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Investigating the effect of thermal loading on geothermal piles in stratified soils

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Abstract
Energy pile is a type of foundation that simultaneously provides the two goals of structural load transfer and energy conversion. In addition to transferring the structural load of the building to the lower layers, this system also acts as a heat exchanger. In this article, to investigate the effect of soil and geothermal pile on each other, numerical modeling was performed using finite element method using COMSOL software. The main purpose of this study is to investigate the response of geothermal pile in layered soils and compare it with geothermal pile implemented in homogeneous soil. This problem has been performed considering the different soil layers that are on the bedrock and the results have been compared with the experimental data of the geothermal pile placed in the layered soil. The results showed that the properties of soils and the location of loose and dense layers in the depth of the soil have a significant effect on the type of behavior of the pile, so the deformations and stresses obtained from the numerical analyzes are related to the modulus of elasticity and in other words, to the hardness of the soil. It conducted that the value of the strain obtained from the numerical analysis of the pile placed in multi-layered soil is between the value of the pile strains in the case where the homogeneous soil is only loose or dense. The conclusion of obtained results is that the vertical stresses and strains of the pile placed in multi-layered soil at the depth of the earth's surface are in better agreement with the vertical stresses and strains of the pile placed in loose soil. The modulus of elasticity of soil with average density of type 2 is 74% higher than the modulus of elasticity of loose soil considered in the analysis, which has led to a 27% reduction in displacement, a 40% increase in compressive stress and a 77% reduction in vertical strain. The same change in the modulus of elasticity of the soil layers caused a change in the values of stresses and pile stresses in the state of layered soil. Also, the 40% change in the modulus of elasticity of type 2 and 3 soils has caused the amount of displacement to decrease by 17% and the amount of compressive stress and strain to increase by 11% and decrease by 27%, respectively. The results of the numerical analysis showed that the type of soil and the way it is located in the depth have a significant effect on the behavior of the geothermal pile.

Keywords: Geothermal energy pile, FEM, COMSOL, renewable energy

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1 Introduction

Due to the ever-increasing population, the demand for the use of energy resources is increasing rapidly. For this reason, fossil fuels are exploited more than usual. Therefore, to reduce the effect of greenhouse gases, we need to change the process of using conventional energies to renewable energy sources. A lot of thermal energy is locked in the earth's core. If this energy is used effectively, it will be enough for the sustainable development of the country in the future. Geothermal energy is one of the environmentally friendly energy sources. The recent advances in science, the high rate of energy and the problems caused by the import and export of fossil fuels have caused geothermal energy to receive special attention. Heat exchangers use geothermal surface energy to supply heat and cold to the building. By using this green and renewable energy model, long-term building costs and greenhouse gas emissions will be significantly reduced. The maximum amount of energy consumption inside the building is used to maintain the comfort temperature. A sustainable design of the structure can reduce this energy consumption to a great extent by combining two main items. One item is the use of renewable energy sources to meet most of the energy needs and the other is a good thermal design to reduce the needs by reducing the amount of heat exchange between the building and the external environment. From an economic point of view, using this method for providing heat to buildings and residential places is more cost-effective than the methods that use fossil fuels. Therefore, pollution caused by the consumption of other fuels, which leads to the production and emission of greenhouse gases, can be avoided to a large extent. Energy foundations use the most basic structural elements and combine them with geothermal energy transfer mechanism. Geothermal piles, which are also referred to as energy piles or thermal absorbers, are a type of energy foundation that uses underground geothermal energy for cooling and heating the building. The first geothermal piles were built in Austria in the early 1980s (Brandl, 2006). The difference between conventional piles and geothermal piles is the high density polyethylene (HDPE) pipes that are installed inside the pile and the heat transfer fluid flows through them. The fluid is connected to the heat pump system that is installed inside the building and is used for heating and cooling the building.

According to the research conducted in all parts of the world, the thermo-mechanical behavior of energy piles has been investigated by field and centrifuge tests. Among the studies, we can mention the experiment of Laloui et al. (2006) which was carried out on a real scale. In that experiment, it was observed that the axial stress caused by the temperature applied to the pile has a higher value compared to the stress resulting from mechanical loading. Based on the field test of this work, the effects of soils on energy pile were investigated by using the finite element method. The main purpose was to investigate energy pile response in various soils. This was performed by considering some different hypothetical layers with the bedrock under them and their results which included displacement, strain, and stresses induced by thermal load compared with four layered soil experimental data (Sheshpari, 2018). McCartney et al. (2010) conducted a centrifuge test model of thermo-active foundations, in which the desired foundation was heated to a temperature of 60°C and then lowered to a temperature of 25°C. The results showed an increase in the capacity and resistance of the pile during heating. An analysis on the simultaneous effect of thermo-mechanical loading on a geothermal pile laboratory model was performed by Wang et al. (2011). The purpose of that experiment was to investigate the amount of changes in bearing capacity. They reported that temperature is one of the important factors that affects the bearing capacity of piles. Bodas Freitas et al. (2013) developed a symmetric numerical model in Adina finite element software. Considering different values for volumetric thermal expansion coefficient of concrete, they evaluated the effect of the relationship between volumetric thermal expansion coefficient of soil and pile. Goode et al. (2014) performed a centrifuge test on an energy pile located in sandy soil. The result of their considerations was based on the rise of the pile head and thermal axial strain of the pile due to its heating. To investigate the thermo-hydro-mechanical behavior of the energy pile Dupray et al. (2014) conducted a finite element multi-physics analysis and stated that the heating-cooling periods have an important effect on the pore water pressure changes in soils with low permeability. Houston et al. (2015) by conducting a study on the settlements caused by the heat of energy piles in unsaturated soil showed that soil suction, net normal stress and temperature are the most important factors for estimating the amount of settlement. Saggu and Chakraborty (2015) investigated the behavior of support and friction piles in loose and dense sandy soil under various thermal cycles by simulating with the finite element method. Their results showed that even after the progressive cooling of the pile after different thermal cycles, the axial stress along the length of the pile tends to increase, the main reason of which is the difference in expansion between the pile and the soil during thermal loading. Located in saturated sand, an energy pile with a diameter of 1 meter and a length of 20 meters was modeled using ABAQUS finite element software, where the effect of sand density, diameter and length of the pile on the change of horizontal stress of the energy pile was analyzed. Fifty thermal cycles with four different ranges of temperature cycle (between 5 and 20°C) were considered. The analysis showed that the effect of the initial density of sand on the final drop of horizontal stress after fifty thermal cycles is insignificant. It also showed that increasing the length of the pile with the ratio of length to diameter remaining constant results in the same amount of horizontal stress drop. But if the diameter of the pile remains constant, increasing the length of the pile leads to a decrease in the horizontal stress drop (Ng et al., 2016). A numerical and analytical study was conducted to analyze the interaction between the energy pile and the soil around it. The study showed that the lateral friction stress at the interface between soil and pile changes in different soil layers. This matter means that the lateral force is influenced by the characteristics of the soil (Li et al., 2017). In order to analyze the long-term behavior of the energy pile, a laboratory model of it was built in dry sand soil. In addition to the mechanical load, it was subjected to a cycle of heating/cooling thermal load. This test showed that increasing in the number of thermal cycles results in increasing the axial force of the pile. In this experiment, the first thermal cycle caused the highest amount of pile settlement, while with the increase in the number of cycles, this value gradually decreased (Nguyen et al., 2017). Guo et al. (2018) conducted a numerical study on the long-term thermal performance of energy piles located in multi-layer soil. They concluded that thermal boundaries have a special effect on soil temperature in the long term compared to soil heterogeneity. Sani and Singh (2018) conducted a two-dimensional finite element modeling with the aim of investigating the response of unsaturated soils to thermal loading. They reported that as the saturation ratio increases, the soil temperature decreases respectably. Also some analytical solutions have been presented by researchers. Cossel (2019) with considering a single energy pile embedded in a homogeneous four-layer soil prepared analytical solutions for displacement, stress and strain. The stiffness of soil was constant with depth. Peric et al. (2020) presented analytical solutions in a single end bearing geothermal pile with four-layer soil. Fang et al. (2022) presented that cyclic thermal loading for energy piles in loose soil induces compressive stress in the pile. Their study showed that stresses increase with increasing the number of cycles imposed to the pile.

According to the dual goals for energy piles, these piles are simultaneously under two different types of loading, namely mechanical load and thermal load. This issue affects the resulting displacement, stresses and strains, so the effects of thermal loads must be considered in the design of energy piles. It requires a complete understanding of the thermo-mechanical behavior of heat exchanger piles. For this reason, in the current study, the main focus is on recognizing and investigating the thermal response of energy piles in different soils. This study is based on a set of experimental results conducted and reported in a four-story building located in Lausanne, Switzerland. A schematic view of the actual soil profile is shown in Figure. 1. This structure consists of a four-layer soil located on bedrock. For a more detailed investigation of the effect of heat on the soil, each layer of that soil profile has been considered individually in the modeling. The numerical results of the calculations have been compared with the results of the original test data and validated against full scale pile tests.

2 Experimental characteristics of energy piles

According to Laloui et al. (2006), the test conducted in Lausanne included a four-story building with 97 piles of 26 meters with a diameter of 1 meter. The level of underground water is almost the same as the surface of the earth. The geothermal pile is subjected to a heating and cooling cycle. In this test, the temperature applied to the pile is considered the same throughout the length of the pile. The amount of temperature applied to the pile at different times is specified in Table 1.

Table 1. Temperature values applied to the pile.

Temperature Gradient (°C)	Time (day)
0	0
2	5
21	12
10	15
3	28

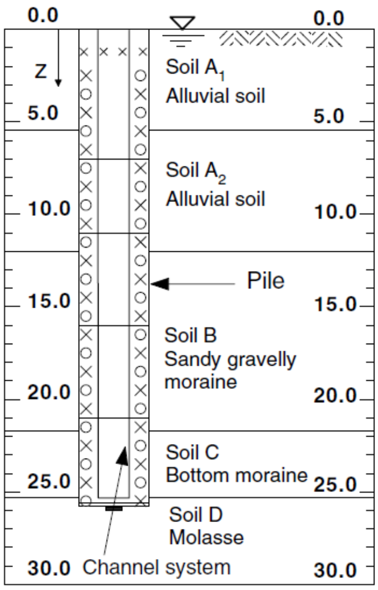

Figure 1. View of the test site in Lausanne.

3 Finite element model

The finite element method is one of the most common and powerful ways to investigate the thermo-mechanical behavior of energy piles. Experience has also shown that this method provides appropriate results in accordance with laboratory results and physical models. In this study, COMSOL 5.3 Multiphysics software was used to model thermo-hydro-mechanical (THM) behavior. This software has various modules, such as structural mechanics, heat transfer, fluid flow, etc. and is able to couple them. It also allows the user to edit the modules according to the desired problem by entering the desired variables. The geometry of this model is considered axially symmetrical because of the circular cross-section of the pile shape and the same characteristics of stratigraphy. As shown in Figure. 2, the radius of the pile is 0.5 m and its length is 26 m, and the total height of the mesh is 52 m. Part A of the figure is the numerical model of single-layer and homogeneous soil located on bedrock, and part B is the case of multi-layer soil, which is in accordance with the validated model.

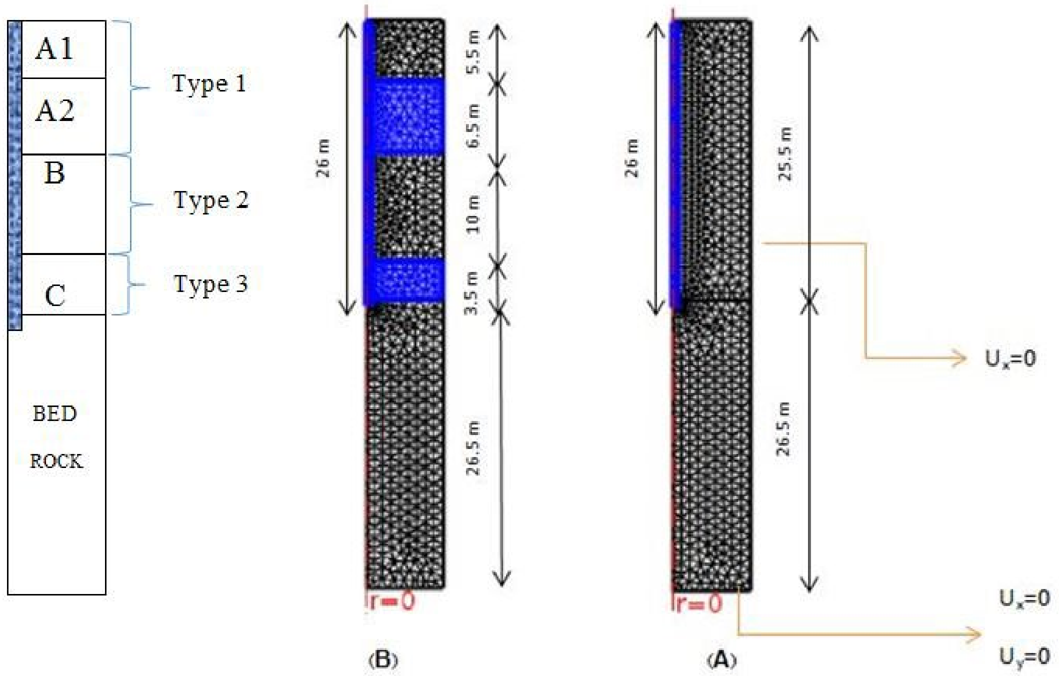

Figure 2. Finite element mesh and mechanical boundary conditions.

In this numerical model, the mechanical boundary conditions are such that the right vertical boundary only has the freedom to move in the vertical direction, while the bottom boundary is not able to move in any way. This model is completely free from the top and the left border is considered as the axis of symmetry. The contact surface between the body of the pile and the soil is considered quite hard and uneven. This means that there is no relative movement between the pile and the soil. Drainage is also allowed from the upper and right borders. Thermal loading has been applied to the pile by applying temperature changes as mentioned in Table 1. In this case, the model is allowed to exchange heat from the external boundary. Positive displacement is directed upward. In compression the axial stress and strain are negative. A compressive axial force was assumed negative, so heating the pile conduced positive change.

4 Material properties

The properties of the materials modeled in this model as linear thermo-elastic are in accordance with Laloui et al. (2006). Using Eqs. (1) and (2), bulk modulus and shear modulus have been converted to elasticity modulus and Poisson's ratio:

$$E = \frac{9KG}{3K+G} \quad (1)$$

$$\nu = \frac{E}{2G} - 1 \quad (2)$$

Heat capacity is 2.4×10^{6} J/m^3/°C equal for all soil layers and is 2×10^{6} J/m^3/°C for bedrock and concrete pile. The thermal conductivity is considered 1.8W/m/°C for the soil, 1.1W/m/°C for the bedrock and 2.1W/m/°C for the energy pile. Other characteristics are reported in Table 2. According to the given properties, it is possible to compare the presented soils. Homogeneous soil type 1, which includes A1 and A2, is loose soil; soil type 2 or the same layer B is medium and soil type 3, which is the same layer C, is considered dense.

Table 2. Material properties used in the finite element model.

Porosity	Poisson's ratio	Elasticity (MPa) Modulus	Bulk Modulus (MPa)	Shear Modulus (MPa)	Density (kg/m^3)	Soil
0.1	0.14	259	122	113	2000	A1
0.1	0.14	259	122	113	1950	A2
0.35	0	451	59	1000	2000	B
0.3	0	634	83	1400	2200	C
0	0.16	1273	620	550	2550	bedrock
0	0.176	33700	17381	14313	2500	pile

5 Numerical analyses

In this section, the results of the numerical model are presented and matched with the values obtained from the experimental results. To investigate the thermal behavior of the pile, a heating-cooling cycle, which included a 12-day heating period followed by a 16-day cooling period, was applied to it. The graphs show the change in location, strain and stress of the heat exchanger pile at different depths. In Figures. 3-5, positive vertical displacement is shown in the upward direction, and tensile stress is considered positive. In this study, in addition to the fact that analyses were performed for three different types of single and homogeneous layers, it also includes the multi-layer state. Fig. 3 shows the vertical movement of the pile head during 28 days for the four mentioned situations. As shown in Table 2, the first layer has a lower shear modulus than the other layers. Accordingly, it has the highest displacement. As can be seen in Figure. 3, the largest range of values obtained from optical fiber results is in the range between the numerical results of multi-layer soil and type 3 soil. In a similar way, the displacement obtained for the multi-layer soil system is very close to the displacement value of the soil layer type 1. On average, with every 2 degrees Celsius increase in temperature, the head of the pile has been moved by 0.26 mm in dense soil, which is one thousandth percent of the total length of the pile.

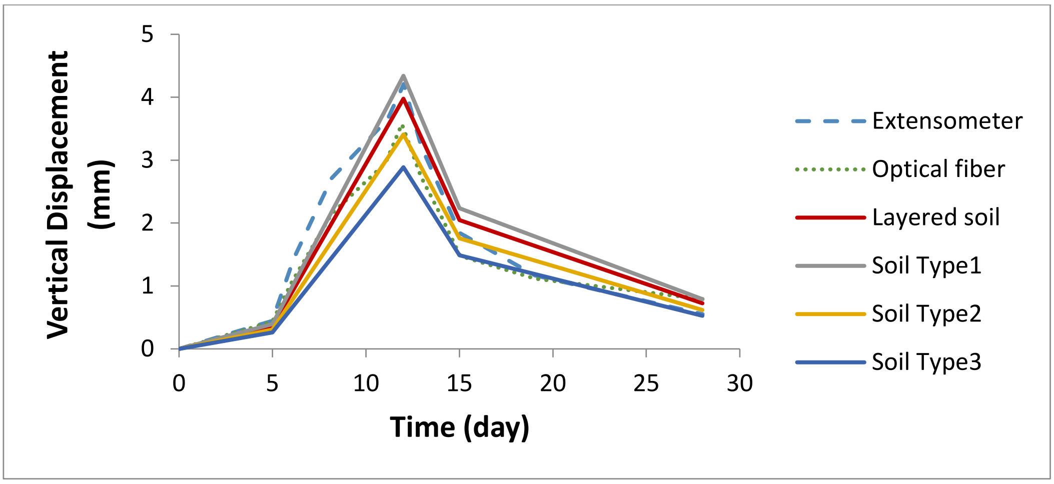

Figure 3. Vertical movement of the pile head over time.

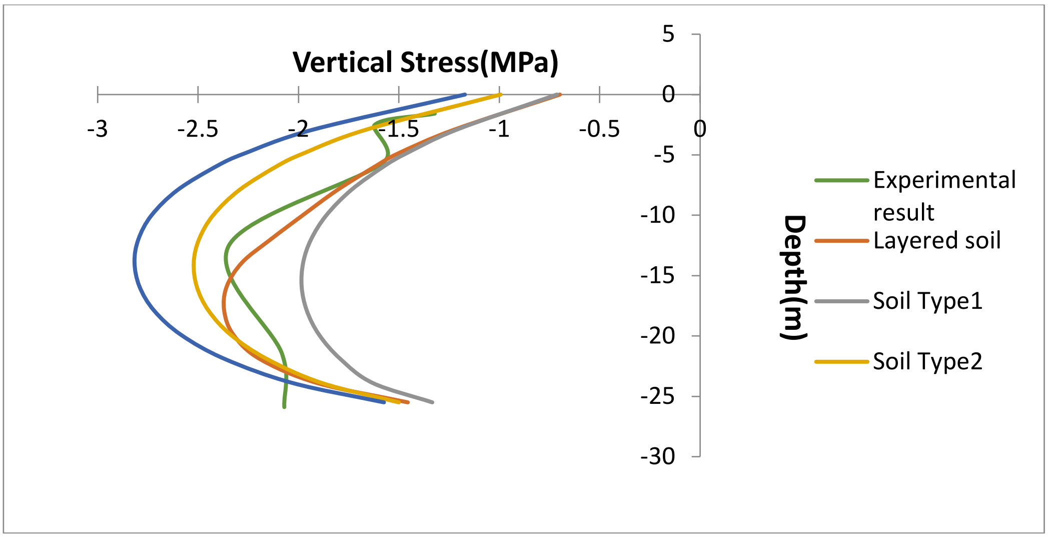

Figure 4. Pile vertical stress during the heating period.

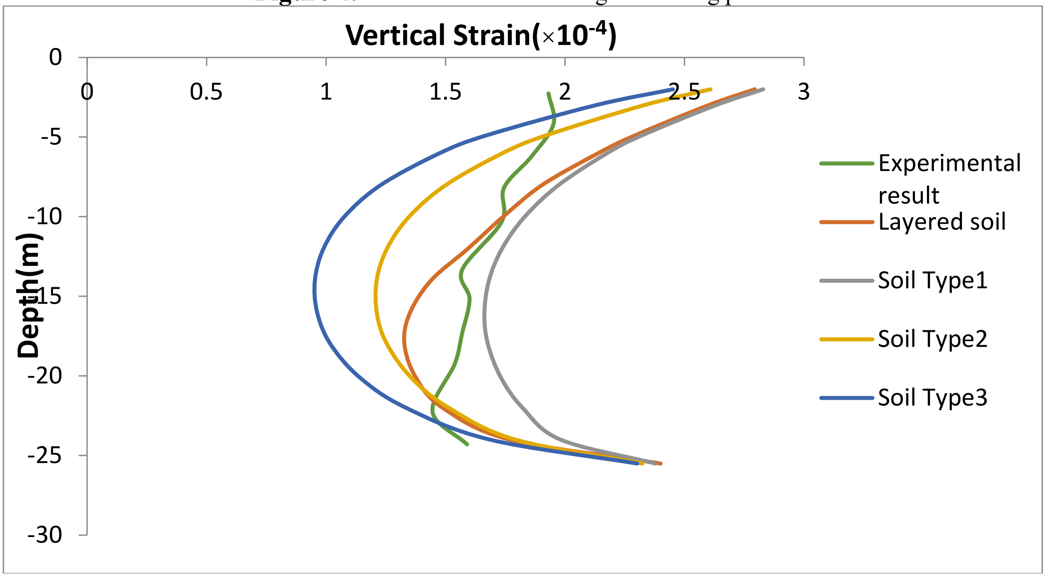

Figure 5. Changes of pile vertical strain by depth during the heating period.

The changes of pile vertical stress at different depths during the heating period are shown in Figure. 4. Obtained results show that the stresses of the numerical model of the multi-layered soil system and soil type 1 at the top of the pile and near the ground surface are more consistent with the values of the experimental results, while the stresses of the type 3 soil at the bottom of the pile are more consistent with the experimental results. As can be seen in this diagram, the highest values of vertical stresses occur in the middle part of the pile (almost in the middle of the pile). This matter shows itself clearly especially in analyses where the soil is completely homogeneous. In all cases, the highest amount of stress occurs in the middle part of the pile (approximately between the depths of 10 m and 20 m). When different layers have been used in numerical modeling, this maximum vertical stress is inclined towards the bottom of the middle of the pile. Of course, it is obvious that this article depends on the type of the soil considered. According to Table 2, the type 3 soil layer has a higher modulus of elasticity among other soil layers. Consequently, as shown in Figure. 4, its stress value is higher than other cases.

Figure. 5 shows the changes of the vertical strain inside the pile during the heating period. The strains related to multi-layered soil in the upper part of the pile are very close to the values related to type 1 soil. This degree of similarity between the values continues up to the boundary between the two soil layers of type 1 and type 2, and from that level on, the distance between them increases. As can be seen, over time, the layered soil diagram becomes closer to the soil strain values of types 2 and 3. The strain associated with the experimental results in the upper and surface depths of the soil has the highest degree of coordination with the layered soil results. Meanwhile, the strain obtained from the field test in the lower depths has a better match with the numerical model of soil type 3.

The changes of the vertical strain of the pile in terms of depth at the end of the cooling period are presented in Figure. 6. One of the remarkable points in this figure is that the results of the field test are close to the results of the numerical model of soil type 3 (almost dense). The values of the vertical strain associated with multi-layered soil in the upper parts (close to the ground surface) are similar to the values of the numerical model of homogeneous soil type 1 (almost loose soil). As the obtained results show, the experimental results are placed between the two graphs of layered soil and type 3 soil (approximately dense). In this diagram, it can be seen that in the numerical models, the values of the vertical strains at the end of the pile have reached an almost constant value. This article can be interpreted according to the presence of bedrock. Another important point regarding this part of the results is the significant difference (about 50%) of the vertical strain in the middle of the pile length in the results of the analysis in two cases of almost loose homogeneous soil (type 1) and almost dense homogeneous soil (type 3). As expected, as the soil becomes looser (in homogeneous soil analyses), the values of vertical strain increase.

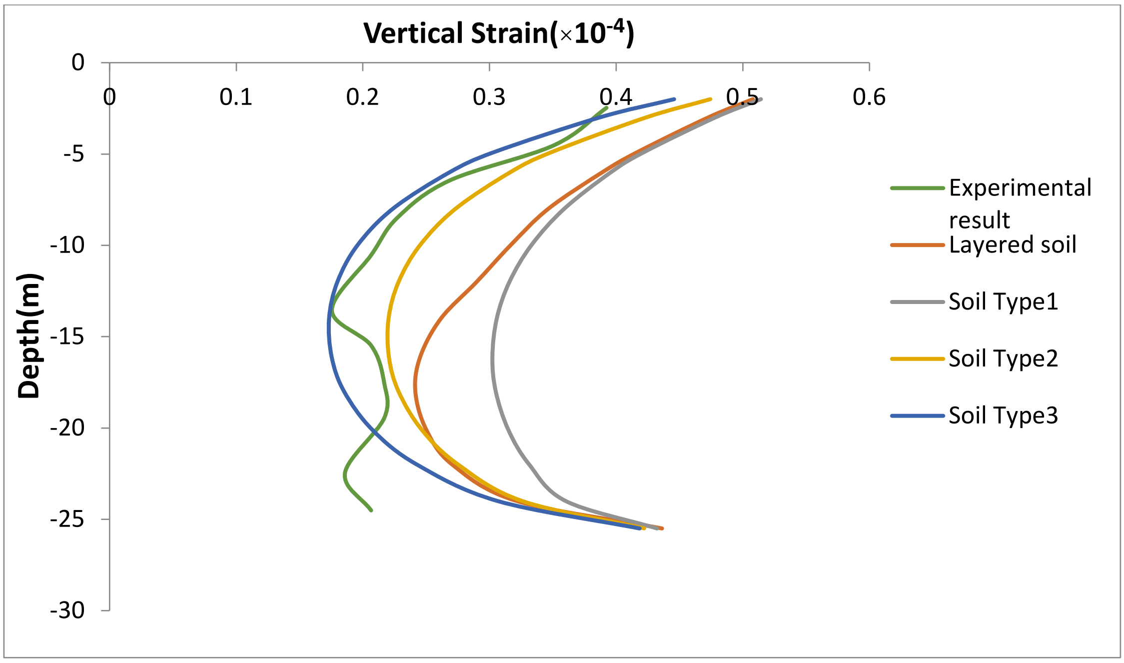

Figure 6. Variations of pile vertical strain according to depth during the cooling period.

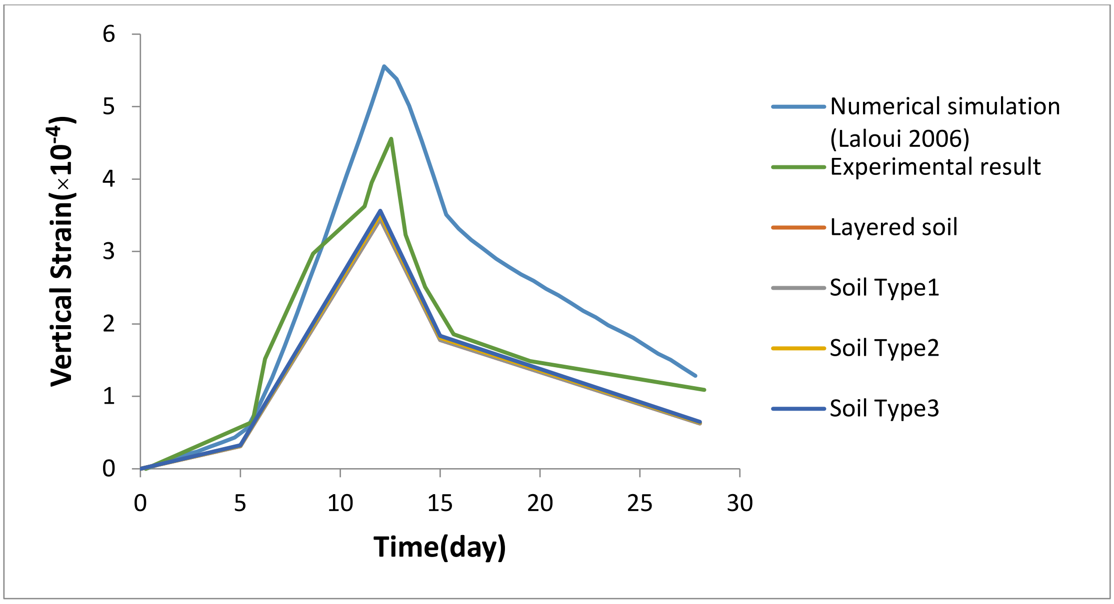

Figure 7. Variations of pile radial strain at constant depth.

Figure. 7 shows the changes of the radial strain of the energy pile for different situations in a period of 28 days at a constant depth. As it is known, the numerical results obtained in this study are completely consistent with each other and have a good match with the values of the experimental results.

Figure. 8 shows the radial strain changes of the pile at the end of the heating period at different depths. At surface depths, the results of the layered model are closer to the results of type 1 soil, but at the lower depths of the pile, it is more consistent with type 2 and type 3 soils. It should be noted that with the increase in the amount of heat, the amount of strains also increases. Another noteworthy point in this diagram is that when the pile is placed in almost dense homogeneous soil (type 3), more radial strain is created in the pile in the entire depth of the pile, compared to other soils. It seems that the high density of the soil has caused more connection to the pile and this has increased the radial strain in this soil. This interpretation gets stronger from the fact that in almost loose soil (type 1), the smallest radial radius can be seen in the body of the pile.

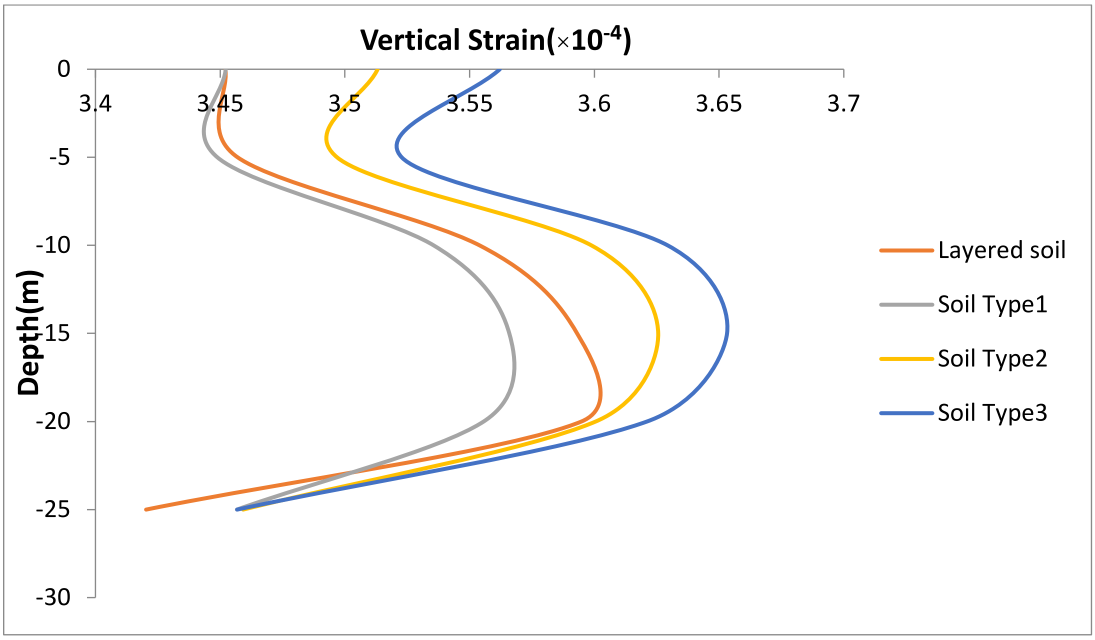

Figure 8. Radial strain changes of the pile at the end of the heating period.

6 Conclusions

In this study, numerical modeling was performed to investigate the behavior of geothermal piles in different soils under thermal loading. It should be mentioned that in all the analyses performed with COMSOL software, the ends of the piles were resting on the bedrock. To investigate this issue, different analyses were done based on two different parts. In the first case, the real soil profile was considered as non-homogeneous and layered, which included three different types of soil on the bedrock. In the second case, the soil environment only includes a homogeneous soil layer (similar to the three different types of soil considered in the first case) on the bedrock. These two different states were subjected to thermal loading and the results of strains and stresses were compared with each other. In the results of this research, the effects of different soils and layers were clearly observed in the response of thermal energy piles implemented in these soils. The behavior of the thermal pile depends on the type and characteristics of the soil and the amount of load on the pile. The results of this research, which deals with the problem of soil layering in thermal piles, show that heat changes the amount of stress and strain in such a way that with the application of heat, the vertical stress increases with increasing depth. The results of this research showed that the response of soil with different layers is among the responses of single-layer models, so loose soil is located on one side and medium and dense soil is located on the other side. In other words, the presence of different layers in the soil causes a change in the strain and stress values compared to the state where the soil is homogeneous. One of the noteworthy points in the obtained results is that the vertical stresses and strains of the pile placed in multi-layered soil at the depth of the earth's surface are in better agreement with the vertical stresses and strains of the pile placed in loose soil. The modulus of elasticity of soil with average density of type 2 is 74% higher than the modulus of elasticity of loose soil considered in the analysis, which has led to a 27% reduction in displacement, a 40% increase in compressive stress and a 77% reduction in vertical strain. The same change in the modulus of elasticity of the soil layers caused a change in the values of stresses and pile stresses in the state of layered soil. Also, the 40% change in the modulus of elasticity of type 2 and 3 soils has caused the amount of displacement to decrease by 17% and the amount of compressive stress and strain to increase by 11% and decrease by 27%, respectively. The results of the numerical analysis showed that the type of soil and the way they are located in the depth have a significant effect on the behavior of the geothermal pile. Since non-homogeneous soil layers are observed in nature, it is necessary to determine the real behavior of such soils and the geothermal piles implemented in them because of different soil layers. Different layers and especially the presence of the loose layer and its location in the desired soil profile should be given special attention.

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