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THERMO-MECHANICAL BEHAVIOR AND STRUCTURAL DESIGN OF GEOTHERMALLY ACTIVE PILES

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Abstract

Contemporary living and the need for renewable energy sources demand innovative "green" technologies that offer structural improvement and simultaneously provide more economical and long-term cost-friendly solutions. In geotechnical engineering, shallow thermo-active geo-structures look like one of the most promising concepts. Thermo-active geo-structures may include base slabs, piles, retaining walls, and supporting elements for tunnels, such as linings and anchors, which besides the mechanical (bearing) function have a thermal function working as heat exchanger systems. In most cases, these structures are piles, whose behavior could be predicted using different approaches. Utilizing foundation systems as heat exchangers has received significant public interest worldwide, as these energy geo-structures can constitute a clean, renewable, and economical solution for space heating and cooling. Thermo-active geo-structures are considered innovative alternatives to traditional Ground Source Heat Pump (GSHP) systems for space heating and cooling, having the potential to reduce the upfront cost of the GSHP systems. Hence, the structural element gets an additional thermal function such as piles, retaining walls, tunnel linings pavements, etc. This way they will be loaded by thermal change or difference in temperature which must be considered during the design phase. The most common type of energy geo-structures are energy piles, most likely due to their significant geometrical similarities with the thoroughly studied traditional vertical borehole systems, attempting to adapt the available thermal design methods for the traditional borehole systems for energy pile design, commercial aspects, benefits of using Energy Geotechnical Structures (EGS) compared to standard Borehole heat exchanger systems.

Keywords: Geotechnical engineering, thermos-active structures, geothermal energy, geothermal pile.

1. Introduction

The foundation of a structure represents a connection between the structure and the supporting soil. Through the foundation, mechanical loads are transferred to the soil. In the design of every geostructures, the behavior of soil plays a primary role. For energy geostructures, an energy supply role is added to the conventional role of the foundation as structural support. The so-called Energy piles are generally subjected to monotonic or cyclic temperature changes, depending on the season of operation or daily thermal energy requirements of the building. They are subjected to daily cyclic temperatures from intermittent operations of the ground source heat pump (GSHP) with natural or forced ground thermal recoveries during the non-operating times of the GSHP [1]. The long-term temperature changes that occur along the length of the energy pile, caused by the effects of heating and cooling, can significantly affect the stress state around the pile, and therefore its load-bearing capacity. The cyclic processes of heating and cooling affect the volume changes of the pile, but also the soil surrounding it. The pile elongates when heated, and contracts when cooled, which causes additional axial tensile stress, which further affects the soil-pile interaction. All these additional effects that occur from the activity of the energy piles can affect the load-bearing capacity and stability of the pile. Therefore, it is important to take them into account when designing geothermally active structures. Given that geothermal piles, compared to conventional piles, have additional impacts, there are no precise design methods to verify the geotechnical strength of energy piles [2]. For years, designers have designed buildings with energy piles based on empirical understandings or with a conservative approach, increasing the safety factor (Boönnec, 2009, Knellwolf et al., 2011).

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2. Physical processes involved in exploitation of the energy piles

The exploitation of energy piles involves complex physical processes related to heat transfer and mechanical behavior. Heat transfer in energy piles occurs through conduction within the pile material, convection within the circulating fluid, and conduction or convection in the surrounding soil, depending on moisture content and groundwater flow. These thermal interactions influence the temperature distribution within the pile and the soil, affecting the pile's structural response. Additionally, thermal expansion and contraction of the pile due to temperature variations introduce thermomechanical stresses, which must be considered in design to prevent structural damage or excessive deformation. The efficiency of energy piles depends on factors such as pile material properties, pipe configuration, soil thermal characteristics, and operational conditions. Understanding these physical processes is crucial for optimizing energy pile performance, ensuring both structural stability and effective geothermal energy exchange.

2.1. Principle of the heat transfer in the soil

Soil is a multiphase material with a complex heat transfer mechanism, which includes conduction, convection, radiation, evaporation and condensation, ion exchange and freeze-thaw processes. As shown in Figure 1, the main mechanism of heat transfer in the soil is conduction, followed by convection. The figure illustrates different heat transfer mechanisms in soil based on the D_{10} effective grain size (ranging from clay to gravel) and the degree of saturation. It identifies six key processes: thermal redistribution of moisture, vapor diffusion due to moisture gradients, free convection in water, free convection in air, heat radiation, and heat conduction as the dominant mechanism. The transitions between these processes depend on the soil's particle size and moisture content. Finer soils (clay and silt) are dominated by moisture-driven heat transfer, while coarser soils (sand and gravel) experience convection and radiation effects, particularly at lower saturation levels. Thermal conduction is also possible if there is a phase change of water (latent heat during evaporation and condensation). Radiation is of minimal importance (1%) and is limited to the upper soil layers. Thaw-thaw processes, although they can make heat transfer more effective, are recommended to be neglected for thermo-active foundations for geotechnical reasons. [3]

The total heat transfer q_{tot} can be defined according to the expression (Rees et al. 2000):

$$q_{tot} = q_{cond} + q_{l.conv} + q_{v,conv} + q_{lat}$$

Where q_{tot} represents heat transfer by conduction, $q_{l.conv}$ represents heat transfer by fluid convection, $q_{v,conv}$ represents heat transfer by evaporation, and q_{lat} represents latent heat transfer.

Latent heat transfer occurs as a result of phase changes of pore water (evaporation) and depends on the amount of vapor transfer occurring in the soil pores. It increases with decreasing water content and can be expressed as follows:

$$q_{lat} = L_0 \rho_l \vartheta_v$$

Where L_0 represents the latent heat of vaporization, ρ_l represents the density of water, and ϑ_v represents the rate of evaporation.

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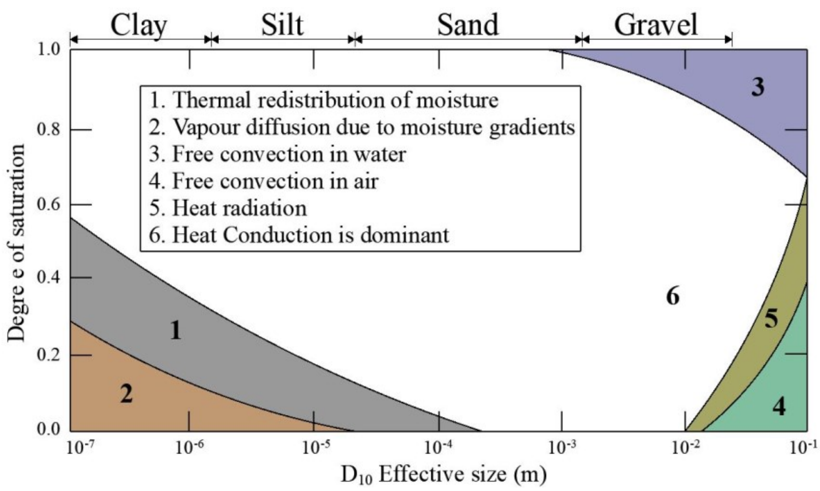

Figure 1. Dominant heat transfer mechanisms in soil in relation to grain size and soil saturation (adapted from Farouki 1986)

Thermal convention occurs between thermodynamic systems that are moving relatively to each other. In soils, the solid phase is static: hence convection can only occur in the water or (pore) gas phase. The heat transfer by fluid convection, $q_{l.conv}$ and the heat transfer for evaporation (pore gas) $q_{v,conv}$, are defined by the following expressions:

$$q_{l,conv} = c_l \rho_l \vartheta_l \Delta T$$

Where c_l is the specific heat capacity of the pore water, ρ_l is the density of the water, ϑ_l is the velocity of the water, and ΔT is the temperature change.

$$q_{v,conv} = c_v \rho_v \vartheta_v \Delta T$$

Where c_v is the specific heat capacity of the soil vapor, ρ_v is, the density of the soil vapor, ϑ_v represents the evaporation rate, and ΔT is the temperature change.

Thermal conduction is a process where heat is transferred from one part of a medium to another, without visible movement in the medium. Thermal energy is transferred from molecule to molecule. According to Fourier's law, the heat flux for a heat volume Q through an arbitrary surface A during a time t is the heat flux per unit area, q_{cond}, generated by conduction is defined by the expression:

$$q_{cond} \frac{Q}{At} = -\lambda \Delta T$$

Where λ represents the thermal conductivity of the medium, Δ is the gradient parameter and T is the temperature.

Changes in moisture content of the soil causes changes in the thermal properties of it, especially in unsaturated soils (Farouki 1981). The evaporation of water in the soil induces a temperature gradient and water vapor can move through the pores towards the lower vapor pressure. If the temperature is lower in the new location, condensation occurs, releasing heat and changing the amount of water in the soil. These changes in moisture content affect the thermal properties of the soil by changing the saturation degree but also contribute to the process of heat transfer. This process is important in soil with high porosity and high temperature differences.

2.2. Heat transfer in the Energy Pile

The temperature difference between the ground, the pile, and the fluid that carries the heat through the geothermal installation drives the heat transfer in the geothermal system. The mechanisms involved in this process are shown in Figure 4, namely convective heat flow between the fluid and the pipe, conductive heat flow in the pipe wall, conductive heat flow in the concrete pile, conductive heat flow

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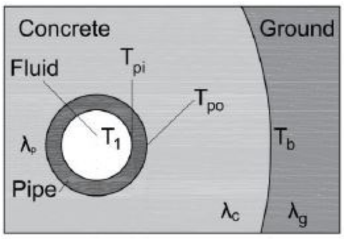
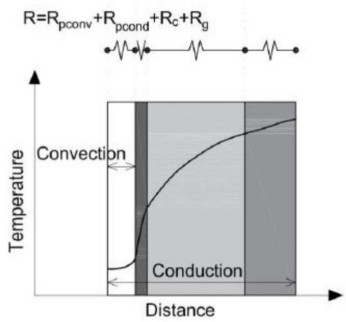
in the soil, and convective heat flow in the soil, if the geothermal water flow rate is greater than 0.5 – 1.0 m/day (Loveridge and Powrie 2012).



a)



b)

Figure 2. Heat transfer mechanism in energy piles (a) plan view of the energy pile and surrounding soil (b) lateral view of the energy pile and surrounding soil (Loveridge and Powrie 2012)

According to Lee et al. (2009) the total usable heat extracted through the energy loops can be calculated using the following equation:

$$q_{tot} = Q_{in} - Q_{out} = mc_{fluid}(T_{in} - T_{out})$$

Where m is the mass flux density of the circulating fluid, c_{fluid} is the heat capacity of the circulating fluid, Q is the total heat extracted, T_{in} is the inlet temperature, while T_{out} is the outlet temperature.

In the design of energy piles, the instantaneous steady state is assumed to be the internal heat transfer between the heat fluid and the outer surface of the concrete. The temperature difference between the fluid in the pipes and the edge of the heat exchangers ΔT can be calculated based on the thermal resistance of the heat exchanger:

$$R_{tot} = \frac{T_s - T_f}{q}$$

Where T_s is the temperature of the soil-pile interaction, T_f is the temperature of the fluid carrying the heat and q is the heat flow per meter of the GSHP exchanger. The total thermal resistance can be divided into the thermal resistance of the individual components of the geothermal construction, i.e.:

$$R_{tot} = R_{fluid} + R_{pipe} + R_{concrete} + R_{ground}$$

The thermal resistance of the fluid circulating in the pipes is calculated by the equation:

$$R_{fluid} = \frac{1}{2n\pi r_i h}$$

Where r_i is the inner radius of the pipe, n represents the number of pipes, and h is the coefficient of heat transfer through convection. The value of the thermal resistance depends on the number of pipes, their disposition, the thickness of the concrete layer, as well as the thermal conductivity of the concrete and the thermal characteristics of the fluid that transfers heat.

The thermal resistance of the pipe is represented by the following equation:

$$R_{pipe} = \frac{ln(r_0/r_i)}{2n\pi k_p}$$

Where r_0 is the outer radius of the pipe, while k_p denotes the thermal conductivity of the pipe material.

Regarding the thermal resistance of the concrete cross-section, its steady state can be calculated using the thermal resistance equation of a cylinder, but assuming an effective internal radius of that cylinder r_{eff}. [4]

The thermal resistance of concrete using the equivalent diameter approach is given by:

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$$R_{concrete} = \frac{ln(r_b/r_{eff})}{2\pi k_c}$$

Where r_b is the radius of the circle, k_c is the thermal conductivity of the concrete, and r_{eff} is the effective radius

$$r_{eff} = r_0\sqrt{n}$$

The equivalent cylinder approach does not consider the position of the pipes. The mechanism is graphically shown in the figure below:

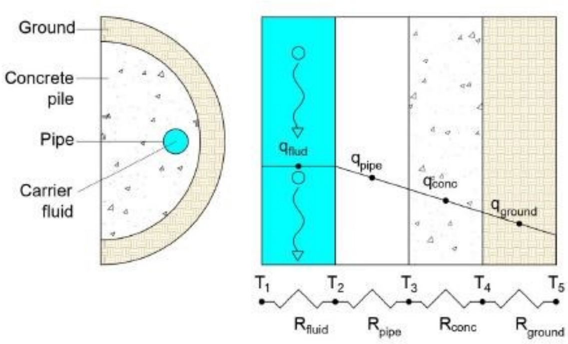

Figure 3. Description of the heat transfer mechanism from the primary circulation of the energy pile to the ground [3]

It should be noted that the concrete layer usually depends on the construction design (the placement of the reinforcement cage) and because it is important to avoid thermal interactions between cold and hot pipes, the value of the shape factor can only be partially optimized. Loveridge et al. (2014) have proposed tables for determining the thermal resistance of piles. According to the tables, it can be concluded that with a larger pile diameter, lower thermal resistance, and thinner concrete layer, thermal contact between the pile and the soil would be better, with an optimal number of pipes according to the diameter of the pile (increasing the number of pipes can cause more thermal interactions between hot and cold pipes and reduce the efficiency of the system). Although these tables can offer a first idea of the characteristic configuration suitable for an energy pile, it is needed to be used more advanced tools for the design of the entire system and for monitoring the long-term behavior of the geothermal system. [4]

3. Thermo-mechanical behavior of energy piles

Thermal and mechanical loads application to energy piles introduces new aspects in the response of these piles compared to conventional piles which are typically subjected to only mechanical loads. This is a result of coupled heat transfer and deformation of materials. Different approaches can be used to investigate the response of energy piles, subjected to mechanical and thermal loads. These include full-scale in situ tests, model-scale laboratory tests, and centrifuge tests. To interpret the response of energy piles these must be considered: idealizations and assumptions, classifications of energy piles, temperature, vertical and radial strains due to thermal loads, vertical displacements, shear stresses and vertical stress due to thermal and mechanically loads, and freedom degrees. [5]

<u>Idealizations and assumptions</u>: Soil layers surrounding the pile are not fully horizontal, also thermal and mechanical loads cause non-uniform variations of the temperature, stress, strain, and displacement within and around the pile. In the calculations of energy piles, soil layers are assumed to be fully horizontal, and it is assumed that temperature, stress, strain, and displacement are uniform and representative of the energy pile response. [6]

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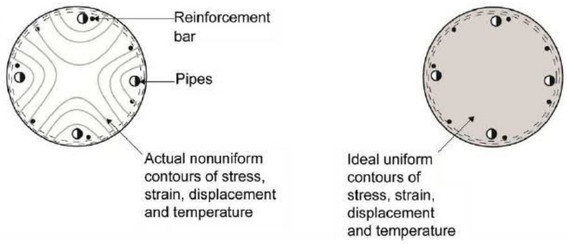

Figure 4. Idealization of stress, strain, displacement and temperature fields within energy piles

In Fig. 4 is shown comparison between the actual and ideal stress, strain, displacement, and temperature distribution in a circular cross-section of a geothermal pile, composed by concrete column with embedded reinforcement bars and pipes. The left side of the figure illustrates the real scenario, where the presence of reinforcement and pipes causes nonuniform contours due to material discontinuities and thermal effects. The right side of the figure represents an idealized condition where these properties are uniformly distributed, assuming a homogenous material without interruptions. This comparison highlights the impact of embedded elements on structural behavior and the challenges in achieving uniform performance

Classification of energy piles: Classification of energy piles can be done according to various criteria. The commonly used classification is related to the technique because of its influence on the response of the energy pile. Another criterion of classification refers to the bearing behavior of the pile [7].

Temperature variations: Due to geothermal operation in energy piles, the temperature can develop notable variations. For known boundary conditions, the rate of temperature variations depends on the thermal power applied to the pile, as well as on the thermohydraulic properties of both surrounding ground and the pile. [8]

Vertical and radial strains due to thermal load: For energy pile under thermal loads, expansive strains are generated during heating and contraction strains during cooling. These strains are usually not uniform with depth. End-restraint provided by the presence of the ground and superstructure determines the evolution of the strains. Besides vertical strains, because of the applied thermal loads also radial strains develop in energy piles. Vertical and radial strains caused by the temperature variations can be observed for the same temperature variation which is applied to the energy pile. But, because of the different dimensions, length, and diameter of energy piles, the vertical and horizontal displacements of the pile, associated with the considered strains are markedly different.[9]

Vertical and shear stress due to thermal and mechanical loads: Thermal loads along energy piles describe at best a linear distribution of the vertical displacement with depth, and at worst scenario a nonlinear distribution of these vertical displacements, which become more prominent with increasing compressibility and slenderness of the pile. These should be taken into consideration during the analysis of both rigid and deformable piles. Shear stress at energy piles are mobilized in opposite directions of the deformations induced by the thermal loads, to ensure equilibrium with the surrounding soil from the so-called null point of the shear stress. Mobilized shear stresses magnitude depends on the restraint conditions.[3]

Freedom degrees: Another factor determining the response of the energy pile under mechanical and thermal loads is the end-restraint. In this context, the degree of freedom can effectively characterize the degree of restraint of energy piles.[8]

4. Numerical modelling of the energy piles

Two cases of geothermal piles, free head pile and end bearing pile were analyzed using the software Plaxis 2D. "Plaxis 2D" is a finite element software for geotechnical engineering applications. When working in PLAXIS 2D, the geomaterial is considered in a three-phase (solid/liquid/gas) porous medium, but the gas pressure is taken as constant, which is widely accepted in geotechnical engineering. In both cases, it was used an axisymmetric model, placed in a half-space with dimensions x_{max}=20 m

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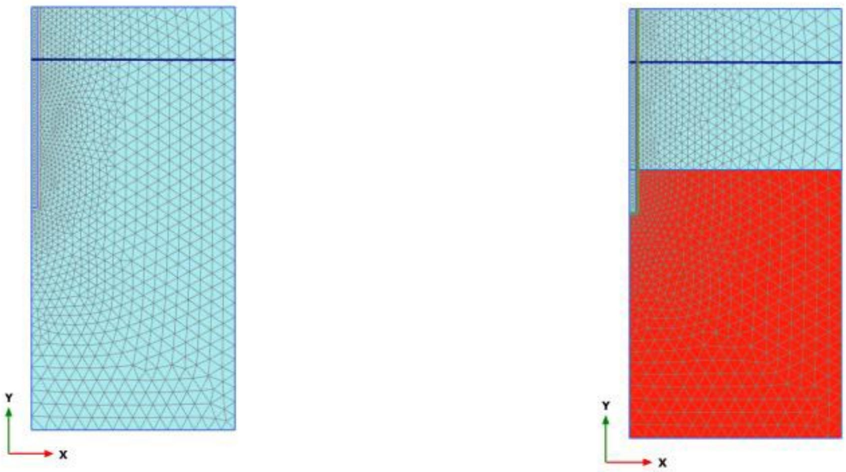
and y_{max}=40 m. The piles were modeled with a length of 19.0 m and a diameter of 0.60 m. In the first case for free head pile there is only one layer of clay with the thickness of 40 meters (blue color in the model in Figure 9a), while in the second case for end bearing pile, it consists of two layers, the first layer of clay with 16 meters (blue color in the model, Figure 9b) and the layer of limestone of 24 meters (red color in the model Figure 9b). Material's properties for soil layers and the pile are given in the Table 1. During the analysis, volumetric finite elements were used, with a "fine" finite element mesh.



a) b)

Figure 9. Plaxis models, a) Free head pile in clay layer; b) End bearing pile in clay and limestone layers

The piles were calculated according to the Mohr-Coulomb laws. The load was applied in four phases for both cases. The material parameters for both cases and loading phases are given in the tables below:

Table 1. Material properties of the models

		Case 1 – Free head pile		Case 2 – End-bearing pile		
Parameters	Unit	Concrete	Clay	Concrete	Clay	Limestone
General						
Model*		LE	MC	LE	MC	LE
Unsaturated unit weight	kN/m^3	25.00	21.00	25.00	21.00	25.50
Mechanical						
Young's modulus	kN/m^2	31.5 E6	55.00 E3	31.5 E6	55.00 E3	2.60 E6
Poisson's ratio	-	0.20	0.30	0.20	0.30	0.1517
Cohesion	kPa	-	2.00	-	2.00	
Friction angle	º	-	35.00	-	35.00	
Dilatancy angle	º	-	5.00	-	5.00	
Thermal						
Heat capacity	$J/T/K$	800	890	800	890	784
Thermal conductivity	$W/m/K$	2.100	4.450	2.100	4.450	1.100

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Soil density	t/m^3	2.500	2.735	2.500	2.735	2.250
Thermal expansion	$1/K$	1.0 10E-5	1.0 10E-4	1.0 10E-5	1.0 10E-4	1.0 10E-6

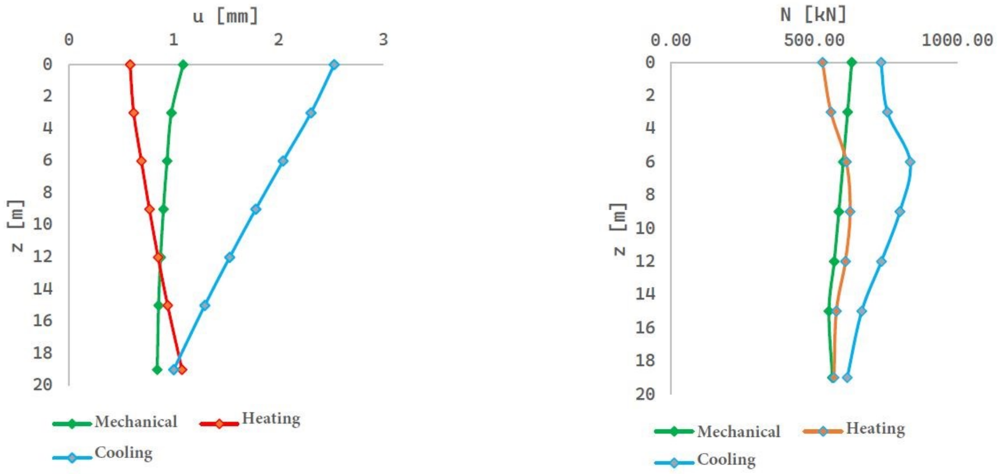
Table 2. Loading phases

Phase	Loading type	Specifics
Phase 1	Starting phase	-
Phase 2	Mechanical load	F=3500 kN
Phase 3	Thermo-mechanical load - heating	Harmonic temperature variation ∆T=8 °C, t=20 days
Phase 4	Thermo-mechanical load - cooling	Harmonic temperature variation ∆T=8 °C, t=20 days

As previously mentioned, a free head pile and end-bearing pile are analyzed in three characteristic phases: (1) mechanical loading, (2) thermomechanical loading – heating and (3) thermomechanical loading – cooling. A linear temperature change of 8 $°K$ is given in the two phases of thermal loading respectively. The aim is to determine the thermomechanical behavior of the pile under the action of mechanical and thermal loads. During the analysis, the most characteristic changes shown are the displacements $[u]$, axial force $[N]$, vertical stresses $[\sigma_{yy}]$ and shear stresses $[\tau]$ along the length of the circle, for mechanical loading, thermomechanical loading-heating and thermomechanical loading-cooling.

4.1. Case 1 – Free head pile

From the obtained results it shows that in the case of a free head pile, under the action of the mechanical load a decrease in the magnitude of the displacements along the length of the pile is shown. This is also due to the increase in the strength of the soil layer along the length of the pile, driven by the activated mobilized friction strength along the length of the pile. In the heating phase of the pile in summer, under the action of the displacement that causes the lifting of the pile head on one side, and on the other hand the mechanical load acts vertically downwards, so finally the total displacements decrease in this phase. This causes additional effects on the state of stress. According to the results, in the cooling phase, an additional increase in the total displacements occurs at the pile head, which follows as a result of a decrease in the axial force (Fig. 10a).



a) b)

Figure 10. a) Change in displacements along the length of the pile from three load cases; b) Change in axial force along the length of the pile from three load cases.

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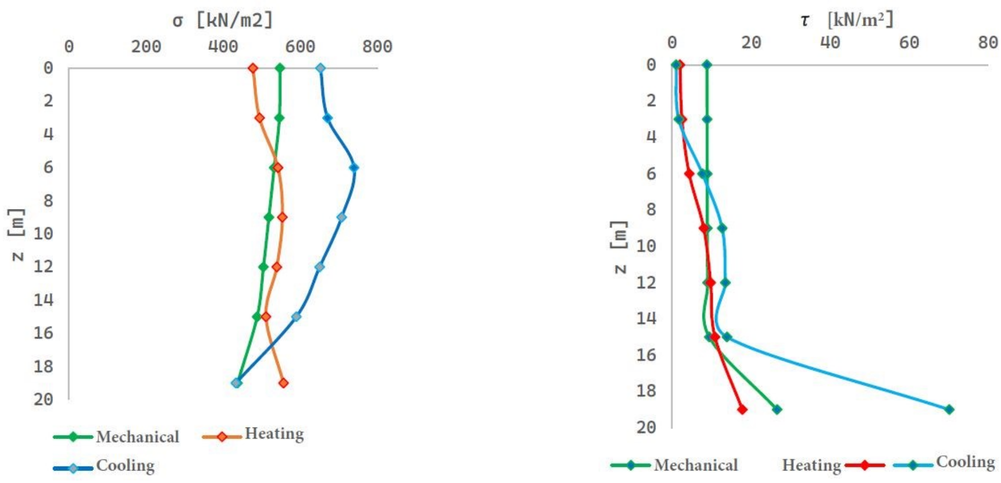
Considering that during the operation of free head pile, friction is additionally included, and additional mobilized friction stress occurs, the axial force from the mechanical loading phase decreases along the length of the pile. As mentioned earlier, in the thermomechanical loading phase - heating, it is shown a decrease in the total displacements at the pile head, which results in an increase in the axial forces inside the pile. On the other hand, the increase in the displacement of the pile head leads to a reduction in the axial force during the thermomechanical loading phase – cooling (Fig. 10b).

Regarding the normal stresses they decrease with the depth of the pile. From the aspect of the stresses within the pile itself, analogous to the situation with axial forces, in the phase of mechanical loading there is a reduction of the normal stresses along the length of the pile, which is due to the activation of the influence of friction. Regarding the thermomechanical loading - heating, due to the reduced displacements of the pile head, greater normal stresses occur in the pile itself, while due to the increased displacements of the pile head, reduced normal stresses occur (Fig. 11a).



a) b)

Figure 11. a) Change in normal stresses along the length of the pile from three load cases; b) Change in shear stresses along the length of the pile from three load cases.

Unlike normal stresses, shear stresses are mobilized in the opposite direction of the pile body, to ensure equilibrium with the surrounding soil. According to the analysis, in the case of thermomechanical loading – heating due to the elongation of the pile, the friction strength decreases in the upper part and increases in the lower part of the pile. On the other hand, due to the shrinkage of the pile, the friction strength increases towards the head of the pile, while it decreases towards the base of the pile. By including friction, the bearing capacity of the pile also increases (Fig. 11b).

4.2. Case 2 – End-bearing pile

From the results obtained in the analysis of end-bearing pile, it is shown that under mechanical loading, displacements are approximately equal to zero due to the fixed head of the pile itself. In contrast to this case, in the case of thermomechanical loading – heating of the pile, because the base of the pile is prevented from moving, a larger displacement occurs near the head. On the other hand, in the case of thermomechanical loading – cooling larger displacement near the head of the pile occurs as a result of the shrinkage towards the base of the pile (Fig. 12a).

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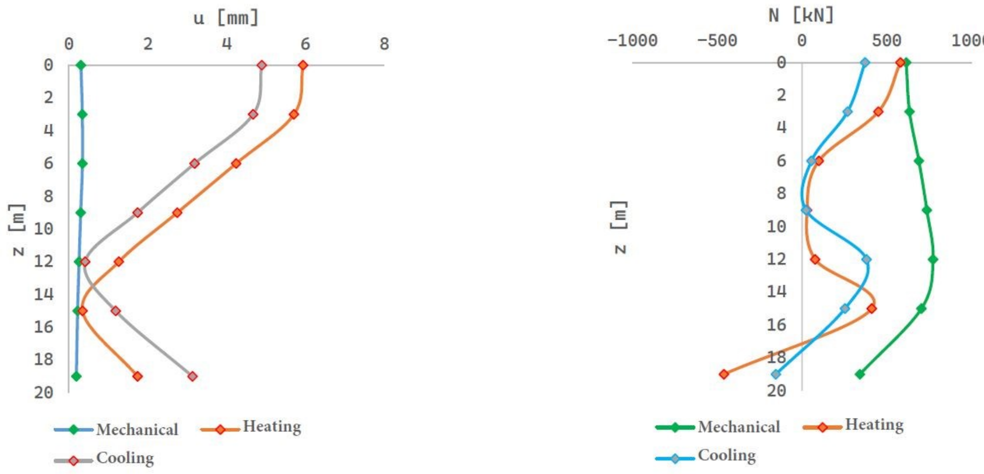
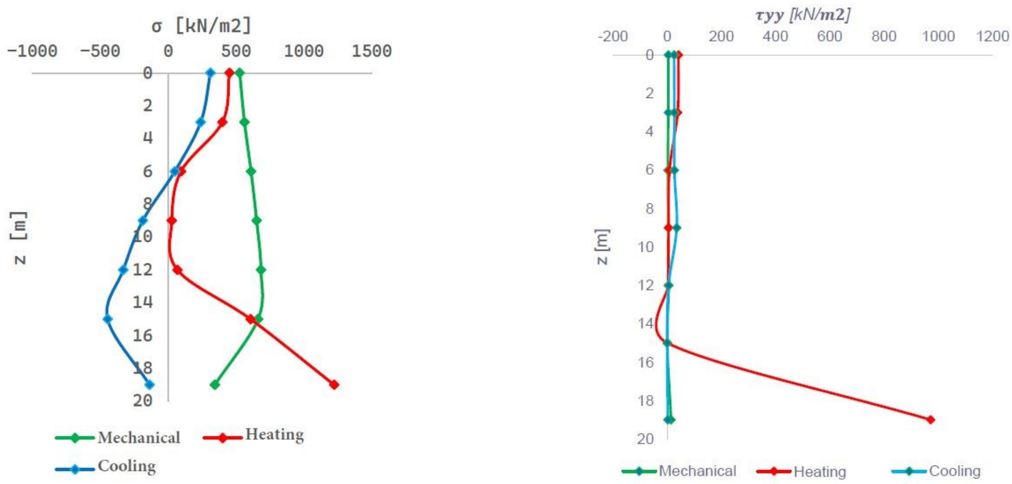


a) b)

Figure 12. a) Change in displacements along the length of the pile from three load cases; b) Change in axial force along the length of the pile from three load cases.

In end-bearing pile, during the thermomechanical loading phase – heating, additional load on the pile head occurs, resulting in an increase in the normal forces and the frictional strength. Additionally, due to the elongation of the pile, the strength of the base of the pile increases. Conversely, during the thermomechanical loading phase – cooling, cooling causes a decrease in the normal forces and the frictional strength. Due to the shrinkage of the pile, the strength of the pile base decreases (Fig. 12b).

From the aspect of normal stresses, it is noticed an increase of them in the case of mechanical loading along the length of the pile. In a heating situation, additional stresses appear at the base of the pile, due to the limitation and inability to move. In the case of cooling, a decrease in normal stress occurs, during which they turn into tension and the pile tends to fracture (Fig. 13a).



a) b)

Figure 13. a) Change in normal stresses along the length of the pile from three load cases; b) Change in shear stresses along the length of the pile from three load cases.

As mentioned earlier, the heating phase causes additional load on the pile head, which in addition to increasing the normal forces, also increases the frictional strength at the pile base and increases the base strength. During the cooling phase, there is a global decrease in the normal forces, and additionally decreases the frictional strength. Due to the shrinkage of the pile, the basic strength also decreases (Fig. 13b).

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5. Conclusions

A numerical analysis was performed using software based on the finite element method, in order to determine the thermomechanical behavior, resulting in important recommendations that could be applied in design in practice. For the design of energy circuits, it is necessary to include all the elements that are crucial for their proper design: (1) determination of thermal actions, (2) displacements of the upper structure, (3) resistance of the pile and (4) resistance of the soil.[12]

Based on the research conducted in this paper, regarding the thermomechanical behavior of energy piles, the following conclusions and recommendations could be drawn:

- Considering that energy piles are loaded with mechanical and thermal actions, their design must consider the effects of temperature changes on the pile and the surrounding soil.
- According to the results obtained, in case of free head pile, under the action of mechanical loading and heating, there is a decrease in the value of the displacements, with the appearance of additional stresses in the pile itself. On the contrary, during the thermomechanical effect of cooling, larger displacements occur, and smaller additional stresses in the pile.
- In the end-bearing pile case, during the heating phase, an additional load occurs on the pile head, which increases the stresses in the cross section, as well as the friction strength. The cooling phase leads to a global decrease in normal forces and frictional strength.
- During the cooling phase, for end-bearing pile the basic strength decreases due to the shrinkage of the circuit. Conversely, during the heating phase, the basic strength increases due to the elongation of the circuit.
- Considering that longer energy piles involve proportionally greater changes in length, it can be concluded that longer energy piles loaded with the same mechanical load are characterized by greater stresses caused by thermal actions.
- In the analysis, the vertical changes in stresses caused by mechanical and thermal actions must be considered along the entire length of the energy piles and the most stressed section along the pile should be checked. Displacements should also be considered, especially at the head of the pile.

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