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Energy piles: behavior and geoenvironmental challenges

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Abstract

Energy piles, also referred to as thermal piles, which provide a sustainable energy source, represent an interdisciplinary advancement in the fields of geotechnical and environmental engineering, and their application has increased rapidly over the past decades. Due to the growing importance of this topic, numerous studies have been conducted on energy piles, and several review papers have addressed different aspects of their behavior. However, no comprehensive study has yet been reported that brings together recent advances in methods for evaluating the displacement behavior of energy piles in both saturated and unsaturated soils. To date, much of the existing research has focused on the thermal behavior of energy piles, while the mechanical and chemical aspects have often been neglected. This article provides a comprehensive evaluation of the findings of previous studies and highlights areas requiring further investigation. In particular, the effects of several factors, including soil saturation, loading mechanisms, the mechanical and thermal properties of the soil, and pile configuration, on the displacement behavior of energy piles are investigated. Moreover, the long-term performance of energy piles is discussed, and a comprehensive example of an element subjected to thermal and chemical loading is presented, suggesting a novel direction for future research.

1. Introduction

Over the last few decades, population growth and limitation in international unsustainable energy resources have contributed to the increasing need for innovative resources of energy. In an attempt to find a renewable resource, civil engineers have coupled the conventional piles and heat exchangers and introduced thermal piles intending to extract electricity from geothermal energy sources to design energy-efficient buildings. The concept of energy piles was first introduced and used in Austria in the 1980s [1] and developed across Europe, North America, and Asia [2]. Piles, in the first place, have the function of bearing the load of the structure and are responsible for the stability of a building. Heat exchangers, on the other hand, extract thermal energy from the soil. Therefore, it is of significant importance to take into account and evaluate the factors that affect energy piles displacement as well as efficiency. This is a clean source that provides energy for heating and cooling demand for smart buildings and improves the air quality of the environment by reducing carbon dioxide .

In recent years, a substantial amount of research is devoted to the thermal behavior of geothermal piles both in saturated and dry soil. These studies used analytical [3], numerical [4-6] and experimental [7-11] approaches to simulate conditions close to reality. However, it is important to bear in mind that researchers in the field of energy piles have not dealt with the real case scenario and evaluated the idealized circumstances. The existing accounts [12] fail to

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treat all affecting factors together, so it is useful to write a paper that puts these parametric investigations and their sources of errors together. The motive of this article is to present existing literature focusing on the displacement behavior and to suggest the direction for future studies. Additionally, this work presents the result of a parametric study of unsaturated soil under thermal load. at last, it highlights the areas in which future research will need to be undertaken.

When it comes to analysis or design, the preliminary aspects that need to receive critical attention are geometry, boundary conditions, material characteristics, and loading [13]. Fig. 1 shows the schematic representation of a single energy pile with a slab considering heat and moisture transfer. The first and second sections of this article report former investigations and various methods of demonstrating the displacement of single and group piles in saturated and unsaturated soil. Moreover, the long-term performance is discussed in both conditions. The last part presents the result of a single element in unsaturated soil under thermal load in the presence of the contaminants. The conclusion highlights areas in which there is limited availability of literature and suggestion for future works.

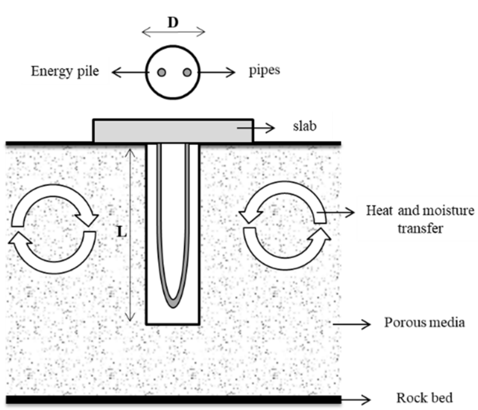

Fig. 1. Schematic presentation of energy pile

2. Displacement in Saturated Soil

In general, conventional piles are categorized into 5 main types as sheet piles, end bearing piles, semi-floating piles, friction piles, and soil compactor piles. The loading on conventional pile would be generally in the form of mechanical load and prior studies have noted almost every aspect of it. Energy piles, on the other hand, have been developed in the form of end bearing, semi-floating, and floating piles. To determine the displacement of energy piles, many of the researchers idealized soil to be fully saturated and loading to be both thermal and mechanical. In recent years various methods have been proposed to demonstrate the displacement of energy piles in saturated soil, and one of the most innovative approaches for a group of piles is the concept of interaction factor method.

2.1. Interaction factor method

The interaction factor method was first studied by Poulos (1968) for the prediction of settlement for bored pile groups [14]. Ghasemzadeh et al. used this concept to investigate pile-soil-pile interaction for a group of inclined piles under dynamic loading. They modeled pile and soil using springs and dashpots and proposed an analytical solution to calculate displacement [15]. In another article, they developed a numerical analysis of battered piles under lateral and axial static loading [16]. In both of these articles, the soil was considered to be fully saturated and the impact of mechanical parameters of soil and pile configuration on displacement was observed. While there are not many studies on inclined energy piles, these works can be used as a reference for future research.

Another study drew attention to the interaction method and used it to demonstrate the vertical displacement of a group of semi-floating piles under thermal load [17]. This method employs the elastic principle of superposition for the simplest configuration of a group of two piles. The interaction factor is defined as an additional displacement of the adjacent pile due to the loading of the source pile and it can be implied that the interaction factor is directly proportional to vertical displacement. This study does not consider the impact of thermal and mechanical load together. Moreover, it did not take into account the influence of non-adjacent pile displacement in demonstrating the displacement of the receiver pile.

After that, another work [18] extended the concept of interaction factor to a group of end-bearing piles under thermal load and reported effects of the presence of stiff soil strata on the interaction factor. This study proposes a correction to the former formula for the interaction factor and expressed it as Eq. (1) below:

$$\Omega\left(corected\right) = \Omega\left(floating\right) + F_b\left(\Omega(end-bearing) - \Omega(floating)\right) \quad (1)$$

where $\Omega\left(floating\right)$ is defined as the factor of interaction for predominantly floating thermal piles, F_b is a correction factor signifying the presence of the bearing soil stratum and $\Omega(end-bearing)$ articulates interaction factor for predominantly end-bearing thermally activated piles resting on infinitely rigid soil strata. This study [18] not only fails to consider the same points as [17] but also does not discuss rock bed characteristics affecting energy pile performance.

2.2. Saturated soil studies

2.2.1. Pile configuration effect

The existing literature and reviews on pile design configuration are extensive [19, 20] and mainly focus onmodeling approaches and the geometrical characteristics of piles. Previous experimental and numerical studies on floating piles [28-30] have shown that, as the distance between piles increases, pile–pile interaction decreases, and each pile gradually starts behaving as an individual pile. Therefore, it was reported in [17] that, beyond a specific distance between piles, no additional displacement occurs. In this study, only a square pile group was considered, whereas, in practice, piles are rarely arranged in a perfectly symmetrical configuration. Moreover, another study investigated the efficiency of pile groups based on bearing capacity by considering the distance between piles [31]. The results of this study revealed that, as the pile spacing increases, nonlinearity decreases, resulting in changes in pile group efficiency between 1 and 1.4. Another point discussed in the same study is that, as the number of piles increases, pile–pile interaction and, consequently, displacement also increase. However, the effect of the stiffness of adjacent piles within the soil was not taken into consideration, and further investigation was suggested for future studies. Moreover, energy piles may require maintenance over time, or not all piles may operate simultaneously. Therefore, a general method needs to be developed for the computation of displacement under such variable operating conditions.

To date, studies have mainly considered symmetrical pile groups and have revealed that the position of a pile within the group affects its displacement, with the center pile experiencing the maximum displacement and the corner pile experiencing the minimum displacement. In these studies, all piles within the group were assumed to be identical, the applied force was assumed to be distributed uniformly, and the loading of the pile group was considered to be purely thermal. Under thermal loading, it was reported that, as the slenderness ratio of the piles, defined as the ratio of the energy pile length to its diameter, increases, the interaction between piles considerably increases [17]. Likewise, another study [21] investigated the effects of pile depth and diameter on the displacement of a pile with a free head under both heating and cooling conditions. Based on the results of this study, under thermal loading, the effect of pile diameter on displacement is negligible, whereas pile length is a critical factor. This finding is consistent with the results of other studies, which showed that the foundation aspect ratio affects the induced thermal stresses, with greater stress and displacement resulting from a larger aspect ratio [22, 23]. All of the aforementioned studies considered circular piles and did not investigate other geometrical configurations of either individual piles or pile groups.

Moreover, existing studies [24-26] have focused on pipe configuration and the effects of pipe density, geometry, and pile–pipe interaction on the thermal behavior of energy piles. In one of these studies, in-situ thermal response and thermal performance tests were conducted experimentally, and the results were compared with long-term numerical simulations. The results showed that cast-in-place energy piles have better thermal performance compared with geothermal heat exchangers; however, thermal interference between pipe loops reduces their performance. This study also provided a design chart illustrating the effects of thermal interference and long-term soil temperature changes in the vicinity of energy piles. In addition, another study specifically investigated the effects of the velocity of the fluid circulating within the pipes and its thermal conductivity on displacement behavior under various loading conditions and pile design configurations. The results of this study revealed that, among the various parameters affecting load–displacement behavior, temperature is the most important parameter, and increasing the thermal load results in lower head displacement [27].

Overall, the reviewed studies indicate that pile configuration has a significant influence on the displacement and thermo-mechanical behavior of energy piles. Pile spacing, number, position, slenderness ratio, pile length, and pipe configuration affect pile–pile interaction, thermal interference, and displacement response. Larger spacing reduces interaction, whereas increasing the number and slenderness ratio of piles generally increases interaction. However, most existing studies have focused on symmetrical groups of circular piles and simplified operating conditions, while the effects of irregular pile arrangements, different pile geometries, variable pile operation, and the interaction between pile and pipe configurations remain insufficiently investigated.

2.2.2. Pile head and toe restraint

While a large volume of published studies investigates free head energy piles, some recent studies noted the impact of base and head restraint on different conditions. One study emphasizes on the dependence of changes in the volume of pile and position of the null point, the direction of volume change and displacement on the restriction of the pile due to the superstructure and surrounding soil [32]. Besides, another study simulates a group of energy piles in saturated soil and employs the interaction factor method to consider the influence of slab on displacement behaviours of the group [33]. In addition to that numerical studies have been carried out depicting the impact of applying thermal load on the displacement depending on the position of a null point [21, 34-36]. One of these studies considers the impact of the stiffness of pile and soil in its evaluation and reports on the movement of a null point with respect to restraint. Results reveal that increasing pile head restraints leads to the upward movement of the null point position while increasing stiffness of soil surrounding the energy pile causes the null point to move downwards.

Another study [21] reports that for piles with free head displacement, change of temperature causes significant displacement while in the restrained head it results in axial stresses. Since in practical cases neither of these two happen, these two conditions represent the upper and lower limit of displacement. Other comprehensive studies are proposed recently concerning different cyclic thermo-mechanical loading, head restraint condition in terms of rigidity of structure which report on bearing capacity and thermo-volumetric strains of the pile [37, 38].

The reviewed studies demonstrate that pile-head and toe restraint strongly influence the distribution of thermal displacement and stress in energy piles. Free-head conditions generally result in greater thermal displacement, whereas increasing restraint limits displacement and promotes the development of axial stresses. The position of the null point is also affected by both pile-head restraint and the stiffness of the surrounding soil. Nevertheless, practical energy piles generally operate under intermediate restraint conditions rather than fully free or fully restrained conditions, highlighting the need for further investigation of realistic structural restraint and cyclic thermo-mechanical loading conditions.

2.2.3. Impact of loading on displacement

Since the main function of a pile is to maintain the serviceability of a structure, it is vital to investigate the load-displacement behaviours of deep foundations. Several studies [39-42] are conducted on a single pile with and without head restraint under monotonic thermal load using numerical and experimental approaches and suggest that for both cases results are conservative and similar which means head restraint has no significant result on the displacement of a single pile. Moreover, they compare the heating and cooling mode concerning the reversibility of process and displacement. In addition to that a study on a full-scale energy pile under thermo-mechanical load analysed stress-strain behaviours and concluded that when the value of the mechanical load is small, thermal load impact on displacement is significant [43,44].

One study [45] reported the displacement in terms of soil movement and stated that energy piles subjected to heat undergo uplift displacements which result in soil heave. Piles in cooling mode experience downward displacements and settlements which is in agreement with other experimental results [46]. Another study is conducted with monotonic thermal loading and discussed displacement of energy piles and maximum thermally induced stress change [47]. A recent study identifies the impact of thermal loading and geometrical configuration on bearing capacity of the piles and their serviceability by calculation of the null point position [48]. This study reports that variation of mobilized shaft resistance will not lead to geotechnical failure, furthermore, oversized energy pile has lower serviceability performance compared to conventional piles.

Up to now, mainly numerical approaches were proposed with cyclic loading and only a few cycles of thermal loading had been considered. Results of current studies display when external loading exceeds the available shaft resistance then cyclic ratcheting will develop. Moreover, while the cyclic thermal loading remains constant, the response of the pile appears to stabilize with time, yet more research is required to confirm this mechanism [41, 49-52]. According to the results of previous studies, the larger mechanical and thermal loads will result in higher displacement and the impact of the magnitude of thermal loading is linearly proportional to vertical displacement [21]. Moreover, it is reported in several studies that the first cycle of thermal loading causes higher strain compared to sequential cycles and results in higher displacement [53-55]. An experimental study draws attention to the effects of cyclic thermal loading on bearing characteristics and displacement. It reveals that when a vertical load is bigger than the situation where nonlinear settlement initiated, temperature change causes irreversible head settlement [56].

While most of the research is focused on thermal loading, a study evaluated strains developed in two types of energy pile embedded in loos and dense sandy soil due to mechanical and thermal loading. The purpose of this study is to compare results with the design limit capacity of the pile and it concluded that more attention should be given to mechanical load compared to thermal load [57]. Another study considered combined mechanical and cyclic thermal loading with consideration of cyclic plasticity and observed the impact of pile-head rigidity and soil confinement. Based on the results of this study axial capacity of pile and shaft resistance decreases over time and cycles of thermal loading [58]. Furthermore, a recent and innovative study [59] considered the impact of thermal loading on the mechanical response of piles in performance-based-design considering deformation and failure mechanism and reports that the serviceability-limit-state impact should be taken into consideration.

Another comprehensive study takes into account the impact of cyclic thermal loading and consolidation on serviceability and displacement in the long term. It was observed that ratcheting displacement occurs regardless of OCR ratio while the settlement rate is dependent on OCR [60].

The literature indicates that both mechanical and thermal loading play important roles in the displacement behavior and serviceability of energy piles. Heating generally induces upward displacement or soil heave, whereas cooling produces downward displacement and settlement. Increasing mechanical or thermal loads generally increases displacement, and repeated thermal loading may result in irreversible settlement and cyclic ratcheting, particularly when the mechanical load exceeds the available shaft resistance. Although several studies have investigated cyclic thermo-mechanical loading, most have considered a limited number of cycles, and further research is required to clarify long-term stabilization, ratcheting mechanisms, and serviceability under realistic combined loading conditions.

2.2.4. Mechanical properties of soil

To observe the effect of soil mechanical properties on the thermal response of piles among various studies available [61], one study [21] investigated parameters of the angle of shearing resistance, soil Young's modulus, and Poisson's ratio. It is reported that soil stiffness is insignificant analyzing displacement of energy piles, while it significantly affects stress, however, it is in contradiction with previous findings of [17, 18] and with that found by Poulus for conventional piles under mechanical loading [62]. Moreover, it is stated that the angle of shearing resistance and Poisson's ratio have a smaller effect compared to soil stiffness for both restrained and unrestrained energy pile. Another study using the interaction factor approach for floating piles accounts that smaller values of the Poisson's ratio of the soil will increase the interaction factor for an elementary group [17]. Moreover, the displacement interaction increases for higher uniformity of the soil modulus. Another article [63] analyzed soil-concrete interface behavior experimentally using a modified direct shear test and stated that for cohesive soils response of interface depends on the history of stress. According to this article, the angle of friction increases due to heating and results in cohesion decrease, yet displacement due to variation of this parameter is not reported here .

One study investigates the impact of the mechanical load of superstructure constantly applied on piles in clayey soil and examined the relation of creep and the time-dependent displacements. Results show the influencing factors related to the rate of creep are mainly soil type, soil texture, applied stress level, and temperature [64, 65]. Another experimental study conducted in-situ tension thermo-mechanical test to consider the effect of the plasticity index on head displacement and reports that temperature and plasticity influences creep rate. Results represented showed that creep rate in highly plastic soil increases as a result of an increase in temperature which results in additional time-dependent displacement [66, 67]. The results represented here are in contradiction with that found by Poulus for conventional piles under mechanical loading [62].

One study considering the impact of soil particle size and particle properties states that as particle size increases sensitivity to temperature changes decreases. Besides, temperature sensibility increases because of the organic content of the soil which means the impact of thermal load on these soils is more significant than other types. Another significant point discussed in this article is irreversible settlements due to the mechanical loads when it exceeds 40% of the ultimate capacity of the soil. Yet it is reported that conventional safety factors are adequate to avoid mechanical failure due to thermal loads [68].

The mechanical properties of the surrounding soil have a complex influence on the displacement and thermo-mechanical response of energy piles. Soil stiffness, Poisson's ratio, shear strength, plasticity, stress history, and creep characteristics can affect pile–soil interaction and time-dependent displacement, although their relative importance varies with soil type and loading condition. In particular, temperature can increase creep in highly plastic soils and consequently contribute to additional displacement. However, the findings regarding the importance of soil stiffness are not fully consistent among existing studies, indicating that further research is needed to clarify the combined effects of soil mechanical properties, temperature, and long-term loading history

2.2.5. Thermal properties of soil

Among various studies [69] exploring the thermal properties of soil, one experimental study used the thermal cone dissipation test to demonstrate the in-situ properties of soil [70]. This study presents an extension to the well-known cone penetration test improving the drawback of the former methods. other studies focused on the effect of thermal expansion, thermal conductivity, and specific heat reported that higher soil to pile thermal expansion coefficient ratio will result in higher displacement [17, 21]. Furthermore, Thermal conductivity and specific heat found to have a very small effect on the displacement behavior of piles. These results are confirmed in other works where a similar conclusion is drawn [22, 23].

One study that considers the impact of head restraint on thermal expansion concludes the larger values of thermal expansion will lead to larger displacements. This study considers both heating and cooling modes and suggests that the effect of boundary conditions will be insignificant as time passes [21]. This is while for piles with restrained head, stress changes due to changes in thermal expansion coefficient are dependent on the duration of thermal loading and for short periods can be negligible. Furthermore, another study considers the impact of various boundary conditions on soil response and thermal parameters in the short term [71]. This is while none of the mentioned studies discuss displacement variation due to changes in the thermal properties of soil.

Moreover, there are other aspects of the impact of thermal properties of soil on the study of energy piles that are not investigated previously. Thermal properties of soil may have considerable impact concerning energy harvesting and the environment in the long term. Future studies need to focus on result of using energy piles in the surrounding environment.

Existing studies suggest that the thermal expansion coefficient of the soil relative to that of the pile is an important parameter governing thermal displacement, whereas soil thermal conductivity and specific heat have generally shown a limited influence on pile displacement. Larger thermal expansion tends to produce greater displacement, although the influence of boundary conditions may become less significant over time.

Despite these findings, the available literature provides limited information on how variations in soil thermal properties affect long-term displacement and the surrounding thermal environment. Therefore, further investigation is required to better understand the role of soil thermal properties in the long-term performance and environmental effects of energy piles.

2.2.6. Impact of nonlinear soil deformation

Another study modified the previously mentioned interaction factor method and examined the importance of non-linear soil deformation impact on displacement in a group of piles [72]. The method used for this purpose is an extension of the method first proposed by Poulos [62] for conventional piles under mechanical load that has been modified for energy piles under thermal load [73]. While Soil behavior is complex and deformation is, in reality, non-linear, it involves elastic or plastic stress-strain behavior and as mentioned by previous works it worths noting the impact of this parameter in future studies [74, 75]. The results of this study [72] expose that under thermal loading nonlinearity of soil deformation causes a decrease in pile displacement in comparison to the situation of linear soil deformation. The extent of decrease in displacement is related to various factors such as soil mass modulus, the near-pile soil modulus, the pile numbers and the spacing between the piles. It remarks that the classical interaction factor method is rather conservative and tends to overestimate displacements.

The reviewed research shows that considering nonlinear soil deformation can significantly change the predicted displacement of energy pile groups. In comparison with linear soil models, nonlinear soil behavior generally results in lower predicted pile displacement, with the magnitude of this reduction depending on soil stiffness, near-pile soil properties, pile number, and pile spacing. Consequently, conventional interaction-factor methods may provide conservative estimates by overpredicting displacement. Since soil behavior is inherently nonlinear and may involve both elastic and plastic deformation, incorporating nonlinear soil response is important for obtaining more realistic predictions of energy-pile displacement

2.2.7. Impact of soil depth, layering, and anisotropy

A previous study employing the interaction factor method identified that depth of soil layer affects the displacement of piles. It is discussed that a lower depth of soil will result in an increase in displacement [17]. Yet this study does not discuss the impact of geotechnical properties of soil and soil anisotropy, moreover, up to now, there is not enough literature on energy piles placed on rock bed and impact of rock properties on performance and displacement.

A recent study [52] represented a modified interaction factor for both floating and end-bearing energy piles which can be employed for both uniform and non-uniform soils. An important point of this study is the presentation of two models defined as layer model and continuous model that exhibits the lower boundary and upper limit of displacement and can be used for practical purposes. Another study investigates the nonlinear response of pile-soil in layered soil under torque by proposing a new method of calculation [76]. The aim is basically to introduce an easy method that can be applied in the practice field and to save time and reduce calculational costs.

Various studies [77, 78] reported that the thermomechanical behavior of soil is directly influenced by its grain size. Soil is generally divided into fine-grained and coarse-grained. For both fine and coarse-grained soil, the dominant factor is loading history which in fine-grained soil defined as OCR. Soils with small OCR value of one or slightly bigger undergo contraction which is mainly because of rearrangements and rotation of soil particles. This is while at higher OCR thermo-elastic expansion occurs and permanent contraction decreases [79]. Coarse-grained soils show a similar mechanism; however, the dominant factor is the void ratio and confining pressure. Soils with low densities and high confining pressure show contraction at high temperatures. This amount of volume change is smaller in comparison to fine soils [80, 81]. Displacement is not investigated in any of these articles and further studies might be conducted focusing on this point in the future .

To observe the impact of soil anisotropy a study of single end bearing pile compared completely isotropic soil with an anisotropic soil [82]. The anisotropic soil under consideration is sandy on the upper layers and clayey on the bottom and the results indicate that the isotropic model compared to the anisotropic model underestimates the measured displacement. Moreover, it depicts vertical displacement of the pile over time and envisages vertical displacements of the pile tip and head overtime. Initial displacement of pile head under mechanical load is affected by soil anisotropy and it shows larger displacement for the anisotropic soil. Subsequent histories of displacement are affected by anisotropy and result in smaller subsequent vertical displacements for the anisotropic soil. This is while not much research is conducted on this topic and further study is crucial to confirm the result of this study. The existing studies indicate that soil depth, layering, stress history, grain size, and anisotropy can substantially affect the thermo-mechanical response and displacement of energy piles. Reduced soil depth may increase displacement, while layered and anisotropic soil conditions can produce responses that differ considerably from those predicted using homogeneous and isotropic assumptions. In particular, isotropic models may underestimate measured displacement in anisotropic soils. Despite the development of modified interaction-factor approaches for layered and non-uniform soils, the effects of rock properties, detailed soil layering, and anisotropy on long-term energy-pile displacement remain insufficiently investigated and require further validation.

2.2.8. Soil-pile interaction

There are many experimental and numerical studies directed toward the interaction between an energy pile and soil, through analysis of thermo-mechanical behavior of energy pile focusing on axial stress development and changes in shaft friction and volume change of pile and surrounding soil. Yet these studies do not discuss the impact of these parameters on displacement and it is suggested to do further investigation for future [23, 83-85].

Other studies [1, 86] mention that interaction of soil and the pile is directly affected by seasonal temperature changes which result in expansion and contraction of the thermal pile, alters mobilized shaft resistance and causes additional stresses. Moreover, the study of induced displacements appears to be mainly reversible and their impact is negligible [87].

Other studies focus on the impact of structural interaction of pile-soil [88, 89], bearing capacity and variation of the length of the thermal pile and reports that because of the uncertainty of soil behavior, the distribution of thermal stress is inhomogeneous. Yet the most significant factors affecting the peak value and distribution manner of stress are the thermal and physical properties of the structure and the host soil. The results of one of these studies indicate that first, the soil properties influence the lateral friction stress which means it changes at the interface of different layers, yet the impact of this point on displacement is not covered in these articles and further investigation is suggested. Besides, tip displacement increases significantly with an increase in covered loading. After a specific load, the displacement of the pile increases sharply which would affect safety while it could be prevented by redesigning the length of the pile. Another study reports that the bearing capacity of the pile is not affected by thermal loading.

Another study reports that stress-strain behavior at the cross-section of energy piles is non-uniform and this has resulted from thermal demand of structure. It is stated that area close to ground loops experiences maximum temperature change and during heating causes only compressive stress, while cooling creates only tensile stress. this leads to non-uniform deformation of soil and non-uniform strains at each cross-section which is in contradiction by other findings [89].

The reviewed literature confirms that soil–pile interaction is a fundamental mechanism controlling the development of axial stress, shaft resistance, thermal expansion and contraction, and displacement in energy piles. Seasonal temperature variations can modify pile volume and mobilized shaft resistance, while soil properties and structural loading influence the distribution of thermal stresses along the pile. However, although numerous studies have examined thermo-mechanical interaction and stress development, their direct implications for pile displacement have received comparatively less attention. Therefore, further studies are needed to establish a clearer relationship between soil–pile interface behavior, thermal stress distribution, shaft resistance, and displacement under realistic loading and soil conditions.

2.2.9. The temperature changes, heating duration, and climatic conditions

There are various studies available on heat transfer mechanism, storage, recovery, and enhancement in energy piles [90-93]. A Research on sandy soil reports the impact of duration of thermal loading during cooling and heating mode [21], based on the results of this study cooling results in pile head settlement and heating causes heave and this will be more significant in steady-state condition compared to transient analyses. it is proven that the trend of thermal axial stress can be an indication of displacement, yet future studies may be done with a focus on finding the time of the critical displacement and performance efficiency .

Another experimental study considers the impact of heating and cooling on a full-scale energy pile and reports displacements associated with expansion and contraction of the pile itself and surrounding soil [87]. This study lacks an assessment of the impact of the material property on displacement behavior; thus, further investigation can be done on this subject in the future. Other research analyzed the temperature of the soil, concrete, and fluid and discussed the impact of temperature on displacement, stress development and bearing capacity [94, 95]. It is stated that bearing capacity and strain increases with temperature and returns to its initial value when temperature decreases. Moreover, it is indicated that it is a reversible process.

A recent comprehensive study takes two types of floating and end-bearing thermal piles in normally consolidated clayey soil under thermal load and reports thermo-mechanical behavior cyclic heating and cooling. Based on the results of this study climate affects the displacement behavior of thermally activated piles and thermal cycles result in larger irreversible displacement in floating piles compared to end-bearing piles. On the other hand, warm/cold balanced climates have a respective impact on both types of piles. In cold dominated climates, however, the smallest amount of irreversible displacement occurs due to thermal effect [96].

The reviewed studies demonstrate that temperature variation, heating and cooling duration, and climatic conditions have a direct influence on the displacement behavior of energy piles. Heating generally produces pile expansion and heave, whereas cooling causes contraction and settlement, with the magnitude of displacement depending on the duration and thermal history. Repeated thermal cycles can also generate irreversible displacement, particularly in floating piles, while climate conditions influence the magnitude of accumulated deformation. Although existing research has established the importance of these factors, further investigation is needed to identify critical displacement times, long-term performance limits, and the combined effects of seasonal climate and repeated thermal cycles on energy-pile serviceability.

2.3. Long term performance

Since energy piles are an innovation introduced with several important objectives. first to reduce the use of oil and gas as a source of energy, second to design green infrastructures to reduce carbon dioxide and air pollution and third to provide a sustainable and cost-efficient resource. It is of crucial importance to study the impact of using these piles on the environment and society and to determine their efficiency. Among various experimental studies [60, 97] and numerical approaches [98] available in saturated soil assessing long term performance, one depicted design criteria to optimize cost in long term [99] and another work used a thermo-hydro-mechanical finite element analysis for hypothetical thermo-active shafts evaluating structure geometry for short and long term [100]. Furthermore, another study investigates economical aspects and payback periods considering piles in cooling dominated areas [101]. Another research has assessed the seasonal response of energy piles during the construction process with the focus of stresses and strains and efficiency in the long term [67]. There are also other studies focusing on the unbalanced demand of group piles over cycles of heating and cooling and the impact of side shear resistance and the number of cycles on the displacement of energy piles in long term numerically [102, 103].

Most of the current studies evaluating long term performance of energy piles demonstrate the association of cyclic thermal loading and the amount of long-term displacement. One experimental study [104] mentions that under tension load the displacement rate increases rapidly and then becomes nearly constant with time. After that when pile and soil are under thermal load, heat will increase the displacement rate. Consequently, long term displacement of energy piles in 50 years is about 2.3 times of conventional piles. Results of another study indicate under constant head load; thermal cycles induce irreversible pile head displacement. In addition to that, the number of cycles causes irreversible incremental settlement to decrease after each cycle. The results of this study used to develop an asymptotic equation to predict the pile head settlement [105]. Another study reaches a similar conclusion considering thermal cycles and loading due to the operation of building and represents displacement. Thermal axial displacement estimated at the foundation head in comparison to toe is negligible and doesn't affect the building [106].

Another study [103] considered thermo-mechanical response of energy piles subjected to static load and cycles of thermal load in the long term. It is reported that these cycles gradually result in plastic displacement which is mainly a function of side shear resistance, the static factor of safety, the relation of ultimate bearing capacity and shaft resistance. It is concluded that as the amplitude of temperature change increases, displacement in long term increases and approaches shakedown condition

One experimental study utilized dynamic thermal network representation to observe long term behaviours of energy piles. The focus of this study is to discuss the impact of the surrounding environment and structure subsurface. It is concluded that the upper boundary and range of fluid temperature in pipes have great importance in long term performance, yet the impact of these parameters on displacement is not considered [107].

One experimental study [108] considered an energy pile with a large cross-section in saturated soil and examined pile for heating and cooling and presented pore pressure, displacement and pressure of soil. This study determined that long term cyclic thermal loading will result in the development of an uneven strain at different locations. Furthermore, unrecoverable displacement is caused by plastic strain and consolidation of soil under thermal load. This study approached the problem by examining various water flow rate however it failed to consider many other factors. Another article [24] determined the impact of pile configuration and the pipe inside it both numerically and experimentally and compared its results with conventional GHEXs. Results show that cast in place thermal piles have higher thermal efficiency in the long term.

Among available literature, one experimental study investigates the group action effect on displacement behaviour and stress evolution. It observes displacement as a function of the number of operating energy piles and concludes that as the number of operating piles increases thermally induced displacement increases and stresses developed reduces [109].

Overall, the available studies demonstrate that the long-term performance of energy piles is strongly influenced by cyclic thermal loading, pile configuration, soil behavior, and the number of operating piles. Repeated heating and cooling can induce irreversible and plastic displacement, with the magnitude of long-term displacement increasing with temperature-change amplitude, while the displacement response is also affected by side shear resistance, static safety factor, bearing capacity, and soil consolidation. Experimental and numerical studies further indicate that energy piles can provide higher long-term thermal efficiency than conventional geothermal heat exchangers and that increasing the number of operating piles increases thermally induced displacement while reducing the stresses developed in the pile group. Despite these findings, important factors such as the effects of pipe-fluid temperature limits, surrounding environmental conditions, water flow, and their direct influence on long-term displacement remain insufficiently investigated, indicating the need for more comprehensive long-term thermo-hydro-mechanical studies.

3. Displacement in Unsaturated Soil

To determine the intricate behavior of energy piles in unsaturated soil, a comprehensive model that explains the behavior of unsaturated soil is essential. This model should be capable of considering thermal, mechanical, hydrological and chemical aspects of the problem. Various researchers proposed models that considered thermo-hydro-mechanical behavior of soil [110-114] and methods to design piles in unsaturated soil [115]. These models present behavior of unsaturated soil in terms of stress and suction, yet there is another study presenting a new model and formulation that explain soil behavior in terms of stress and degree of saturation [116]. Energy piles are used mainly in urban and suburban abodes which have unsaturated soil and this signifies the importance of studying the behavior of energy piles in unsaturated soil. to date, few studies which are available in an unsaturated soil are either on conventional piles or parametric studies concerned with the evolution of heat in unsaturated soil. Therefore, it is necessary to study the factor affecting the behavior of energy piles in unsaturated conditions for a more accurate demonstration of displacement.

3.1. Load transfer method

Load transfer is the basis for various studies, before this, a study employed load transfer method to propose a robust design model to assess uncertainties in the design of energy piles in saturated soil. Another study used this concept to consider spatial variability impact on the design of energy piles [117]. These studies are mainly concerned with the factor of safety, serviceability and failure mechanism [118]. One study of conventional piles examines the load transfer mechanism in expansive soil and discusses significant changes in the evolution of water infiltration into expansive soil around the pile. First, it examines soil volume expansion which results in vertical movement of soil in an upward direction. Then, it studies the impact of variation of matric suction of soil surrounding the thermal pile on pile-soil interface shear strength characteristics [119]. This study does not examine the thermal concept of energy piles but since there is limited literature on energy piles in unsaturated soil, it can be used as a reference point for future studies.

Another work considers a conventional pile under mechanical load and introduces a computer program to simulate a single pile embodied in an expansive soil and considers its load-displacement response [114] in this study, the influence of water infiltration and suction is taken into account and the displacement is demonstrated based on the traditional load transfer method. furthermore, the universal transfer curve model is used to demonstrate the relative movement of the pile and its surrounding soil. for this purpose, displacement of pile is observed during the infiltration process and it is found out that pile shows uplift displacement and no base resistance. While this study fails to consider thermal loading, yet the heat transfer concept may be added to this program in future studies.

Another method developed by Sellgren predicts the displacement of the single and elementary units of conventional piles in unsaturated soil [120]. He proposed a hyperbolic equation that presented the shape of the load-displacement curve and verified values of head displacement of the pile with experimental results.

Ghasemzadeh developed codes for unsaturated soil and explained the behavior of soil elements under thermo-chemical forces [121]. Not only this study couples impact of heat, hydraulic and mechanical forces but also focuses on unsaturated soil contamination by chemicals that should be of interest to future researchers in this field. Current studies only considered factors concerning the geotechnical and structural issues and there is no study about chemical spices contamination of surrounding soil. In another work, mathematical formulation [122] is presented for the thermo-hydro-mechanical and chemical behavior of unsaturated soil which can be used for assessing the behavior of energy piles.

3.2. Unsaturated soil studies

3.2.1. Soil mechanical properties

While there are various studies available proposing an evaluation of the impact of temperature on soil composition, anisotropy, specific volume, cyclic loading yet there are few studies considering the influence of these parameters on the displacement of energy piles [123, 124]. One study [125] uses an experimental approach to observe the volumetric behavior of soil based on temperature and suction and concludes that temperature change affects stress and strain behavior. Another study observing the impact of thermal loading on hydro-mechanical properties of unsaturated clay reports that displacement is a function of pore pressure, swelling and shrinkage behavior and thermal expansion coefficient [126]. While there are various experimental and numerical studies on the mechanics of unsaturated soil, studies reporting the impact of these factors on the displacement of energy piles are rare.

3.2.2. Soil thermal properties

One numerical study emphasizes that the efficiency of energy piles is highly dependent upon the heating storage capacity of the soil surrounding the pile. This study considers swelling clayey soil and investigates unsaturated soil heating capacity with COMPASS code, which specifically thermal and hydraulic aspects of it were employed [105, 127]. Based on the finding of this article it can be implied that the duration of the heat injection process has a direct influence on the area/volume of soil that could be used for heat storage. The heat injection process resulted in a decrease in the saturation value. Thus, the soil thermal conductivity decreased and the volumetric heat storage capability of the soil increased which means soil with lower initial temperature value is more efficient for heat storage. Similar results are drawn from another study that states the thermal properties of soil are affected by the saturation degree which influences the heat exchange rate and the thermal piles' efficiency. This paper uses a combination of analytical, experimental and numerical approaches to evaluate the heat exchange rate of partially or fully embedded energy piles in unsaturated soils [128]. This is while the displacement behavior is not evaluated in any of these articles.

It is mentioned by various scientists that soil thermal conductivity has a significant impact on heat transfer evolution in unsaturated soils. One of the methods widely used for this purpose is the lattice element method which is a one-dimensional element meshing. One experimental work considered soil filler composite behavior and showed improvement in soil thermal conductivity at low saturation [129]. This is while the validity of this system is narrowed down to a specific system and needs validation. Another experimental study employed a triaxial compression test to investigate the impact of suction on thermal behavior and failure mechanism of unsaturated silt yet the impact of these on displacement is not discussed [130].

3.2.3. Head and end restraint

An experimental study in centrifuge-scale in layers of dry sand and unsaturated silt reported the interaction of soil-pile with various boundary conditions and measured stress and displacement. Moreover, the results of this study show that head restraint and pile stiffness impact are significant and based on the type of foundation heating may result in an increase or decrease of ultimate capacity which affects displacement [131].

3.2.4. Thermal loading and number of cycles and heating duration

An experimental study under centrifuge test on semi-floating energy piles in unsaturated silty soil is conducted. In this test different thermal loads were applied before structural load being carried out and the impact of temperature change on load-displacement behavior is observed. It can be implied that load-bearing capacity increases as temperature increases and at a specific load as temperature decreases displacement increases [132].

Another research is conducted through coupled multi-physics finite element analysis to investigate thermo-hydro-mechanical behavior of an energy pile and found out that the heating-cooling cycles have a significant influence on the changes of pore water pressure in the low-permeability soils around the energy pile, yet displacement behavior is not evaluated in this study [133].

Houston et al. performed a study on thermally induced settlements for an energy pile on unsaturated soil and reported that soil suction, net normal stress, and temperature are key parameters in estimating the settlements [134].

A numerical study using the FEM method considered a single energy pile in different types of unsaturated soil and reports effects of duration of thermal operation and magnitude of heat injection rate on a saturation degree on pile performance. The COMPASS finite element code which is capable of solving Thermo-Hydraulic-Mechanical and Chemical is used for this study [106]. This study can be used for the comparison of the behavior of different types of soil in the unsaturated phase. Although the impact of these factors on displacement is not reported in this study, yet it can be used as a ground for further investigations. There are also other experimental studies available observing the effect of temperature change and suction on properties such as critical state properties, the strength properties of unsaturated soil and water retention characteristics that can be used for the prediction of displacement [78, 135].

3.2.5. Soil-structure interaction

Stewart and McCartney [97, 136] used a centrifuge modeling approach to investigate the thermo-mechanical response of soil-structure interaction. The test results showed that head displacement is affected by soil stiffness which is affected by the sequence of heating-cooling cycles. Upward head displacement slightly decreased for two main reasons which are first because of thermally induced water flow in the soil away from the foundation and second potential down drag effects. This is while thermally induced axial stress, on the other hand, observed to differ slightly during the heating-cooling cycles.

In another study horizontal displacements versus vertical displacements in the interface tests between the kaolin-sand mixture and the steel plate. These results indicate that the vertical displacements at the top of the soil sample could be divided into two stages. During the first stage, all samples underwent a vertical compression. The amount of vertical displacement was smaller for the samples with moisture contents less than the optimum. During the second stage, two samples with low moisture content exhibited expansion. However, the samples with high moisture content continued to compress, but at a much smaller rate than the rates in the first stage [137]. Results show the load-displacement (P-δ) behavior of the energy pile at different temperatures during the heating process. It is noted that the bearing capacity of the energy pile is increased with increased temperature in the pile.

4. Environmental aspects

When studying energy piles as a green foundation, it is necessary not only to study long term displacement behavior but also to consider environmental aspects of using energy piles. So far there are very few studies focusing on long term behavior of thermal piles in saturated, yet there are few studies on unsaturated soil. This section discusses various aspects discussed by current studies and signifies a comprehensive example for future studies.

Long term performance of energy piles has been viewed from different perspectives; an experimental study of the single pile is proposed to demonstrate displacement due to thermal loading and development of pore water pressure to assess the long-term performance and sustainability of an energy pile [138]. another study [139] employs a cyclic load transfer curve to present a probabilistic model to display uncertainties in the design process of energy piles that will result in failure. This study investigates the probability of failure of the system in terms of excessive settlement due to various mechanical and thermal loading under the life cycle of 50 years. The soil was considered to be saturated and numerical results were compared with Monte Carlo simulation and experimental results and a similar approach can be used for unsaturated soil.

A study [140] that explored the environmental impact of three different climatic conditions assessed long term performance of energy and conventional piles and reached the conclusion that thermal piles compared to conventional piles have better environmental performance. It is suggested that for efficiency temperature fluctuations should be taken into account in the design process. This is because energy piles affect the temperature of the surrounding soil after subsequent cycles of thermal loading. Moreover, peak demand required for both the cooling and heating process should gain special attention. This study did not take into account the critical role of structural load in the life cycle performance of energy pile and is focused on saturated soil, yet it can be used for future studies in unsaturated soil.

A study [141] about the impact of the degree of saturation of the soil, the variation of pore-pressure and heat and fluid transfer around geothermal piles, used Green’s function for non-homogenous media to analyse the performance of unsaturated soil around an energy pile. In this article transport of water and heat is taken into consideration by proposing closed-form equations and it is concluded that the duration of thermal loading and relaxation time are critical factors for fluid transport.

A recent study [142] demonstrated experimentally that soil suction and pile-surface roughness can affect the thermo-mechanical response of energy piles installed in unsaturated soil, highlighting the limitations of approaches developed exclusively for saturated conditions. Liu et al. [143] subsequently proposed a thermo-hydro-mechanical framework that explicitly considers temperature and hydraulic conditions in partially saturated soils, further emphasizing the importance of soil saturation in predicting energy-pile behaviour. In saturated ground, groundwater flow can also modify the thermal and mechanical response by enhancing heat transport and reducing thermal accumulation around the pile. Centrifuge experiments by Ouzzine et al. [144] showed that groundwater flow can reduce thermo-mechanical effects and act as a stabilizing mechanism for stress and deformation, while Alqawasmeh et al. [145] demonstrated that both soil layering and groundwater flow can significantly influence the long-term thermal performance of energy piles. While this study introduced a novel approach to the topic, yet it failed to discuss the long-term performance and to consider aspects such as the impact of the presence of contaminants in the soil around the heat source. It is of crucial importance to analyse the transfer of contaminants and do an analysis of its impact on groundwater contamination and the environment in the long term.

Before this, another article uses experimental and numerical approaches to investigate the non-isothermal movement of moisture in Kaolin soil in the unsaturated phase. It considered compacted cohesive soil and used the thermo-hydro-chemical and mechanical models to simulate and experimentally investigate the transport of salts in the soil [146]. A study used a centrifuge test for investigation of strains and displacement of a single pile in unsaturated soil with consideration of the flow of liquid and gas under thermal load [147]. Moreover, a similar study is done in saturated silt [148]. While these studies observe vapor and moisture movement yet displacement behaviour is not seen [149].

4.1. A comprehensive example

As already mentioned, using energy piles may lead to environmental issues such as contamination of groundwater water table as a result of the movement of contaminant spices in the soil subjected to thermal loading. with the increasing use of these piles, in the long run, this may cause serious health issues for both humans and other species. This example takes into account the chemical species transport in the surrounding soil. For this purpose, we used one set of equations, presented by Ghasemzadeh [122] governing the behavior of unsaturated soil, water, heat and solute transport containing reaction in this media to model a deformable unsaturated soil specimen under thermo-chemical load. As it is shown in Fig. 2 heat and the solute source was placed in the middle of the top boundary of a soil sample with 15 cm width by 15 cm height. The mesh consists of 15 by 10 four-node elements. The middle element in the top of the mesh is the source of heat and solute. Soil and solute interaction were modeled by the Freundlich adsorption model. Table 1. shows the properties of soil and solute.

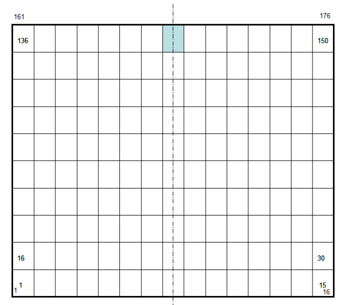

Fig. 2. Mesh in the numerical analysis of THMC problem

Considering the initial temperature to be 95℃ around heat source after two hours of heat the iso values of temperature are shown in Fig. 3. The form of temperature contour is because of water circulation in the soil element. The results of the present study also show changes in the saturation degree which is nearly circular around the heat source and increase toward the bottom of the soil. while the initial degree of saturation assumed to be 0.5, Fig. 4. indicates the final degree of saturation to be between 0.41 around heat source to 0.57 in the bottom limit.

Table 1. Physical characteristics of the soil and solute

Properties	Unit	Values
Diffusion molecular coefficient	D_0 (m^2/sec)	1.0 e-10
Degree of saturation initial	S_r (cm^3/cm^3)	0.5
Porosity	n (cm^3/cm^3)	0.73
Decay coefficient of the solute	λ_1 (1/sec)	1.0 e-4
Decay coefficient of the adsorbed solute	λ_2 (1/sec)	1.0 e-4
Coefficient of longitudinal dispersion	α_L (m)	2.0 e-2
Coefficient of transversal dispersion	α_{tv} (m)	2.0 e-2
Coefficient of Frendlich	K_p (m^3/kg)	1.0 e-3
Coefficient of Freundlich	α	2.0
Density of grain	ρ (kg/m^3)	2780
Molecular masse of solute	M (gr/mol)	237
Calorific capacity of solute	C_{pc} (J/kg°C)	116
Calorific capacity of soil grain	C_{ps} (J/kg°C)	800
Thermal capacity of water	C_{pw} (J/kg°C)	4180
Calorific capacity of vapour	C_{pv} (J/kg°C)	1870
Calorific capacity of air	C_{pg} (J/kg°C)	1000
Thermal conductivity of soil grain	λ_s (W/m°C)	0.9
Thermal conductivity of water	λ_w (W/m°C)	0.6
Thermal conductivity of air	λ_g (W/m°C)	0.0258
Latent heat of evaporation	h_{fg} (J/kg)	2.4×10^6
Initial solved concentration	C_0 (mol/l)	0.25
Initial adsorbed concentration	Cs_0 (mol/l sol)	0.00

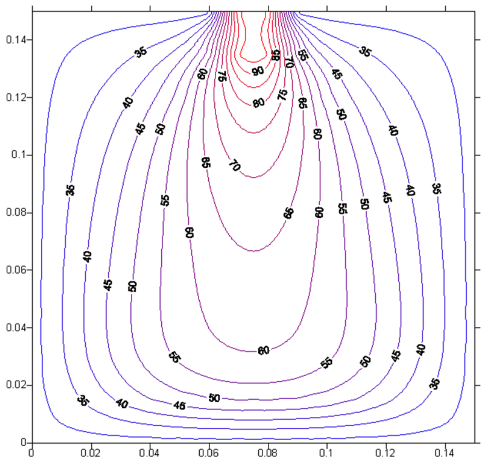

Fig. 3. Iso values of temperature

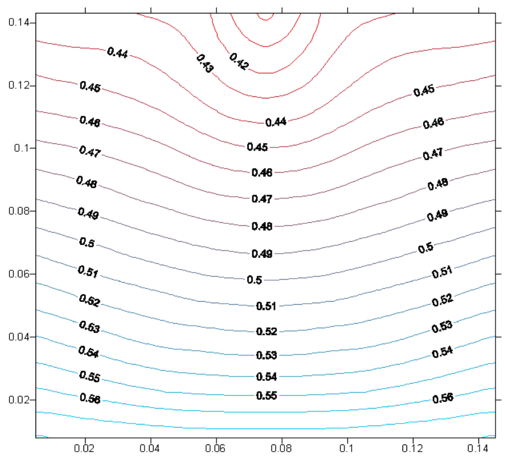

Fig. 4. Iso values of degree of saturation

Moreover, initial porosity assumed to be 0.73 and changes in void ratio and suction are computed and are presented in Fig. 5. and Fig. 6. The void ratio changes from 0.73 to 0.77 and suction varies from 2700 to 4300 kPa.

One important point that is taken into consideration in this study is the concentration of solute and water movement through the soil which is presented in Fig. 7. and Fig. 8. Water moves to the bottom and it returns from lateral boundaries to the source of heat and solute. This circulation is because of the gradient of temperature and also the gradient of concentration. The gradient of temperature make evaporate water around the heat source and condensate it in the further area. The gradient of concentration causes a gradient of osmotic pressure that conducts water to the solute source. Fig. 8 also presents the iso values of solute concentration in the pore solution. Solute concentration is equal to 1 mol/m3 around the solute source. Solute transfer towards the bottom of the specimen and contours expand at the bottom of the sample. Water movement in the soil can interpret this tendency of concentration contours.

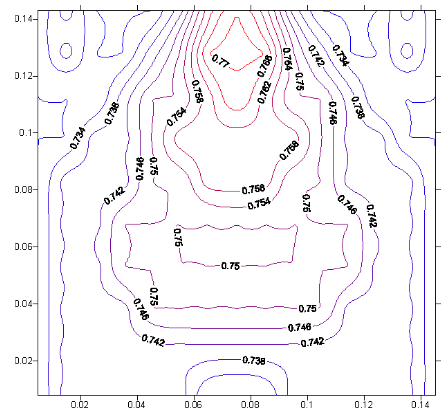

Fig. 5. Iso values of void ratio

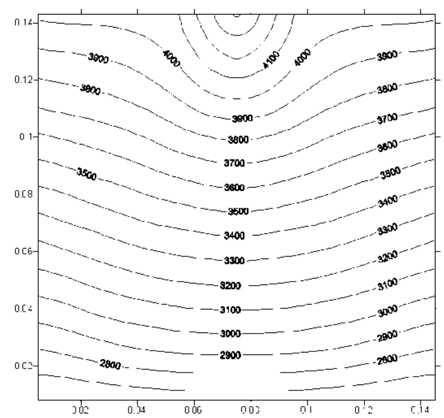

Fig. 6. Iso values of suction

Void ratio is directly proportional to expansion and the maximum expansion occurs around heat source with a void ratio of 0.77 with the suction of 4300 kPa. This expansion generates a displacement of 2.9 mm that can be seen in Fig. 8. The quasi-rigid displacement of the source element and adjacent elements can be interpreted by the high value of suction in this area.

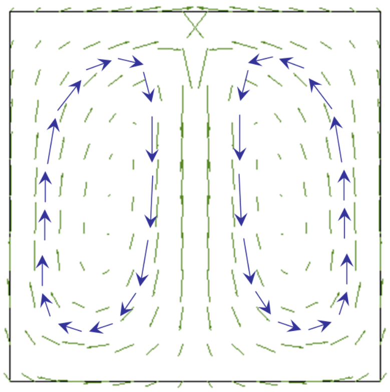

Fig. 7. Velocity vectors in the medium

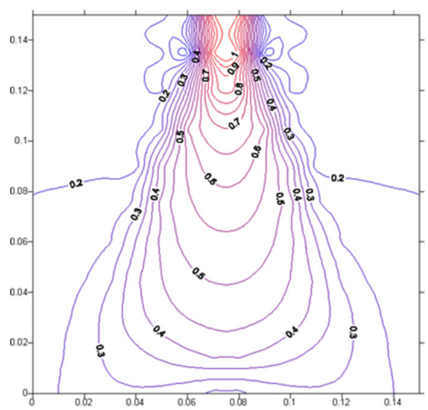

Fig. 8. Iso values of concentration

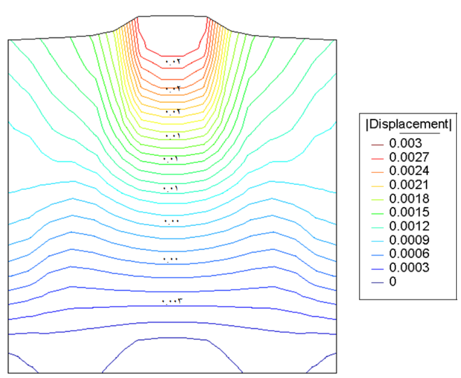

Fig. 9. Iso values of displacement (m)

The results of this numerical study show the importance of the water and chemical movement around energy piles. The most important reason that the movement of chemicals spices due to thermal loading of piles should be taken into consideration is that chemicals may cause contamination of groundwater, deformation, and movement of the foundation. Moreover, depending on the geographical situation and type of chemicals, it may result in the failure of the structure due to corrosion. So, any study of long-term performance of energy piles should account for the presence and movement of chemical species.

5. Conclusion and Recommendations for Future R

esearch

This paper has reviewed the principal parameters affecting the displacement behavior of energy piles investigated to date, with particular emphasis on the methodologies adopted, as well as the strengths and limitations of previous studies. The main objective was to identify the less-explored aspects of energy-pile behavior and to highlight important research gaps that may provide opportunities for future investigations. Based on the comprehensive review of the available literature, several areas requiring further attention can be identified.

First, most previous studies have considered thermal and mechanical loading separately, whereas the combined effects of thermal, mechanical, and chemical loading, including the associated hysteresis effects, have received limited attention. In practice, energy piles may simultaneously experience several interacting loading mechanisms, and their coupled effects can significantly influence pile displacement and soil–pile interaction. Future studies should therefore consider more comprehensive multiphysics loading conditions to better represent the behavior of energy piles under realistic field conditions.

Second, energy piles are typically subjected to cyclic thermo-mechanical loading associated with seasonal heating and cooling demands. The repeated application of thermal and mechanical loads may result in cumulative deformation and changes in load-transfer mechanisms, thereby affecting the long-term performance and serviceability of energy-pile systems. Nevertheless, the long-term effects of seasonal thermo-mechanical cycles remain insufficiently understood. Further experimental and numerical investigations are therefore required to evaluate the accumulation of deformation and the evolution of soil–pile interaction under realistic long-term loading conditions.

Third, energy piles are commonly installed in groups, making the influence of pile arrangement and group geometry an important consideration in their design. Most existing studies have focused on regular and symmetrical pile configurations, while irregular and asymmetric arrangements have received considerably less attention. Future research should investigate a wider range of pile-group geometries and develop practical design charts or guidelines covering different pile spacings, arrangements, and configurations. In addition, many existing studies assume that the applied load is distributed uniformly among the piles within a group. This assumption may not adequately represent actual field conditions, where load redistribution can occur because of differences in pile position, soil–pile interaction, thermal loading, and boundary conditions. Therefore, the actual distribution of mechanical and thermal loads within energy-pile groups requires further investigation.

Another important research gap concerns the constitutive behavior of both the pile and the surrounding soil. Most existing investigations have adopted elastic assumptions for both materials. However, under sufficiently large or repeated thermo-mechanical loads, irreversible deformation, yielding, and plastic behavior may develop in the soil and potentially influence the response of the pile. Future studies should therefore incorporate appropriate elasto-plastic or advanced constitutive models to provide a more realistic representation of energy-pile behavior, particularly under large, cyclic, and long-term loading conditions.

Furthermore, a substantial proportion of the existing literature has focused on energy piles installed in saturated soils, whereas their behavior in unsaturated soils remains comparatively underexplored. In unsaturated soils, thermal loading can interact with changes in matric suction, water content, hydraulic conductivity, and mechanical properties, potentially resulting in behavior that differs significantly from that observed under saturated conditions. Consequently, the mechanisms and findings established for saturated soils should be further investigated and validated under unsaturated conditions, with particular attention to the coupled thermo-hydro-mechanical response of the soil–pile system.

In addition to mechanical and geotechnical considerations, the environmental implications of energy piles require greater attention. Energy piles represent an important component of the transition toward smart, sustainable, and energy-efficient buildings, and their environmental performance should therefore be evaluated comprehensively. Although the energy efficiency and renewable-energy potential of energy piles have been demonstrated in numerous studies, the potential environmental risks associated with long-term thermal operation have not yet been sufficiently investigated. Future research should particularly examine the effects of temperature variations on soil chemistry, chemical species, contaminant mobilization, and groundwater quality. These issues may be especially important at sites where naturally occurring or anthropogenic contaminants are present.

Moreover, despite being considered a green and sustainable technology, the broader environmental consequences of energy-pile systems should be assessed over their entire service life. Their potential effects on the surrounding environment, including air quality, environmental pollution, and human health, should be considered alongside their energy and geotechnical performance. Integrating environmental impact assessments with thermo-hydro-mechanical and hydrogeological analyses could provide a more comprehensive framework for evaluating the overall sustainability of energy-pile systems.

Overall, the review demonstrates that although substantial progress has been made in understanding the behavior of energy piles, significant knowledge gaps remain. The most important areas requiring further investigation include coupled thermal–mechanical–chemical loading, cyclic and seasonal effects, irregular pile-group configurations and load redistribution, nonlinear and plastic soil–pile behavior, unsaturated soil conditions, and the potential environmental consequences of long-term thermal operation. Addressing these issues through coordinated experimental, numerical, and field investigations will contribute to a more comprehensive understanding of energy-pile behavior and facilitate the development of reliable and robust design methodologies.

Ultimately, future research should move toward fully coupled, nonlinear, cyclic, and environmentally integrated analyses of energy-pile systems, while considering realistic field conditions and long-term operation. Such developments are essential for improving the reliability and serviceability of energy piles and for ensuring that their application as a sustainable geothermal energy technology is not only energetically efficient but also geotechnically reliable and environmentally responsible.

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