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A REVIEW ON THE THERMO-MECHANICAL RESPONSE OF ENERGY PILES AND SOIL TO THERMAL LOADING

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Abstract

The effects of climate change increasingly felt today have led to the energy transition from the use of fossil fuels to the use of renewable sources of energy. Today, geothermal energy is increasingly getting attention and, recently, energy piles and underground structures have found increasing use in the exploitation of these resources. This energy is more economic as it saves about 250,000t of fuel each year, more reliable as it is continuous and more environmentally friendly as it releases little or no greenhouse gases in the atmosphere. The energy role added to the structural role of piles increases the loads and stresses on the foundation and therefore can have an impact on them. Moreover, the temperature variation imposed on the piles and the soil alter the soil-structure interaction, of which the effects can be above design limits. The response of energy piles to thermal loading depends on many factors such as soil properties, pile layout and dimensions, boundary conditions, frequency of loading, making their behavior complex compared to conventional piles. This knowledge gap in soil-structure interaction and the lack of appropriate design method of energy piles are some reasons for the potential of geothermal energy being untapped, despite its interesting features. As such, this paper presents the state of art on the thermal and mechanical changes of piles and soils due to thermal loading. The paper starts by explaining the current state of knowledge on energy piles and then it identifies the gaps in existing studies for potential future research. This review on past research about this topic provides a comprehensive framework for future studies, one of which is the use of energy micropiles.

1. Introduction

At ground surface, temperature varies depending on the atmospheric conditions, however as depth increases, this temperature increases reaching about 5000°C in the molten core, at about 6000km below the ground surface. This heat stored in the different layers of the earth has been used 10,000 years ago for bathing through hot pools, then for heating of houses in the 14th century and in 1904, it was first used in Pisa to provide electricity.

Foundations of buildings are increasingly used today for heating and cooling of homes, in which an exchange fluid (either water, water+glycol or a saline solution) circulates in plastic pipes inserted in the foundation, transferring heat from the ground to the building during winter and from the building to the ground during summer.

Foundation piles have been found to be a better extraction technique of geothermal energy compared to wells, pools and boreholes for many reasons: concrete has a higher thermal conductivity and thermal storage capacity than soil and water, it is cheaper since foundations are already structural parts of the buildings and finally the exchange fluid is better protected in the piles (Brandl et al, 2006). However, the energy role, added to the conventional structural role of the foundations, imposes additional thermal loads and stress on them, thereby altering the soil-structure interaction. The temperature variation can lead to some effects on the soils and the piles with consequences on bearing capacity and settlements. The induced effects depend on many factors such as soil properties, pile arrangement and dimensions, boundary conditions, frequency of loading etc. Therefore, it is of utmost importance to study the thermo-mechanical response of soils and piles to thermal loading in order to ensure an adequate design.
This paper presents firstly the observed response of energy piles and soils from literature, then it identifies some gaps and recommendations for future studies. Finally, some comments on the use energy micropiles which are increasingly getting attention, are made.

2. State of art

Soils present varying behavior to temperature loading, depending on the type of soils, soil properties and stress state conditions. An important side effect of soil heating is the possibility for excess pore water pressure generation that may lead to additional flow of water away or towards the heat exchanger, as well as a decrease in undrained shear strength (McCartney et al, 2013). Piles also behave differently depending on the behavior of the soil around them, boundary conditions, arrangement, etc . In order to properly visualize the thermo-mechanical changes induced by thermal loading, piles and soil responses are discussed separately in the following.

2.1. Response of saturated soils to thermal loading

Due to the difference in the relative expansion coefficient of water and soil skeleton, positive excess pore water pressures are induced in saturated normally consolidated soils during heating (Campanella et Mitchell, 1968). When heated in drained conditions, saturated granular soils slightly expand and the deformation is reversible, whereas saturated cohesive soils response to thermal loading depends on the initial OCR (Di Donna et al, 2013). While highly OC soils expand when heated, a NC or slightly OC soils contract irreversibly and nonlinearly as the excess pore water pressures drain out (Fig. 1). It was also observed that increasing OCR, the magnitude of contraction decreased and then gradually started to show a dilative behavior beyond a certain OCR value (Abuel-Naga et al, 2007). The temperature induced volume change is dependent on the stress history and is independent of the magnitude of applied stress. However, the amount of temperature induced volume change is controlled by the plasticity index of the soil wherein with a greater plasticity index show more volume change during heating (Abuel-Naga et al, 2007). Abuel-Naga et al, 2006 also observed that subjecting a normally consolidated specimen to heating/cooling cycle induces an apparent overconsolidation state which resulted in an increase in shear strength. An increase in shear strength due to thermal consolidation will also improve tip resistance (Di Donna et al, 2013). However, saturated

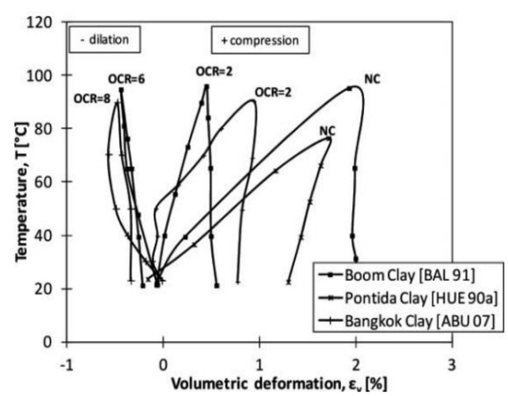

Fig 1. Thermal deformations of various clays under different initial conditions (Di Donna et al ,2013).

overconsolidated soils show a decrease in strength after heating, due to volumetric expansion (Plum et Esrig,1969).
Under undrained conditions, the rate of the thermally induced pore water pressure of soft clays is stress history dependent (OCR) and tends to decrease as OCR increases. The thermally induced pore water pressure of normally consolidated specimen is reversible while the overconsolidated specimens show irreversible behaviour with negative excess pore water pressure when the soil cools down to room temperature (Abuel-Naga, 2006).

2.2. Response of unsaturated soils to thermal loading

Unsaturated soils expand when the overconsolidation ratio is increased, showing similar trends to saturated soils hence confirming the importance of stress state on soil response (McCartney et al, 2013). When subjected to low suction (less than 300KPa) magnitude, the peak shear strength of unsaturated soils decreases with increasing temperatures (Uchaipichat et Khalili, 2009). This is contradictory to the results obtained from triaxial tests performed by Alsherif et McCartney, 2012 who observed a slight increase in peak shear strength with increasing temperature for compacted silt under high suction magnitude. According to Alsherif et al, this may be due to the impact of temperature on the magnitude of excess pore water pressure generation during shearing in low and high suction ranges. The experimental results obtained on a medium plastic clay subjected to high suction (70MPa) showed that increasing suction increases the shear strength. In fact, an increase in residual friction angle from 13°C (in saturated conditions) to 28°C at 70MPa of suction, was observed for clay during drying by Vaunat et al, 2007. These results are in accordance with those of Alscherif et McCartney et al, 2007 who observed an increase in shear strength of soils with increasing suction and increasing net confining pressure. In fact, the friction angle for the silt specimens under high suction was larger ($\varphi = 43°$) than that from tests on saturated soil ($\varphi = 36°$). They suggested that this difference may be attributed to the differences in consolidation of the unsaturated specimens from that of the saturated specimens tested in the consolidated undrained triaxial test. Vaunat et al, 2007 also indicated that the residual strength at a given suction depends only on the applied normal stress and not on the shearing history. In fact, comparison with results of first-shearing indicated that the value of the residual strength measured on pre-sheared sample is close to that obtained at the end of first-shearing under the same vertical stress.

2.3. Response of piles to thermal loading

2.3.1. General pile response

Under free boundary conditions, an energy pile expands when heated and produces a global swelling at the soil surface. However, when it is restrained (example at the top by a building, at the toe by stiff bearing layer or at the side by shaft resistance), the constrained strains (which are less than the free strains) produce thermal stresses and thus increase the axial load on the pile (Bourne-Webb et al, 2009; Laloui et al, 2006; Salciarini et al, 2015; Salciarini et al; 2017). This thermal load can be twice as large as that produced by purely mechanical loading (Bourne-webb et al, 2009). While mechanical loads decrease with depth owing to shaft resistance (Amatya et al,2012; Laloui et al, 2006; Fang et al,2022), thermal loads are rather larger and uniform. Infact, the thermal effects propagate more in the soil than does the mechanical load (Laloui et al, 2006).
Cooling of pile leads to contraction of the pile and development of tensile loads while heating leads to expansion of the pile and development of compressive loads (Bourne Webb et al, 2009; Amatya et al,2012; Salciarini et al, 2015; Salciarini et al, 2017). The axial load distribution developed in the pile in response to heating or cooling will depend on the end restraint provided by the overlying structure and the foundation

materials (Bourne-webb et al, 2009). Moreover, the cooling to heating time ratio per day during cyclic heating and cooling plays a key role in the amount of change of ground temperatures operations (Faizall et al, 2022). In addition, the presence of the building cover on the restrained energy pile slightly reduces the atmospheric effects on the vertical soil temperature distribution near the surface compared with the unrestrained energy pile without building cover (Faizall et, 2012). The strain profiles due to heating and cooling of energy piles suggest that their behavior is thermo-elastic (Laloui et al, 2006; Bourne Webb et al, 2009). However, in terms of pile head settlement, the pile response appears to be thermoelastic if and only the mechanical load is less than 40% of the ultimate resistance (Tanh et al,2013). Above 40%, irreversible settlement develops. Temperature change in the pile leads to increase or decrease in the shaft resistance mobilized by the axial head load alone (Bourne-Web et al, 2009; Amatya et al, 2012). Soil thermal properties also influence soil-structure interaction. Increasing soil thermal coefficient results in a decrease in compression loads on the central pile while an increase in soil thermal conductivity leads to an increase in compression loads during heating. However, increase in soil thermal expansion coefficient and thermal conductivity both lead to an increase in the vertical movement of the raft (upward increase during heating and downward increase during cooling) (Salciarini et al, 2017).

2.3.2. Specificity on pile group

Salciarini et al, 2015. and Salciarini et al,2017 studied the response of energy piles in a group. When heated in coarse-grained soils, all energy piles expanded and experienced an increase in load while the inactive ones experienced a decrease in load. After a month, the temperature of the active piles remained constant while that of the inactive ones increased which led to an increase in load in the inactive piles and a decrease in load in the active piles (Salciarini et al, 2015) as illustrated in figure 2. This is similar to that already discussed for a single pile response. However, in stiff overconsolidated clay, the energy pile layout played a role in pile response. For a single energy pile layout, trends were similar to those of Salciarini et al, 2015 however, when the number of energy piles was increased, the response was different wherein both active and non-active piles experienced decrease and increase in compression loads during heating and cooling respectively. This phenomenon could be explained by considering that the thermal expansion coefficient of the clayey soil was 3.5 times larger than that of the concrete piles. As a consequence of the constraint exerted by the foundation raft to the vertical deformations of the soil, the contact pressures at the soil–raft interface increased with respect to the initial isothermal conditions during the heating stages, producing a net decrease in the axial load at the pile heads. The opposite phenomenon occurred during the cooling stages, when the soil contracted more than the piles and the contact pressure at the soil–raft interface decreased. The difference in behavior between the one energy pile configuration and the 04 pile energy configuration in stiff clay could be explained by the fact that the fraction of the soil that was affected by significant temperature changes during the thermal cycle remains relatively limited when only one thermo-active pile is present in the unit cell (i.e., when the thermo-active pile spacing is relatively large). The resultant of the axial loads at the pile heads still decreased during heating and increased during cooling as in the other cases considered. However, the thermal dilation of the central pile was sufficient in this case to produce an increment in the axial compression load on this single pile, while the response of the other piles remained

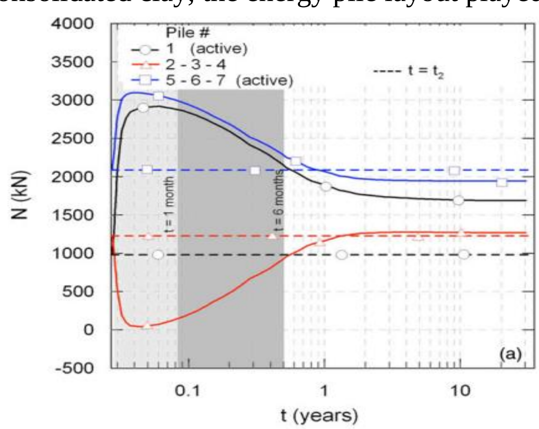

Fig 2. Axial load N versus time at z =-4m during heating of the 09 energy piles configuration (Salciarini et al, 2015).

similar to what had been observed for the multiactive pile layout (Salciarini et al, 2017). The constraints on each energy pile, and therefore the load, depend also on their location below the raft (Mimouni et Laloui, 2013). The variability of pile raft movement,w, () increases with the increasing number of the energy piles in the foundation. The presence of several thermo-active elements can lead to variations in the raft depth of more than 2 cm with respect to those induced by the mechanical loading (Salciarini et al, 2017). A difference in the temperature of piles in a group, for example due to series connection, may result in differential settlement and pile cap tilt (Fang et al, 2022). When energy piles are closely packed, the performance of the system is reduced due to interference effects (Salciarini et al, 2017) and the thermal influence on the ground is greater (Katzenbach, et al, 2008). For energy piles constructed in a loose soil layer, cyclic thermal loading can induce in the piles residual contractive strains and compressive stresses which increase as the number of cycles increase and can exceed the theoretical upper bound of thermal stress (Fang et al, 2022). The other classic piles undergo the cyclic variation of normal stress due to the interaction between the piles (Suryastriyastuti et al, 2013), however Faizall et al, 2022 observed that compared to monotonic heating, cyclic heating can help to decrease thermal interactions between energy piles in a group. This can be beneficial for designing and applying closely spaced energy piles in real operations.

3. **Future research: Energy micropiles**

Micropiles are piles with diameter less than 25cm and usual maximum length up to 12-15m. They are used for underpinning of structures, slope stabilization, earth retention, settlement reduction, structural stability and ground strengthening. Compared to conventional piles, micropiles can be used in proximity to existing structures, when access is limited, when ground and drilling conditions are poor and also when pollution and noise need to be reduced.

Micropiles can be used as single load elements or in groups. The thermal performance of energy micropiles, in terms of specific heat flux, has been found to be encouraging in view of their application in heating, ventilation and air condition if a sufficiently large number of active elements is installed to compensate for the relatively short length of energy micropiles as compared to energy piles. (Ronchi et al,2016). Since they are mostly installed in groups, the effects of thermal loading on the soils and the piles might be greater, however micropiles are known for their high load capacity and their ability to resist compressive, tensile and lateral loads. As such, the behavior of energy micropiles should not be assumed to be similar to that of conventional energy piles. Moreover, pile dimensions play a role in the behavior of energy piles (Saggu, 2019) and consequently of energy micropiles. Therefore, studies need to be conducted on the use of low enthalpy geothermal energy to evaluate the soil-structure interaction due to this type of foundations.

4. **Conclusions**

Although many energy piles and geothermal plants have been installed all over the world, the effects of energy piles still need to be further studied because most past research have been on monotonic thermal loading and short term loading which do not reflect the real conditions of geothermal installations. Research should be conducted considering actual conditions which are cyclic loading and long-term, of which these have been found to produce unwanted effects which could exceed design limits. Moreover, many factors influence the behavior of energy piles making their design more complex than conventional piles. As such, geothermal piles are designed in a conservative manner, with a larger factor of safety, making it more expensive. Hence an appropriate design method that considers all these factors, e.g. end boundary conditions, cyclic loading, pile arrangement and dimensions, soil properties, connection type of piles, pile layout, etc. needs to be developed. In addition, research should be conducted on the use of energy micropiles, which seem to be an innovative technology in the field of the energy geostructures.

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