Thermo-Mechanical Response of Energy Pile in Dry Sand

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Abstract. One of the major challenges for development is to manage the energy demand and supply nexus. Rising demand of fossil fuel produces the green- house gases at higher rate, which causes a significant change in the climatic condition. Nowadays, air conditioning of superstructure demand significant amount of carbon related energy sources, which are harmful and non- renewable. In this regard, geothermal energy pile can be utilized as renewable energy for air conditioning of building as worthy of investment and develop- ment. This novel concept can be used to exploitable thermal energy at shallow depth of earth and reduce the carbon emission to atmosphere. Therefore, in this study the thermo-mechanical response of concrete pile having fluid-carrying pipe has been analyzed by finite element method through thermal and mechani- cal loading. The effect of thermal cycle on pile, temperature distribution in sur- rounding soil, displacement of pile head and toe are studied. The results showed that displacement of pile followed the temperature variation. Moreover, geo- thermal energy piles when heated show more displacement than piles subjected to only mechanical loading.

Keywords: Geothermal Energy Pile; Thermo-mechanical Response; Finite Element Simulation; Temperature Cycle.

1 Introduction

The major challenge for the upcoming generation is to fulfil the energy demand. At present, major stake of energy is produced by the fossil fuel, which is depleting with an alarming rate. Therefore, searching for the new source of energy is necessary to fulfil the energy demand in future. Various researchers are continuously exploring the renewable energy source (i.e.- solar energy, wind energy and geothermal energy pile etc). Among these renewable energy sources, geothermal energy pile is sustainable energy source, which is extracted energy from the shallow depth of earth. Various countries are adopting geothermal energy pile as a sustainable energy source such as-UK, Indonesia, Canada, etc. [1]. Geothermal energy pile can extract energy from the earth for decades without shrinking like fossil fuel [2, 3]. Therefore, utilization of geothermal energy pile can be a cost-effective method and also reduce the consumption of energy demand as compare to standard method [4]. Apart from that, it also reduces the carbon and greenhouse gases emission to environment which is emitted due to use of fossil fuels [1, 2].

From few decades, several researchers have explored the various studies to under- stand the thermo-mechanical response of surrounding soil by utilization of geothermalenergy pile [1, 4–7]. Laloui et al., [5] have conducted the experimental and numerical study on concrete energy pile to calculate the increased load on pile due to thermal stress. Saggu and Chakraborty [7] have conducted the numerical study on different L/d ratio of pile and different relative density of soil. It is observed that negative shearstress generates for high L/d ratio and lower relative density. Faizal et al., [8] have used the graphite and steel fiber in concrete to enhance the heat transfer between con- crete pile and surrounding soil. Arundhuti et al., [4] have used offshore monopile foundation as energy pile to extract heat and observed that high negative shear stressis generated for floating pile with pile head free during heating. Sani and Singh [3] have observed that heat transfer capacity increases with increase in water content of surrounding dry sand. Furthermore, experimental studies conducted to analyze the thermo-mechanical response of geothermal energy pile against temperature cycle [9– 11]. Adinolfi et al., [12] have conducted the thermo-mechanical behavior of energy pile at underground railway site. It is observed that during cooling contraction takes place and axial load is decreased. Inversely, during heating expansion takes place and axial load is increased.

In India, generation and demand of energy is increasing rapidly day by day, which is mainly fulfil by the fossil fuel. However, utilization of energy pile is not fully developed in India, whether several countries like UK, Canada, and Indonesia etc. are utilizing energy pile to extract energy from earth crust. Therefore, in this study, the thermo-mechanical response of geothermal energy pile has been analyzed, which is embedded in Indian dry sand. With this in view, numerical study has been carried out using finite element method software COMSOL Multiphysics under thermal and mechanical loading condition on single floating pile embedded in Indian dry sand. The deformation characteristics of geothermal energy pile have been simulated at different L/d ratio against thermo-mechanical loading. Moreover, shear stress is also analyzed at soil pile interface due to thermal loading.

2 Material and Methodology

A 2-D axisymmetric model of geothermal energy pile has been simulated using FEM software COMSOL Multiphysics. A single floating pile was embedded in Indian standard sand and a U-tube heat exchanger was installed within the pile. The response of different L/d ratio (i.e.- 10, 15 & 20) has been analyzed for thermo-mechanical response of single energy pile embedded in dry sand. In this paper, a concrete pile was considered, which installed in sand. Geometry of pile and surrounding soil was modelled separately and perfect contact was assumed between pile and sand. The pile was experienced with compressive load of 1000kN at pile head. The pile and surrounding sand were modelled as the linearly elastic material. As a mechanical boundary condition, top, bottom and side edge of model was taken as free, fixed and roller respectively. Therefore, bottom edge was constrained in horizontal and vertical direction, whether edges side was constrained in horizontal direction and free to move in vertical direction. Along with thermal boundary condition, heat flux was considered as zero along the sides of the model. The initial ground temperature was assumed as15 ºC [5]. Thermal load has been exerted uniformly along the entire length of energy pile as a temperature boundary condition for the period of 28 days, in which 12 daysis for heating phase and remaining for cooling phase [5]. Furthermore, thermo- mechanical properties of dry sand was adopted from Mondal et al., [13] and elastic modulus and poisson ratio of dry sand was adopted from Hegde and Sitaram [14]. Theproperties of concrete as pile material was adopted from Saggu and Chakraborty [15]. The properties of materials are listed in Table 1. Moreover, fig. 1 shows the typical finite element meshing of pile and surrounding sand with three nodded triangular elements. Piles were 10, 15 and 20m in length with 1 m dimeter. Far field boundary ofsurrounding soil in radial direction was 6.5m from the edge of pile. Bottom far field was placed at a distance of one pile length from the toe of pile [15].

Table 1. Thermo-mechanical property of concrete and sand

Properties	Concrete	Sand
Elastic Modulus (MPa)	$33x10^3$	15
Poison's Ratio	0.2	0.3
Thermal expansion Coefficient (/ºC)	10^{-5}	$1.62x10^{-4}$
Thermal Conductivity (W/m/ºC)	2.1	1.87
Specific Heat Capacity (J/kg/ºC)	800	613.49
Ratio of Specific Heat Capacity	1.56	1.87
Density (kg/m^3)	2500	1630

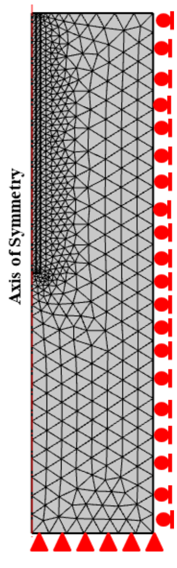

Fig. 1. Mesh of geothermal energy pile

3 Validation of Numerical Modelling

The thermo-mechanical modeling of the geothermal energy piles was validated with the numerical simulation results of the field load test data and the numerical analysis results by Laloui et al. [5]. Laloui et al. [5] in Lausanne, Switzerland subjected a stack to heat stress for 28 days, during which the heating period was applied 12 days followed by 16 days of cooling, as shown in the figure. 2a. The thermal load along thelength of the pile was applied in the order of ΔT=21℃. In this study, the same thermalload was experienced to the pile. The axial compressive load acting on the pile head was 1300 kN. The pile is 26 m long and 1 m in diameter. The energy pile was embedded in a layered soil deposit of alluvial soils, sand and gravel, moraine and molluscs. Laloui et al. [5] numerically simulated a pile loading test in the field using the thermo-elastic-plastic Drucker-Prager model. Thermal and mechanical loading of the pile occurred simultaneously. The Fig. 2b shows the displacement of the pile due to the thermomechanical load.

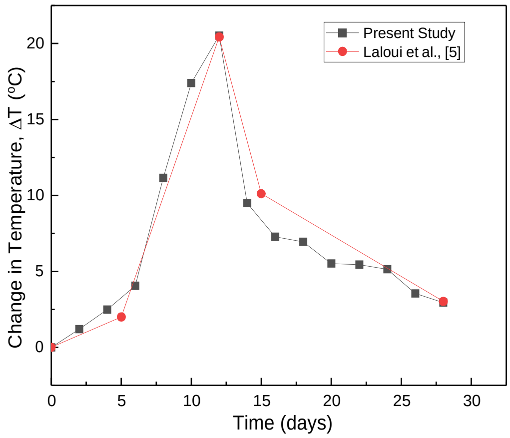

Fig. 2a. Temperature profile of numerical modelling

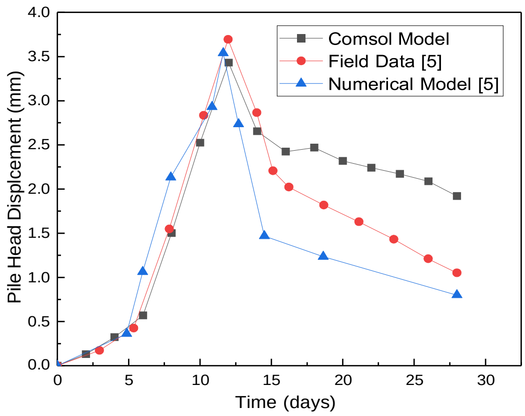

Fig. 2b. Displacement of pile under thermo-mechanical loading.

4 Result and Discussion

In this study, thermo-mechanical response of geothermal energy pile has been analysed using finite element software COMSOL Multiphysics. While numerical modeling, different L/d ratio of pile has also been analysed and nderstand the behaviour of pile against thermo-mechanical loading. Fig. 3 shows the contour image of settlement for different L/d ratio at different loading condition. It is observed that displacement of pile is mainly caused due to mechanical loading. The contour image of geothermal energ pile models are almost similar for mechanical loading, after end of heation and after end of cooling irrespective of L/d ratio. Therefore, thermal loading is not have significant effect on the displacement of pile. It can opined from the fig. 3 that displacement of pile decreases with increase in L/d ratio, which is mainly caused due to higher resistant exhibit by surrounding soil for higher value of L/d ratio. In fig. 3, influence of thermo-mechanical load is more in radial direction as compared to vertical direction. Maximum influence of thermo-mechanical load in radial direction is obtained for L/d ratio equal to 10. Therefore, Maximum displacement is obtained in L/d ratio equal to 10 due less resistance exerted by surrounding soil.

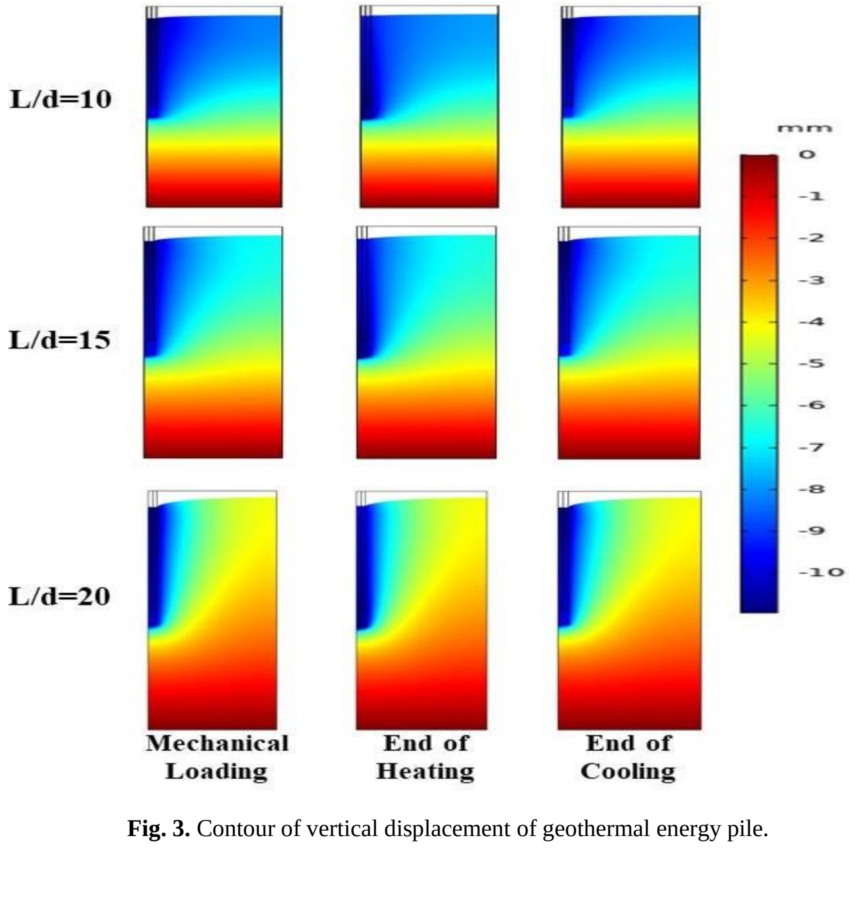

Fig. 3. Contour of vertical displacement of geothermal energy pile.

Vertical displacement of surrounding soil in radial direction has also been investigated for different L/d ratio against thermo-mechanical loading. Fig. 4 depicts the vertical displacement of surrounding soil. From the fig. 4 it can be opined that the displacement of surrounding soil is decreased with increase in the distance from pile. Displacement of surrounding soil is obtained maximum near the pile surface, because the influence of thermo-mechanical load. When heating starts, displacement of surrounding soil starts decreasing due to thermal expansion of soil. It again decreases when cooling phase start due to thermal contraction. However, near the outer surface of surrounding soil displacement of sand is almost similar for throughout the simula- tion period due to negligible effect of thermo-mechanical loading at outer surface of soil.

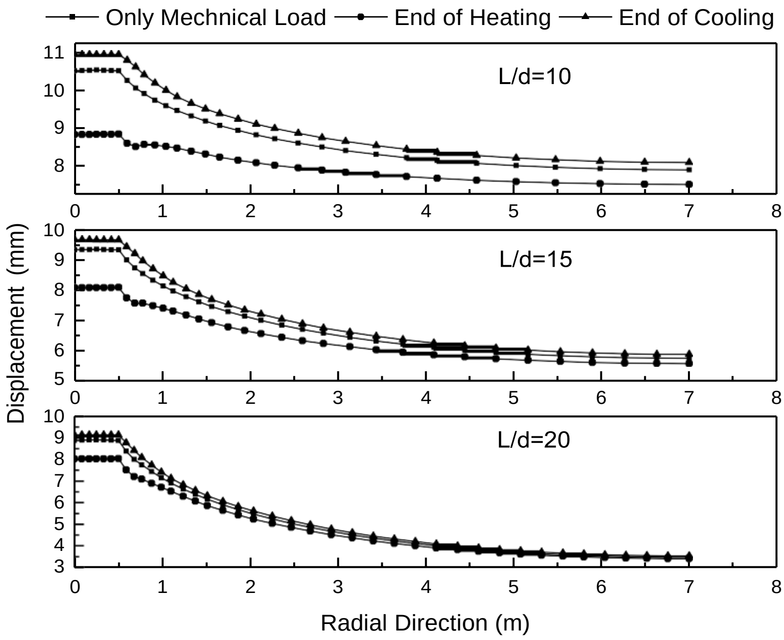

Fig. 4. Vertical displacement of sand in radial direction.

Furthermore, the displacement of pile head and pile base has also been simulated through numerical studies. Therefore, behavior of pile against thermo-mechanical loading could be observed for different L/d ratio. Fig. 5 shows the vertical displacement of pile head and pile base. It can be concluded from fig. 5a that mechanical load is applied on pile headfirst and get stabilized. After that heating is started for the period of 12 days. Thermal expansion occurred during heating phase. Therefore, the displacement of pile decreased due to upward movement of pile during expansion. While cooling phase, the displacement increased due to downward movement of pile during contraction. Fig. 5b shows the vertical displacement of pile base against thermo-mechanical loading. After stabilization of mechanical loading, heating phase started. During heating, displacement of pile base increased due to penetration of pile in downward direction. During cooling, displacement of pile base decreased due to upward movement of pile. However, displacement of pile base during heating phase is less as compared to displacement of pile head due to resistance by sand. Therefore, movement of pile head and pile base is upward and downward respectively during heating and vice versa during cooling phase due to expansion and contraction of pile. Furthermore, Displacement of pile head and pile base is more for L/d ratio equal to 10 as compared to L/d ratio equal to 15 and 20. This is mainly caused due to high resistance exerted on pile due to surrounding sand for higher L/d ratio.

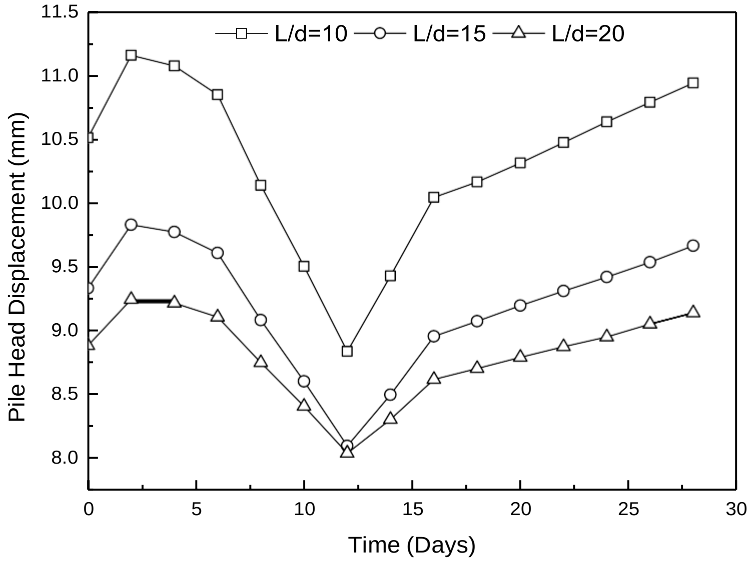

Fig. 5a. Vertical displacement of pile head.

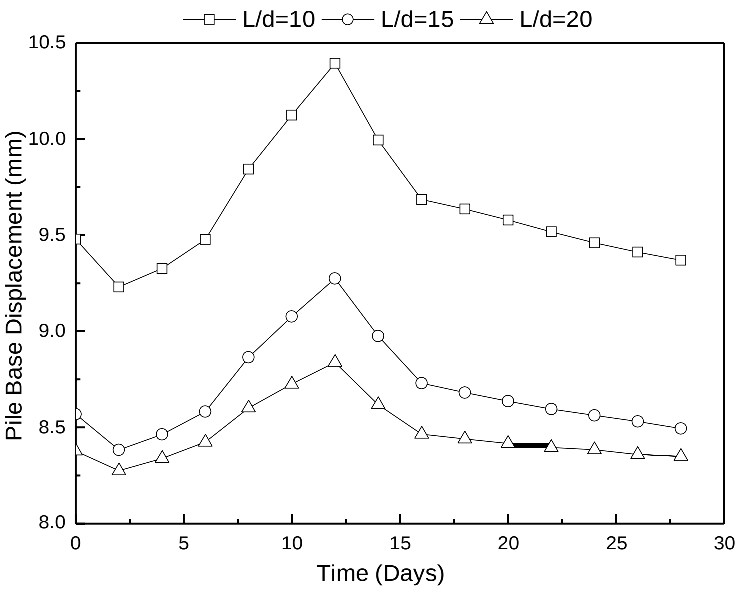

Fig. 5b. Vertical displacement of pile base.

5 Conclusion

This study was illustrated by numerical simulation using finite element software. A numerical analysis was carried out the numerical study on the thermo-mechanical response of the energy pile and understand the pile-soil interaction for Indian dry sand. The results were analyzed and briefly elaborated for thermo-mechanical load- ing, where thermal loading was applied similarly to Laloui et al., [5]. In present study, the displacement of the pile head, pile base and surrounding soil was analyzed as a function of thermo-mechanical load.

- It has been observed that displacement of pile is highest at L/d ratio 10 and lowest for L/d ratio 20.
- The energy pile showed the displacement in downward direction under continuous mechanical load.
- When the pile and surrounding sand are heated, thermal expansion of pile is observed, and while the pile and surrounding sand are cooled together, they exhibit thermal contraction.
- Thermal expansion or thermal contraction of energy pile is negligible in all cases. Hence, it would not affect the stability of the energy pile. The geothermal energy pile can be used to restore the energy of the earth, as well as to secure the stability of the structure.
- Geothermal energy pile is a cost effective method and long-term solution for meeting ventilation requirement of buildings.

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