Energy-piles in the Netherlands: geotechnical behaviour

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ABSTRACT

Shallow geothermal energy is able to provide localised heat sources/sinks or stores. It is a major advantage to be able to incorporate this into structural building elements, with the main advantage of reducing installation costs. However, more detailed knowledge of the geotechnical behaviour is needed to ensure that the foundations are stable and deformations are acceptable. In this paper, the geotechnical issues pertaining to energy-piles installed in soils are studied. First, the general functionality of energy-piles and a proposed conceptual model for such a system are reviewed. Different thermo-mechanical mechanisms incorporated in systems installed in different soil types are discussed, as are possible threats regarding energy-piles. The key areas requiring additional knowledge and quantification are identified, and a framework is proposed to incorporate them into a constitutive model so that detailed design can be undertaken. Ongoing research at Delft University of Technology, designed to address these issues, is introduced.

1. INTRODUCTION

In recent decades, extracting energy and heat from the ground, as an almost unlimited source of energy, has gained attention. In deep geothermal energy projects, heat is extracted from deep geological layers often several kilometres below the ground surface. However, the high costs of drilling technology and practical difficulties have restricted its implementation to large-scale applications (De Moel et al., 2010). Thus, due to their lower cost and reasonable long-term sustainability, shallow geothermal resources, mostly from soil layers, have become an interesting medium for extracting energy. In contrast to deep geothermal systems, the application of shallow geothermal systems are feasible in a wide range of structures, e.g., residential and commercial buildings (Yari & Javani, 2007).

At shallow depths below 5-10m (depending on the region) the Earth's temperature is initially stable and can be used as a heat sink or as a source of energy. Water is circulated through heat exchanger pipes, and for shallow geothermal systems these are often closed. The temperature in the ground is significantly lower than required for space or water heating and therefore heat pumps must be used. These systems are often called ground source heat pump (GSHP) systems. In a heating mode, the ground plays the role of the energy source from which heat is extracted and transferred to the building (via the GSHP), while, in a cooling mode, the heat from the building is rejected to the ground (which acts as the heat sink) (Abuel-Naga, et al., 2015). By using these systems for both heating and cooling, heat can be stored and the systems are more efficient, i.e., they require less electrical input to the heat pump.

Energy-piles (also known as thermal-piles) are one of many kinds of GSHP systems. They are dual-purpose constructions, designed to bear the structural loads exerted from the building as their main purpose, and to exchange heat with the ground as their secondary purpose. They are mostly made of concrete, which has a reasonably high heat capacity and thermal conductivity (Brandl, 2006). The heat exchangers with the ground are mostly U-tubes (plastic tubes in a U shape) inserted in the piles, in which a fluid circulates and carries the heat.

While energy pile systems are becoming popular in some countries, there is no well-recognised geotechnical design standard (Abuel-Naga et al., 2015; Peron et al., 2011) and the design process is mainly based on practical consideration and empirical relations (Boennec, 2009). Often to compensate for this, a higher safety factor is used (in comparison to the design process of a regular pile) (Abuel-Naga et al., 2015) to cover the possible detrimental effects of temperature variation. Although this approach would probably keep the design and construction safe, it could impose un-needed additional costs. To avoid this drawback, a clear understanding of the governing mechanisms occurring during the energy-pile lifetime is a must. Energy pile systems have a more complex soil-structure interaction in comparison to a regular pile. These complexities in behaviour are due to thermal effects on both the mechanical behaviour of the pile and the surrounding soil, as well as their coupled effects. A thorough research plan at Delft University of Technology has been designed to understand the governing mechanisms occurring during the performance of an energy-pile, which consists of laboratory-scale element tests and field tests, as well as producing numerical tools and standards for the purpose of designing energy-piles installed in the Netherlands. This paper focuses on the behaviour of the soil under the coupled thermo-mechanical loads of an energy-pile.

In the next section the effect of pile installation, as the initial stage of construction, on the mechanical behaviour of the soil is discussed. This is followed by a proposed conceptual model in Section 3, which proposes stresses and stress paths that could be generated during the lifetime of an energy-pile. The thermo-mechanical behaviour of both fine and coarse grained soils is then described in Section 4. In Section 5 the possible threats to the energy-pile's structural performance are discussed, followed by a discussion and conclusions in sections 6 and 7, respectively.

2. INSTALLATION EFFECTS

In this work, displacement piles are considered. In this pile system, soil is pushed radially away from the pile centre via a rotating conical tip attached to a steel casing. The soil is then supported temporarily by the steel casing. A pile reinforcement cage, with the heat exchanger U-tube attached, is lowered into the casing, after which concrete is poured into the casing. Following this step, the conical tip is detached from the casing and the casing is removed.

The soil elements close to an energy-pile experience a wide range of stresses and strains during the installation process. As the conical tip approaches a soil element, large radial (compressive) and circumferential or hoop (tensile) stresses are applied, followed by a dramatic reduction of stresses as the drilling tool passes the element (Jardine et al., 2013; White, 2005; Yang et al., 2014). As a result, during each drilling stroke the soil element is subjected to a cyclic load, in which the soil's state varies between the ultimate (critical) state in compression and extension (White, 2005). During displacement-pile installation, one loading-unloading cycle occurs. However, depending on the soil's condition (stiff or soft soils), other installation methods may result in between one to a few tens of cycles to reach the desired depth. Thus, it can be inferred that the soil element is subjected to a mechanical cyclic loading and stress reversal which takes the soil state to, or close to, the ultimate state condition (represented by the line *M* in Fig.1). A schematic stress path that a soil element experiences during installation, with respect to deviatoric and mean effective stress space (q and p, respectively), is shown in Fig.1, where an increase in both p and q are seen, as well as a cyclic path.

To determine the effect of pile installation on the mechanical behaviour of the soil, soil element tests may be undertaken, with the soil element being prepared using the same stress path as it would have experienced during installation. However, this is difficult due to the high levels of stress and strain (White, 2005). Nevertheless, it can be inferred that after the installation process, the structure of the soil is completely or substantially destroyed. A remoulded soil specimen in soil element tests (e.g., triaxial tests) best represents the soil after installation.

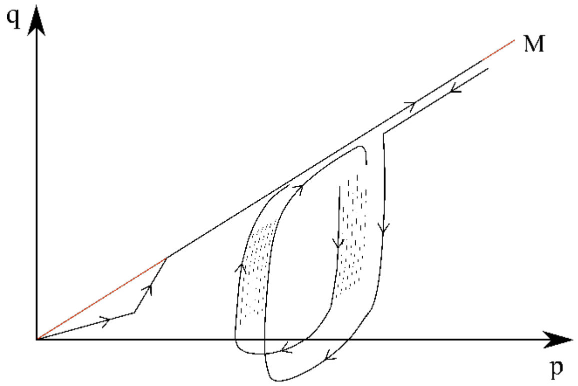
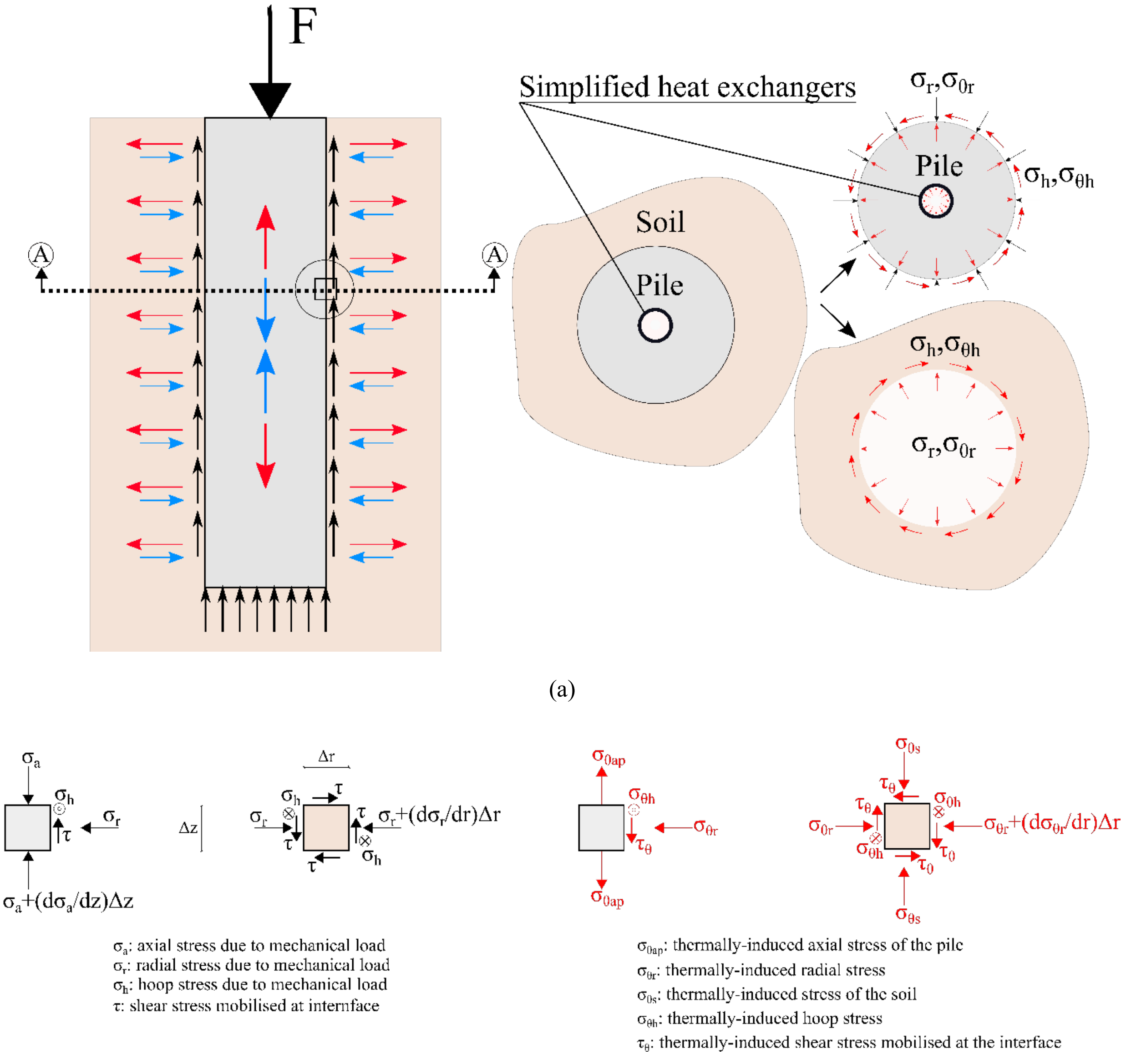


Figure 1: Schematic cycle stress path of a soil element during installation, after (White, 2005)

3. CONCEPTUAL MODEL

Energy-piles are employed for the two main reasons of carrying mechanical loads and exchanging heat with the ground. Therefore, the stresses in the ground consist of both mechanical and thermally-induced stresses, as indicated in Fig.2. These stresses develop and act simultaneously in the ground and on both the pile and the soil in contact with it. The resulting stresses can be studied separately as mechanical and thermally-induced stresses, and added together by using the superposition principle. The external load from the structure constructed on the pile, *F* (Fig.2-(a)), is transferred to the pile and from the pile to the ground. As a result, by considering a pile element at the interface adjacent to a soil element, an axial stress σ_a as well as radial and hoop stresses (σ_r and σ_h) are applied to the pile element, due to Poisson's ratio and the restraints from the adjacent soil (Fig.2-(b)). As the pile undergoes axial deformation (and possible changes in the radial and hoop stresses), the shear stress τ mobilises at the interface. As these elements are in stress equilibrium, stresses are transferred to the soil element at the interface.

When the heat exchange through the U-tubes initiates, the pile expands in all directions. By assuming the temperature is uniformly distributed radially and along the length of the pile, and considering if the pile would be completely free to deform (both radially and axially), no internal stresses would be generated inside the pile. However, depending on the soil state and condition, the pile may be (partially) constrained. As a result, the portion of the volume expansion of the pile that is prevented produces internal stresses which are referred to as thermally-induced stresses. These stresses are (Fig.2-(c)):



(a)

(b) (c)

Figure 2: (a) Stresses developed during the deployment of the energy pile; (b) mechanical stresses; (c) thermally-induced stresses

- $\sigma_{\theta ap}$, thermally-induced axial stress developed inside the pile. This stress is due to the restraint imposed by the surrounding soil in both the axial and radial directions.
- $\sigma_{\theta r}$, thermally-induced radial stress developed at the interface. This stress is the result of prevention of radial displacements (due both to thermal expansion in the radial direction and to the impact of the axial expansion due to Possion's effect), as well as to changes in the thermally-induced hoop stresses.
- $\sigma_{\theta s}$, thermally-induced stresses developed inside the soil. Depending on the soil's type and state, it may undergo both thermo-elastic expansion and permanent contraction during heating. When these volume changes are prevented, thermally-induced stresses are developed inside the soil element.
- $\sigma_{\theta h}$, thermally-induced hoop stress. A combination of radial and axial stress variations at different radii from the interface, as well as an irregular shape of the pile, may produce hoop stresses perpendicular to both the axial and radial stresses.
- τ_θ, thermally-induced shear stress. This stress is mobilised at the interface due to relative displacement between the pile and soil in contact, due to temperature variation and the combined effects of radial, hoop and axial stresses mobilised at the interface.

It should be noted that the above stresses are directly dependent on their interaction with each other and the level of restraint imposed by the ground. As an example, if the pile is installed in a stiff clayey-soil and the pile's radial expansion is confined, then a higher thermally-induced radial stress would be generated and, concurrently, due to Poisson's ratio, higher thermally-induced axial stresses or strains (dependent on the axial restraints of the pile) are produced. This would also lead to differential displacement at the interface and thereby to the generation of shear stresses (τ_θ).

The direction of the thermally-induced stresses depends on both the direction of heat transfer (heating or cooling) and the location of the element on the pile. For instance, the directions of the shear and axial stresses ($\sigma_{\theta ap}$ and τ_θ) at the pile during heating differ when the pile element is located above or below the null point (the point at which the axial stresses are zero, i.e., the point at which the direction of elongation changes). Also, the direction of these stresses becomes opposite during cooling.

The magnitude of the stresses depend on the soil's restraints applied to the pile and the thermo-mechanical behaviour of the surrounding soil. For piles located in fine-grained soils with a high plasticity-index, higher settlements occur due to higher volume contraction during heating. Also, for soils in which the shear strength reduces at elevated temperatures, higher relative displacements may be required to mobilise sufficient shear stress at the interface.

For a typical energy-pile in the Netherlands, heating will be the primary use in the winter, resulting in cooling of the soil, whereas, in the summer, cooling will be used or the system will simply not be in operation; this will result in an annual cycle of temperatures and thermally-induced stresses. More minor cycles may be induced on a daily or weekly basis, but these will be of a significantly smaller magnitude.

4. THERMO-MECHANICAL BEHAVIOUR OF SOILS

In general, the thermo-mechanical behaviour of soils is mostly categorised as thermally-induced volumetric and shear behaviour. In this section the behaviour of soils (both clays and sands) as temperature varies is briefly discussed.

4.1 Thermally-induced volumetric behaviour of soils

Fine-grained soils

The thermo-mechanical behaviour of fine-grained soils is highly dependent on the previous loading history. This can best be shown by the effect of the over-consolidation ratio (OCR) on its mechanical behaviour, which is defined as the ratio of maximum mean effective stress experienced by the soil over the current mean effective stress. When a fine-grained soil is exposed to elevated temperatures, the volume of the soil expands due to thermal elastic expansion; additionally, there is also the possibility of contraction, which is usually plastic and therefore permanent. Which process dominates the overall volume change of the soil directly depends on the OCR value. At low values of OCR (i.e., normally to slightly over-consolidated soils), permanent contraction is normally the dominant mechanism (Abuel-Naga et al., 2007; Cekerevac and Laloui, 2004; Di Donna and Laloui, 2015; Sultan et al., 2002; Towhata et al., 1993; Uchaipichat and Khalili, 2009). This behaviour is attributed to soil particle rotation and rearrangement, similar in behaviour to when an additional compressive load is applied. At higher OCR values, permanent volume contraction decreases (or becomes zero) and thermo-elastic expansion becomes the dominant mechanism (Khalili et al., 2010; Cekerevac and Laloui, 2004). This is mostly due to elastic expansion.

Coarse-grained soils

The volume change of sandy-soils has been reported to be temperature-independent and thus neglected as its variation is very small (Recordon, 1993; Sadrekarimi, 2016; Saix et al., 2000). However, recent studies show that the temperature effect on the volumetric behaviour of sands is similar to clayey-soils, although its magnitude is lower in comparison to clays. The thermo-mechanical behaviour, similar to clays, is also dependent on loading history, although different mechanisms are involved which can often be described by confining pressure and void ratio (p and e). At low densities and high confining pressures (representing the wet side of the critical state line), an increase in temperature leads to volume contraction, whereas, as the density increases or the confining pressure decreases, the behaviour would be mostly thermo-elastic expansion (Liu et al., 2018; Ng et al., 2016). Further increases in temperature are observed to result in the dominating mechanism asymptoting toward thermo-elastic expansion, independent of the soil's density.

4.2 Thermally-induced shear behaviour of soils

Fine-grained soils

The thermally-induced shear behaviour of fine-grained soils depends directly on the soil's constituents and mineralogy. Thus, through an increase in temperature, the peak shear strength (Abuel-Naga et al., 2007; Cekerevac and Laloui, 2004; Hueckel and Baldi, 1991; Hueckel et al., 2009; Kuntiwattanakul et al., 1995; Ng et al., 2016), the stress ratio at the critical state (Ghahremannejad, 2003; Hueckel and Baldi, 1991; Kuntiwattanakul et al., 1995), and the elastic bulk and shear moduli (Zhou et al., 2015) may increase, decrease or remain unchanged.

Coarse-grained soils

The mechanical behaviour of coarse-grained soils, e.g., sands, is mostly recognised due to their shear behaviour. Most experimental results indicate a temperature-independency for the shear behaviour of coarse-grained soils (Agar et al., 1987; Graham et al., 2004; Yavari et al., 2016). However, few studies show a reduction in the peak shear strength and secant modulus in dense sandy-soils as the temperature increases (Liu et al., 2018).

4.3 Behaviour of soils during heating-cooling cycles

When soils (both fine and coarse grained) are subjected to heating-cooling cycles, permanent volumetric strains can be produced which may accumulate (Bai and Su, 2012; Di Donna and Laloui, 2015; Ng et al., 2016; Ng et al., 2016; Ng and Zhou, 2014; Sadrekarimi, 2016; Vega and McCartney, 2015). The highest strain produced normally results from the first cycle and the additional strains reduce as the number of cycles increase; this is known as hardening behaviour. Eventually, the soil reaches a thermally-stable condition in which further applied heating-cooling cycles would not develop permanent volumetric strains and the resultant volume change would only be due to thermo-elastic expansion.

4.4 Coupling behaviour

The volumetric behaviour has a strong impact on the shear behaviour in a system that has restraints. The shear stress on the pile's circumference directly depends on the applied normal stress. If the volume of a soil is reduced, the normal stress and consequently the shear strength are also reduced (in materials with frictional strength). Several coupling processes between the pile and the surrounding soil may result in volume reduction. When the soil is applied to heating-cooling cycles, due to the hardening behaviour of soils the volume of a soil adjacent to the pile may decrease. The consecutive expansion-contraction of the pile, due to temperature variation, imposes mechanical cyclic shearing at the interface which also may result in volume reduction of the soil. Thus, further settlement may occur as the shear strength and thereby bearing capacity reduce.

5. POSSIBLE THREATS

A number of extra potential threats arise in energy-pile systems in comparison with regular pile systems. These possible threats are due to thermo-mechanical behaviour of both the surrounding soil and the pile, as well as their coupling effects. These threats are summarised as (Abuel-Naga et al., 2015):

1. Exceedance of axial internal stresses inside the pile with respect to both its compression and tension strength limits
2. Reduction in shaft resistance
3. Additional settlement

Another possible threat that might emerge during the performance of the energy piles is cold winters. When the fluid in the U-tube is at a negative temperature, a freezing front may develop in the soil close to the energy-pile. During freezing of the water and phase transformation from liquid to ice, latent-heat is released, which can be advantageously captured by the system. In this case, the water in the soil element becomes frozen and the performance of the soil-pile system is influenced by frozen-soil mechanical behaviour. As a consequence of the freezing, the surrounding soil may heave (due to the expansion of the frozen water and additional water attracted to the ice), which may impose upward displacement to the pile and consequently to the structure above it. In the case that the pile is (partially) axially restrained due to the building loads on top of it, the heave induces additional axial stresses in the pile.

At a later stage the frozen soil may thaw due to seasonal changes or a lower need of energy. This could result in a transfer of load to the pore water (especially if additional pore water had been attracted to the ice), and a reduction in effective stress and therefore strength. The freezing-thawing cycles (in consecutive years) may result in accumulated settlements exceeding the allowable settlement considered for the soil-pile system. As a result, the serviceability of the system may be threatened. In addition, the reduction of heave from freezing may result in negative skin friction mobilisation, and thus to a reduction of the pile's load capacity.

6. DISCUSSION

Previous sections have demonstrated how the mechanical behaviour of the soil in contact with an energy-pile can change due to pile installation and temperature variation, as well as additional stresses that may be applied due to soil-restraints on pile/soil volume change. All these effects are coupled together and may result in one or more of the possible threats mentioned in Section 5. It is clear that while this simplified conceptual model is useful for understanding which stress levels and paths should be considered for soil testing, it would not be adequately accurate for pile design. Therefore, to consider all the involved processes, a rigorous numerical simulation is required. This should account for the thermo-mechanical behaviour of the pile, the surrounding soil and the interface layer through a fully coupled analysis.

The thermo-mechanical behaviour of the concrete, as a homogeneous material, is mostly known, and its thermo-mechanical properties vary in a narrow range. However, the mechanical behaviour of soils varies significantly as mentioned before. Temperature effects on both the volumetric and shear behaviour in accordance to a soil's loading history and mineralogy should be accounted for in the constitutive equations of material behaviour, as it is the core of any numerical simulation. These are crucial factors that may change the design procedure. For instance, the volume and shear strength reduction of the soil at elevated temperature may result in additional settlements which may exceed the designed allowable settlement. Therefore, the geometry of the pile (diameter and/or length), or even the concrete type may need to be revised. The same scenario may apply when considering freezing-thawing cycles. The constitutive model implemented in numerical simulations should be capable of capturing the hardening effect of soils when subjected to heating-cooling cycles. This is essential when designing the appropriate allowable load (F) for the pile or determining its appropriate geometry, in order to keep the accumulated settlements within the admissible range.

Shallow depths (less than 50m) in the Netherlands consist of soil layers of a wide range of soil types, including peats, clays, silts, sands and a mixture thereof. Most of these soils are normally or slightly consolidated, which have the highest thermally-induced effects (mostly on volumetric behaviour). Also, the water level is high enough to keep these soil layers in the fully-saturated condition. Thus, in order to investigate the thermo-mechanical behaviour of soils, temperature-controlled element tests such as triaxial and direct shear tests on fully saturated soils should be conducted, and the results be incorporated into a constitutive model as the core of any numerical simulation. The constitutive model should be able to predict the temperature effects on the shear and volumetric behaviour of the soil as well as being consistent with real-world governing laws.

7. CONCLUSIONS

In this paper, a brief description of the functionality of energy-piles and the processes that may affect their performance has been presented. A focus was made on the behaviour of the soils, which may impact the behaviour of the pile (both settlements and bearing capacity). These processes include the installation and temperature effects on the mechanical behaviour of the soil and the pile. It can be concluded that the thermo-mechanical behaviour of an energy-pile is complex and requires accurate characterisation of the material behaviour, as well as a capable numerical model, to enable appropriate design.

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