DESIGN ASPECTS OF AN ENERGY PILES

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Abstract. *The paper deals with the issue of thermomechanical loading of the energy pile, which is also subjected to thermal stresses compared to a conventional pile, which is required to carry only static loads. In the context of the thermal volumetric changes of the energy pile, the stiffness of an upper structure, and a behaviour of the contact between the pile and the soil environment, we are presented with a problem that goes beyond standard design procedures. The issue is presented by a parametric study that evaluates the thermal load, the stiffness of the upper structure preventing thermal volumetric changes of the pile, but also the pile soil contact properties that have a major influence on the pile-soil friction and therefore the pile bearing capacity. The study was carried out using the Thermo-Pile software developed by the Soil Mechanics Laboratory of the University of Lausanne. This paper gives an overview of the differences in the design of energy piles and highlights the potential risks in their design.*

Keywords

Geothermal energy, energy pile, thermomechanical loading, pile design, numerical simulation.

1. Introduction

At present, when not only the consumption but also the price of energy is constantly increasing [1], it is quite understandable that alternative sources are increasingly coming to the foreground [2]. These sources provide the benefit of significantly lower environmental emissions when technology and operation are properly implemented [3]. In the context of conventional civil engineering, the most common type of alternative energy source used is shallow geothermal energy [4], [5], which can be used at depths of the first tens to hundreds of metres. For the extraction of shallow geothermal energy, so-called energy geo-structures (EGS) are used, which are structures or parts thereof that are in contact with the soil environment and perform primarily a static and stabilising function. The secondary function of these structures is their use for the exploitation of shallow geothermal energy [6], [7]. Thermal energy is then transported by means of a fluid flowing in pipes that are integrated in the underground parts of these structures and subsequently recovered by means of a geothermal pump, e.g., for heating. The functionality and efficiency of EGS are mostly sufficient for commercial applications. However, the widespread application of these technologies is hampered by many factors: absence of experts in the design of such structures, the problematic determination of the thermomechanical loads of EGS and, finally, the lack of validated analysis and design procedures [8], [9]. One of the most common types of EGS is the classical pile foundation, which, combined with the thermal energy extraction function, is referred to as an energy pile [10], [11]. This type of design is discussed in the following text.

2. Theory of Thermomechanical Load of an Energy Pile

The thermomechanical load of an energy pile is the load that is made up of the following two parts:

- the mechanical load, which is derived from the classical static load from the upper structure,
- and the thermal load, which is induced by the volumetric changes due to the change in temperature of the pile and the adjacent soil environment. Two typical situations can be mentioned here. In winter, the thermal energy is extracted from the subsoil by the energy pile, and the temperature of the pile is lowered,

resulting in contraction and settlement of the pile. In summer, the situation is reversed, the system is used as air conditioning, the pile expands as a result of the stored thermal energy, and again exerts a deformation load to the upper structure. The sum of the effects of the above loads must be less than or at most equal to the bearing capacity of the pile. It is necessary to assess not only the first limit state, but especially the serviceability limit state, which is often the most critical for piles and is also directly affected by thermal stresses.

There are several means to design a pile subjected to mechanical loading. However, only some of them can be applied to the energy pile. Here, a brief classification into two basic groups, including their typical representatives, is given:

- Field tests: static pile load test, which is performed at non-system piles. The result of such a test is the load transfer curve of the pile head, on the basis of which the system piles are subsequently realised. Other field methods include dynamic or static penetration tests, etc.

- Calculation methods: Basic analytical approaches, which are based on determining the bearing capacity compound of the pile shaft and the pile tip resistance, can be mentioned here. Here it is necessary to mention the fact that a much larger settlement for pile tip resistance is required to mobilise the full pile tip resistance compared to the settlement required to mobilise the pile shaft resistance. Thus, the pile tip resistance may not actually be mobilised. In addition, numerical methods can be included among the calculation methods, which, unlike previous methods, allow the combination of mechanical and thermal stresses on the energy piles. In particular, software based on the finite element method can provide a comprehensive assessment of the proposed structure that involves the energy pile, the upper structure, and the soil environment system [12], [13]. Another alternative is the use of Thermo-Pile software, which is produced by the Soil Mechanics Laboratory of the University of Lausanne (Swiss Federal Institute of Technology Lausanne EPFL). Due to the focus of this article, this software is described in more detail, and a sample calculation is presented in the third chapter.

The Thermo-Pile software is based on the finite difference method and has been developed for the solution of energy piles subjected to thermomechanical loading, i.e., for the determination of the stress-strain behaviour of an energy pile. The following simplifications are included in the software:

- The 1D scheme is used, which allows the solution to be taken only in the axial direction. Therefore, solutions in the radial direction are not supported.

- The pile properties (diameter, Young's modulus, coefficient of thermal expansion) are assumed to be constant during the calculation.

- The soil properties and the pile-soil contact (interface) are also considered constant. Therefore, any temperature dependence of the soil-pile contact parameters cannot be considered.

The pile is divided into several rigid elements during the calculation, which are connected by springs that represent the stiffness of the pile itself. Each of the pile elements is in an elastoplastic relationship with the surrounding soil. The first element of the pile is constrained by a linear spring that simulates the stiffness of the upper structure. The last element of the pile interacts with the spring, which describes the resistance of the pile tip.

The pile-soil contact (interface) is described by the t-z function (called a load transfer curve) according to the method of Frank&Zhao [15], or the transfer function can be defined manually using two elastic lines and one horizontal plastic line. Fig. 1 graphically documents the mentioned t-z function. The left part of the figure documents shaft friction, and the right part of the figure documents pile tip resistance. The horizontal axis "z" represents the vertical deformation (or displacement) of the pile element (settlement is indicated negatively) and the vertical axis "t_s" shows the mobilised pile shaft and the tip resistance.

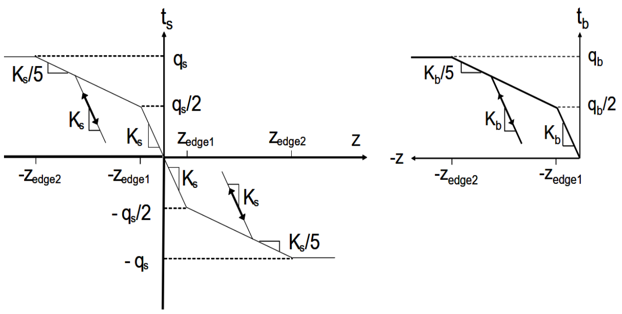

Fig. 1: Load transfer curves modified after Frank and Zhao in software Thermo-Pile [14].

The contact of the pile with the upper structure is described by a spring with a constant stiffness Kh (kPa/m). This simplification is quite satisfactory within the concept of the software; however, it should be noted that only a complex numerical solution that considers the interaction "energy pile - upper structure - soil environment" or monitoring on the actual structure will give a representative picture of the pile-structure contact behaviour. The interaction or a stiffness of the upper structure will also be significantly reflected in the energy piles activation, this means thermal activation of all piles or only some of them. It can be said, in terms of the serviceability limit state, that if all piles are thermally activated, the uniform settlement with all pros and cons occurs. In particular, the underground infrastructure that is not dilated may be at risk. However, the uniform settlement is not a serious risk in terms of its structural stability for the upper structure. If only some piles are activated, uneven settlement is manifested with all consequences. In the summer period, when thermal energy is stored, the contribution of the piles to the transfer load is higher than in the winter period. However, this depends not only on the ratio of the thermal expansions of the pile and the soil environment, but also on the degree of thermal influence of the soil environment around the pile. The information provided above is only a description of the qualitative behaviour. The negative consequences mentioned can be partially or fully eliminated by a proper static design in combination with optimisation of the amount of extracted or stored geothermal energy.

The character of load transfer from the upper structure to the subsoil is an important element determining the interaction "energy pile - upper structure – soil environment":

- Friction piles, where load transfer is mainly provided by pile shaft resistance. The presented parametric study is devoted to the friction pile.
- End-bearing piles whose pile tip is in contact with an incompressible base. The embedment or restraint of the pile in an incompressible base will have a significant effect on the deformation behaviour of the system "energy pile - upper structure – soil environment". Similar property of the system is presented here [16]. Taking into account the thermal expansion of concrete 1 mm per 10 m per 10 °C, it is possible to estimate the behaviour of a 15 m deep pile with a temperature gradient of approximately 35 ° C between winter and summer. The temperature gradient for the above example is ΔL = 1 * (15 / 10) * (35 / 10) = 5.25 mm. Since the pile tip is embedded or resting in an incompressible base, the extensions can propagate only in the upper direction. The above-mentioned dilatation will be smaller because the system "energy pile - upper structure - soil environment" has not been considered in the example.

3. Parametric Study of Energy Pile

The aim of the parametric study is to illustrate the theoretical information mentioned in the second chapter. The focus is on the stiffness of the upper structure, which is the main variable parameter. The calculation of a friction pile (depth 15 m, diameter 1 m) separately in two types of soil subjected to a static load of 2.5 MN and a temperature load of 30 ° C. The study was solved by using Thermo-Pile software, and the following text also gives its short user guide. Only parts directly related to the input parameters of this parametric study are described. Further details, including the computational theories used, are described in detail in the user guides [14], [15]. Four basic dialogue boxes are present in the software:

The first dialogue box is used to enter the soil properties. The number of layers, the lower boundary of each layer, the number of sublayers, and the groundwater level are entered. In this study, a geological layer of 30 m depth is assumed, without the groundwater table. In the second part of the dialogue box "Soil Properties", the soil parameters (internal friction angle φ, cohesion c, unit weight γ, and internal friction angle at contact δ) are entered. In this study, two types of soil with the following parameters are used:

- CG (gravely clay): φ = 30°, c = 5 kPa, γ = 19 kPa, δ = 2/3 φ,
- CI (clay with medium plasticity): φ = 20°, c = 30 kPa, γ = 21 kPa, δ = 2/3 φ.

The second dialogue box is used to enter the pile parameters. The length of the pile, the diameter of the pile, Young's modulus E, and the coefficient of thermal expansion α are entered. In this study, a 15-m deep pile is modelled, with a diameter of 1 m, E = 2.8E7 kPa, α = 1.0E-5 °C-1.

The third dialogue box is used to enter the pile-soil contact parameters and the parameter that describes the stiffness of the upper structure. The pile bearing capacity is necessary for calculation, it can be entered manually, or we can use one of the approaches according to DTU Empiric, DTU analytic, Lang&Huder [14], [15]. In the last part of this dialogue, the pile-soil contact behaviour can be described using the t-z function. Theories according to Frank&Zhao [15] can be chosen separately for cohesive and non-cohesive soils, or the t-z functions can be entered manually (Fig.1). In this input section, it is also possible to enter the stress-strain properties of the soil under the pile tip. In this study, the calculation of the pile bearing capacity "DTU analytic" is chosen. The t-z functions are determined according to Frank&Zhao theory. The stiffness of the upper structure is considered in the study as Kh = 0, 100, 200, 400 and 800 MPa/m.

The fourth and final dialogue box is used to enter mechanical and thermal loads. The temperature loads can be entered manually (constant for the whole pile), or by using a *.txt file with the option of variable temperature loads along the pile. The static load of 2.5 MN is identical for all variants (using of the two above mentioned types of soils CG and CI). The assumed increment of temperature is 30 ° C. Thus, only the temperature difference is considered in terms of thermal stress.

Figure 2 describes the behaviour of the pile in soil CG (φ = 30°, c = 5 kPa), while Figure 3 presents the behaviour of the pile in soil CI (φ = 20°, c = 30 kPa). Each figure is composed of two parts; the top part describes the axial stress in the pile as a function of depth, and the bottom part shows the vertical displacement of the pile elements as a function of depth. The colour scale according to the legend also shows the effect of the stiffness of the upper structure. The black curve also shows the axial stress and the settlement of the pile without considering the thermal load.

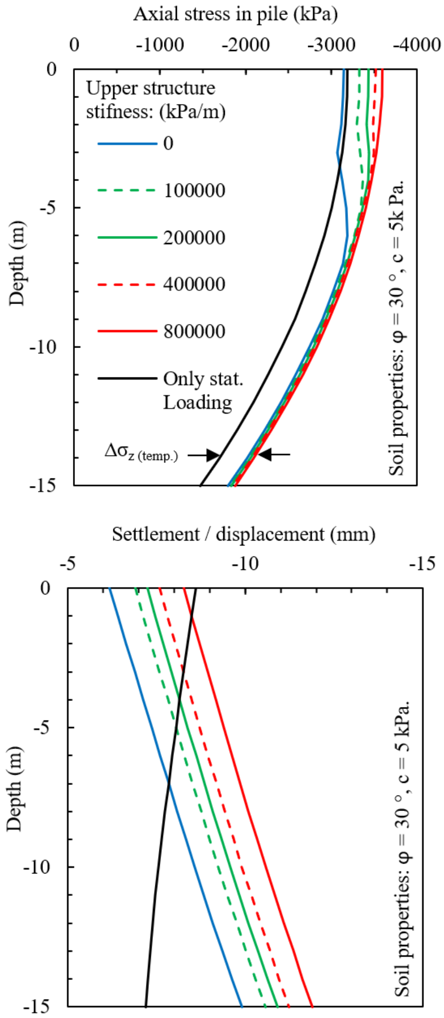

Fig. 2: Axial stress (- sign is compressive) and pile settlement in soil CG φ = 30 °, c = 5 kPa.

The stiffness of the upper structure is unimportant without thermal loading, therefore, it can be said, that this black curve (Fig.2 and 3) is identical to all stiffnesses of the upper structure. Figure 3 shows the behaviour of the pile in soil CI and does not contain the continuous red curve that represents the stiffness of the upper structure of 800 MPa/m. The reason is that the strength properties of soil CI are significantly lower compared to soil CG, therefore, the pile was easier pushed into the subsoil without increasing the axial stress in the pile. Clearly, the increase in axial stress increment $\Delta\sigma_{z(temp.)}$ is equal to 12.6% (pile in soil CG) and 6.1% (pile in soil CI). This corresponds to the fact that soil with higher strength parameters more restricts deformation of the pile, and therefore the thermal load is more reflected in the stress concentration in the pile itself. These values are also valid for the pile head in combination with the maximum observed stiffness of the upper structure.

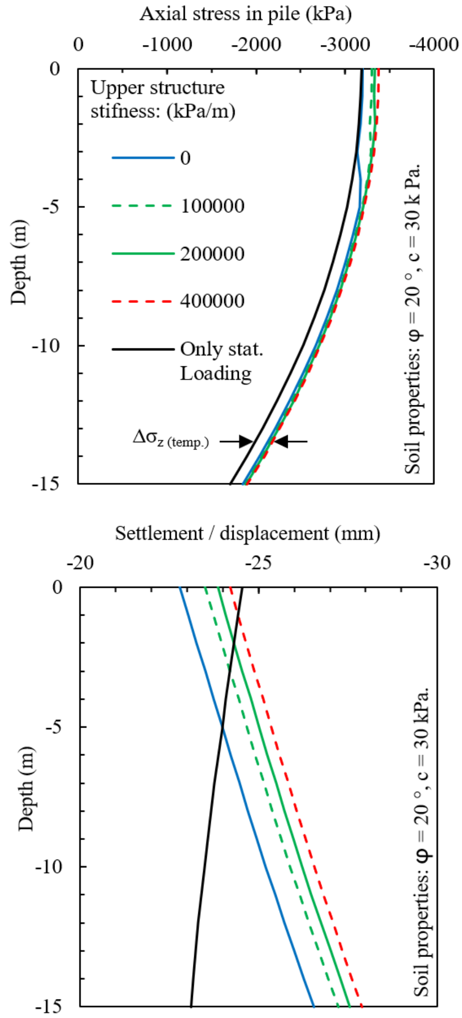

Fig. 3: Axial stress (- sign is compressive) and pile settlement in soil CI φ = 20 °, c = 30 kPa.

Intermediate values of the upper structure stiffness do not significantly affect the change in increase in axial stress over most of the pile length. Only in the first 1/4 of the length can be observed the decrease in axial stress in the pile, which occurs due to the yielding of the contact between the pile and the soil. However, as the stiffness of the upper structure increases, the deformations of the pile begin to push to the subsoil, which also means a decrease in the degree of yielding in the upper part of the pile head. The bottom parts of Figures 2 and 3 are devoted to the description of pile deformation behaviour. It is important to highlight the differences in scale of the horizontal axis in Figures 2 and 3. The coloured curves describe the thermally loaded pile with the variant of upper structure stiffnesses. The black line demonstrates the behaviour of the nonthermal loading pile. The intersections of these black and coloured curves represent the point at which the differences in the displacements are identical before and after thermal loading. If the stiffness of the upper structure increases, this intersection also increases.

4. Conclusion

The purpose of this article was to summarise some aspects that must be considered during the design of the energy pile. Compared to the standard approach to pile design, the thermal load is the main aspect that significantly changes the design of an energy pile. The importance of the following aspects was presented:

- the upper structure stiffness,
- the strength properties of soil,
- and the effect of thermal loading on the settlement of upper structure.

The increase in temperature inside the pile assuming zero stiffness of the upper structure (scenario without the upper movement restriction) results in a change in axial stresses inside the pile. In this scenario, in the upper 1/4 of the pile length near the contact with the upper structure, the axial stress decreases with increasing temperature. The axial stresses in the lower part of the pile are higher compared with those of the standard non-thermal pile. The settlements in the upper half of the pile are lower compared to the standard non-thermal pile, in the lower half of the pile the settlements are higher in compared to the non-thermal pile. This manifestation results from the free upward movement of the upper part of the pile due to the thermal expansion.

However, if the stiffness of the upper structure is considered, which limits the upward vertical movement of the energy pile, (assuming the identical temperature increment), then an increase in axial stresses manifests itself in the pile. This increase in axial stresses in the upper part is greater with the higher stiffness of the upper structure. Towards greater depths and thus a greater distance from the contact with the upper structure, the influence of the magnitude of the stiffness of the upper structure on the axial stress decreases, approximately in the half length of the pile the influence of the stiffness of the upper structure is eliminated. In the contact of the pile and upper structure, the settlements are lower compared to the non-thermal pile, but in the greater depth, the settlements of thermal pile exceed the settlements of non-thermal pile. The higher the stiffness of the upper structure, the higher the settlements are investigated.

The presented study shows that the higher soil strength parameters cause a higher increase in axial stresses in the pile due to the restriction of pile deformations in the stronger soil.

The possible negative consequences of thermal stresses can be minimised both by appropriate structural design and by optimising the geothermal operational regime. However, currently there is insufficient information on the long-term behaviour of these structures. One thing is the sustainability of the source of the geothermal energy, another thing is the effect of cyclic stresses on the pile-soil contact and on the subsoil under the pile tip. The result of the cyclic expansion and contraction of the pile is a gradual reduction in the strength parameters at the pile-soil contact and, also an undesirable gradual settlement of the pile [17], [18], [19], which can adversely affect the long-term function of the structure in terms of the serviceability limit state.

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