International Journal of GEOMATE, March, 2017, Vol. 12, Issue 31, pp. 112-120
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: http://dx.doi.org/10.21660/2017.31.6538

ASSESSMENT OF STRESS-STRAIN BEHAVIOR OF ENERGY PILES INSTALLED IN SAND

*Anant Aishwarya Dubey and Suresh Kumar

Indian Institute of Technology, (B.H.U) Varanasi, India

*Corresponding Author, Received: 00June 2016, Revised: 04 August 2016, Accepted: 30 Nov. 2016

ABSTRACT: The geothermal piles are dual functional geostructures which provide sub-structural support to the building and also fulfill the energy demands in terms of its climate control. For efficient design of geothermal piles, it is necessary to evaluate the thermo-mechanical behavior of geothermal piles. The purpose of this study is to evaluate the behavior of geothermal heat exchanger pile installed in sand, subjected to a coupled thermo-mechanical loading. Initially, in this study a full scale field test is simulated and results are compared. In the second phase, parametric study by varying mechanical and thermal loading on the geothermal pile placed in dense sand, is performed. In this study, the sand and geothermal pile are simulated as axis-symmetrical models, where pile is considered to be thermo-elastic in nature and sand is considered as Mohr-Coulomb elastic-plastic material. Coupled Temperature-Displacement analysis is applied in order to simulate the observed experimental results. It is shown that the simulated model is able to reproduce the major thermo-mechanical effects for the selected full scale model approximately. Stress and strain behavior along with the depth of energy pile induced by thermo-mechanical loading has been reported. It was concluded that when mechanical load value is comparatively low, the thermal variation influences the induced axial stress while at higher mechanical load the stress behaviour is nearly constant at different temperature variation.

Keywords: Geothermal Piles, Numerical Modelling, Thermo-Mechanical Analysis, Thermal response of pile.

1. INTRODUCTION

Growing population with advancing development has impacted the surrounding environment with multiplied pollution in the attempt to meet the energy demands. To achieve the increased demand of energy with minimal the toxic pollutant as by-products, the advancement of sustainable and renewable energy sources, is necessary. One of the most dependable source of renewable energy has been emerged as geothermal energy. With geothermal heat exchanger structures, it is possible to extract energy in form of heat, from the ground to fluid-filled pipes casted in concrete and then it can be transferred to building environments.

In spite of the rising recognition of the advantages of energy piles, there is still understanding void in comprehension of the load transfer mechanism of heat exchanger piles under thermo-mechanical loading (Laloui et al, 2006). For energy piles, the reinforced concrete piles are often favored over the steel piles because of better thermal conductivity and thermal storage capacity of concrete, which signifies concrete piles as an ideal medium for geothermal heat absorber (Brandl 2006).

There are three major ways to analyse the behaviour of geothermal piles, as following:

1.1 Full scale In-situ tests

To analyze the behavior of energy pile in actual field condition, a test energy pile equipped with various sensors including load cells and strain gauges, is installed in-situ and the behavior of pile in different thermal loading is recorded. A typical setup of test pile use by Laloui et al. (2006) is shown as following:

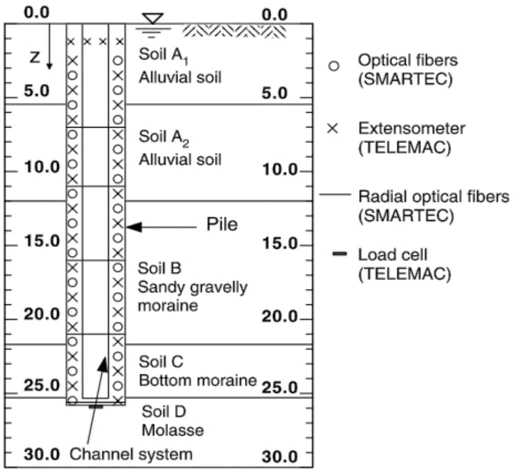


Figure 1 Typical test pile and instrumentation setup for field study (Laloui et al. 2016)

First full scale in-situ test to evaluate thermo-mechanical behaviour of heat exchanger pile was done by Brandl et al. (1998, 2006). An instrumented pile, forming part of an operational GSHP system of 143 piles, was installed during construction works for a rehabilitation centre in Bad Schallerbach, Austria. A seven-storey building is supported by these piles, which were part of a piled raft. The test pile was equipped with fissure meters at three levels, and thermo-elements at five levels and pressure cells at the toe and the head of pile. Data extraction was done intermittently in different seasons of the year for several years.

Second field trial on geothermal piles was undertaken at École polytechnique fédérale de Lausanne (EPFL) by Laloui et al. (2003, 2006), Switzerland. They reported pile uplift and temperature-induced axial stress in the pile is higher as compared to that caused by the mechanical load.

Amis et al. (2008) and Bourne-Webb et al. (2009) performed energy pile field trials in Lambeth College, London, UK. The test site is located within the grounds of the Clapham Centre of Lambeth College in South London.

1.2 Laboratory scale and centrifuge modelling

Laboratory scale modelling is another effective alternative to assess the behaviour of energy piles. These models are cost effective and also assist to categorize the analysis for particular parameters. To produce the field like geostatic stress condition in order to investigate stress-strain behaviour of heat exchanger piles the Centrifuge models are developed.

McCartney et al. (2010) carried-out centrifuge model tests heat exchanging centrifuge scale deep foundations under 60°C heating and subsequent cooling to 25°C and reported an improvement in shaft capacity of the piles caused by heating which causes increase in confinement stress.

Wang et al. (2012) evaluated the load carrying capacity of laboratory scale model heat exchanger piles applying coupled thermo-mechanical loading and reported that temperature should be considered as an important parameter since it influences the load carrying capacity of the piles.

Wang et al. (2012) performed centrifuge experiments considering coupled thermo-pore-mechanical FE analysis on heat exchanger piles in saturated and partially saturated silt, respectively. They studied the strain-displacement behaviour of the scaled pile and temperature distribution adjacent to the pile assuming the soil region as linearly elastic and isotropic.

Goode et al. (2014) also investigated Centrifuge test on energy piles in sand. They perceived uniform thermal axial strain profile for pile due to heating of the pile and reported upward shift of the pile head.

Kramer et al. (2014) performed laboratory scale modelling of energy pile by applying thermal load on pile via liquid (ethyl-glycol and water) with an inbuilt PVC pipe in order to simulate the real phenomena of thermal load transfer. They concluded increase in velocity of flowing fluid escalates the performance of the energy pile, though, as higher velocity of fluid requires more power, it may have unfavorable effect on seasonal performance factor of the system. They also reported that variation of circulation speed doesn’t affect the temperature of surrounding soil significantly. It was established by the laboratory scale model testing that the positive and negative temperature gradient have equal and opposite effects on the heat transfer and on soil temperature increment. It should be noted that, it was not a centrifuge model, so stress analysis was not performed.

Ng. et al (2014) carried out centrifuge study and reported that when temperature increases the pile capacities of heat exchanger piles also increased, with respect to the initial pile capacity of the reference pile. The increase in pile capacities was attributed to an increase in ultimate shaft resistance and toe resistance. It was deduced that for a pile subjected to a temperature increase, its increase in capacity is mainly contributed by the increase in shaft resistance.

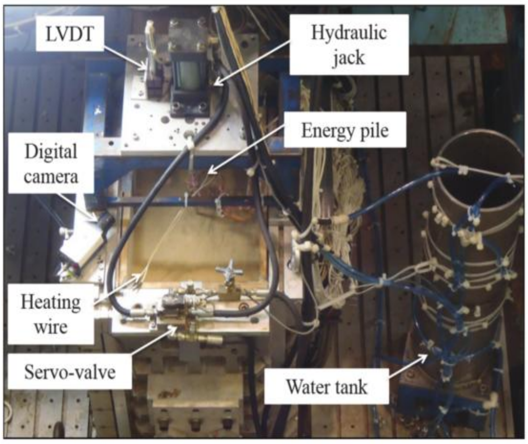


Figure 2 Overview of typical model package for centrifuge (Ng et al. 2014).

1.3 Numerical Simulation and Analysis:

Another effective way to analyze the Thermo-Mechanical behaviour of energy pile is by application of theoritical and Numerical Simulation methods, employing techniques like finite element analysis to study the complex behavior of energy piles. The benefit of numerical modelling over scale modelling and field study is that varying the different constraints, parametric studies can be performed.

Laloui et al. (2006) carried out finite element

(FE) analyses of heat exchanger piles. They reported that the thermal piles might experience an uplift as differing to the conventional piles, which usually settles when a static dead weight of building acts.

Amatya et al. (2012) investigated the results obtained from in-situ tests on energy piles during heating and cooling. They witnessed that the temperature of the pile after a thermal recovery cycle, was always marginally higher than the initial temperature in each trial, signifying a aggregation of thermal magnitude around the test pile.

Design charts were proposed by the Ground Source Heat Pump (GSHP) association for probable axial stress and pile head displacement of heat exchanger piles. They anticipated that with an increase in pile temperature, the axial stress and pile uplift also increses.

Ghesami-Fare and Basu (2013) carried-out heat transfer analysis on heat exchanger piles employing finite difference method and reported that heat transfer happens in radial direction from geothermal piles.

Arson et al. (2013) studied the effect of presence of air pocket at the soil– pile interface in heat propagation from the geothermal piles in dry sand. They perceived that an insulating effect is induced by air pocket at the pile–soil interface and therefore, transmitted heat is appeared to be less to the ground, when compared to the case of perfect bonding, which results in in better heat transfer to the pile from soil. They also detected that debonding due to presence of air pocket has a critical influence on the bearing capacity of the pile due to decrement in the frictional resistance of the soil.

Mimouni and Laloui (2014) numerically considered the radial strains and its effect on the soil–structure interaction for the heat exhanger piles.

Saggu et al. (2014) studied stresses and displacement of the energy piles in sand and the surrounding soil under cyclic thermo-mechanical loading using the software package Abaqus Simulia. They applied 50 cycles of thermal loading of ΔT = 21°C on different load magnitudes and concluded that Negative Shear stress is generated near the pile head in the soil and The ultimate capacity (limit load) of the energy pile is unaffected by temperature changes.

Di Donna and Laloui (2015) investigated the effect of cyclic heating of the pile on the settlement behavior and reported that, the pile settlement rises for the initial five heating cycles and after that the settlement becomes approximately constant. They also concluded that additional settlement induced over the settlement owing to mechanical load, is in the order of 10%, which may have been caused probably due to application of thermal loads.

2. SIMULATION AND PARAMETRIC STUDIES

In this paper an axisymmetric, nonlinear transient thermo-mechanical finite element analyses have been simulated for a friction pile (floating) in dense sand media. The pile and soil geometries are generated as separate parts utilizing FE software Abaqus simulia 6.16.

2.1 Validation of Finite Element Model under Thermo-Mechanical Loading

For the scrutiny the simulated programmes reliability a full scale in-situ pile was simulated and the results were compared, which were found to be in decent agreement with the reported results.

The Full scale test chosen for validation of simulation method, was the test performed at EPFL by Lyesse Laloui as availability of data and work done on the model was found to be convincingly extensive.

The results of finite element analysis performed on heat exchanger piles under combined thermo-mechanical loading, have been validated by contrasting the simulation results with the in-situ pile load test data and numerical simulation results reported by Laloui et al. (2006).

Laloui et al. (2006) executed energy pile load tests in-situ at Lausanne, Switzerland for a period of 28 days which included heating duration of 12 days and cooling duration of 16 days. The diameter of the pile was 1 m and length of the pile was 26 m, correspondingly. The variation in temperature simulated was ΔT = 21 °C.

Mohr–Coulomb model was used for analysing the soil stress–strain response. The pile is assumed to be thermo-elastic in Nature.

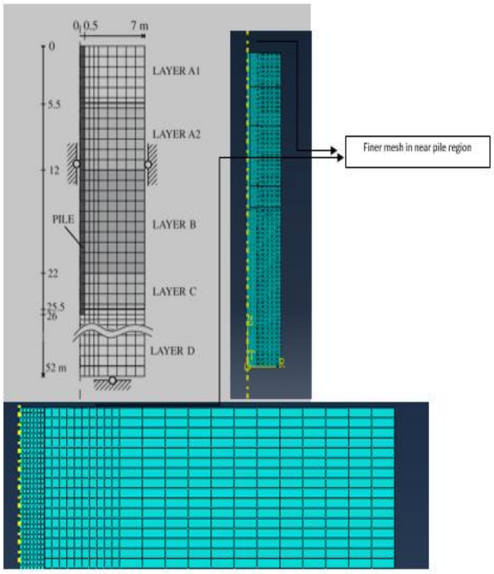


Figure 3 EPFL energy pile-soil profile, Mesh elements used for simulation (mesh elements near pile element are kept finer and in far boundary the mesh is coarser)

A total of 10645 element are used for simulation of three different sizes with minimum being 0.005625 m^2 in near regions to the pile and maximum is 0.0675 m^2 in far field regions while in the finite element analysis by Laloui et al, coarse 634 elements were considered.

Table 1 Material Properties Used for First Validation (Laloui et al, 2006)

Properties	Soil A1	Soil A2	Soil B	Soil C	Soil D	Pile
Mechanical Properties						
Poisson's Ratio (υs)	0.14	0.14	0.2	0.2	0.15	0.2
Elastic modulus (Es) in MPa	259	259	451	634	3865	27800
Mohr–Coulomb Plasticity Properties						
Frictional angle (ϕ)	30°	27°	23°	27°	-	-
Dilation angle (ψ)	0	0	0	0	-	-
Apparent cohesion (c_s) in Pa	5000	3000	6000	20000	-	-
Thermal Properties						
Thermal conductivity (k_s) in (W/m °C)	1.8	1.8	1.8	1.8	1.1	2.1
Specific heat (C_s) in (J/°C)	1200	1230	1200	1091	785	800
Coeff. of thermal expansion (α_s)(/°C)	10^{-5}	10^{-5}	10^{-4}	10^{-4}	10^{-6}	10^{-5}

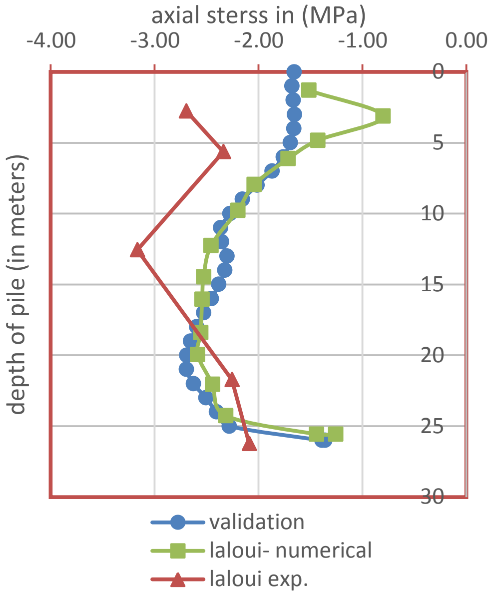


Figure 4 Comparison between Present Simulation Results and Experimental and Numerical Simulation Performed by Laloui et al, 2006.

The pile was installed in a multi-layered soil deposit which consists of alluvial soils, sandy gravelly moraine and mollase. 1,300 kN load was applied axially on the pile. Laloui et al. (2006) simulated the in-situ pile test numerically considering a thermo-elasto-plastic, Drucker–Prager model for soil and the pile was considered as linear elastic model. In the present simulation, axisymmetric, thermo-mechanical finite element analysis of a similar 26 m long pile with 1 m diameter is performed by applying the coupled temperature-displacement analysis step in Abaqus Simulia 6.16. The elastic and thermal material properties for the concrete pile and the soil layers have been adopted from Laloui et al. (2006) and are reported in Table 1. Thus, the results of Simulation were found to be in good agreement with experimental results.

2.2 Axis-symmetrical Model details used in this study

Figure 5 displays geometry of pile and soil and the Finite Element mesh for the pile–soil region. The far-field soil boundary in the vertical direction has been situated at fifteen times distance of the pile diameter from the axis of symmetry and centre of pile. The soil boundary at the bottom is located at one pile length (i.e. 15 meters) distance from the bottom tip of the pile.

The far-field soil boundary in the vertical direction has been restrained for horizontal displacement by applying roller support and the soil boundary at the bottom has been controlled for both vertical and horizontal displacements by applying pinned support. The thermal boundary conditions are provided in the simulation, which includes heat flow through the far-field in vertical and the bottom boundaries of the mesh. Heat flux is supposed to be nil from axis of symmetry to pile and soil. The ambient soil temperature is presumed to be 15 °C (Laloui et al. 2006). The Finite Element region has been assigned using axisymmetric thermally coupled four node bilinear displacement and temperature elements (CAX4T) for both soil and pile. Shear strain localization might occur close to the pile–soil interface, and as a consequence, shear band development may take place in the first column of elements following to the pile shaft. Hence, a refined mesh has been used nearby the pile–soil interface for soil.

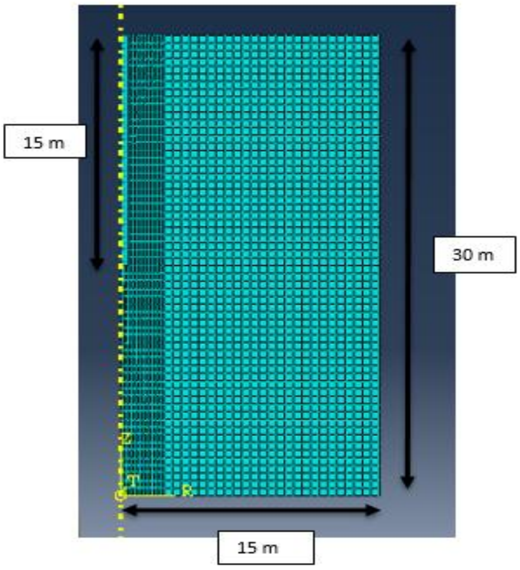


Figure 5 Pile soil Geometry and the FE mesh for pile soil domain for present simulation.

CAX4T elements were generated with minimum size of 0.005625 m^2 in near regions of pile and maximum mesh size of 0.0675m^2 in far field regions. The material properties used for the simulation and parametric studies are given as follow:

Table 2 Material Properties Used for Parametric studies

Properties	**Homogeneous sand**	**Geothermal Pile**
Mechanical Parameters		
Poisson's Ratio (υs)	0.2	0.2
Elastic modulus (Es) (MPa)	70	27800
Mohr–Coulomb plasticity parameters		
Frictional angle (ϕ)	30°	-
Dilation angle (ψ)	0	-
Apparent cohesion (c_s) (Pa)	5000	-
Thermal Properties		
Thermal conductivity(k_s) (W/m °C)	1.8	2.1
Specific heat (C_s) (J/°C)	1200	800
Coefficient of thermal expansion (α_s)(/°C)	10^{-5}	10^{-5}

The interfaces between the energy pile and the sand surfaces have been simulated as frictional contact in the tangential direction. The coefficient of friction (μ) between soil and concrete pile is considered as tanϕ, where ϕ is the internal friction angle of soil (saggu et al, 2014). In the normal direction a rigid contact between the pile and the soil, with zero penetration has been assumed.

A linear varying gap conductance value has been assigned for heat conduction between pile and sand. It is presumed that when the distance between the pile and the soil is nil, then the contact conductance between sand and pile is perfect.

3. RESULTS AND DISCUSSION

The thermo-mechanical analyses is done on the pile by for six different mechanical load cases varying from 50 kN to 2000 kN and three thermal variation for a period of 28 days which are ΔT = 15 °C, ΔT= 25 °C and ΔT=35°C.

These combinations generates a total of different 18 thermo-mechanical load cases. Three aspects were mainly analysed in the study, Axial Stress, Radial Stress and Radial Strain Behaviour along the length of pile. A generalize analyses was performed based on the performance of energy pile based on the comparison of these aspects.

A simplified study plan can be given as shown in figure 6.

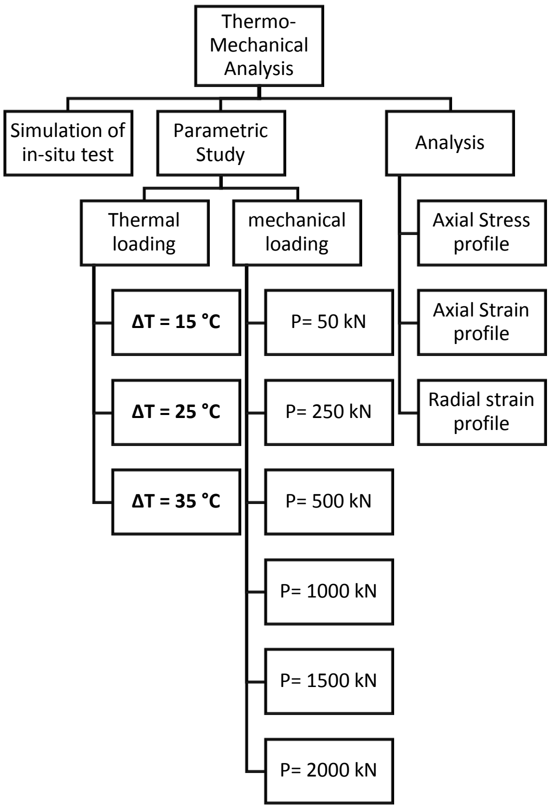
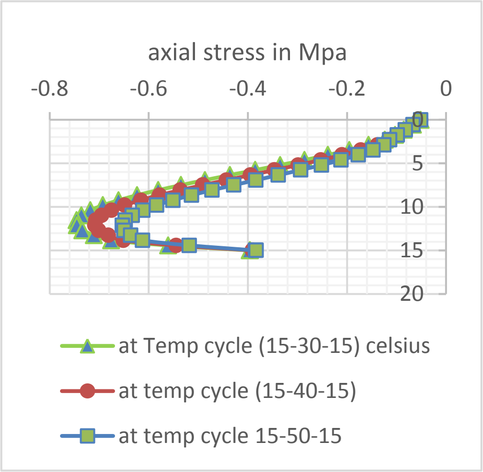
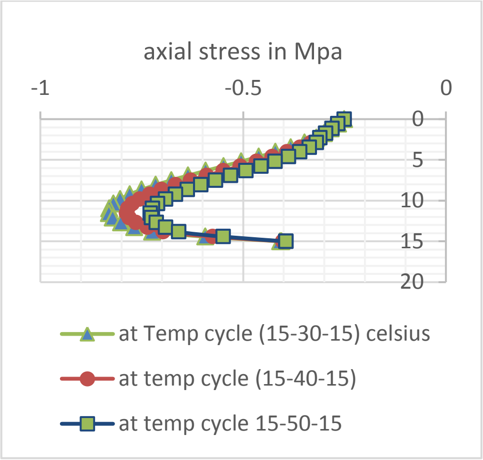


Figure 6 Synopsis of Investigation performed including different thermo-mechanical load case details.

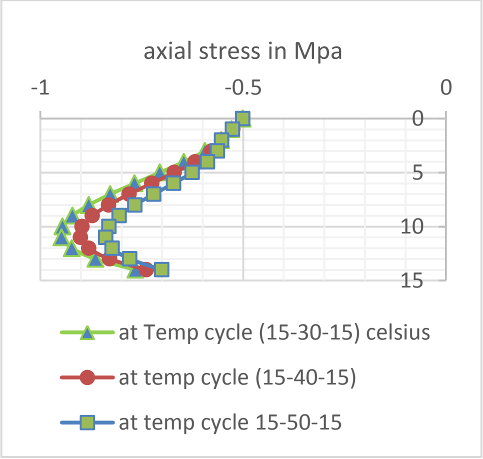
3.1 Axial Stress in Pile after a complete cycle of Heating and Cooling cycle



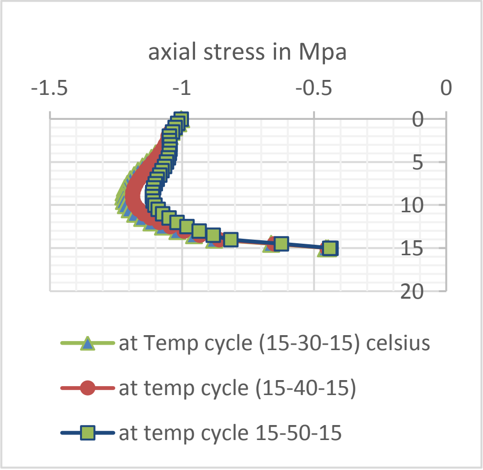
(a) 50 kN Axial axial Load



(b) At 250 kN axial Load

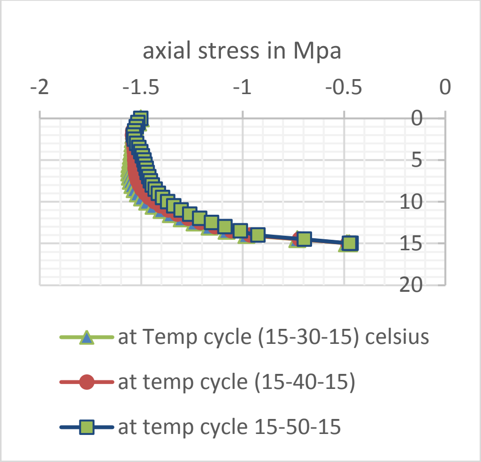


(c) 500 kN axial load

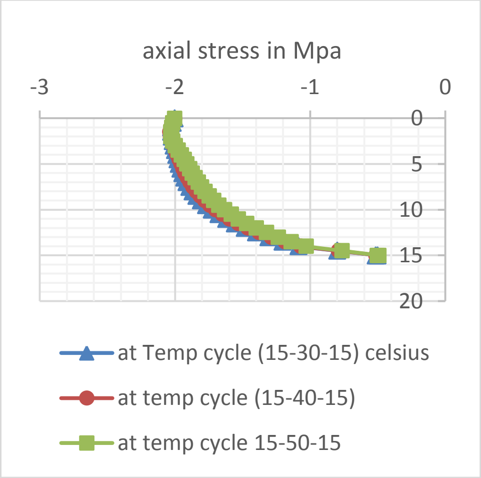


(d) 1000 kN axial load

Figure 7 Axial Stresses in Pile after Heating-Cooling Cycle at different loading at (a). 50 kN load (b). 250 kN load (c). 500 kN load (d). 1000 kN load (e). 1500 kN load (f). 2000 kN load

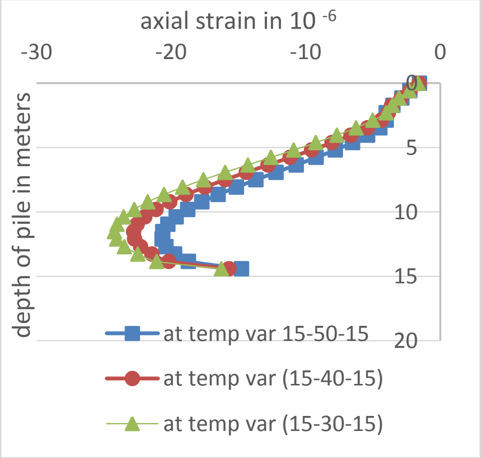


(e) 1500 kN axial load

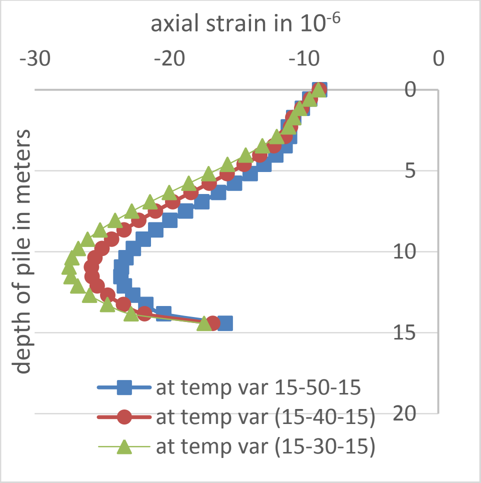


(f) 2000 kN axial load

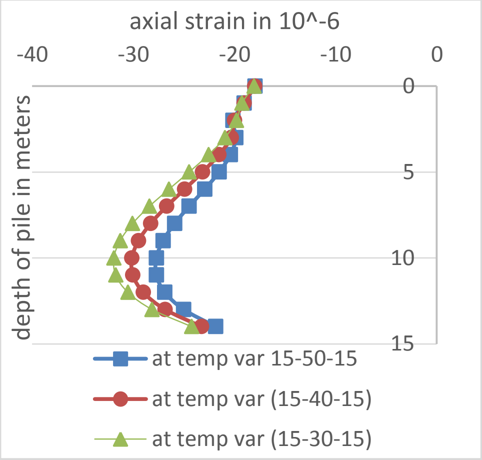
3.2 Axial Strain in Pile after a complete cycle of Heating and Cooling cycle



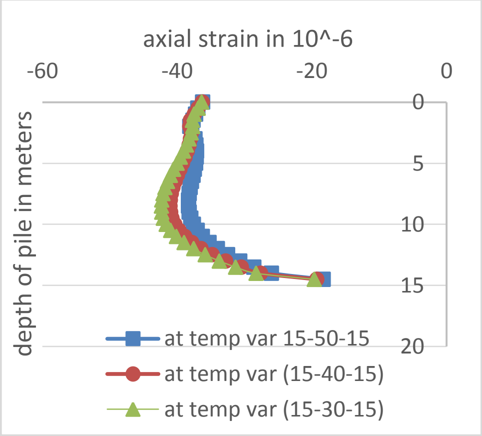
(a) 50kN Load



(b) 250 kN Load

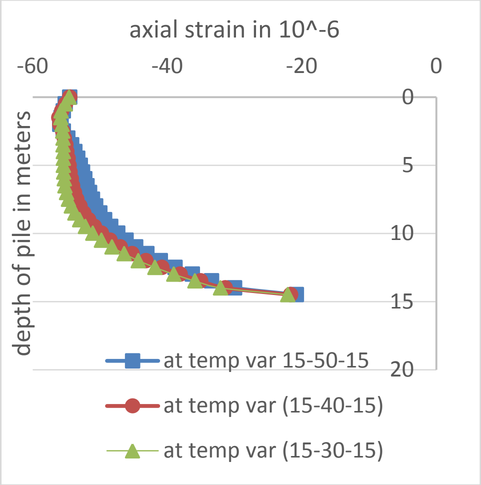


(c) 500 kN Load

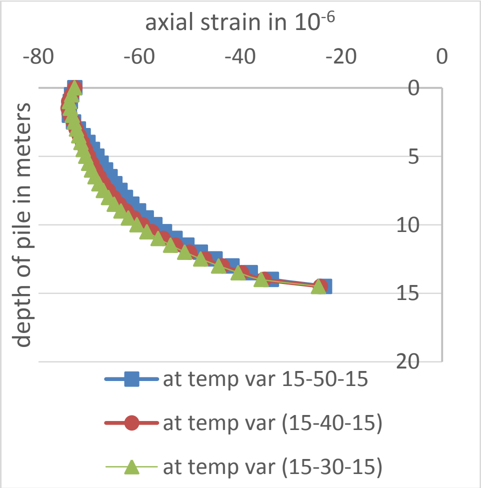


(d) 1000 kN load

Figure 8 Axial Strain in Pile after Heating-Cooling Cycle at different loading at (a). 50 kN load (b).250 kN load (c). 500 kN load (d). 1000 kN load (e). 1500 kN load (f). 2000 kN load



(e) 1500 kN Load



(f) 2000 kN Load

4. CONCLUSION

Geothermal Pile subjected to heating at different loading, varying both thermal load and mechanical load was analysed for a floating pile of diameter 1 meter and length 15 meter in dense sand.

The stress strain behaviour is analysed and it may be concluded that at low mechanical load the axial stress generated on the pile varies significantly with variation of thermal loading while, when Mechanical Load is at higher end (above 1000 kPa), the axial stress along the depth varies lesser. So it may be deduced that when mechanical load value is low the thermal variation influences the axial stress produced and at higher mechanical load the stress behaviour is nearly constant at different temperature variation, so the axial stress along the pile is majorly due to applied mechanical load.

It should be noted that here, thermal loading is not directly compared with mechanical loading quantitatively. As, the mechanical and thermal load are different in nature. The Conclusions are limited to the applied thermal loading cases only. If the thermal loading is increased enormously further, it may dominate to influence the stress-strain behaviour of pile. However, the temperature variation chosen here are based on rational temperature variation of different seasons.

Larger axial strain were noted at the tip of pile and sand surrounding the energy pile near head of pile.

References:

[1] Abaqus/Standard User’s Manual, Version 6.16 (2016), Dassault Syste`mes Simulia Corporation, Providence, Rhode Island, USA.

[2] Amatya B.L., & Laloui, L. (2012). Thermo-mechanical behavior of energy piles, (6), 503–519.

[3] Amis, A., Bourne-Webb, P., Amatya, B., Soga, K. & Davidson, C. (2008), "The effects of heating and cooling energy piles under working load at Lambeth College". Proc. 33rd Ann. and 11th Int. DFI Conf., New York, article no. 1620.

[4] Arson C, Berns E, Akrouch G, Sanchez M, Briaud JL (2013) Heat propagation around geothermal piles and implications on energy balance,ISBN (13): 978-84-939843-7-3, 628–635

[5] Bourne-Webb, P., Amatya, B. L., Soga, K., Amis, T., Davidson, C. & Payne, P. (2009). "Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycle". Geotechnique 59, No. 3, 237–248, http:// dx.doi.org/10.1680/geot.2009.59.3.237

[6] Brandl, H. (2006). "Energy foundations and other thermo-active ground structures". Ge´otechnique 56, No. 2, 81–122, http:// dx.doi.org/10.1680/geot.2006.56.2.81.

[7] Donna A. Di, Torino P., Loria,. (2015). Numerical study of the response of a group of energy piles under different combinations of thermo-mechanical loads different combinations of thermo-mechanical loads, (February 2016). http://doi.org/10.1016/j.compgeo.2015.11.010

[8] Ghesami-Fare O, Basu P (2013). A practical heat transfer model for geothermal piles. Energy Build 66:470–479

[9] Goode, J.C., III, Zhang, M., and McCartney, J.S. (2014). Centrifuge modelling of energy foundations in sand. In ICPMG2014 – Physical Modelling in Geotechnics: Proceedings of the 8th International *Conference on Physical Modelling in Geotechnics*, pp. 729–735. doi:10.1201/b16200-100

[10] GSHP Association (2012) Thermal pile design, installation and materials standards.

[11] Kramer, C., & Basu, P. (2014). Performance of a model energy pile in sand. International Conference on Physical Modelling in Geotechnics, 2014, 1–6. http://doi.org/10.1201/b16200-106

[12] Laloui, L., Nuth, M., & Vulliet, L. (2006). Experimental and numerical investigations of the behaviour of a heat exchanger pile. *International Journal for Numerical and Analytical Methods in Geomechanics*, *30*(8), 763–781. http://doi.org/10.1002/nag.499

[13] McCartney, J.S., and Rosenberg, J.E. (2011) Impact of heat exchange on side shear in thermo-active foundations. In Geo-Frontiers at Advances in Geotechnical Engineering. ASCE, pp. 488–498. doi:10.1061/41165(397)51.

[14] Mimouni, T., & Laloui, L. (2014). Towards a secure basis for the design of geothermal piles. *Acta Geotechnica*, *9*(3), 355–366. http://doi.org/10.1007/s11440-013-0245-4

[15] Ng, C., Shi, C., Gunawan, A., Laloui, L., & Liu, H. L. (2014). Centrifuge modelling of heating effects on energy pile performance in saturated sand. *Canadian Geotechnical Journal*, 1045–1057. http://doi.org/10.1139/cgj-2014-0301

[16] Saggu, R., & Chakraborty, T. (2014). Cyclic Thermo-Mechanical Analysis of Energy Piles in Sand. *Geotechnical and Geological Engineering*, *33*(2), 321–342. http://doi.org/10.1007/s10706-014-9798-8

[17] Wang W, Regueiro R, Stewart MA, McCartney JS (2012) Coupled thermo-poro-mechanical finite element analysis of a heated single pile centrifuge experiment in saturated silt. In: Hryciw RD, Athanasopoulos-Zekkos A, Yesiller N (eds) Proceedings of GeoCongress 2012 (GSP 225). ASCE, 4406–4415