to determine that position and estimate the additional pile force. Meanwhile, studies about bearing characteristics of energy pile groups are also important, and simplified analytical methods for energy pile groups are badly needed due to deficiency relating to engineering application.

In this study, the perfect line elastic model is adopted to describe the relationship between the pile base settlement and the pile base load, and the response between the pile shaft and surrounding soils is also simulated by the line elastic model. Based on the assumption that the pile shaft and end resistance are in the elastic stage, a new simplified method is proposed to estimate the zero point of displacement variation, and the additional pile axial force was calculated by using the proposed method. The finite-line-source model was adopted to estimate the temperature distribution among surrounding soils, and the factors affecting the distribution were also analysed. The temperature distribution obtained by the proposed method was compared with that obtained from the finite-element model, and the analysis results show that the proposed method can be used to estimate the temperature distribution accurately. A method for estimating interactions caused by heating between energy piles is proposed, and a comparison between the results obtained by the proposed method and those obtained using Abaqus software on energy pile was done to verify the accuracy of the proposed method. The analysed results show that reasonable predictions can be made without expensive and time-consuming analyses by means of the method proposed in this paper.

Assumption and solution to the simplified method

Even though there are many existing methods for analysing the settlement of pile foundations and the load-transfer mechanism of a single pile, these methods are not very applicable to energy piles due to the temperature load. The behaviour between the pile shaft and surrounding soils in this paper is described by a simple bilinear model, as shown in Figure 1(a). From the bilinear relationship shown in Figure 1(a), it can be seen that the pile-side friction increases linearly with gradually increasing relative displacement between the pile shaft and surrounding soils. When the pile–soil relative displacement reaches the value s_{u1} , the shear stress at the interface between the pile side and surrounding soils changes. This relationship can be expressed in the following equation

$$1. \quad \tau(z) = k_s \Delta s_z \quad \Delta s_z \leq s_{u1}$$

where $\tau(z)$ is the shaft shear stress at a given depth z , Δs_z is the pile–soil relative displacement developed in the pile–soil interface

Figure 1. The load-transfer mechanism analysis model of a single pile for (a) shaft friction and (b) end resistance

at a given depth z and k_s are empirical coefficients determined by laboratory test or by back-analysis of field test results.

As Figure 1(b) shows, the relationship between the pile-end loads and settlements until the ultimate bearing capacity can also be expressed by the bilinear model based on the existing research results (Xie *et al.*, 2013).

$$2. \quad \tau_b = k_b s_b \quad s_b \leq s_{ub1}$$

where τ_b is the pile-end resistance and s_b is the pile-end settlements, and the relationship between the pile-end settlements and loads is shown in Figure 1(b). When the displacement of the pile-end soil is within s_{ub1} , the stiffness of the pile-end soil is k_b . The coefficient k_s , as the initial stiffness of the shaft stress–relative displacement relationship at the pile–soil interface, can be obtained as (Randolph and Wroth, 1978; Wang *et al.*, 2012; Zhang *et al.*, 2010, 2016)

$$3. \quad k_s = \frac{G_s}{r_0 \ln(r_m/r_0)}$$

The initial soil stiffness at the pile base, k_b is written as the following expression

$$4. \quad k_b = \frac{4G_{bs}}{\pi r_0 (1 - \nu_{bs})}$$

where G_{bs} and ν_{bs} are the shear modulus and Poisson's ratio, respectively, of the soil at the pile end.

As per the conclusion expressed by Wang *et al.* (2019), the applied load at the energy pile head cannot be heavier than the value which will lead to non-linear settlement at the pile top. The relative displacement between the pile shaft and surrounding

soils is less than the value of s_{u1} as Figure 1(a) shows; the zero point of displacement change is considered as the origin, and the length from the zero point to the pile head has the value of l_1 , as shown in Figure 2. Assuming that the settlement of soil at the pile end caused by heating was negligible and the pile base settlement, $\Delta s_{b\Delta T}$, due to heating is written as the expression

$$5. \quad \Delta s_{b\Delta T} = \lambda_p \Delta T (L - l_1)$$

l_1 , the zero point of displacement change due to heating from the top of the pile, can be written by the equilibrium expression

$$6. \quad \begin{aligned} & \int_0^{l_1} 2\pi r_0 k_s (\lambda_p - \lambda_s) \Delta T l \, dl \\ &= \int_0^{L-l_1} 2\pi r_0 k_s (\lambda_p - \lambda_s) \Delta T l \, dl + \pi r_0^2 k_b \lambda_p \Delta T (L - l_1) \end{aligned}$$

where λ_p is the coefficient of linear expansion for the pile, λ_s is the coefficient of linear expansion for soils surrounding the pile and ΔT is the temperature increase of the pile body. Thus, the zero point of displacement change l_1 can be obtained by using the following equation

$$7. \quad l_1 = \frac{k_s (\lambda_p - \lambda_s) L^2 + r_0 k_b \lambda_p L}{2k_s (\lambda_p - \lambda_s) L + r_0 k_b \lambda_p}$$

From Equation 7, it can be seen that the position of the zero point of displacement change of the pile top has no direct relationship to the temperature change of the pile body. The main factors that influence the position of the zero point of displacement change

Figure 2. Zero point of displacement change

are the initial soil stiffness at the pile base, the shear stiffness of soils surrounding the pile and coefficients of linear expansion for the pile and surrounding soils. In addition, the additional axial pile shaft force from the pile head to the zero point can be obtained by the following equation, while the relative displacement between the pile shaft and surrounding soils is less than s_{ub1} .

$$\Delta p_z = \int_0^z 2\pi r_0 k_{s1} \Delta T (\lambda_p - \lambda_s) (l_1 - l) dl$$

8.

The analytic solutions to Equation 8 can be expressed as the following equation

$$\Delta p_z = 2\pi r_0 k_{s1} \Delta T (\lambda_p - \lambda_s) l_1 z - \pi r_0 k_{s1} \Delta T (\lambda_p - \lambda_s) z^2$$

The additional axial pile shaft force from the pile end to the zero point can be obtained by using the following equation

$$\Delta p_z = \pi r_0^2 k_b \Delta T l_2 \lambda_p + \int_0^z 2\pi r_0 k_s \Delta T (\lambda_p - \lambda_s) (l_2 - l) dl$$

10.

The analytic solutions to Equation 8 can be expressed in the following equation

$$\Delta p_z = \pi r_0^2 k_b \Delta T l_2 \lambda_p + 2\pi r_0 k_s \Delta T (\lambda_p - \lambda_s) l_2 z - \pi r_0 k_s \Delta T (\lambda_p - \lambda_s) z^2$$

11.

In multilayered soils, assuming that the zero point of displacement change is in the i th layer, the length from the i th layer soil heat to the zero point is l_1 , as shown in Figure 3. The zero point of displacement change can be obtained by using the following equation

$$\begin{aligned} & \sum_{j=1}^{i-1} \int_{l_j}^{l_{j+1}} 2\pi r_0 k_{sj} (\lambda_p - \lambda_{sj}) \Delta T dl + \int_0^{l_1} 2\pi r_0 k_{si} (\lambda_p - \lambda_{si}) \Delta T dl \\ &= \sum_{j=i+1}^n \int_{l_j}^{l_{j+1}} 2\pi r_0 k_{sj} (\lambda_p - \lambda_{sj}) \Delta T dl \\ &+ \int_0^{L_i - l_1} 2\pi r_0 k_{si} (\lambda_p - \lambda_{si}) \Delta T dl \\ &+ \pi r_0^2 \left(L - l_1 - \sum_{j=1}^{i-1} L_j \right) \Delta T \lambda_p k_b \end{aligned}$$

12.

Figure 3. Calculation model for the zero point in multilayered soils

All the parameters in the preceding equation are shown in Figure 3. The additional axial pile shaft force from the pile head to the zero point can be obtained by the following equation, assuming that the relative displacements between the pile shaft and surrounding soils are in the first linear stage in all the multilayered soils

$$\Delta p_z = \sum_{j=1}^{i-1} \int_{\sum_{m=1}^j l_m}^{\sum_{m=1}^{j+1} l_m} 2\pi r_0 k_{sj} (\lambda_p - \lambda_{sj}) \Delta T \left(\sum_{i=1}^{i-1} L_i + l_1 - l \right) dl + \int_{\sum_{m=1}^j l_m}^z 2\pi r_0 k_{si} (\lambda_p - \lambda_{si}) \Delta T \left(\sum_{i=1}^{i-1} L_i + l_1 - l \right) dl$$

13.

The additional axial pile shaft force from the pile top to the zero point can be obtained by using the following equation

$$\Delta p_z = \pi r_0^2 k_b \Delta T \left(L - \sum_{j=1}^{i-1} L_j - l_1 \right) \lambda_p + \sum_{j=1}^{n-i+1} \int_{\sum_{m=1}^j l_m}^{\sum_{m=1}^{j+1} l_m} 2\pi r_0 k_{sj} (\lambda_p - \lambda_{sj}) \Delta T \left(\sum_{i=1}^{n-i+1} L_i - l_1 - l \right) dl + \int_{\sum_{m=1}^{n-i+1} l_m}^z 2\pi r_0 k_{si} (\lambda_p - \lambda_{si}) \Delta T \left(\sum_{i=1}^{n-i+1} L_i - l_1 - l \right) dl$$

14.

In order to determine the specific position of layers in Equation 14, the following procedure can be adopted for calculation.

- Confirm the values of k_{sj} according to the relative displacements between the pile shafts and surrounding soils obtained in the preceding step.
- Assume that the zero point is in the lowest layer – that is, the n th layer, shown in Figure 3.
- Calculate to obtain the solution of l_1 .
- If the solution of l_1 is negative, then assume that the zero point is in the $(n-1)$ th layer, as shown in Figure 3.
- Continue to calculate the solution to Equation 12 until a positive value of l_1 is obtained.
- Then, calculate the additional axial pile shaft force using Equations 13 and 14 along the pile shaft in multilayered soils.

The finite-line-source model

The two-dimensional model was initially studied by Eskilson (1987), in which a line heat source has a finite length from the ground surface to a certain depth h along the z -axis, as shown in Figure 4. This model has been widely used and developed to simulate temperature conduction (Man *et al.*, 2010, 2011). The initial temperature uniformity in a semi-infinite medium is t_0 . At a given time, the finite-length uniform line heat source perpendicular to the boundary surface with a strong degree q_1 (W/m) begins to give off exothermic (or endothermic) heat. Using the principle of the virtual heat source method, a virtual line heat source at the symmetrical position of the boundary surface to the line heat source is assigned, as shown in Figure 4. An analytical solution has been derived by the method to ensure the boundary condition of constant temperature on the surface, which takes the form of Equation 15 (Man *et al.*, 2010). In this paper, the finite-line-heat-source model is adopted to simulate the thermal expansion in the surrounding soils around the pile.

$$t(r, z, \tau) = \frac{q}{4\pi k} \int_0^H \left\{ \frac{\operatorname{erfc} \left[\frac{\sqrt{r^2 + (z-h')^2}}{2\sqrt{\alpha\tau}} \right]}{\sqrt{r^2 + (z-h')^2}} - \frac{\operatorname{erfc} \left(\frac{\sqrt{r^2 + (z+h')^2}}{2\sqrt{\alpha\tau}} \right)}{\sqrt{r^2 + (z+h')^2}} \right\} dh'$$

15.

where H is the length of the energy pile; z is the vertical position of the calculation point; τ is the time computing heat transfer; $r = [(x-x')^2 + (y-y')^2]^{1/2}$; $\operatorname{erfc}(z)$ is an error function and has the characteristic of $\operatorname{erfc}(z) = 1 - (2/\pi^{1/2}) \int_0^z \exp(-\mu^2) d\mu =$

Figure 4. The finite-line-source model

$(2/\pi^{1/2}) \int_0^\infty \exp(-\mu^2) d\mu$; k is thermal conductivity (W/(m K)); and $\alpha = \lambda/\rho c$ (m^2/s) is thermal diffusivity, where ρ (kg/m^3) is density and c ($\text{J}/(\text{kg K})$) is specific heat capacity.

Around the surrounding soils, the thermal diffusions can be approximately estimated by the following expression, derived from Equation 15

$$T(r, z, \tau) = \frac{T_r^\tau}{A_r^\tau} \int_0^H \left\{ \frac{\text{erfc} \left[\frac{\sqrt{r^2 + (z-h)^2}}{2\sqrt{\alpha\tau}} \right]}{\sqrt{r^2 + (z-h)^2}} - \frac{\text{erfc} \left[\frac{\sqrt{r^2 + (z+h)^2}}{2\sqrt{\alpha\tau}} \right]}{\sqrt{r^2 + (z+h)^2}} \right\} dh' \quad (16)$$

T_r^τ is the temperature at the pile shaft at the middle point of the pile length and A_r^τ is the value at the middle point of pile length when $r = r_{\text{pile}}$; A_r^τ can be expressed in the following equation

$$A_r^\tau = \int_0^H \left\{ \frac{\text{erfc} \left[\frac{\sqrt{r_{\text{pile}}^2 + (0.5H-h)^2}}{2\sqrt{\alpha\tau}} \right]}{\sqrt{r_{\text{pile}}^2 + (0.5H-h)^2}} - \frac{\text{erfc} \left[\frac{\sqrt{r_{\text{pile}}^2 + (0.5H+h)^2}}{2\sqrt{\alpha\tau}} \right]}{\sqrt{r_{\text{pile}}^2 + (0.5H+h)^2}} \right\} dh' \quad (17)$$

The thermal diffusions around the surrounding soils obtained from Equations 16 and 17 were identical to that calculated by the finite-element method, as shown in Figure 5. The parameters in the analysis adopted the values from Table 1, for both the finite-element method (using Abaqus software) and the proposed method.

Analysis of energy pile group

In order to estimate the vertical displacements of energy pile groups subjected to thermal loads, the interaction method of conventional pile groups could also be performed to analyse the interaction between energy piles. The pile displacement along the pile depth caused by the other piles enduring heating could be considered as the composition of a series of units of the pile shaft. The pile could be divided to obtain enough computational units that could satisfy the computing requirement. The changes in displacements for every computational unit could be estimated by the following expression

$$\Delta s_n = \lambda \frac{\Delta t_n + \Delta t_{n+1}}{2} \Delta l \quad (18)$$

Figure 5. The temporal distribution of temperature along the soil radial direction

Table 1. Parameters of finite-element model

Parameter	Value	Parameter	Value
E_{pile} : GPa	30	C_{soil} : J/(kg K)	1305
E_{soil} : MPa	20	γ_{pile} : kN/m^3	25
λ_{pile} : $^\circ\text{C}^{-1}$	1.74	ν_{soil}	0.35
λ_{soil} : $^\circ\text{C}^{-1}$	1.16	c_{soil} : kPa	15
α_{pile} : W/(m K)	1×10^{-5}	γ_{soil} : kN/m^3	20
α_{soil} : W/(m K)	6×10^{-6}	ν_{pile}	0.15
C_{pile} : J/(kg K)	1706	Φ_{soil} : $^\circ$	30
r_{pile}	0.5	H_{pile}	30

Δs_n is the change in displacements for the n th computing unit, Δl is the length of the corresponding unit, Δt_n is the change in temperature at the top of the n th computing unit and Δt_{n+1} is the change in temperature at the end of the n th computing unit; Δt_n and Δt_{n+1} could be estimated by Equation 16. The total change in displacements for the pile could be obtained by summing up changes in displacements of all computing units, as shown in the following equation

$$\Delta u_{ij}^{\Delta t} = \sum_{m=1}^n \Delta s_m \quad (19)$$

$u_{ij}^{\Delta t}$ is the displacement of pile i due to the increase in temperature at pile j , Δt is the increase in temperature at pile j , Δs_m is the changes in displacements for the m th computational unit of pile i . The total increase in displacements for pile i in the energy pile group caused by other piles enduring heating can be estimated approximately by the following equation

$$\Delta u_i = \sum_{j=1}^n u_{ij}^{\Delta t} \quad (20)$$

As described earlier, the displacement of pile i in the pile group can be expressed as the sum of the self-additional displacement caused by its own heating and the additional displacements caused by the other piles at its position. Assuming that the number of piles in the pile group is n , the additional displacement of pile i can be expressed as

$$21. \quad U_{it} = \Delta u_{ii}^{\Delta t} + \sum_{j=1}^n u_{ij}^{\Delta t}$$

In this formula, U_{it} is the total additional displacement of pile i , n is the pile number of the group, $\Delta u_{ii}^{\Delta t}$ is the increase in displacement of pile i due to its own heating and $\sum_{j=1}^n u_{ij}^{\Delta t}$ is the increased displacement of pile i caused by other piles due to heating.

The zero point of displacement change can be obtained by using Equation 7, and the displacements at the pile top can be obtained by using Equations 7 and 17.

Case study

The behaviour of pile groups has been studied by many scholars in the past decades. However, researches about the interactions between energy piles are quite limited. Many tests have been carried out to study the responses of piles due to change in temperature, and the tests' results provided some great insight into the thermo-mechanical response of energy piles subjected to heating. However, existing tests mainly focused on single piles. However, mechanical interactions between the piles may occur when only a part of the foundation is thermally activated piles – for example, the case described by Mimouni and Laloui (2015). As a result, different displacements between energy piles and conventional piles could develop and induce potential damage to the supported structure. Due to the lack of experimental data

about the interaction between energy piles, the finite-element method was adopted in this paper to analyse the interaction between energy piles. The parameters used in the calculation model were consistent with that shown in Table 1, and the layout of the 3×3 pile group is shown in Figure 6; the distance between two closely adjacent piles was 3 m. The extension of the simulated domain was chosen to be large enough to avoid boundary effects, as shown in Figure 6. The finite-element analysis adopted the sequential thermo-mechanical coupling method. The implication of this method is that stress does not affect temperature distribution, but temperature causes stress changes. In the process of heat-conduction analysis, the heat-conduction elements were adopted and the three-dimensional stress elements were adopted in the process of coupled thermo-mechanical analysis. The pile adopted the elastic model and the soils adopted the Mohr–Coulomb elastoplasticity model in the process of coupled thermo-mechanical analysis.

The proposed method is an approximate calculation method, and the thermal parameters of soil and pile are regarded as identical, excepting the value of the expansion coefficient. The existing tests mainly focused on a single pile to study the responses of piles due to change in temperature, and experimental data about the interaction between energy piles were rare. Therefore, the finite-element method is adopted to compare with the results obtained by the proposed method. The zero point of displacement change in this case study is estimated to be 18 m below the pile head, and the case study applied a temperature increase of 20°C. The parameters in the analysis using Abaqus adopted the values from Table 1. The parameters used in this case for the finite-line-source model are also listed in Table 1. Comparisons between the results from Abaqus and those computed by the proposed approach are shown in Figure 7. The results show that the pile-head displacements caused by heating calculated by the proposed method are generally consistent with the finite-method results.

Figure 6. Layout of energy pile group: (a) pile location plan and (b) 3-D mesh calculation sketch

Figure 7. Comparison of results between the proposed method and the finite-element method (Abaqus)

Conclusions

On the assumption that the pile shaft and end resistance are in the elastic stage – that is, the applied pile head load should not be heavier than the value from which non-linear settlement occurred on the load–settlement curve – the following conclusions can be obtained.

- A new simplified method is proposed to estimate the zero point of additional displacement along the pile depth. The position of the zero point has no obvious relationship to the temperature change in the pile body. The main factors that influence the point are the initial soil stiffness at the pile base, the shear stiffness of soils surrounding the pile and the coefficients of linear expansion for the pile and surrounding soils.
- A simplified method for calculating the additional pile axial force caused by heating is also proposed.
- The finite-line-source model can be adopted to estimate the temperature distribution among surrounding soils. The temperature distribution obtained by the finite-line-source model has good agreement with that obtained using Abaqus software, and the analysed results show that the proposed method can be used to estimate the temperature distribution accurately among surrounding soils.
- A method for estimating the interaction caused by heating between energy piles was proposed. The calculated results obtained by the proposed method have good agreement with those obtained using Abaqus software. The analysed results show that the proposed method can be used to estimate the interaction between energy piles with accuracy.

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