Thermo-mechanics behaviour of energy pile subjected by monotonic thermal loading

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Abstract:

The mechanics behaviour of an energy pile subjected to monotonic thermal loading is analyzed in this study by using finite difference method. A model of perfectly elastic energy pile surrounded in elastic soil mass is proposed to observe the influence of thermal diffusion in transient time operation. The results provide that thermal dilatations obtained in the system with delta temperature 10°C give slightly addition to elastic stresses. The horizontal area influenced by thermal diffusion is inferior to 30 times diameter of pile. Two heuristic examples in elastic perfectly plastic condition are studied to compare the effect of interface soil-structure in steady-state condition. The first example assumes having perfectly contact between soil-energy pile while the second example introduces interfaces between soil-energy pile which allowed sliding and detachment. The interfaces are assumed as purely frictional interfaces with Mohr-Coulomb criteria. It is shown that total deformation of energy pile with interfaces is smaller than those without interfaces that prove the workability of interfaces. The interfaces remain behaving in elastic manner. The failure of energy pile is then predicted when it's subjected to thermally cyclic loading due to its seasonal time operation, which controlled by degradation of interface criteria.

Keywords: Energy pile, shallow geothermal energy, heat transfer, thermo-mechanic, interface

1 Introduction

Energy piles are an integration of heat exchanger pipes with structural pile foundations. They aim to be bi-function foundations, to support static load of building as well as serve the building with thermal needs. They extract shallow geothermal energy in ground soil and transmit the heat via heat exchanger pipes which embedded on them. Heat exchanger pipes are connected to heat pump in order to produce thermal energy required for the building. The process of heat transfer from ground soil to the building is based on delta temperature in each circuit with energy conservation equilibrium.

U-shaped pipes were employed from the viewpoint of economic efficiency and workability as the best type of heat exchanger pipes for energy piles [1]. A heat carrier fluid as heat transfer medium is circulated inside the heat exchanger pipes to avoid the freezing at the inclination angle [2]. Brandl (2006) stated that glycol–water mixtures have proved as the most suitable one [3].

The energy piles can load and unload the seasonal storage which means that they work in seasonal time operation. In winter geothermal energy can be withdrawn to warm the building, thus a cooling of the ground arises. In summer the cooled down ground can be used for cooling the building through the ceilings [4]. This seasonal time operation has advantage to keep the energy balance. From the study of Frankfurt Main Tower application, Quick (2005) concluded that to work in seasonal operation system, energy piles are required a very low or zero groundwater flow in saturated soil so that heat convection and vapour diffusion are negligibly small [4].

Due to their bi-function and no need to be constructed separately, energy piles system reduces significantly cost installation and land use. This method provides also an excellent means of reducing CO_2 emissions and can greatly assist in meeting renewable energy targets required as part of building regulation [5].

Certain studies and applications have been developed in last decade, such as: Main Tower in Frankfurt-Germany (1999), Keble College in Oxford-UK (2001), Dock Midfield Zurich Terminal Airport-Switzerland (2003), Lainzer Tunnel Vienna-Austria (2004), etc. The problems concerned of the energy piles application take place at the response of soil and pile under thermally loading during their time operation and its impact to the design capacity of energy piles and structures above.

The field experiment at Laboratory of soil mechanics at EPFL Switzerland resulted that the soil behaves in elastic manner when the temperature variations are in the order of 20°, but starts behaving in a plastic way beyond this range [6]. The pile behaves in contraction during winter operation time (cooling piles) so that heating piles in summer operation time create pile dilatation [7]. It is also pointed out that the thermal loading may induce pile uplift due to thermal dilatation, additional stress related to thermal stress, and also lateral friction by the change of normal stress [7].

Numerical models are conducted in this study to observe the behaviour of a single energy pile under transient time operation given and until steady state condition. Two heuristic examples are proposed in elastic perfectly plastic condition to study the effect of interfaces between soil and energy pile. The interfaces assume to behave in purely frictional condition with Mohr-Coulomb criteria.

2 Theoretical Background

2.1 Thermal Properties

Burger et al. (1984) stated that until the depth 10 meter below surface, external temperature and radiation affect mostly soil temperature. Temperature varies in time and depth as function $T(z, t)$: where $T(t)$ is subjected to thermal cycle loads in annual external temperature, and $T(z)$ is leaded by conduction and convection waves' propagation [8]. The function of temperature forms a sinusoidal wave, as following equation:

$$T(z, t) = T_{ave} + A_o e^{-\frac{z}{d}} \left[sin \left(\omega t - \frac{z}{d} \right) \right].$$ (1)

where T_{ave} is the average annual soil temperature, A_o is maximum annual amplitude, z is the depth in which temperature is investigated, d is the damping depth of annual fluctuation, and ω is the annual radial frequency.

At depth 50 m below the surface, temperature is no longer influenced by external thermal flux and no longer varies by annual sinusoidal waves. This zone is where the internal terrestrial flux or deep geothermal source energy takes place, defined as $\vec{q} = 0,0544 \ W/m^2$. Temperature increases regularly in depth with geothermal gradient 1-3°C / 100 m [9].

2.2 Energy Conservation

Conservation of energy in energy piles system is categorized by soil's saturation degree and the presence of groundwater flow. The seasonal operation system assumes that only conduction heat transfer occurs, which governed by the 2nd thermodynamics law as below:

$$C_v \frac{\partial T}{\partial t} = div \ [\lambda \ grad \ T]$$ (2)

where C_v is heat capacity of soil $(J/m^3 °C)$, λ is thermal conductivity $(W/m°C)$, T is temperature $(°C)$, and t is time (s) .

2.3 Thermo-mechanics behaviour

The change of temperature both in concrete pile and soil will produce thermal dilatation that will modify the deformation of material. The value of thermal dilatation ε^{th} depends strongly on thermal expansion coefficient α, as following equation:

$$\varepsilon^{th} = \alpha \Delta T. \tag{3}$$

At thermo perfectly elastic condition, the total deformation ε obtained is then a sum of elastic deformation ε^e due to static load and the thermal dilatation ε^{th} caused by thermal load. This change of deformation induces additional normal stress which will modify also the shear stress between soil and pile. The normal stress σ_n is governed by linear product of elasticity modulus and elastic deformation:

$$\sigma_n = E\varepsilon^e = E\left(\varepsilon - \varepsilon^{th}\right). \tag{4}$$

3 Application to a single energy pile

Numerical models are conducted in perfectly elastic condition to observe the effect of thermal diffusion in transient time operation given and in elastic perfectly plastic condition to study the effect of interface soil-structure at steady state condition. Two heuristic examples are proposed to compare the behavior of energy pile with and without soil-pile interfaces. All models are subjected by monotonic thermal loading by using finite difference code FLAC 3D.

TAB. 1 – Thermal Properties [10]

		Soil	Concrete
Thermal conductivity	W/m^2	1.5	1.8
Specific heat extraction	J/kg °C	800	880
Coefficient of thermal expansion	J/°C	5x10^{-6}	1x10^{-5}
Bulk modulus	MPa	20	20000
Shear modulus	MPa	7.5	7500
Density	Pa	1950	2500

The problem under study concerns a single energy pile with diameter 60 cm and length 10 m, resting in a homogeneous soil mass. The horizontal and vertical limits of the soil mass are fixed with radius horizontal and depth 20 m in order to avoid mechanical and thermal disturbances due to limit conditions. The presence of groundwater flow is neglected, in assuming that energy pile is located in fully-saturated soil. Average ground temperature is defined as 14°C. The soil has internal terrestrial heat volume r as 0,001 W/m^3 and terrestrial surface flux $\vec{q}$ at depth 20 m as 0,0544 W/m^2. Seasonal surface temperature affects the propagation of temperature in depth until 10 m below the surface. According to that fluctuation, we set seasonal heat-carrier fluid temperature inside the pile for producing thermal energy required. In this numerical approach, temperature along the pile is assumed to be homogeneous though it varies with the season: for winter mode operation the inlet temperature is set on 4°C, and for summer mode operation is 22°C. The thermal properties of each material are summarized in Table 1.

3.1 Effect of thermal diffusion in transient time operation

We observe the influence of monotonic thermal loads during six months time operation. There is no static load applied in the pile and the heat temperature diffuses in the range of 10°C. The results show that the pile behaves in contraction during the cooling pile (winter) and in dilatation during the heating pile (summer) which in accordance to the precedent research works as mentioned in literatures. Therefore, cooling pile operation causes downward displacement in pile head so that the soil has downward settlement. In heating pile operation, head uplift displacement and soil upward settlement occur. Figure 1 shows the evolution of head displacement in time operation which starts to increase and decrease at 10^6 second (1 day) of cooling/heating loads.

By the increment of time operation, settlement at soil surface raises and stays steady since radius 16 m as shown at Figure 2. It concludes that the horizontal area influenced by thermal diffusion is inferior to 30 times diameter of pile.

Figure 3 shows that the thermal dilatations obtained are in the range ± 1 mm and the values increase about 0,2 mm from 1 day thermal loading to 1 season thermal loading. Referring to this condition, thermal stresses along the pile at final operation time is about ± 10 kPa and change a little amount to the initial elastic stresses as shown at Figure 4.
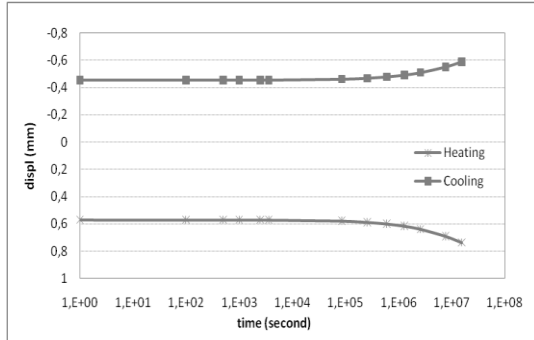
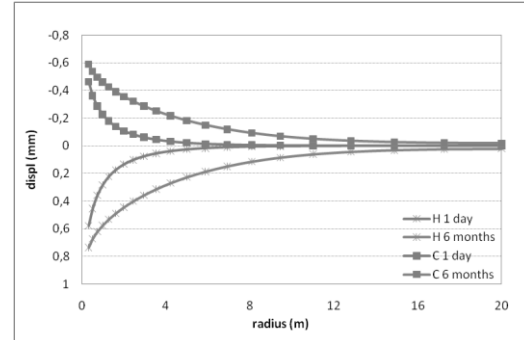FIG. 1 – Evolution of uplift displacement in thermal loading

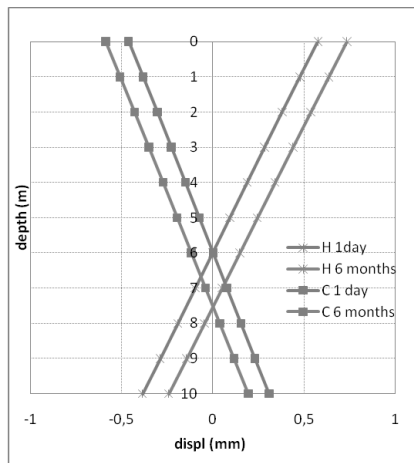FIG. 2 – Evolution of surface settlement in thermal loading

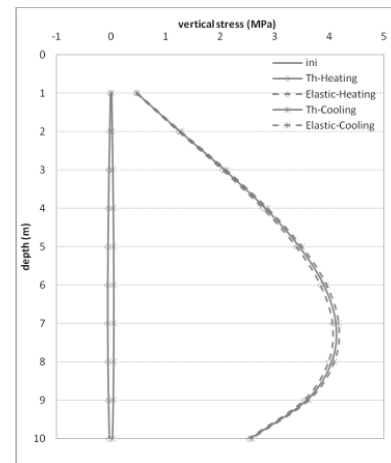FIG. 3 – Evolution of pile displacement in thermal loading

FIG. 4 – Axial stress of energy pile in 6 months thermal loading

3.2 Effect of interface in steady-state condition

Since the response of piles to vertical loads strongly depends on the friction at the soil-pile interface, it is of major interest to take into consideration the interface condition in the analysis of the behaviour of energy piles under thermal loads.

Two heuristic examples are conducted to study the effect of interface between soil and energy pile. The first example assumes having perfectly contact between soil-energy pile while the second example introduces interfaces between soil-energy pile.

Analysis of interface behaviour is carried out in classical frictional model governed by the Mohr-Coulomb criteria :

$$|\tau| = \sigma_n \, tan \, \varphi_i + c_i, \tag{5}$$

where τ and σ_n denote the shear and normal stress at the interface, respectively ϕ_i and c_i are the friction angle of interface and cohesion factor at interface. In this case study, the interfaces behave in purely frictional condition, with frictional interface angle $\varphi_i = 30°$ which is equal to the friction angle of the soil. The interfaces properties are shown in Table 2.

Three interfaces are applied around the energy pile: two vertical interfaces at plane XY (interface 1) and plane YZ (interface 2) and one horizontal interface in the bottom of pile at

plane XZ (interface 3) as can be seen at Figure 5. Vertical interfaces are only able to slide but horizontal interface is assumed to support detachment. In this study case, the monotonic thermal loading is applied only in cooling pile operation. It is subjected to energy pile until the system reaches steady-state condition.

There are difference vertical displacements obtained if we consider the presence of interface: the values become smaller 1 mm that proves that the system structure is more bound (Figure 6). The workability of interface has increased the stiffness of joint structure. The tangential displacement at vertical interfaces is shown at Figure 7. The results show that the vertical displacement between pile and soil which has interfaces between them is slightly different due to purely frictional condition of interfaces.

The interfaces remain behaving in elastic condition because the shear stresses obtained are smaller than the maximum shear stresses as shown at Figure 8. This is due to high value of normal and shear stiffness of interfaces. For the further study, it should be considered the value of interface parameters to obtain the results more proper.

TAB. 2 – Properties of Interfaces : Mohr Coulomb Criteria

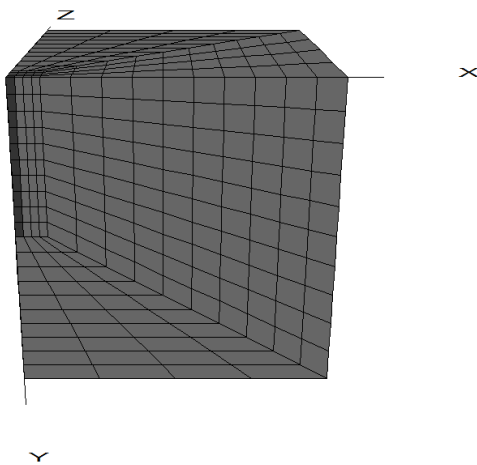|		Soil	Interface 1	Interface 2	Interface 3
Normal stiffness (kn)	MN/m^3	-	22	22	22
Shear stiffness (kt)	MN/m^3	-	8,33	8,33	8,33
Cohesion (c)	kPa	20	1	1	-
Friction angle (ϕ)	°	30	30	30	-

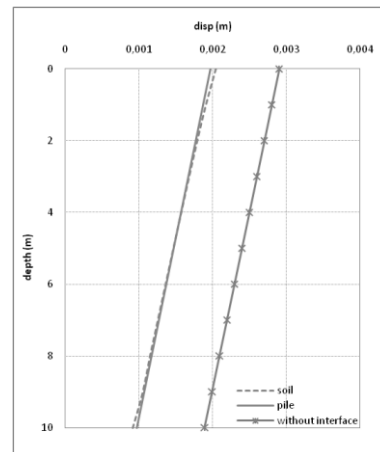FIG. 5 – Cross section of model

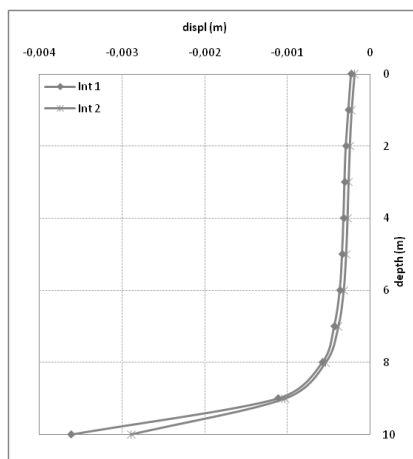FIG. 6 – Comparison of vertical displacement with/without interface
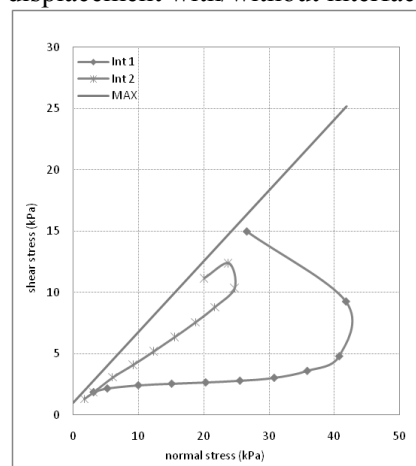

FIG. 7 – Tangential displacement at interfaces

FIG. 8 – σ_n vs τ Curve

4 Conclusions

Energy piles are bi-function foundations which support the load of structure and serve thermal energy to the building as heat exchangers. They extract the heat from shallow geothermal energy, and then reject it back for the balance energy system. Their utilisation of renewable energy in thermal building system provides an innovative eco-friendly building technology. Energy piles can work in two system operations: only cooling/heating operation system for tropical or glacial countries, and the seasonal cooling-heating operation system for four-season countries. The former one tends to not reach balance energy thus it needs combination with solar panel system [11], and the later one is the favourable for its automatic balance energy.

Numerical models of a single energy pile have done to analyze its mechanics behaviour subjected by monotonic thermal loading by using finite difference code FLAC3D. Two cases are proposed: thermo perfectly elastic analysis in transient time operation and thermo elastic perfectly plastic analysis until the system reaches steady-state condition. The effect of the presence of interface is observed with purely frictional interfaces condition governed by Mohr-Coulomb criteria. The study analyzes two heuristic examples: an energy pile with perfectly contact and with interfaces between soil-structure. The monotonic thermal loading gives slightly addition to elastic stress of material in the range of temperature diffusion 10°C. The behaviour of interfaces under monotonic thermal loading also remains in elastic due to purely frictional interfaces condition with high stiffness.

In energy balance's point of view, seasonal operation system is the most favourable one. However if we look from the point of view of mechanics durability, the pile will be subjected with repeated thermal loads cooling and heating during annual operation time. This phenomenon occurs alternately at transient condition that will provoke the degradation of mechanics behaviour, especially the failure at interface plane.

Further study should be conducted in thermally cyclic loading that occurs in seasonal mode operation. Our final goal is to determine the interface failure between soil-structure due to cyclic solicitation in thermal regime. Shahrour and Fezaie (1997) have introduced a constitutive law for the interface soil-structure under mechanical cyclic loading. We aim to adopt this constitutive law to thermal regime by simulating some numerical model and applying some field experimental test.

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