

Structural Behaviour of Concrete Energy Piles in Thermal Loadings

E. H. N. Gashti, M. Malaska, K. Kujala

Abstract—The thermo-mechanical behaviour of concrete energy pile foundations with different single and double U-tube shapes incorporated was analysed using the Comsol Multi-physics package. For the analysis, a 3D numerical model in real scale of the concrete pile and surrounding soil was simulated regarding actual operation of ground heat exchangers (GHE) and the surrounding ambient temperature. Based on initial ground temperature profile measured in situ, tube inlet temperature was considered to range from 6°C to 0°C (during the contraction process) over a 30-day period. Extra thermal stresses and deformations were calculated during the simulations and differences arising from the use of two different systems (single-tube and double-tube) were analysed. The results revealed no significant difference for extra thermal stresses at the centre of the pile in either system. However, displacements over the pile length were found to be up to 1.5-fold higher in the double-tube system than the single-tube system.

Keywords—Concrete Energy Piles, Stresses, Displacements, Thermo-mechanical behaviour, Soil-structure interactions.

I. INTRODUCTION

IN addition to their main role of transferring mechanical loads from buildings into the ground, energy pile foundation structures are used for energy production purposes. High energy production prices and global efforts to replace fossil fuels with renewable energy have made this relatively new technology a popular source in heating/cooling systems [1]. When using ground heat exchangers (GHE) as energy production systems in pile foundations; thermal variations in pile shaft and surrounding soil are inevitable. These temperature variations can affect the mechanical behaviour of pile foundations and result in extra thermal stresses and deformations relative to those created by the reference temperature of the system before GHE operation.

The energy pile system is based on absorbing/rejecting heat from/to the ground during winter/summer modes, with the aim of producing heating/cooling energy. During winter time, a heat carrier fluid which is colder than the pile shaft and surrounding soil is inserted via tube inlets into the system. This fluid is able to absorb heat from pile and soil and carry it to tube outlets (Fig. 1). The fluid temperature at the tube outlets is increased by thermal equipment housed inside the

building to reach the standard temperature for normal consumption (e.g. in radiators).

Variations in the mechanical behaviour of pile structures occur as contraction/expansion during winter/summer modes. These opposing processes are caused by injection of heat carrier fluid colder/hotter than the pile shaft and soil during winter/summer. Use of energy pile foundations is of great benefit if pile geotechnical and structural resistance remains within the standard ranges recommended. Despite large numbers of energy pile foundations being installed during recent decades [2], e.g. in Austria (Lainzer Tunnel) [3], Switzerland (Dock at Zurich airport) [4] and Germany (Frankfurt main tower) [5], there are still challenges with this technology. These can be attributed to insufficient knowledge of the thermo-mechanical behaviour of energy pile structures.

This study analysed a concrete energy pile foundation fitted with single and double U-tubes. The 3D numerical model used in the analysis (Comsol Multi-physics package) was based on a real-scale pile shaft and ambient soil and reflected the real operation of GHEs embedded in the pile shaft during winter mode. When modelling thermo-hydro-mechanical behaviour, static thermal loading mode was selected and linear thermo-elastic behaviour was taken into consideration for both pile and soil domains. The contact between pile and soil was assumed to be perfect (without relative movements between domains). Extra thermal stresses and deformations were calculated for both single- and double-tube systems and the main differences between these systems were identified. The findings of the study can be used in the design of energy pile foundations and to prevent overestimated conservative assumptions, such as inclusion of large safety factors.

II. CONCEPTUAL BACKGROUND

Piles with free constraints at head and toe expand/contract in heating/cooling operations, resulting in additional thermal deformations. The degree of pile deformation without the presence of constraints at pile ends and friction at pile-soil interfaces is given by [6]:

$$T_{-Free} = \alpha \cdot \Delta T \quad (1)$$

Considering the real conditions of systems, i.e. including frictional interfaces and restraints at pile heads and toes, actual deformation is given by:

$$T_{-Obs} \leq T_{-Free} \quad (2)$$

$$T_{-Rstr} = T_{-Free} - T_{-Obs} \quad (3)$$

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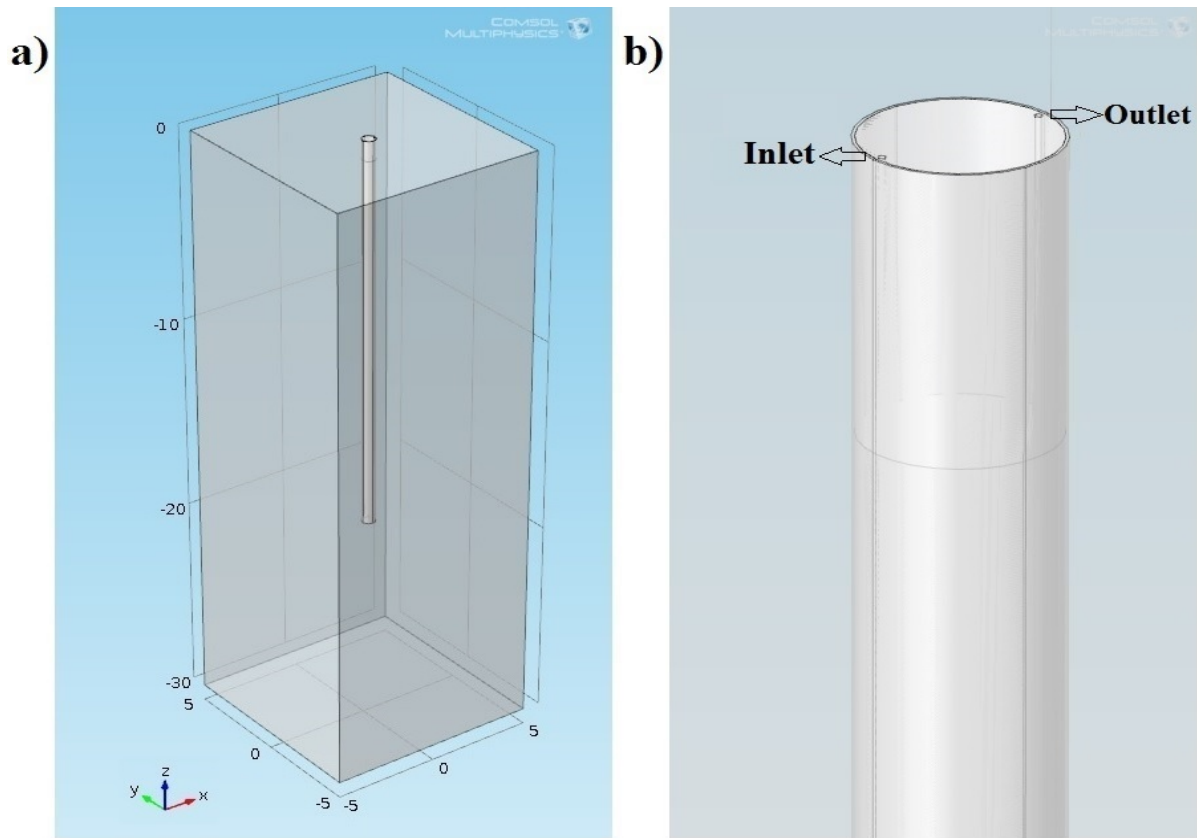


Fig. 1 Energy pile specifications used in numerical modelling (a) Geometry of system, (b) U-tube configuration

Resisted thermal strains result in thermal stresses, as a result of which pile axial thermal force is calculated as:

$$P_T = -EA_{T-Rstr} \quad (4)$$

III. MODEL DESCRIPTION

A circular concrete pile foundation of 20 m length and 60 cm diameter and with two different configurations of GHE (single-tube and double-tube) incorporated was selected as the study object. The distance between adjacent energy piles was assumed to be 10 m to prevent overlapping thermal effects. Hence, the lateral soil domain extension of the model was selected as 10 m x 10 m and soil depth as 30 m ($L + 10$ m) where L is pile length [7]. The diameter of the U-tubes used in the model was taken to be equal to 25 mm and heat carrier fluid rate was set at 0.324 (m^3/h). Physical properties of the heat carrier fluid corresponding to those of water were selected. The soil was assumed to have the thermo-mechanical properties of soft clay, while thermo-mechanical data on concrete were extracted from the software library [8], [9]. The thermo-mechanical properties of materials used in the model are shown in Table I.

The software used for model simulations in thermo-hydro-mechanical analysis is able to calculate simultaneously heat transfer from heat carrier fluid to pile shaft and surrounding soil and the mechanical behaviour of domains. Unsteady state

simulation with static thermal loading for the heat carrier fluid at tube inlets was selected. The temperature of the fluid at tube inlets was varied linearly from 6°C to 0°C over a 30-day period. A temperature above 0°C was chosen to prevent soil freezing effects on the system, while the initial value of 6°C was selected based on an initial ground temperature profile measured in situ (Finnish environment). The thermal regime around the pile shaft at the beginning and end of the simulation in winter mode are shown in Fig. 2. As can be seen from the figure, the soil domain extension was wide enough to prevent thermal overlap effects between piles. For thermal boundary conditions, the vertical surfaces of the soil domain were assumed to be adiabatic, while mean monthly temperature was used for the upper surface and constant temperature for the bottom surface.

TABLE I
THERMO-MECHANICAL PROPERTIES OF MATERIALS USED IN THE MODEL

Thermo-mechanical properties	Materials	
	Soft clay	Concrete
Density (kg/m^3)	1812	2400
Heat capacity ($\text{J}/\text{kg K}$)	1845	880
Thermal conductivity ($\text{W}/\text{m K}$)	1.1	1.8
Young's modulus (MPa)	15	32e3
Shear modulus (MPa)	5.62	12e3
Coefficient of thermal expansion ($1/\text{K}$)	5e-6	1e-5
Poisson's ratio	0.33	0.33

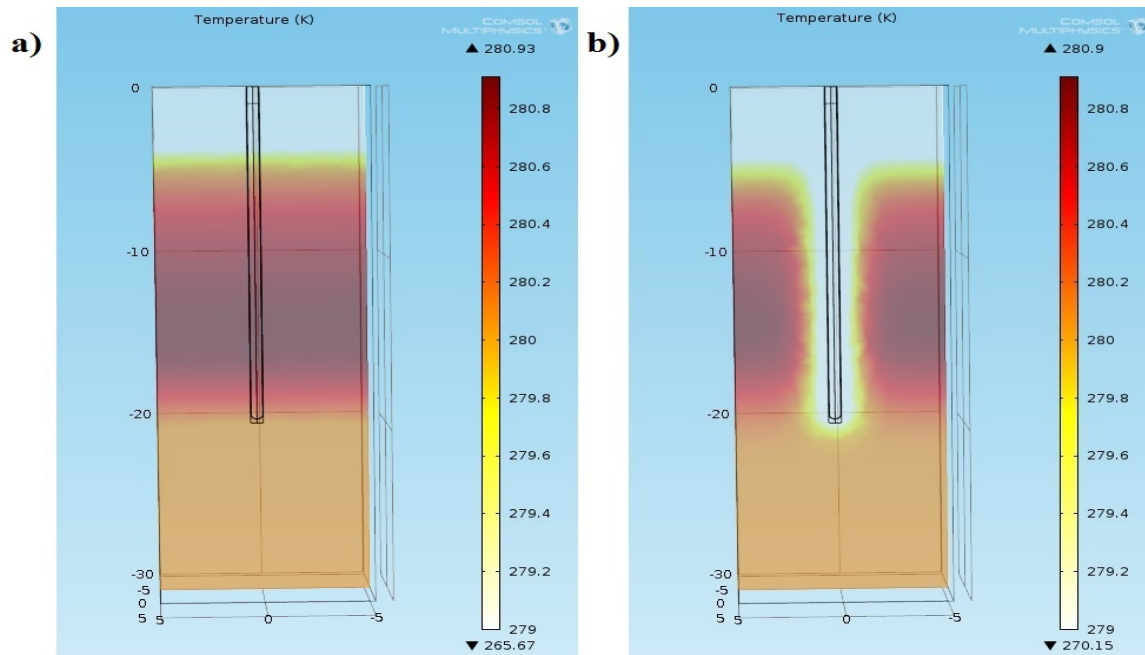


Fig. 2 Thermal regime around the pile shaft during winter mode (a) At the beginning of simulation (reference temperature), (b) at the end of simulation (day 30) (Unit K)

Homogeneous isotropic linear thermo-elastic behaviour at both soil and pile domains was assumed in model simulations. The perfect contact conditions selected for the pile-soil interface meant that possible relative movement between pile and soil was precluded. Owing to the symmetry of the model, the constraints selected for the soil domain were rolling for vertical surfaces, fixed for the bottom surface and free constraint for the upper surface. The pile was assumed to be fixed at the head due to its connection with the superstructure and free at the toe owing to the contraction process (winter mode – no resistance in front of upward pile movement).

IV. RESULTS AND DISCUSSION

For design purposes, piles with fully free and fixed constraints at head and toe are normally considered in analyses. In reality, however, pile behaviour is somewhere between fully free and fixed constraint conditions [10]. In this study, owing to pile performance during winter mode (contraction process) and the rigid connection between pile head and superstructure, as a conservative assumption fully fixed constraint at head and free at toe were selected for the analysis.

A. Thermal Stresses

Maximum thermal stresses generated over the pile length at different points of the pile cross-section for single and double U-tube shapes are shown in Fig. 3, where a positive sign denotes tensile stress and a negative sign compressive stress. The thermal stresses generated beside the tube inlet for both single- and double-tube shapes were much larger than the stresses at the pile centre (Fig. 3). This behaviour resulted from higher thermal concentration in the vicinity of U-tubes

than at the centre of the pile, as reported previously by Gashti et al. [1].

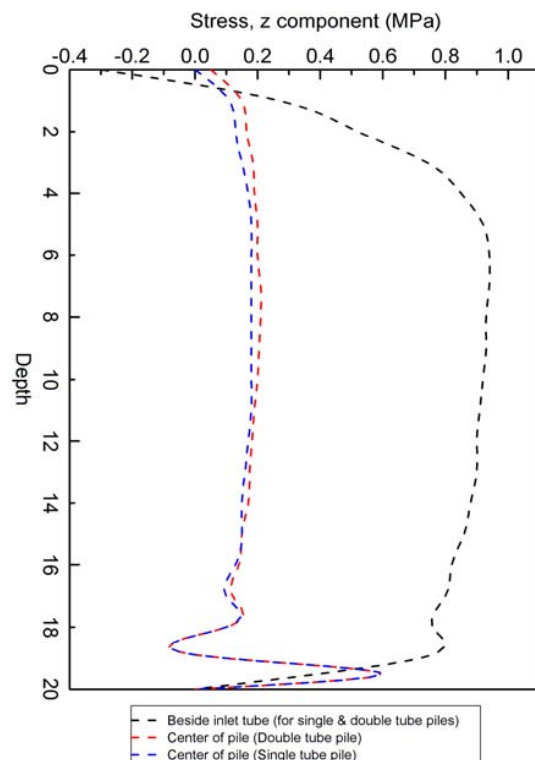


Fig. 3 Maximum thermal stress (MPa) generated over the pile length in the contraction process on day 30 of simulation

It was further apparent that the thermal stresses generated at the pile centre were slightly larger for the double-tube pile than the single-tube pile. However, the difference was not statistically significant and thus should not be considered in a design context. Sudden stress fluctuations around the pile toe were due to rapid changes in the pile temperature profile in this zone. These changes resulted from U-curve effects at the end of the pile, which were able to generate high fluctuations in the temperature profile in this area. Maximum tensile stress in the vicinity of inlet tubes occurred at around 6 m depth and reached a value of 1 MPa, while that at the pile centre was found to be around 0.2 MPa. It should be noted that these stresses are relative to the strain reference temperature at the beginning of simulation as shown in Fig. 2 (a). As can be seen in Fig. 2, the average temperature difference between pile shaft at day 30 and reference temperature at the beginning of simulation was around 6°C.

B. Displacements

Piles with heating/cooling operations expand/contract and result in additional thermal displacements. Fig. 4 shows these displacements for winter mode pile operation on days 10, 20 and 30 of simulation. Displacements with a positive sign denote upward movement and those with a negative sign denote downward movement. Owing to the fixed constraint at the head of the pile due to the rigid connection between pile and superstructure, no movement was observed at this point for either single or double U-tube shapes (Fig. 4). The null-point (point with zero displacement) position was very similar for the single and double U-tube shapes.

With the decrease in fluid temperature at the tube inlet over time, pile displacement was observed to increase over the simulation. Maximum displacement was found to occur at the pile toe and was around 0.55 mm and 0.75 mm for single and double U-tube shapes, respectively, a 1.5-fold difference.

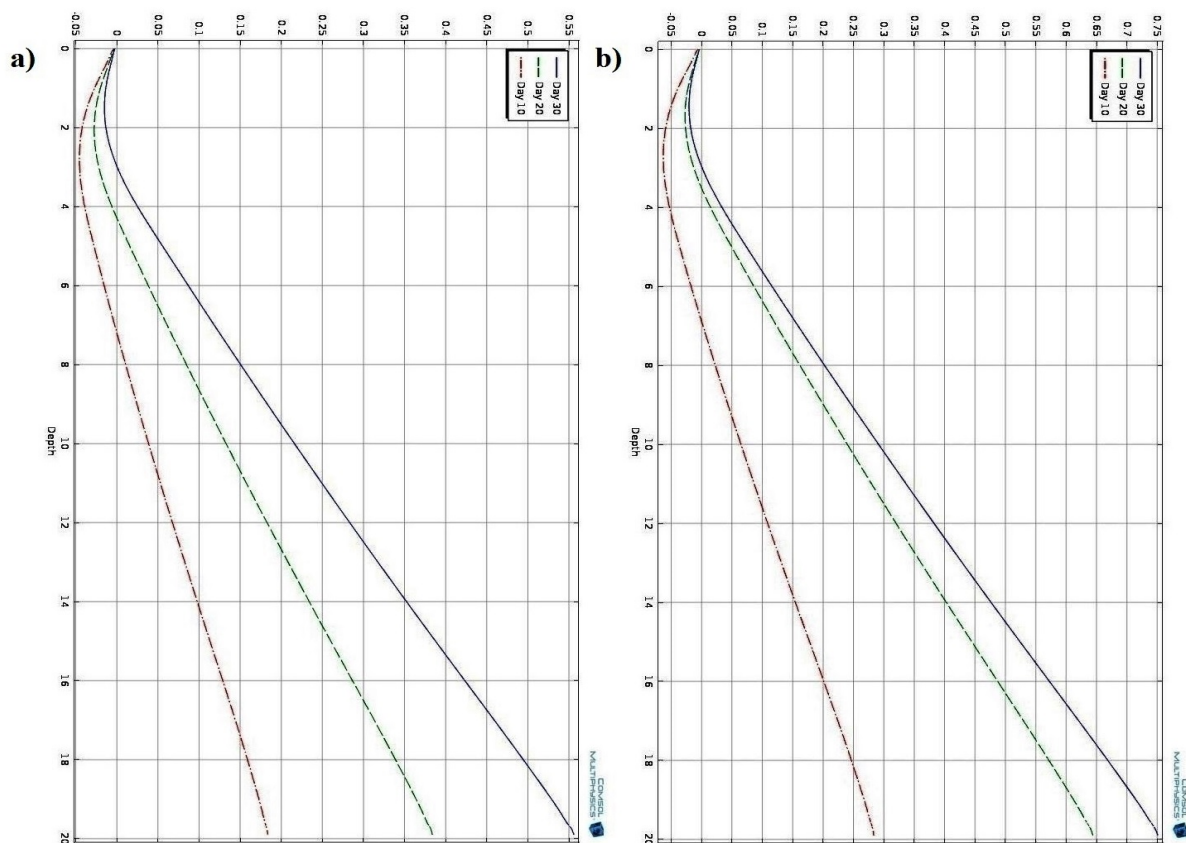


Fig. 4 Displacements (mm) over the pile length on days 10, 20 and 30 of simulation a) Single tube, b) double tube

V. CONCLUSIONS

Energy pile foundations, dual-purpose structures playing a role in energy production systems and building foundations, have become a popular new technology recently. Since such energy production structures can result in temperature changes in pile and soil domains and therefore generate extra thermal stresses and deformations, studies on potential pile failure in

both geotechnical and structural aspects are essential. This study used a three-dimensional model to analyse different configurations of U-tubes embedded in energy piles. In a concrete pile 60 cm in diameter, two different shapes of U-tubes (single-tube and double-tube) were simulated and analysed for significant differences. From the observations, the following major conclusions were drawn:

1. There was no significant difference in the thermal stresses generated by two different shapes of U-tube (single and double tubes). Thus when calculating the extra thermal stresses in energy piles, the results obtained for single-tube systems can be extended to double-tube systems.
2. Maximum displacement occurred at the pile toe and was 1.5-fold higher in the double U-tube system than in the single-tube system. Thus for structures prone to settling, more attention must be paid to calculating the displacement of double U-tube systems.
3. For single and double U-tube shapes, there was no significant difference in the null-point position over the pile length. However, the null-point position tended to be slightly higher in the double U-tube system than in the single-tube system.

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