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Analysis of Multiphysics Problems Related to Energy Piles

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Abstract: Deep foundations which transfer the mechanical loads from buildings to the ground and also serve as heat exchangers are called energy piles. Energy piles have been used for space heating and cooling in residential and commercial buildings. Temperature changes in the ground influences its moisture content. This paper examines the effect of soil moisture content on the shaft resistance of a pile. Tests were carried out in the laboratory to determine the mechanical properties of an interface corresponding to various soil moisture contents. COMSOL is used to model the load-deformation behavior of a 10m long pile embedded in a soil with variable moisture contents based on temperature fluctuations.

Keywords: coupled analysis, heat and moisture transfer, contact modeling, energy piles.

1. Introduction

Geothermal energy has been used for space heating and cooling in residential and commercial buildings. One way of achieving this goal is to make use of the foundations of buildings which allow lowering the installation costs of such systems. Deep foundations which transfer the mechanical loads from buildings to the ground and also serve as energy exchangers are called energy piles (Brandl, 1998). These piles contain tubes to circulate fluid that accelerates the heat transfer. The thermal energy coming from the building is transferred into the ground for cooling purposes in the summer. The process is reversed in the winter for heating the building. The schematic view of an energy pile is shown in Figure 1.

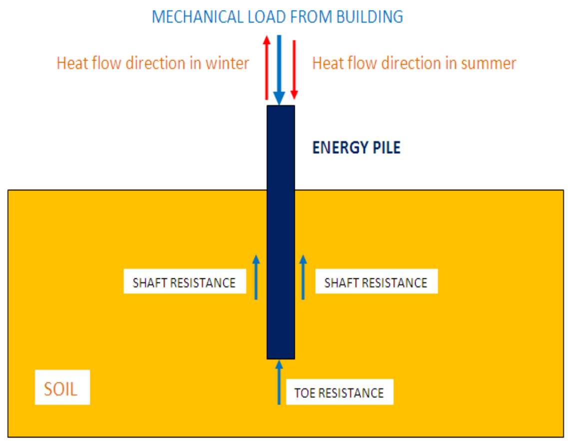

Figure1. Dual function of an energy pile: Heat transfer and the transfer of building load to soil mass.

The efficiency of energy piles depends on their dimensions, the heat and moisture transfer characteristics of the soil and the type of pile material. In addition to the convection heat transfer due to the fluid flow in the tubes within the pile, heat transfer also takes place between the pile and the soil. This process can be divided into (1) heat conduction between the pile material and the soil, (2) heat conduction within the soil mass, and (3) heat convection via subsurface fluid flow (Abdelaziz et al., 2011).

Heat transfer and fluid flow in soils are strongly coupled processes. The authors (Infante et al. 2011) published the results of an investigation on the heat and moisture transfer problems around an energy pile in the proceedings of the previous COMSOL Conference. In their paper, the results of an experimental study were presented first. COMSOL was used successfully to simulate the heat and moisture transfer in the soil column of an experimental investigation. Subsequently, the finite element analysis was extended to the analysis of an energy pile (without including the mechanical aspects of the problem). Figure 2 shows the moisture content distribution in the soil mass as a function of time. Such changes in moisture content could be caused by thermal gradients induced in the soil.

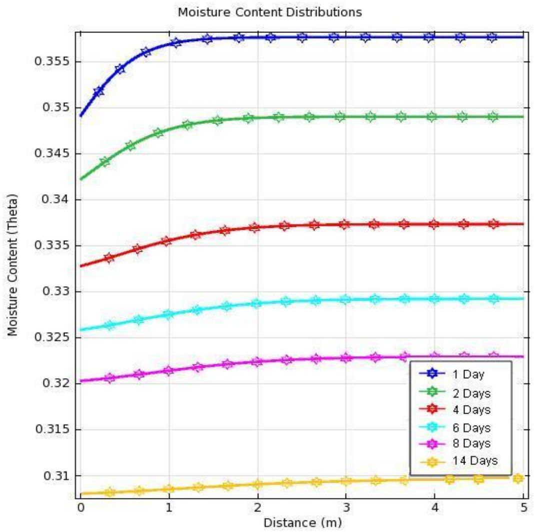

Figure 2. Moisture content distribution in the soil mass as a function of time. The changes in the moisture content are the result of thermal gradient. The pile shaft is located at Distance=0 m. Analysis was carried out using COMSOL Multiphysics Code.

Figure 3 shows the temperature distribution in the soil mass as a function of time.

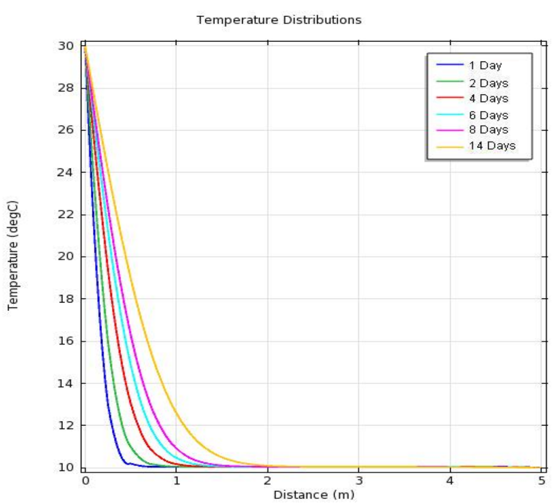

Figure 3. Temperature distribution in the soil mass as a function of time. The pile shaft is located at Distance=0 m. Analysis was carried out using COMSOL Multiphysics Code.

It is well known that the changes in moisture content strongly affect the mechanical (i.e. stress-strain-strength) behavior of soils. In other words, mechanical behavior and fluid flow are coupled processes. Therefore, the load transfer function of an energy pile is not independent from its heat transfer function. A full investigation of the behavior of an energy pile requires an analysis that takes into consideration the mechanical, thermal, and fluid flow aspects of the problem simultaneously.

Piles transfer the building loads to the ground (1) at the surface of the pile shaft and (2) at its toe (Figure 1). In the calculations of these two components of load transfer from an energy pile to the soil mass, the following physics needs to be considered. Temperature changes cause moisture movement in the soil. This changes the stress-strain-strength behavior of the soil. Similarly, the adhesion and the friction angle at the interface between the soil and the pile surface are affected.

The objective of the present study is to determine the amount of load carried by a pile shaft for increasing values of axial displacement at the pile head. It is assumed that the pile is subjected to an axial load. The properties of the contact zone between the soil and the energy pile are expressed as a function of moisture content of the soil. A solution of this multiphysics problem requires the simultaneous use of Structural Mechanics, Heat Transfer, Geomechanics and Subsurface Flow Modules. In the present analysis using COMSOL Multiphysics Code, the thermal and hydraulic effects on the soil behavior are taken from a paper published in the COMSOL Conference 2011 (Infante et al. 2011). In the future, the problem will be solved using a coupled analysis.

In the present study, the shaft resistance of a pile is calculated by using the Contact Modeling option in COMSOL Multiphysics code.

2. Laboratory tests of moisture effect on the soil–pile interface behaviour

In order to investigate this problem, experiments were conducted to determine the changes taking place in load transfer capacity of an interface (contact zone) between a soil mixture and a steel plate representing the surface of the pile shaft (Fu et al. 2012). In the numerical analysis, the soil mass and the “contact zone” between the soil and the pile need to have mechanical properties specified as a function of soil moisture content. The test data given in Table 1 show the effect of variation in moisture content (w) on the interface friction angle and adhesion between a soil mixture and a steel plate. The test data also include the friction angle and cohesion of a soil mixture with different moisture contents as shown in Table 2.

Table 1. Effect of moisture content on interface friction angle and adhesion.

Moisture content	Interface Friction angle (δ)(°)	Adhesion (f_2) (kPa)
w=10%	25.1	10.6
w=15%	26.5	11.5
w=17.5%	28.3	13.9
w=21.5%	27.2	12.3

Table 2. Effect of moisture content on soil mixture friction angle and cohesion.

Moisture content	Friction angle (φ)(°)	cohesion (f_1) (kPa)
w=10%	27.6	12.4
w=15%	28.4	13.1
w=17.5%	33.8	16.8
w=21.5%	29.4	15.1

From these two tables, it can be seen that the peak strength parameters of the soil-steel interface were lower than those of the soil-on-soil. This finding is significant to design the energy piles since it will mean that in the case of smooth steel interface, the shear strength parameters of soil-on-soil should not be used as those of the soil-pile interface.

3. Shaft Resistance of a Pile – Conventional Calculation and Numerical Analysis

In geotechnical engineering practice, the shaft resistance of a pile is determined using Equation 1. (Das, 2002)

$$Q_S = \Sigma\, r_s\, p\, \Delta L \qquad [1]$$

Where Q_S = the shaft resistance.
p = perimeter of the cross section of the pile.
ΔL = incremental length of the pile.
r_s= adhesion and frictional component of unit shaft resistance

The frictional component (f) of the unit shaft resistance is determined by Equation [2]

$$f = K\, \sigma'_v\, \tan\delta \qquad [2]$$

where K= effective earth pressure coefficient,
σ'_v = effective vertical stress at the depth under consideration and δ = the interface friction angle.

These equations are used to determine the effect of variations in the soil moisture content on the shaft resistance of a bored pile. It is assumed that the pile is 10 meters long with a 0.6 meters diameter. It is also assumed that this energy pile is installed in a soil deposit with identical properties as the kaolin-sand mixture tested in the laboratory investigation. The shaft resistance of this pile is calculated using the conventional method (Eq. 1) for moisture contents listed in Table 1. Figure 4 shows the relationship between the moisture contents and the shaft resistance. When the interface has the optimum moisture content (w=17.5 %), the Q_S has the largest value.

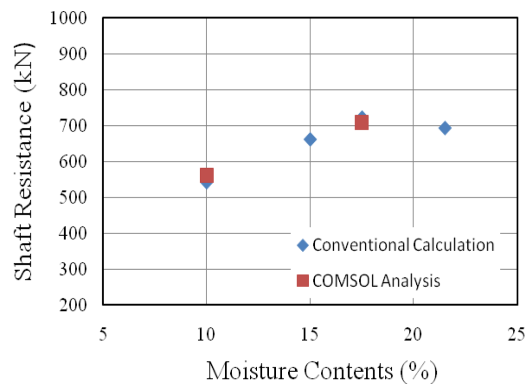

Figure 4. The pile shaft resistance versus moisture contents

The steps followed in the finite element analysis of the present study are explained below.

A single pile shown in Figure 5 is divided into a convenient number of sections. In the analysis of this pile, each section was 1 m high and the total number of sections was ten.

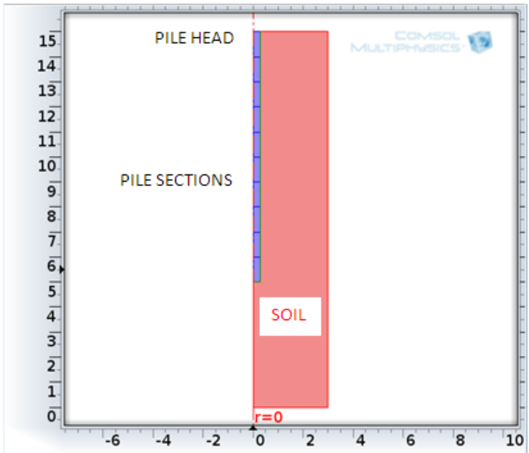

Figure 5. Pile sections

These sections are subjected to a different magnitude of lateral earth pressure, which depends on the location of a pile section from the ground surface and the method of pile installation. In the analysis, the interaction between a pile section and the soil is treated as a contact mechanics problem. The contribution of each pile section to the shaft resistance of the entire pile was determined by analyzing each section separately.

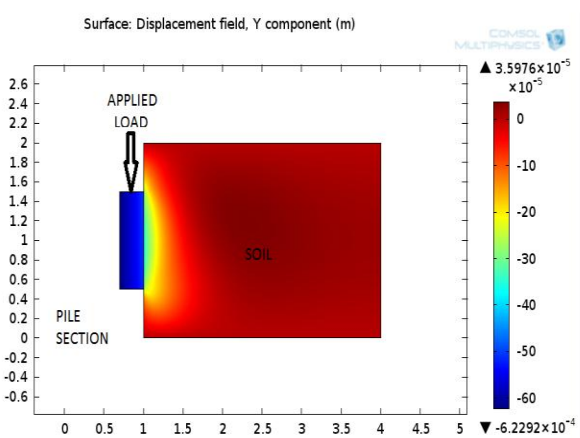

Figure 6. Shaft resistance (32373 N) versus vertical displacement of one of the pile sections.

The analysis requires the elastic modulus of the soil at the depth where the pile section under consideration is located, the interface strength parameters and the soil strength parameters. The elastic modulus of soil is assumed to be a function of the stress level. For simplicity, Eq. 3 proposed by Kondner (1963) for the calculation of elastic modulus is used.

$$E = K p_a \left(\frac{\sigma_3}{p_a}\right)^n \qquad [3]$$

Where E is the elastic modulus, *K* and *n* are the model parameters; p_a is the atmospheric pressure; and σ_3 is the minor principal stress.

The interface friction angle and the adhesion are listed in Table 1. It is assumed that the adhesion between soil and pile section is not a function of stress and it has the same value for all pile sections. Therefore, the finite element analysis was conducted only for the frictional resistance of each pile section and the effect of adhesion is added to the shaft resistance subsequently.

The applied load versus the corresponding movement of each pile section is shown in Fig. 7, where the uppermost pile section is labeled as #1, and the deepest section is #10.

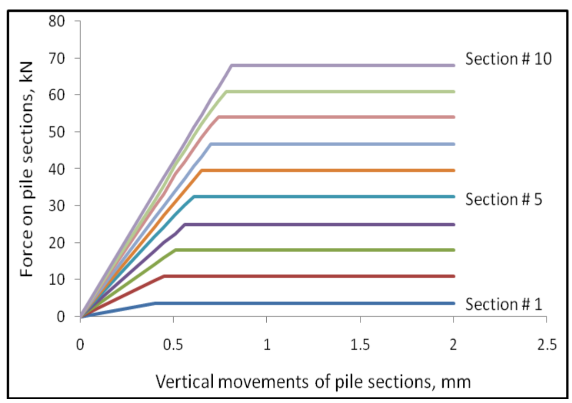

Figure 7. Applied load versus vertical movement of each pile section. (COMSOL results)

The total shaft resistance is the sum of the resistance of all pile sections. The calculation of the total shaft resistance does not require a finite element analysis. The maximum applied load that can be carried by all pile sections can be added together to find the total shaft resistance using Eq. 3. However, if one wants to know the amount of pile shaft movement for a specified load below the total shaft resistance, a curve relating the load carried by the pile shaft to pile shaft movement as shown in Figure 8 would be required. This figure is obtained by adding the load carried by individual pile sections (Fig. 7) for a given pile section movement.

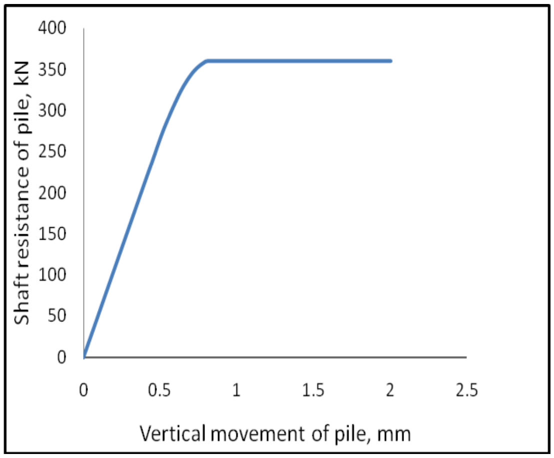

Figure 8. Shaft resistance versus vertical movement of the pile (w=10%) obtained from Figure 7.

The shaft resistance shown in Fig. 8 does not include the effect of the adhesion which would add another 200 kN to the shaft resistance. The shaft resistance calculated by COMSOL compares well with the results of textbook calculations as shown in Figure 4. Using the Contact Modeling approach allows the pile head displacements to be calculated.

4. Conclusions

- The shaft resistance of an energy pile can be calculated using the Contact Modeling capabilities of COMSOL Multiphysics code.
- The vertical movements of a pile head as a function of load carried by the pile shaft can be determined for various soil moisture contents using the procedures described in this paper.
- Because the soil moisture content can be affected by temperature changes in the soil, the working model described in this paper can readily be used in the analysis of energy piles.

5. Recommendations

- The procedure needs to be extended to include the toe resistance of the energy pile.
- The effects of interactions among the pile sections need to be determined.
- The calculation of the soil elastic modulus should be improved to include the effect of stress level.

6. References

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