Modelling Thermo-mechanical Behaviour of Geothermal Energy Piles under Cyclic Loading

Nanwangzi WU[1] and Yixiang Gan[1]
[1]School of Civil Engineering, The University of Sydney, NSW 2006, Australia
Corresponding author's E-mail: yixiang.gan@sydney.edu.au

Abstract
In recent years, utilisation of geothermal energy is becoming more popular worldwide. Such technique helps people to reduce the carbon footprint by less consumption of air-conditioning and it can be considered as one of sustainable energy resources. The geothermal energy pile is one of solutions combining properties of ground heat source exchangers (GHSE) and structural functions. In this paper, thermo-mechanical behaviour of geothermal energy piles was studied by using finite element analysis (FEM). To find mechanical response of energy piles, the numerical simulation is established to investigate safety performance of geothermal energy piles under different loading conditions. The thermal expansion for energy piles and surrounding soil are considered during operation. Individual thermal loading cycles and multiple thermal loading cycles are also presented in this study for short- and long-term performance. As the pile is heated and cooled, axial displacement of pile settles and heaves, respectively. It was found that relatively stationary settlement will be achieved after several heating and cooling cycles. Stabilised settlement behaves linearly with temperature variation and formed a different stiffness slope with the pile free expansion line. Moreover, 30 thermal cycles were performed to study long-term behaviour of the energy pile settlement. The preliminary results could warrant further studies for the serviceability design of geothermal energy piles.
***Keywords**: Geothermal energy; Pile foundation; Soils; Temperature effects; Settlements*

Introduction

Energy piles, also known as geothermal energy exchange pile, serve as one of solutions that combine properties of ground heat source exchanger (GHSE) and structural components of the buildings. This technique helps reduce carbon dioxide emission by subtracting or injecting thermal energy into the ground and save land for the building. Ghasemi-Fare et al. (2013) reported that initial temperature difference, soil thermal conductivity and radii of the piles and circulation tubes are the major parameters which affect energy output of energy piles and influence the ground temperature distribution.

Consideration has been taken for thermal expansion of soil and piles (Suryatriyastuti et al., 2016), but mechanical response during heating and cooling in individual cycle was not clear. Bodas et al. (2013) examined the change of pile axial stress under different thermal expansion coefficient and soil stiffness. It was found that thermal expansion of soil and soil stiffness significantly impact the axial stress of the pile. Ng et al. (2014) compared lightly over-consolidated soil and heavily over-consolidated soil subject to thermal cycling in laboratory environment. Two in-situ experiments have been performed by Bourne-Webb et al. (2008) and Laloui et al, 2006 also known as Lambeth College test pile and EPFL test pile, respectively. Yavari et al., (2014) used commercial finite element code Plaxis 2D to simulate in-situ mechanical behaviour of the energy pile by ignoring thermal expansion on soil. A small-scale energy pile on clay was tested by Yavari et al. (2016) and presented the detailed temperature and settlement measurements for each lading cycles.

In this paper, numerical simulation of thermal-mechanical behaviour of a small-scale geothermal energy pile is studied by considering coupling effects of thermal expansion in soil and the pile. Pile settlement under thermal loading was investigated and predicted based on this numerical study.

Numerical Modelling

A small-scale energy pile is investigated here for predicting mechanical behaviour under long-term thermal loading conditions and settlement effect of individual energy pile subjected to axial load under thermal load is studied by assuming constant underground temperature (Brandl, 2006, Murphy et al., 2014 and Popile, 2001). The surrounding soil (Speswhite China Clay) is compacted to void ratio 0.79 and soil is fully saturated. A 20-mm diameter model pile is installed before compaction process with height 600 mm under soil surface. Pile centre is 270 mm away from edge of circular container and bottom of pile is 300 mm from bottom of container. Pore pressure is assumed to be zero at top of soil surface. The constitutive parameters of soil are referred to Lv et al. (2017): a centrifuge mechanical test pile was simulated by ABAQUS. The model dimension and material parameters are similar as Yavari et al. (2016).

The finite element analysis was performed by using the commercial FEA software, ABAQUS V6.16. Two-dimensional axisymmetric model, fully coupled 4-node temperature-pore pressure-displacement element (CAX4PT) and 4-node bilinear displacement-temperature element (CAX4T) are used to simulate the soil and pile, respectively. Circular hollow section aluminium pile is modelled by solid pile with the equivalent mass density. Soil is modelled by the modified Cam-clay model and pile is described by linear-elasticity model. For contact properties, the friction coefficient at the soil-pile interface is assumed to be tanϕ. Note that a relatively large thermal conductance is chosen to avoid thermal resistance behaviour at pile-soil interface. Soil and pile constitutive parameters are summarized in Table 1 and other relevant parameters are in Table 2. Since soil is compacted, the lateral stress coefficient is given by Meyerhof as $K_0 = (1 - \sin\phi)\mathrm{OCR}^{0.5}$. We took mid-height of pile as average K_0, and OCR is calculated approximately as160. As a result, K_0=8 is adopted for simulation and it is within a reasonable range. Initial geostatic displacement tolerance was set 0.6 mm.

Table 1. Parameters of the pile and soil in numerical modeling

* Soil properties are adopted from Lv et al., (2017).

Parameters	Pile (CHS aluminium)	Clay (Speswhite China Clay)
Consititutive model	Linear-elastic	Modified Cam-clay
Density (ton/m^3)	0.32	1.45 (dry unit weight)
γsat(kN/m^3)	N/A	18.53
Young's modulus E(kPa)	1.3E7	N/A
ν*	0.33	0.25
M*	N/A	0.98
λ*	N/A	0.14
κ*	N/A	0.012
e_0*	N/A	1.6
e_1	N/A	0.79
ϕ*	N/A	25°
ψ	N/A	0°
k(m/s)*	N/A	1E-8
Thermal expansion(/°C)	2.3E-5	1E-6
Thermal conductivity(W/(m°C)	237	1.5
Specific heat capacity(J/ton/°C)	9E5	1.269E6

In numerical modelling, the size of meshes is fine enough until no significant mesh influences (Fig. 1). Mechanical loading and ±1°C thermal loading are treated as loading conditions into this numerical study to estimate the pile settlement. One mechanical loading test performed to check ultimate loading capacity for single pile. The, the pile temperature is varied in ±1°C with the ambient temperature of 20°C for 30 cycles under 0, 100, 200, and 300 N mechanical loads, equivalent to 0%, 20%, 40% and 60% pile ultimate capacity, respectively. Each thermal cycle runs in one day (24 hours). For simplicity, A1 corresponds to the ultimate capacity test, A2, A3, A4 and A5 correspond to four thermal loading tests. Three thermal loading stages are illustrated in Fig. 2 during the thermal cycles.

Table 2. Relevant parameters in numerical modeling.

Specific weight of water (kN/m^3)	9.81
Friction coefficient	0.47
Thermal conductance (W/(°C*m^2))	500
Lateral earth coefficient, K_0	8

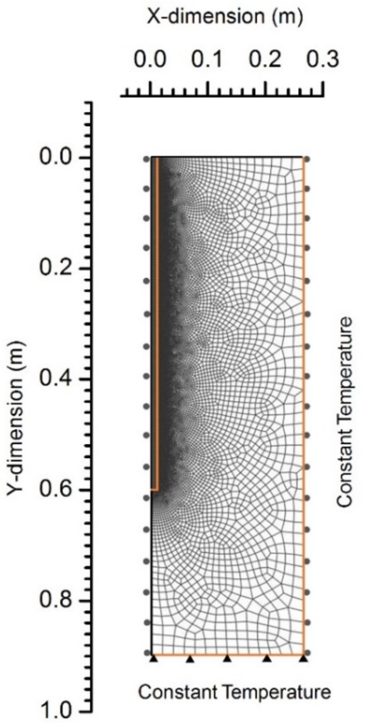

Fig. 1: FEA Meshes and boundary conditions.

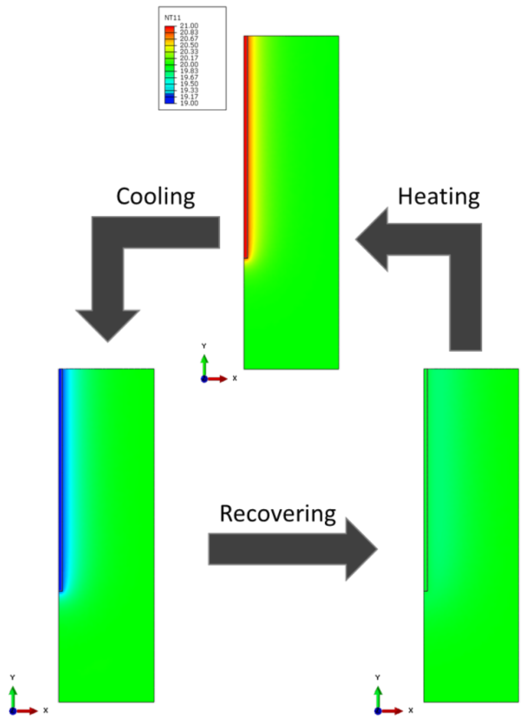

Fig. 2 Three loading stages of thermal cycles.

Result and Discussion

The load-settlement curve for entire test sequence is shown in Fig. 3. Mechanical load test A1 shows estimated ultimate capacity load around 550 N corresponding to the settlement of 10% pile diameter (2mm). Followed by 0 N test (A2) under 30 thermal cycles, it shows that pile heaves instead of settles. Then, 100N (A3), 200N (A4) and 300N(A5) tests indicate same trend as Yavari et al (2016) that a higher mechanical load results a higher irreversible thermal settlement. The cumulated thermal settlement for tests A2-A5, i.e., settlement after mechanical loading, in each test is predicted: -0.0293mm, 0.0106mm, 0.0191mm and 0.0298mm, respectively. Moreover, it is interesting that irreversible settlement after unloading is smaller than thermal settlement in numerical modeling in each test.

Further explanation in temperature-displacement graphs (Fig. 4) presents that temperature induced settlement is stabilized in first three cycles. For mechanical combined thermal loading conditions (A3, A4 and A5), it is obvious that the first thermal cycle in simulation has the largest irreversible settlement increment. In Fig. 4, the plie free expansion line is plotted here as reference. A certain angle between pile free expansion line and stabilized lines from simulations can be easily observed. Moreover, the numerical results are approaching linear elastic behavior in the end. In other words, no further settlements occur by heating and cooling the pile.

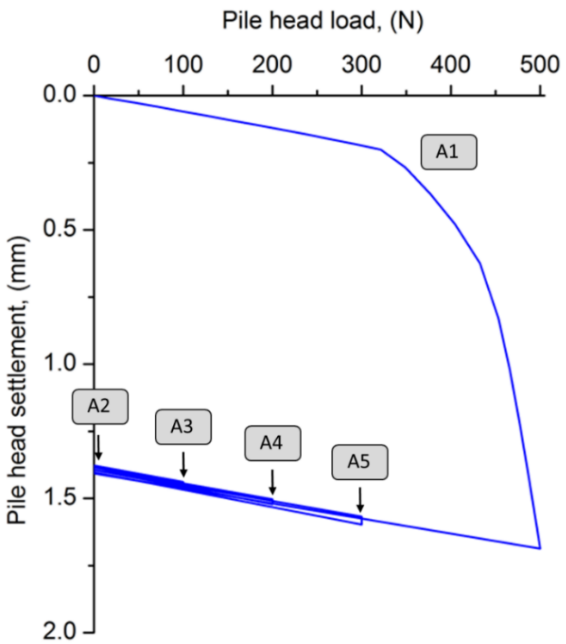

Fig. 3: Pile head load-displacement curve

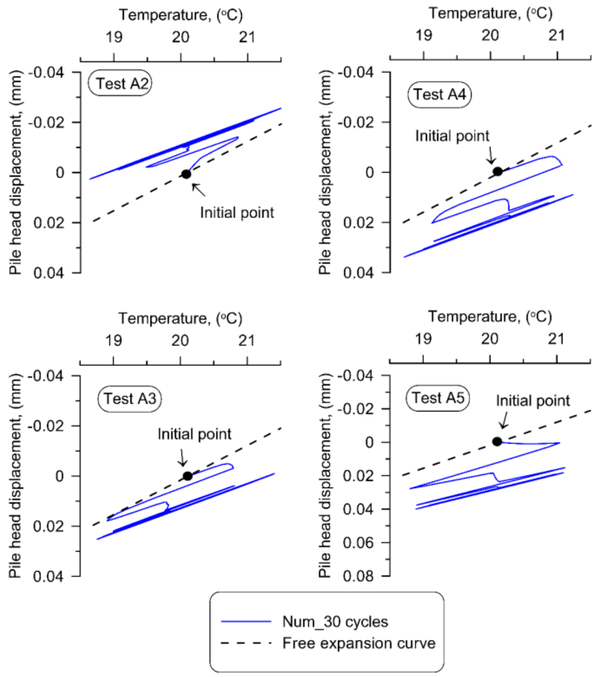

Fig. 4: Pile head settlement versus temperature change during 30 thermal cycles.

The results in Fig. 5 show the offset irreversible settlement of head pile in each recovering phase among 30 thermal cycles. It can see that, the effect of temperature cycles on settlements significantly depends on the applied mechanical load. Pile settles more when higher load is applied. The resulting settlement progressively achieves stable state due to densification process in each thermal cycle. Thermal induced settlement reaches stabilisation within 3 thermal cycles for three non-zero mechanical loading conditions and after 1 cycle for the zero mechanical loading. Explanation of negative settlement under zero mechanical loading is that equilibrium state after unloading mechanism have not yet been reached within 800 min of the unloading period, and the pile continually moving upward during the thermal cycles. The explanation of why numerical simulation is able to predict progressive settlement is because the use of the soil constitutive model, the modified Cam-clay model is chosen instead of Mohr-Coulomb failure criteria. Cam-clay criteria follows porous elasticity rule that could more effectively simulate densification process during thermal cycling loads. Whereas Mohr-coulomb model in such low temperature variation may not well describe actual soil behaviour.

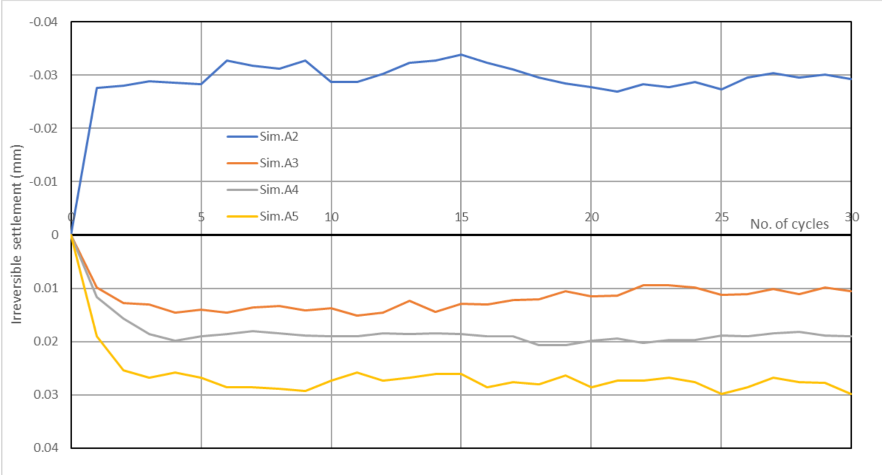

Fig. 5: Irreversible normalized displacement of pile versus number of thermal cycles

Conclusion

The thermal mechanical behavior of a geothermal energy pile under cyclic thermal loading is modeled using the finite element method. The small-scale model energy pile under combined mechanical and thermal loads has been investigated in term of settlement. It can be found that: (1) the settlement of pile reaches stability after several thermal cycles; (2) the relative settlement for thermal load is small compare with mechanical load; and (3) the energy pile may stay safe under the current setting of thermal-mechanical loading condition.

Further investigation is needed by comparing this numerical prediction with the actual physical model experiments. The thermo-mechanical coupled constitutive model may affect settlement of energy pile, and moreover the scale effects should also be considered for full-scale energy pile installations. The preliminary results shown in this paper could warrant future numerical studies for the serviceability design of geothermal energy piles.

References

Bodas Freitas, T., Cruz Silva, F., & Bourne-Webb, P. (2013). The response of energy foundations under thermo-mechanical loading. In *Proceedings of 18th international conference on soil mechanics and geotechnical engineering* (Vol. 4, pp. 3347-3350).

Bourne-Webb, P. J., Amatya, B., 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 cycles. *Géotechnique*, *59*(3), 237-248.

Brandl, H. (2006). Energy foundations and other thermo-active ground structures. *Geotechnique*, *56*(2), 81-122.

Ghasemi-Fare, O., & Basu, P. (2013). A practical heat transfer model for geothermal piles. *Energy and Buildings*, *66*, 470-479.

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.

Lv, Y. R., Ng, C. W. W., Lam, S. Y., Liu, H. L., & Ma, L. J. (2017). Geometric Effects on Piles in Consolidating Ground: Centrifuge and Numerical Modeling. *Journal of Geotechnical and Geoenvironmental Engineering*, *143*(9), 04017040.

Murphy, K. D., McCartney, J. S., & Henry, K. S. (2015). Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations. *Acta Geotechnica*, *10*(2), 179-195.

Ng, C. W. W., Shi, C., Gunawan, A., & Laloui, L. (2014). Centrifuge modelling of energy piles subjected to heating and cooling cycles in clay. *Geotechnique letters*, *4*(4), 310-315.

Popiel, C. O., Wojtkowiak, J., & Biernacka, B. (2001). Measurements of temperature distribution in ground. *Experimental thermal and fluid science*, *25*(5), 301-309.

Suryatriyastuti, M. E., Burlon, S., & Mroueh, H. (2016). On the understanding of cyclic interaction mechanisms in an energy pile group. *International Journal for Numerical and Analytical Methods in Geomechanics*, *40*(1), 3-24.

Yavari, N., Tang, A. M., Pereira, J. M., & Hassen, G. (2014). A simple method for numerical modelling of energy pile's mechanical behaviour. *Géotechnique Letters*, *4*(April-June), 119-124.

Yavari, N., Tang, A. M., Pereira, J. M., & Hassen, G. (2016). Mechanical behaviour of a small-scale energy pile in saturated clay. *Géotechnique*, *66*(11), 878-887.