Numerical investigation of behavior of energy piles in saturated fine-grained soil

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Abstract

The current study aimed to examine the behavior of energy piles in saturated fine-grained soils using the finite element method. The proposed thermo-hydro-mechanical model could demonstrate the energy pile behavior in most practical conditions such as under thermal, mechanical, or thermomechanical loading. Based on the obtained results from this study, the thermal expansion of the pile and temperature variation in the soil affect vertical effective stress in the soil. Since vertical effective stress is an important parameter in estimating bearing capacity and consolidation settlement of the bearing system and controls the stability of superstructure, the effects of thermal loading on vertical effective stress of soil and consequently, on bearing capacity of pile needs to be investigated accurately. For this purpose, a comprehensive parametric study was accomplished. Based on the results, the elastic modulus, Poisson ratio, thermal expansion coefficient of solid grains, void ratio, and coefficient of permeability of fine-grained soil were the most important and effective parameters on bearing capacity and consolidation settlement of energy pile in saturated conditions. Based on the results, the elasticity modulus of the soil has a significant effect on reducing the vertical effective stress of the soil by up to 40 percent of the initial in-situ stress.

Keywords: Energy Piles; Finite Element; Thermo-hydro-mechanical Behavior of Soil; Fine-grained Soils; Thermomechanical Loading.

1. Introduction

The behavior of energy piles have been studied by many researchers. The findings of experimental tests or physical and numerical models, indicate that using pile as a heat exchanger leads to variations in the temperature of pile and surrounding soil [1-3], which can alter the soil inherent properties, such as the creep rate and strength [1, 4, 5]. Additionally, applying thermal load in saturated fine-grained soils can generate excess pore water pressure and subsequently reduce effective stress[6], in which the magnitude of their variation depending on the condition of drainage, the rate of thermal loading, and the permeability of the soil [7-10]. When the soil permeability is very low, drained conditions can occur if the loading process is sufficiently slow [11-14]. The majority of research has focused on the effects of thermal loads on the stress and deformation of the pile, but less is known about how thermal loads affect the behavior of the surrounding soil. Amatya et al. (2012) and Bourne-Webb et al. (2009) presented a procedure that illustrates the energy piles behavior under thermal and thermomechanical loading including distribution of axial force, shear stress, and axial observed strain [2, 11]. Ng et al. (2014) investigated the thermomechanical behavior of energy piles in moderate and heavily overconsolidated clay [14]. The results showed that both energy piles had a ratcheting displacement mechanism under constant pile load and throughout five cyclic loads. A floating energy pile in normally consolidated clay which is under thermal cyclic heating and cooling and also the different magnitude of head load shows two different behaviors. Under the low mechanical load level, the thermomechanical behavior of the energy pile is elastic and reversible, but by applying a high mechanical load level the settlement is irreversible [15]. Nguyen et al. (2019) used both experimental and numerical methods to study the thermomechanical behavior of pile in saturated clay. A comparison of their findings revealed that numerical methods can be helpful for analyzing the behavior of energy piles. Additionally, they discovered that the settlement of the energy pile has a tendency to be reversible following a significant number of thermal cycles [16]. Considering the importance of evaluating energy pile's behavior in different geotechnical conditions, experimental methods have numerous limitations. Hence, numerical methods, which are generally faster and cheaper, can be a useful tool for studying the behavior of energy piles. For this purpose, this paper endeavors to provide an accurate numerical model that can investigate the behavior of energy piles in one of the complex conditions which is thermo-hydro-mechanical (THM) condition. So, it is necessary to prove the suitability of the proposed model by comparing its results with the reliable data from previous studies. Therefore, the numerical and experimental results of an energy pile beneath a four-story building in Lausanne [3] were used for the verification of the proposed model. According to Ravera et al. (2020), the interaction between the thermal pile and other piles will vary depending on the raft foundation [17]. Garbellini and Laloui (2021) examined the behavior of thermal piles and took into account the effect of cracking of the reinforced concrete [18]. Pourfakhrian and Bayesteh (2020) used 3D FEM to simulate the geometrical and mechanical parameters of the pile group with a focus on slab stiffness in order to assess the thermo-mechanical behaviour of the energy piled-raft foundations [19]. Heidari et al. (2022) utilized analytical and numerical methods to investigate the behavior of energy piles under monotonic lateral loading, surpassing soil saturation [20].

In the present study heat transfer and a coupled consolidation analyses have been employed to study energy pile behavior in saturated soil using ABAQUS software. The effect of the mechanical, hydraulic, and thermal characteristics of saturated fine-grained soils on the behavior of the system was studied. According to numerical findings, the vertical stress of soil can be influenced by heat transfer to the soil and pile radial expansion at the pile-soil interface. Since the vertical stress is a key parameter in various methods of evaluating bearing capacity, the variation of vertical effective stress in the soil was precisely studied . The results show that analytical methods for estimating bearing capacity and settlement of piles are not valid for energy piles and based on these observations an appropriate modification is necessary. Although the effect of temperature on the alteration of soil properties was not considered in the current study, it is possible to apply it easily if valid data exists. By developing the proposed model, some graphs could be provided to estimate the thermal consolidation and bearing capacity of energy piles.

2. Thermo-hydro-mechanical modeling of energy pile

In the current study the behaviour of energy piles in saturated soil was simulated using finite element method by ABAQUS software. The ABAQUS has been used for many problems that involving THM modeling [21]. Since the permeability of fine-grained soils is low, at high loading rates the rate of pore water pressure changes is also low. However, at high loading rates, the initial amount of induced pore water pressure is extremely high. Therefore, the separation of the heat transfer (HT) analysis from the analysis of pore fluid diffusion and stress will have a small deviation from the real phenomenon. For modeling the behavior of an energy pile that is placed in saturated soil, three phenomena are involved including the principle of energy conservation, the principle of volume (or mass) conservation, and the principle of equilibrium. The first is for heat transfer and the last two are for modeling a soil matrix consisted of solid and fluid phases. The HT is used to find the distribution of temperature in the whole model. In ABAQUS, the principle of the volume is coupled with the equilibrium law to make it possible to model the consolidation in soils. This analysis is named coupled pore fluid diffusion and stress (CPS). Consequently, by importing the temperature of all nodes from HT to the CPS, it is possible to model the full behavior of an energy pile. To validate modeling, the numerical and experimental results of an energy pile (with 26m length and 1m diameter), presented by Laloui et al. [3], were used. The geotechnical condition in the site (high groundwater level) is appropriate for the intended goals of the present study, which is investigating the thermo-hydro-mechanical behavior of energy piles. The comparison between the results of the present study and those of Laloui's [3] shows the adequate accuracy of the modeling. After calibration of the proposed model, properties of saturated fine-grained soils on the behavior of pile in such medium were investigated in a parametric study. The goal of this parametric study was to illustrate the effect of the most important properties of soil on vertical effective stress under a constant thermal load from the pile.

2.1 Heat transfer (HT) analysis

In this model, the temperature distribution is considered to be independent of the stress-displacement solution; however, there is an inverse dependency. Thus, at first, the HT problem was solved and the solution was inputted into the CPS analysis.

The general energy equation for the HT analysis is solved assuming that heat conduction is governed by the Fourier law:

$$f = -k\frac{\partial\theta}{\partial x} \tag{1}$$

where k is the thermal conductivity $(\mathrm{W/m/^\circ C})$, θ is the temperature $(^\circ\mathrm{C})$, x is the position (m) and f is heat flux $(\mathrm{W/m^2})$ [22].

2.2 Coupled pore fluid diffusion and stress (CPS) analysis

Effective stress is the foundation of the poroelasticity theory, which is applied in ABAQUS. The continuity equation can also take the compressibility of the solid or fluid phases into account. The capability of modeling porous medium ABAQUS considers the presence of two fluids in the medium, usually, water and air, which both of them can have compressibility. Since this study intends to consider saturated soil, the effect of the air phase is neglected and pore fluid is considered to be water. As previously stated, the equilibrium equation and continuity equation for the pore fluid phase in a porous medium serve as the governing equations for the CPS. The total stress, σ_T, is assumed to be made up of pore water pressure, u_w, average pore air pressure, u_a, and effective stress, σ^*, defined by

$$\sigma^* = \sigma_T + [\chi u_w + (1-\chi)u_a] \tag{2}$$

The factor χ depends on the saturation degree and surface tension between solid and water and when the medium is fully saturated being equal to 1.0. Thus, the form of the equation (2) reduces to

$$\sigma^* = \sigma_T + u_w \tag{3}$$

For the fine-grained soil, the water flow through the material is assumed to be governed by

Darcy's law. Under uniform conditions and low flow velocities, Darcy's law states that the rate of volumetric water flow through a unit area of the medium, snv_w, is proportional to the gradient of the piezometric head:

$$snv_w = \hat{k}.\frac{\partial \phi}{\partial x} \tag{4}$$

where s is the saturation, n is the porosity, $\hat{k}$ is the soil's permeability $(\mathrm{m/s})$ and ϕ is the piezometric head which is defined as equation (5).

$$\phi = z + \frac{u_w}{g\rho_w} \tag{5}$$

where z is the elevation from datum (m), g is the gravity acceleration $(\mathrm{m/s^2})$ and ρ_w is the water density $(\mathrm{kg/m^3})$ [22]. Since it is assumed that temperature variation is independent of stress-displacement, the effect of the produced heat due to friction between the pile and surrounding soil is neglected. Validation of finite element model

3. Validation of finite element model

The validation model (VM) considers a 26 m long energy pile with a 1m diameter circular section. It is placed in the corner of a four-story structure in Lausanne, which belongs to the Swiss Federal Institute of Technology (SFIT). Three analytical procedures are used in the VM, which are named in ABAQUS as follows: heat transfer (HT), geostatic, and soil consolidation. The purpose of the HT analysis is to find the temperature distribution in the soil and pile it over a thermal load. After that, results of the HT analysis were inputted in the soil consolidation analysis as nodal temperature to apply heat exchanging effects in the analysis. In geotechnical problems, initial stresses of various material (soil layers and pile) should precisely equilibrate and do not result in any deformation. However, it might be challenging to specify initial stresses and loads that precisely equilibrate in a layered problem with different densities. Therefore, the geostatic analysis checks the equilibrium to determine the stress state that is consistent with the boundary conditions and volume loads of the soil layer. After obtaining the equilibrium conditions in the model, the piles are analyzed by using soil consolidation procedures under mechanical and thermomechanical loads. Fig. 1 shows the geometry, meshing, and mechanical boundary condition of the VM. Each element of soil has 0.5m×0.5m dimension and pile's elements have 0.25m width and 0.5m length. A 4-node linear axisymmetric convection-diffusion quadrilateral element with dispersion control (DCCAX4D) is used in the HT analysis. For problems involving slow dynamics and minimal nonlinearities, implicit algorithms permit the use of larger time steps, enhancing numerical stability and accuracy.

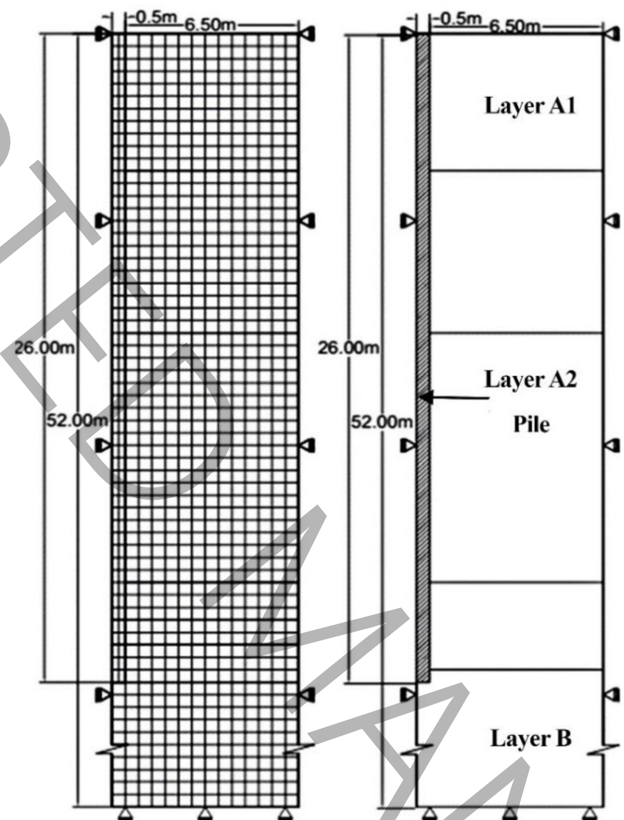

Fig. 1 Model geometry, mechanical boundary conditions, and meshes of the VM.

The convective-diffusive elements for heat transfer analysis in ABAQUS are intended for use in problems that involving heat transportation by a flowing fluid (convection). At the same time, the heat is diffused by conduction in the saturated soil. These elements with dispersion control provide an accurate solution in cases where the transient response of the problem is important [23]. Material properties were adapted from Laloui et al. [3]. These element types increase the accuracy of the HT analysis in saturated conditions [23]. In the geostatic and soil consolidation analysis, an 8-node axisymmetric quadrilateral, biquadratic displacement, bilinear pore pressure, reduced integration (CAX8RP) is defined for the elements of those soil layers that surround the pile (including layers A1, A2, B, and C). This element type can consider stress, pore pressure, and displacement in saturated soil. The pile elements have an 8-node biquadratic axisymmetric quadrilateral (CAX8) element type and an 8-node biquadratic axisymmetric quadrilateral reduced integration (CAX8R) is assumed for layer D. The reason for using the CAX8 and CAX8R elements without pore pressure degree of freedom is that the pile and layer D are assumed to be impermeable. Reduced integration function prevents shear locking in soil elements [23]. A rough contact between the pile and surrounding soils is considered. To restrain any relative movement between pile and soil layers, the surfaces of pile and soils are tied together, which these assumptions are in line with the case study [3].

3.1 Material properties

The soil around the pile is generally of granular material. Thus, to simulate the behavior of frictional materials, the Drucker-Prager model with associated flow rule is used. Both the pile and layer D exhibit thermo-elastic behavior and plastic behavior is not considered for them. Except for the expansion coefficient of the layer B and C, for which Batini et al. [24] reported the lower value in the same stratigraphy near the case site (200m distance between the two project locations), there is not any difference in selected parameters. The shear modulus (G) and bulk modulus (K) were converted to the elastic modulus (E) and Poisson's ratio (υ) based on equations (6) and (7). The mechanical and hydraulic properties as well as the thermal properties are summarized in Table 1 and Table 2, respectively.

Table 1. The mechanical and hydrological properties of the pile and soils VM [3].

Soil layer	Unit weight	Porosity	Permeability	Young modulus	Poisson's ratio	Friction angle	Cohesion
	ρ	η	K	E	ν	Φ	C
	kg/m^3		m/sec	MPa		°	kPa
A1	2000	0.1	2×10^{-6}	259	0.14	30	5
A2	1950	0.1	7×10^{-7}	259	0.14	27	3
B	2000	0.35	1×10^{-6}	451	0	23	6
C	2200	0.3	1×10^{-6}	634	0	27	20
D	2550	-	-	1273	0.16	-	-
Pile	2500	-	-	33700	0.176	-	-
Note: thermal expansion coefficient of water, $\beta'_f = 10^{-5}$							

$$E = \frac{9KG}{3K + G} \tag{6}$$

$$\upsilon = \frac{E}{2G} - 1 \tag{7}$$

Table 2. The thermal properties of the pile and soils in VM [3].

Soil layer	Unit weight	Thermal conductivity	Heat capacity	Solid grain expansion coefficient
	ρ	Λ	ρ_c	β'_s
	kg/m^3	W/m/°C	J/m^3.°C	°C^{-1}
A1	2000	1.8	2.4×10^6	10^{-5}
A2	1950	1.8	2.4×10^6	10^{-5}
B	2000	1.8	2.4×10^6	2×10^{-5}
C	2200	1.8	2.4×10^6	2×10^{-5}
D	2550	1.1	2.0×10^6	10^{-6}
Pile	2500	2.1	2.0×10^6	10^{-5}
Note: Fluid dilation coefficient $\beta'_f = 10^{-5}$				

3.2 Boundary and initial condition

In the VM, two sides of the numerical model are restricted against the horizontal movement, and two model directions—horizontal and vertical—are also restricted, as shown in Fig. 1. The soil is permitted to drain from the top of the model and right-hand sides. The pile and layer D are assumed to be impervious. Therefore, there was no drainage from the soil-pile interface. The heat is allowed to dissipate from the bottom and right-hand side of the model. Additionally, the ground surface maintains a constant temperature.

3.3 Mechanical and thermo-mechanical loading

Similar to Laloui's [3] assumption, it is assumed that in Test 1 and Test 7 temperature varies along with the pile over 28 days similar to Fig. 2. In Test 1, the pile is only subjected to thermal load, and it is allowed to expand freely from its head. However, the pile head is subjected to a mechanical loading in Test 7 with a magnitude of 1300 kN, which caused axial compression stress in the pile. To apply mechanical loading in Test 7, the soil consolidation analysis was added after the geostatic analysis. Then another consolidation analysis was performed to apply temperature variation corresponding to Fig. 2 for Test 7.

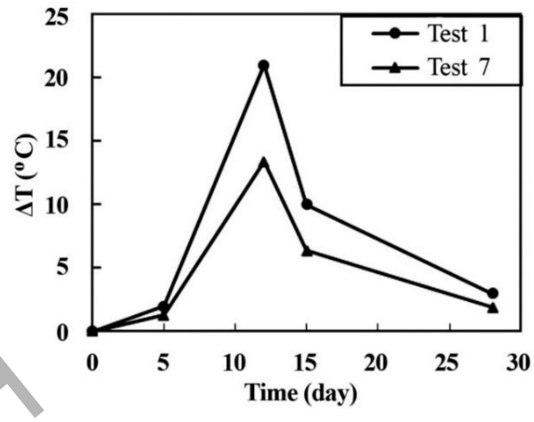

Fig. 2. Temperature values imposed on the pile.

3.4 Comparison between numerical results and experimental test data

By comparing the results of VM with the numerical and experimental results from Laloui et al. [3], the reliability of the proposed modeling method is evaluated. Three different aspects of the pile behavior were considered, including the head displacement of the pile (Fig. 3), vertical strain (Fig. 4), and vertical stress (Fig. 5) along with the pile. Fig. 3 shows the head displacement of the pile for a thermal load according to Test 1 in Fig. 2. As the pile head is free to expand, by applying thermal load it expands in an upward direction. Fig. 3 shows good conformity between the results under thermal loading. If the soil around the pile did not exist, the pile was free to expand. However, in the presence of the soil, it resisted against thermal deformation of the pile. Therefore, the pile enforced some deformation to the adjacent soil, which could lead to producing stress in the pile and surrounding soils. Therefore, if the proposed model can demonstrate induced thermal strains along with the pile, it can be deduced that produced stresses are correct. Figure 4 demonstrates that the VM's results are in good agreement with Laloui's funding, and it can therefore be inferred that the VM is able to predict vertical strains resulted from thermal loads on the pile. Finally, to evaluate the ability of the proposed model to consider both the thermal and mechanical loads' effect on the pile behavior, the variation of vertical stress of pile under thermomechanical loading was investigated. Based on the obtained results in Fig. 5, it can be deduced that the VM had some deviation in the upper layer, which was less noticeable in lower layers. Altogether from Fig. 3, Fig. 4, and Fig. 5, it can be concluded that the proposed model has the required accuracy to simulate the energy pile behavior under thermal and thermomechanical loading.

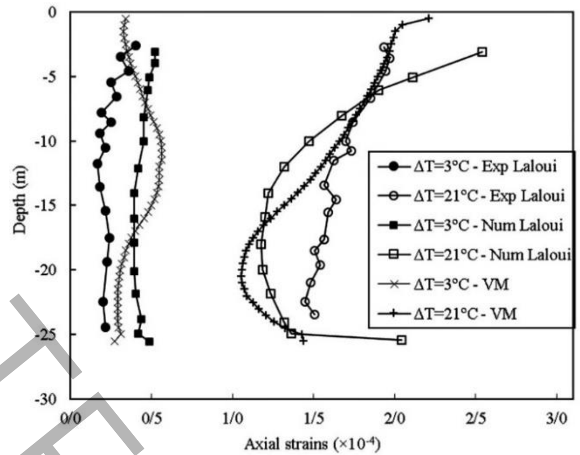

Fig. 3. The pile head displacement during heating and cooling within Test 1-VM and Laloui's results

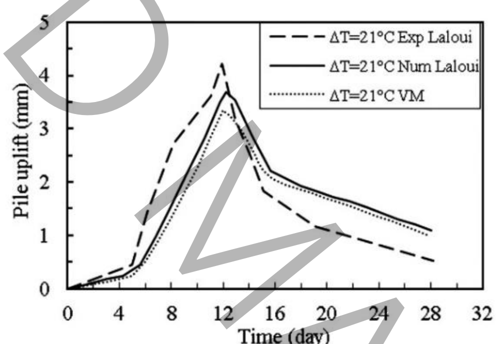

Fig. 4. Vertical strains along with the pile under thermal loading corresponding to Test 1.

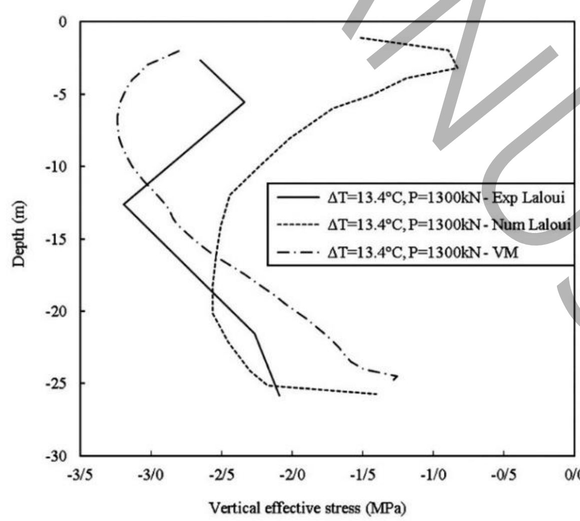

Fig. 5. Vertical stress in the pile under mechanical (1300 kN) and thermal (Test 7 in Fig. 2) loading.

3.5 Parametric study of the pile behavior in fine-grained soils: a parametric study (PS)

Based on the results, Fig. 6 and Fig. 7 show the variation of effective vertical stress in the adjacent soil to the pile under the effect of imposing thermal and thermomechanical loading, respectively. By comparing these results, it can be concluded that a fraction of vertical effective stress variations in the soil is related to thermal loads.

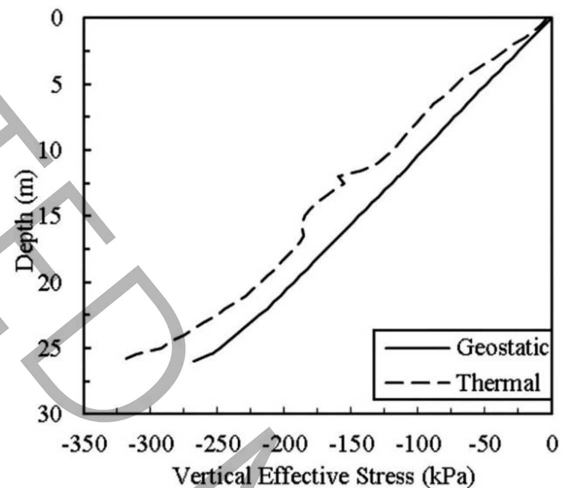

Fig. 6. Vertical stress in surrounding soils – Test 1, Max Temp = 21˚C.

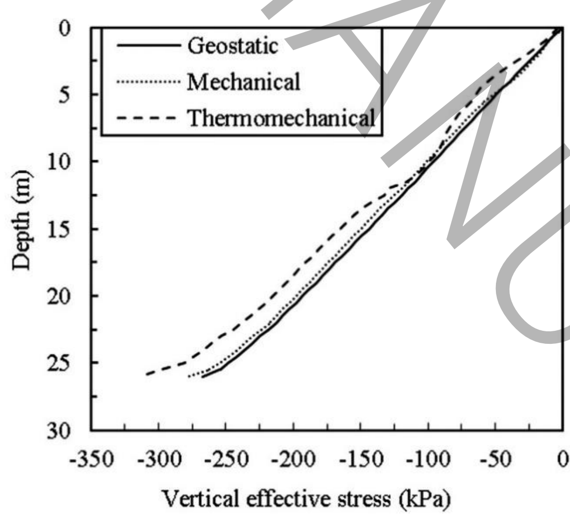

Fig. 7. Vertical stress in surrounding soil – Test 7, Max Temp = 13.4˚C.

As shown in Fig. 8, it can be observed that the soil reached equilibrium in a stress state soon after reaching a steady-state in the HT. This can be related to the effect of temperature change in the soil and pile on the variation of soil stress. A slight difference in reaching stress equilibrium is because of fewer hydraulic conductivity in comparison with thermal conductivity. After reaching equilibrium in pore water diffusion and thermal transfer, the stress state reached a stable condition.

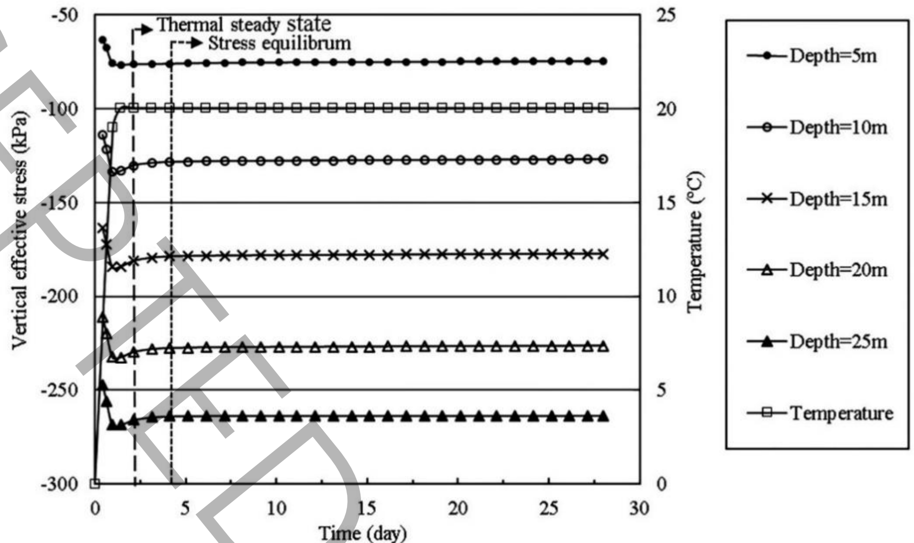

Fig. 8. Comparison between the variation of temperature and effective vertical stress in surrounding soils during the 28-day heating of the pile with 20˚C.

Since effective vertical stress is an important parameter for predicting bearing capacity and settlement of piles, it is essential to determine effective parameters on their variation under thermal loads. Regarding Fig. 6 and Fig. 7, it can be observed that the various layers of the soil in this model lead to complex results. Thus, some simplifications for identifying important parameters on the effective vertical stress of surrounding soil are considered [24]. For this purpose, a parametric study (PS) was implemented by assuming a pile in a single layer consisting of saturated fine-grained soil. The PS model was a 10-meter-long pile with a 0.5-meter diameter. In the PS model, the properties of fine-grained soils for thermal, hydraulic, and mechanical parameters were obtained from Mitchell and Soga [4], and Rajapakse [25], respectively. The material properties for the primary simulation of the PS are presented in Table 3 and properties of the subset models are summarized in Table 4.

Table 3. Material properties used for the primary PS model.

Material type	Density	Young Modulus	Poisson's ratio	Friction angle	Cohesion	Permeability	Void ratio	Solid grains expansion coefficient	Thermal conductivity	Heat specific
	Kg/m^3	MPa		°	kPa	m/sec		1/°C	W/m.°C	J/kg.°C
Pile	2500	25000	0.2	-	-	-	-	1×10^{-5}	2	800
Soil	1800	2	0.4	26	5	1×10^{-10}	0.5	1×10^{-5}	1.5	1000

*Thermal expansion coefficient of pore water=1.5×10^{-4}

Table 4. Material properties used for the subset PS models.

Parameter	Unit	Quantity
Elasticity Modulus	MPa	2,4,6,8,10,12,14,16,18,20
Poisson's ratio	-	0.2,0.25,0.3,0.35,0.4
Solid grains expansion coefficient	$\times10^{-7}$ °C^{-1}	1,5,10,50,100,500,1000
Permeability	$\times10^{-12}$ m/sec	1~10^8
Void ratio	-	0.5,1,2

The plastic behavior of the soil was modeled with Mohr-Coulomb with a non-associated flow rule. Mechanical, thermal, and drainage boundary conditions are the same as those used for the VM. Fig. 9 represents a geometry, element mesh, and mechanical boundary condition of the PS model. In PS models, there is no mechanical load on the pile and the pile is free to expand from its head. All over the pile, a constant thermal load with $20°C$ magnitude and 30 days duration is imposed and a rough contact is assigned between the pile and soil. The analysis procedures and element type were the same as the VM. The lateral earth pressure was calculated as follows.

$$K = 1 - \sin\phi \quad (8)$$

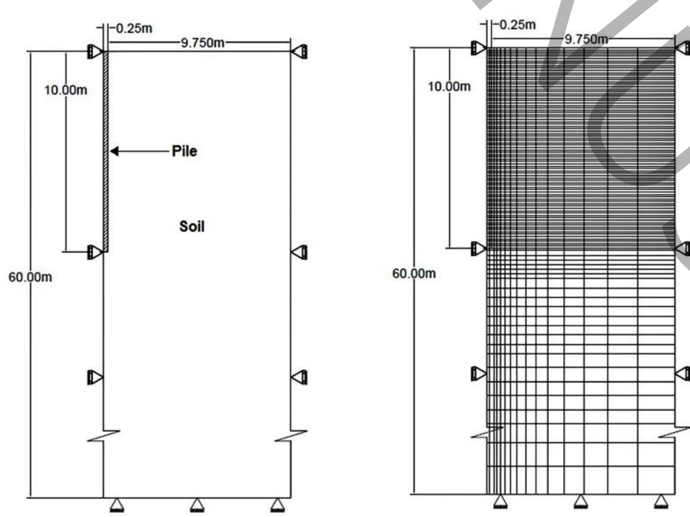

Fig. 9. Finite element mesh, model geometry, and mechanical boundary – PS models.

4. Results and discussion

4.1 Parametric study results

In this section, the results of parametric studies for different values of thermal expansion coefficient of pore water and solid grains, elasticity modulus, Poisson's ratio, void ratio, permeability coefficient, specific heat, and thermal conductivity of soil are performed to determine their effects on effective vertical stress. In this study by comparing effective vertical stress of the soil in geostatic state and under thermal loads, it was found that variation of effective vertical stress in soils was independent of specific heat and thermal conductivity of the soil. Although poor plastic properties were selected for the soil, no plastic strain was observed along the contact surface of the soil and pile. Thus, the parametric study for plastic properties was neglected. However, the other mentioned parameters in the first part of this section had effects with different magnitudes.

To achieve an outline of the effect of each parameter, the sum of the vertical stress of the soil under thermal loads along the interface with the pile was normalized to the sum of effective vertical stress in the geostatic state based on the following equation.

$$\Delta\sigma'(\%) = \frac{\sum \sigma'_{thermal}}{\sum \sigma'_{geostatic}} - 1 \quad (9)$$

Although Equation (9) can cause some deviations, due to observed linear variations of vertical stresses with depth in geostatic state and under thermal load, this relationship can be a simple approximation of the effects of the parameters. Therefore, the effect of each parameter and the magnitude of its impact can be estimated.

4.2 Effect of elasticity modulus

Fig. 10 shows an outline of the effect of pile's radial expansion on the surrounding soil. The heating of the pile leads to its expansion axially and radially. However, the surrounding soil resisted against the free thermal radial expansion ($\varepsilon_{free,rad}$) of the pile. Hence, a fraction of free radial expansion could occur, which was named as observed radial strain ($\varepsilon_{\text{obs},rad}$). The difference between the observed and free strains was blocked strain ($\varepsilon_{block,rad}$), which raised the applied horizontal stress ($\sigma_{H,im}$) in the soil. Similarly, increasing in horizontal stress in the soil was observed by DI Donna and Laloui [13]. Then, due to Poisson's effect, increasing the horizontal stress caused a reduction in the effective vertical stress ($\sigma_{V,out}$). If the properties of the pile were assumed to be constant, effective parameters in this phenomenon would include the elastic modulus and Poisson's ratio of the soil.

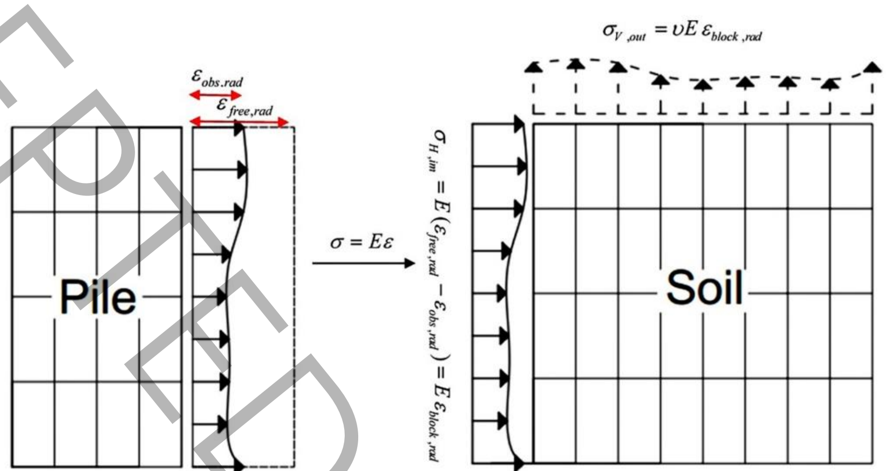

Fig. 10. A schematic view of the pile radial thermal strains and imposed thermal stress effects from the pile to the surrounding soil.

A parametric attempt was conducted to examine the effect of elasticity modulus variation on the effective vertical stress under thermal load (Fig. 11). This parameter with the various magnitude of elasticity modulus the same as given values for PS 1 to PS 10 and with other properties mentioned in Table 3 was used for the parametric study. As expected, it was observed that increasing elasticity modulus resulted in decreasing effective vertical stress in the soil under thermal loading.

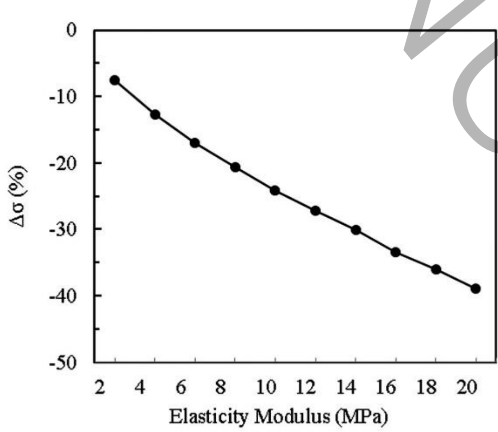

Fig. 11. The effect of elasticity modulus on the variation of effective vertical stress in soil under thermal loading;

the elasticity modulus of soil varied between 2 to 20 MPa.

4.3 Effect of Poisson's ratio

According to what was discussed in the last part, Poisson's effect on the soil can reduce the effective vertical stress. To ensure this and quantify the effect of the Poisson's ratio on vertical effective stress of the soil, various magnitudes of the Poisson's ratio with constant elasticity modulus were investigated. The obtained results confirmed the initial hypothesis presented in Fig. 10 and they are summarized in Fig. 12 based on Equation (9). As it can be deduced, increasing the Poisson's ratio leads to decreasing the effective vertical stress in the soil under thermal loading.

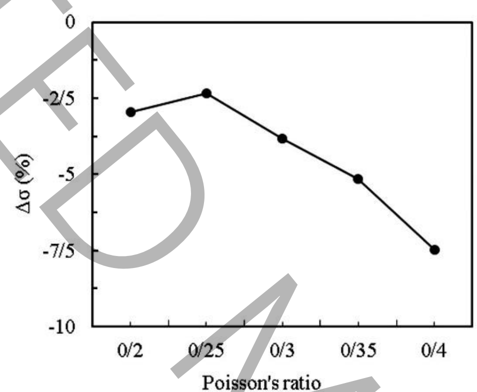

Fig. 12. The effect of the Poisson's ratio on the variation of the effective vertical stress in the soil under thermal loading. The input values of the Poisson's ratio are based on the proposed values for PS 11 to PS 15.

4.4 Effect of expansion coefficient of soil grains

As shown in Fig. 13a, the saturated soil consists of two phases: pore water and solid grain. When heat transfers to the soil (Fig. 13a), both phases are expanded. Since the expansion coefficient of pore water is usually more than that of solid grains, pore water resists against grains expansion and results in increased pore water pressure. As shown in Fig. 13b, by concerning constant total stress, increasing pore water pressure causes to decrease effective stress. As there is little variation in the value of the pore water expansion coefficient, it is assumed to be constant and equal to $1.5\times10^{-4}\,°C$.

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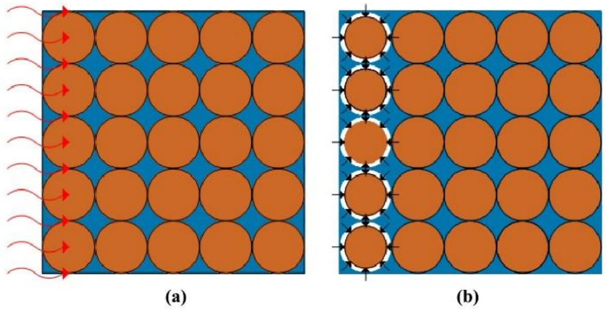

Fig. 13. A schematic view of (a) the heat transferred from the pile to the soil; (b) contraction of soil grain due to pore pressure.

As shown in Fig. 14, it was observed that under thermal loading, increasing the expansion coefficient of solid grains results in increased effective vertical stress in the soil to an extent more than the geostatic state. These results are consistent with the concept presented in Fig. 13b.

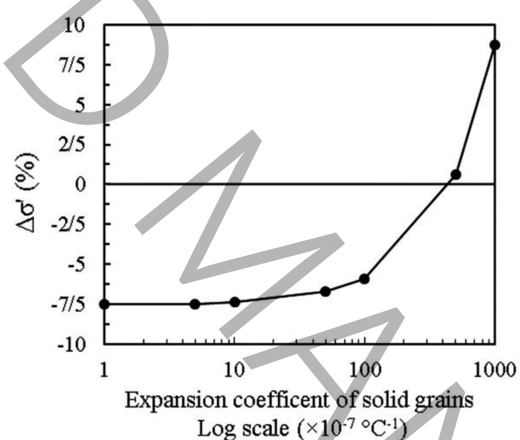

Fig. 14. The effect of the expansion coefficient of solid grains on the variation of effective vertical stress in the soil under thermal loading; the expansion coefficient varied between 10^{-7} to 10^{-4} °C^{-1}.

4.5 Effect of permeability

When the permeability of the soil increases, the thermally induced pore water pressure according to Fig. 13b can be dissipated faster. Thus, less excess pore water pressure remains in the soil and consequently, less reduction will occur in the effective vertical stress. This hypothesis for different values of permeability of the fine-grained soils has been investigated and the results presented in Fig. 15 approve its validity.

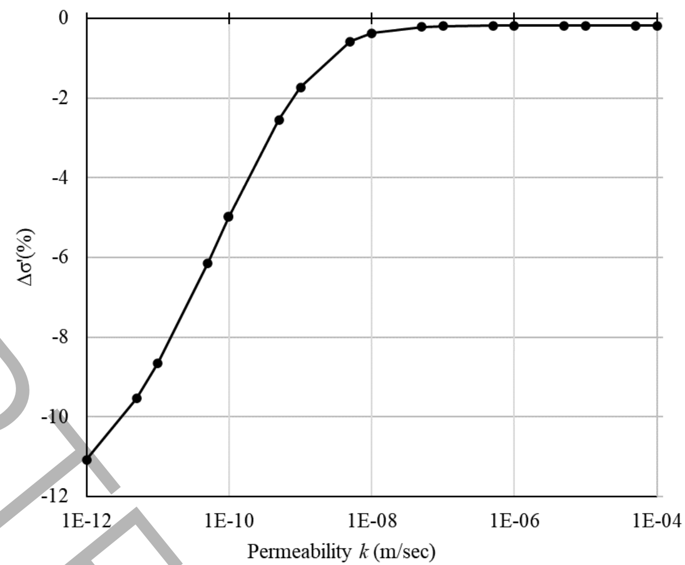

Fig. 15. The effect of permeability on the variation of effective vertical stress in the soil under thermal loading; permeability varied between 10^{-12} to 10^{-4} m/sec.

4.6 Effect of void ratio

The void ratio played two important roles in the thermo-hydro-mechanical behavior of the soils. At first, it had a considerable impact on the heat conductivity of the soil. On the other hand, in a unit volume of the saturated soil, increasing the void ratio means allocating more portions to pore water in comparison with solid grains volume. Hence, under the effect of temperature, more volume of pore water can expand and more pore water pressure will develop (similar to Fig. 13b). Consequently, the void ratio determines the amount of increase in pore water pressure under thermal loading. Fig. 16 shows the effect of the void ratio increase on the decrease of the effective vertical stress in the soil.

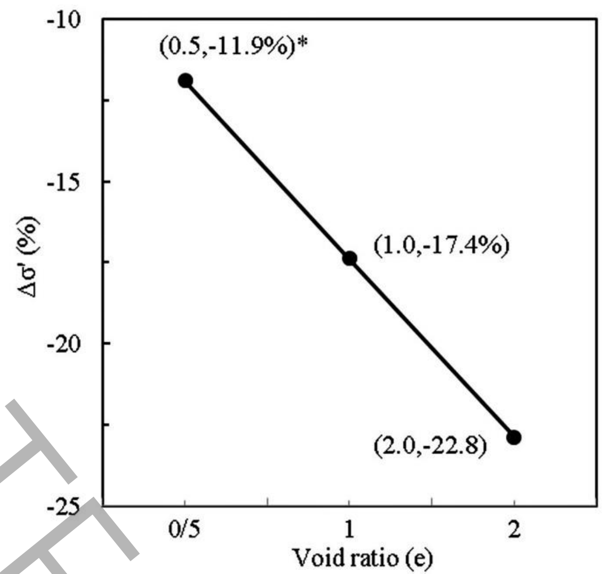

Fig. 16. The effect of the void ratio on the variation of effective vertical stress in the soil under thermal loading (PS 28 to PS 30).

As stated, the behavior of the energy pile in the saturated soil was more complicated than that of the energy pile in the dry soil. The main reason for this complexity was the effects of pore water on soil behavior. The proposed THM model in the current paper led to a deeper understanding of temperature effects on the bearing system. By applying thermal load on the pile, in addition to raising the temperature of the pile, could lead to heat transfer to the surrounding soil. This, in turn, causes thermally induced stresses and deformations in the pile and surrounding soil. Thus, increasing the temperature had two main effects on the surrounding soil. First, it imposed horizontal stress from the pile to the soil. Second, it induced an excess pore water pressure in the saturated soil. These two effects reduced the vertical effective stress of the soil. As effective vertical stress is a key parameter for estimating bearing capacity and settlement of pile foundation, its changes under thermal loads must be evaluated accurately.

By considering constant properties for the pile, the first effect was due to radial expansion of the pile that imposed horizontal stress to the adjacent soil. Because of the existing Poisson's effect in the soil, the imposed horizontal stress from the pile to the soil caused a decrease in effective vertical stress. According to Fig. 10, Poisson's ratio, elasticity modulus, and probably the thermal expansion of the soil influenced the magnitude of vertical effective stress changes. This probability arose from that the soil's thermal expansion could control the Pile's radial expansion and withstand it (Fig. 10). As can be seen in Fig. 13b, if the expansion coefficient of the soil increases, it prevents the pore water expansion and results in a reduction in the induced pore pressure. Therefore, the nonlinear effect of the thermal expansion coefficient of the soil on the variation of the effective vertical stress in Fig. 14 can be related to these two circumstances. Altogether, increasing Poisson's ratio and elasticity modulus leads to more decrease in effective vertical stress.

The second effect was the result of transferring heat from the pile to the adjacent soil. Hence, thermal expansion occurred in two phases of saturated soil structure. Since the expansion coefficient of pore water is usually greater than that of solid grain, increasing temperature leads to increasing pore water pressure in the soil. By considering constant total stress, increasing pore pressure reduces the effective stress. The amount of the thermally induced pore water pressure depends on the void ratio, permeability, and thermal expansion coefficient of solid grains and pore water. These parameters control effective vertical stress changes under thermal loads. The void ratio determines the volume of pore water. Thus, when the temperature in the soil increases, this void ratio determines the volume of pore water that can expand. As a result, as illustrated in Fig. 16, with increasing the void ratio, more pore water pressure is induced in the soil. Due to the low permeability of the fine-grained soil, the thermally induced pore water pressure disappears slowly. As shown in Fig. 15, increasing the permeability leads to a lower decrease of vertical effective stress. The effect of the thermal expansion coefficient is similar to permeability, both of which result in lower pore water pressure to remain in the soil, as presented in Fig. 13.

Different from previous research, this study proposes a THM model for analyzing energy pile behavior in saturated soil. It shows that the thermal expansion of the pile and transferred heat to surrounding soils can change the vertical effective stress of the soil, with the magnitude of this change depending on the hydraulic and mechanical properties of the soil. This gap has been addressed in the present study, which comparatively investigates the effects of soil parameters on variation of vertical effective stress of soil, which an important parameter in evaluating bearing capacity and settlement of pile.

5. Conclusion

This paper presented a thermo-hydro-mechanical model to study how energy piles behave in saturated fine-grained soils. The results proved that numerical models are powerful tools for investigating the behavior of energy piles in various conditions. It was found that the transferred heat from the pile to the adjacent soil increased the temperature of the surrounding soil. Moreover, thermal loads affected the soil behavior, which could change the effective vertical stress in the soil and induce excess pore water pressure. These changes are more obvious in fine-grained soils as they have low permeability. The importance of vertical effective stress variation is that it could lead to a change in the bearing capacity and settlement of the pile. Thus, a parametric study was performed on the soil properties to determine effective parameters on the soil behavior under thermal loads. The following conclusions are taken from the findings:

1. The importance of the surrounding soil was discussed in more detail and new concepts of soil effect on energy piles were presented.

2. The fine-grained soil usually has less hydraulic conductivity in comparison with heat conductivity. Thus, the equilibrium in the soil body is attained shortly after reaching a steady-state in the HT. In other words, the vertical effective stress of the soil varies until reaching a steady-state in the HT.

3. When heat is transferred to the soil, the thermal properties of the soil do not affect its effective vertical stress. Their main role is to determine the volume of soil, which is under the effect of thermal load piles.

4. Variation of elastic and hydraulic properties of soil influences its vertical effective stress. Under the thermal load, the plastic strain does not occur in the soil. Therefore, their effects on the variation of vertical effective stress in the soil are neglected.

5. Increasing elasticity modulus, Poisson's ratio, and void ratio under thermal loads cause a greater decrease in effective vertical stress in comparison with geostatic conditions.

6. Increasing the permeability and thermal expansion coefficient of soil solid grains can reduce the induced excess pore water pressure, and as a result, the vertical effective stress of the soil under thermal load is reduced.

7. The effect of temperature on the effective stress of the soil should be considered in the calculation of the bearing capacity and settlement of energy piles.

The effect of vertical effective stress variation on pile bearing capacity and thermal consolidation requires further investigation, which will be addressed in future research.

References

[1] G.A. Akrouch, M. Sánchez, J.-L. Briaud, Thermo-mechanical behavior of energy piles in high plasticity clays, Acta Geotechnica, 9 (2014) 399-412.
[2] P. Bourne-Webb, B. Amatya, K. Soga, T. Amis, C. Davidson, P. Payne, Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles, Géotechnique, 59(3) (2009) 237-248.
[3] L. Laloui, M. Nuth, L. Vulliet, Experimental and numerical investigations of the behaviour of a heat exchanger pile, International journal for numerical and analytical methods in geomechanics, 30(8) (2006) 763-781.
[4] J.K. Mitchell, K. Soga, Fundamentals of soil behavior, John Wiley & Sons New York, 2005.
[5] C. Zhou, J. Xu, C.W.W. Ng, Effects of temperature and suction on secant shear modulus of unsaturated soil, Géotechnique Letters, 5(3) (2015) 123-128.
[6] A. Edalat, M. Khodaparast, A.M. Rajabi, Scenarios to control land subsidence using numerical modeling of groundwater exploitation: Aliabad plain (in Iran) as a case study, Environmental Earth Sciences, 79(21) (2020) 494.
[7] H.M. Abuel-Naga, D.T. Bergado, A. Bouazza, Thermally induced volume change and excess pore water pressure of soft Bangkok clay, Engineering Geology, 89(1-2) (2007) 144-154.
[8] B. Bai, Z. Su, Thermal responses of saturated silty clay during repeated heating–cooling processes, Transport in porous media, 93 (2012) 1-11.
[9] C. Cekerevac, L. Laloui, Experimental study of thermal effects on the mechanical behaviour of a clay, International journal for numerical and analytical methods in geomechanics, 28(3) (2004) 209-228.
[10] R. Fuentes, N. Pinyol, E. Alonso, Effect of temperature induced excess porewater pressures on the shaft bearing capacity of geothermal piles, Geomechanics for Energy and the Environment, 8 (2016) 30-37.
[11] B. Amatya, K. Soga, P. Bourne-Webb, T. Amis, L. Laloui, Thermo-mechanical behaviour of energy piles, Géotechnique, 62(6) (2012) 503-519.
[12] A. Di Donna, L. Laloui, Numerical analysis of the geotechnical behaviour of energy piles, International journal for numerical and analytical methods in geomechanics, 39(8) (2015) 861-888.
[13] M. Khodaparast, M. Kiani, H. Bayesteh, Numerical study of bearing capacity and consolidation settlement of energy piles in fine-grained soils, in: Energy Geotechnics, Proceedings of the 1st International Conference on Energy Geotechnics, 2016, pp. 57.
[14] C.W.W. Ng, C. Shi, A. Gunawan, L. Laloui, Centrifuge modelling of energy piles subjected to heating and cooling cycles in clay, Geotechnique letters, 4(4) (2014) 310-316.
[15] A. Vieira, J.R. Maranha, Thermoplastic analysis of a thermoactive pile in a normally consolidated clay, International journal of Geomechanics, 17(1) (2017) 04016030.
[16] V.T. Nguyen, N. Wu, Y. Gan, J.-M. Pereira, A.M. Tang, Long-term thermo-mechanical behaviour of energy piles in clay, Environmental Geotechnics, 7(4) (2019) 237-248.
[17] E. Ravera, M. Sutman, L. Laloui, Analysis of the interaction factor method for energy pile groups with slab, Computers and Geotechnics, 119 (2020) 103294.
[18] C. Garbellini, L. Laloui, Thermal stress analysis of energy piles, Géotechnique, 71(3) (2021) 260-271.
[19] L. Pourfakhrian, H. Bayesteh, Effect of slab stiffness on the geotechnical performance of energy piled-raft foundation under thermo-mechanical loads, European Journal of Environmental and Civil Engineering, 26(9) (2022) 3681-3705.
[20] B. Heidari, A.A. Garakani, S.M. Jozani, P.H. Tari, Energy piles under lateral loading: analytical and numerical investigations, Renewable Energy, 182 (2022) 172-191.

[21] S. Jeong, H. Lim, J.K. Lee, J. Kim, Thermally induced mechanical response of energy piles in axially loaded pile groups, Applied Thermal Engineering, 71(1) (2014) 608-615.
[22] M.P. Ahola, Thermo-hydro-mechanical Coupled Modeling: Big-Ben Experiment, TC3: DECOVALEX-Phase III, Center for Nuclear Waste Regulatory Analyses, 1994.
[23] K. Hibbitt, Sorensen, ABAQUS/CAE User's Manual, Dassault Systems Simulia Corp., Providence, RI, USA, 2016.
[24] N. Batini, A.F.R. Loria, P. Conti, D. Testi, W. Grassi, L. Laloui, Energy and geotechnical behaviour of energy piles for different design solutions, Applied Thermal Engineering, 86 (2015) 199-213.
[25] R.A. Rajapakse, Pile design and construction rules of thumb, Butterworth-Heinemann, 2016.

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