ANALYSIS OF ENERGY PILES UNDER CYCLIC THERMAL LOADING

Chiara Iodice, Raffaele Di Laora
Università della Campania 'Luigi Vanvitelli', Aversa, Italy
chiara.iodice@unicampania.it, raffaele.dilaora@unicampania.it

Claudio Tamagnini
Università di Perugia, Perugia, Italy
claudio.tamagnini@unipg.it

Giulia MB Viggiani
University of Cambridge, Cambridge, UK
gv278@cam.ac.uk

Alessandro Mandolini
Università della Campania 'Luigi Vanvitelli', Aversa, Italy
alessandro.mandolini@unicampania.it

Abstract

Laboratory tests on soil specimens show that normally consolidated clay experience volumetric collapse during heating which stabilizes within few cycles. The work at hand deals with the effect of this collapse on the performance of energy piles in terms of settlements. To this end, a series of coupled thermo-hydro-mechanical FE simulations via the commercial software Abaqus have been performed, considering a single free-head energy pile embedded in a NC clay layer subjected to a constant mechanical load and to 5 heating/cooling cycles. The soil behaviour is described by means of two advanced hypoplastic constitutive models for clays, one of which possessing a feature which allows to capture the thermally induced volumetric collapse. Accumulation of cyclic settlements and excess pore water pressure is predicted for both models with higher values in the case of volumetric collapse. While the excess pore pressure distribution stabilizes within few cycles, the accumulation of the settlements does not show a meaningful decrease from one cycle to the other. The obtained results agree with the data from small scale tests on an isolated energy pile in NC clay. The numerical model has demonstrated capable of capturing the essential aspect of the soil/pile system response and can thus be used to investigate the complex interaction processes occurring in real piled foundations incorporating energy piles.

1. Introduction

The designers of pile foundations incorporating energy piles (i.e., piles capable of exchanging heat with the soil to satisfy the heat demand of buildings, Brandl, 2006) should focus on two main aspects: i) the evaluation of the thermally induced axial force distribution along the pile axis; ii) the assessment of the additional permanent settlement of the pile head caused by thermal cyclic loading.

While the first aspect has been widely investigated (see, e.g., Laloui et al., 2006; Bourne-Webb et al., 2009; Sutman et al., 2019; Iodice et al., 2020 and 2021), the second topic has been much less studied, probably due to the difficulties encountered in performing numerical analyses and/or laboratory or field tests. Moreover, with reference to clayey deposits, a major feature of the thermo-mechanical behaviour is the strong dependence of the volumetric response to thermal loading on the previous loading history (see, e.g., Campanella and Mitchell, 1968; Burghignoli et al., 2000; Cekerevac and Laloui, 2004; Vega and McCartney, 2014). Indeed, contrary to heavily overconsolidated clays which dilate with increasing temperature, normally consolidated and slightly overconsolidated clays experience volumetric contraction when heated in drained condition, due to a decrease in the shear strength of the individual interparticle contacts which turns out in a partial collapse of the soil structure and, thereby, in a decrease in the void ratio with accumulation of irreversible strain. The thermally induced contraction stabilizes within few cycles when additional contacts between the particles are established. As concerns the undrained conditions, Campanella and Mitchell (1968) show that the pore water pressure - temperature relation tends to be hysteretic from the early temperature cycles. Other important experimentally observed effect of thermo-mechanical coupling are not delt with due to space limitations.

The thermal behaviour of clay can affect the performance of the energy foundations. Recent studies have shown accumulation of irreversible displacement and pore water pressure for energy piles subjected to cyclic temperature variations (Ng et al., 2014; Wu et al., 2018).

The present work aims at providing a contribution to the better understanding of the main phenomena controlling the cyclic behaviour of energy piles installed in soft clays in terms of settlements. To this end, several nonlinear, fully coupled thermo-hydro-mechanical FE simulations have been performed on a single ideal energy pile installed in a normally consolidated clay layer, modelled with an advanced inelastic constitutive equation as well as with a model possessing a feature which allows to capture the main aspects of the coupled thermo-mechanical behaviour of the soil.

2. Numerical modelling: details of the model and constitutive equations employed for the soil

The problem considered in the numerical simulations consists in the mechanical and thermal loading of a single energy pile, 25 m long with a diameter of 0.5 m, embedded in NC clay. The pile is wished in place and is subjected to two values of mechanical load (30% and 60% of the pile bearing capacity evaluated employing analytical formulae, R_t), followed by 5 thermal cycles (fig. 1).

All the details concerning the model dimension, the mesh discretization, the pile properties, the thermal and mechanical load paths along with the selection of parameters for the advanced constitutive models can be found in Iodice et al. (2021).

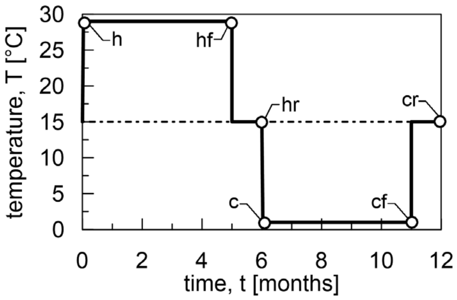

Fig 1. 1-year temperature variation (h: heating; hf: continuous heating; hr: rest after heating; c: cooling; cf: continuous cooling; cr: rest after cooling).

To predict the accumulation of irreversible strain and pore water pressure caused by cyclic loading, an alternative approach to kinematic hardening and Bounding Surface plasticity theories, consists in formulating the constitutive equations in rate-form within the framework of the theory of hypoplasticity with internal state variables (Kolymbas, 1991; Tamagnini et al., 2000; Mašín, 2019).

Within this framework, Mašín has developed a constitutive equation for fine grained soils (Mašín, 2005) incorporating the main features of Critical State Soil Mechanics and the intergranular strain concept (Niemunis and Herle, 1997). The model has been subsequently improved and from now on is referred to as the "Hypo" model. Note that, in this model, the thermal expansion/contraction of solid particles alone does not induce any volume change in the solid skeleton.

Recently, the hypoplastic model has been enhanced by Ma et al. (2017) to describe the thermo-mechanical coupling effects and allow the accumulation of irreversible contractive volumetric strains in NC conditions, using the concept of the shakedown proposed for cyclic mechanical loading by

Mašín and Khalili (2012). This model from now on is referred to as the "Hypo-T" model.
For the implementation of the two models into the code Abaqus Standard 6.14 a stress point algorithm consistent with the evolution equations provided by the constitutive model must be defined and incorporated into the code through a standard user interface for user-defined constitutive models, i.e., the UMAT routine. Such UMAT routine is already available for the isothermal version of the Hypo model, from the SoilModels.com website. For the thermo-hypoplastic model Hypo-T, the standard adaptive Runge-Kutta-Fehlberg algorithm of order 2/3 (RKF-23 algorithm), with adaptive substepping and error control - similar to the one employed by Tamagnini et al., (2000) for sand hypoplasticity – has been modified by the Authors in order to account for the higher level of thermo-mechanical coupling existing in the constitutive equations.
The implementation of the model has been positively validated against the predictions made by Ma et al. (2017) for a drained isotropic consolidation test with thermal cycles on a NC reconstituted illite clay, performed by Campanella and Mitchell (1968).

3. Results of FE analyses

Fig. 2 shows the evolution with time of the vertical displacement at the pile head over 5 full thermal cycles. In isothermal condition the response of the models is clearly the same. It can be noticed that the overall downward displacement predicted by the Hypo-T model during the cyclic temperature variations is the largest as a consequence of the thermal collapse of the NC clay. For both load levels and models, the accumulation of irreversible displacements increases almost linearly with the number of cycles, without showing any stabilization. For the larger static load at the pile head ($Q= 0.6R_t$), due to the higher stress level in the soil and the stronger non-linearity in its mechanical response, the magnitude of the thermally induced displacements is larger.

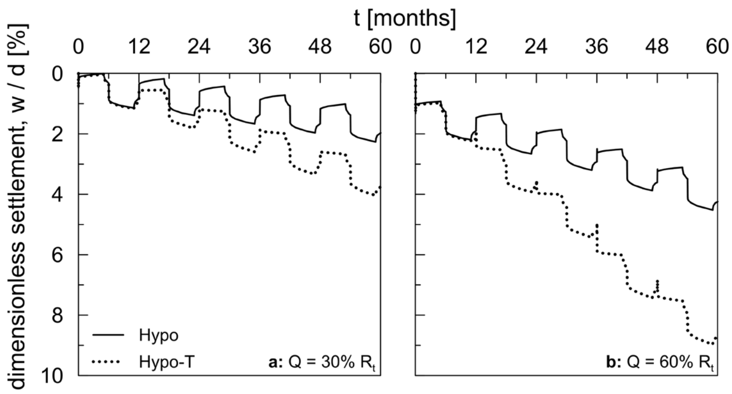

Fig 2. Dimensionless global settlement, free-head pile (Hypo and HT models).

It is interesting to note that at the very beginning of the thermal loading stage the response predicted with the two models is almost identical. To understand this result, it is useful to clarify some fundamental aspects of the behaviour of a saturated soil subjected to a temperature increase.
In absence of volumetric collapse, solid grains experience a volumetric deformation and since the thermal expansion coefficient of the water is larger than that of solid grains (i.e., $\alpha_w > \alpha_s$) the water expands more than the void volume does due to the temperature increase. In drained conditions, this would produce a net water flow leaving the heated soil volume. However, in undrained conditions, the pore water would experience an increase in pore pressure necessary to guarantee the volumetric deformation compatibility between the two phases.
In presence of thermally induced volumetric collapse, the soil skeleton contracts for a positive increase in temperature. It follows that, in drained conditions more water will flow out of the heated soil volume as compared to the case in which no thermal volumetric collapse occur, while in undrained conditions a larger excess pore water pressure will develop. This is clearly visible from figure. 3 which provides the evolution with time of excess pore pressure (at various depths along pile shaft and at pile

base) that is higher for the Hypo-T model.
As far as the response during the thermal cyclic loading is concerned, at the interface, both models predict a progressive accumulation of excess pore water pressure at a decreasing rate which stabilizes within about 3 cycles. Underneath pile base the pore pressure - temperature relationship is hysteretic. To note that the whole process is accompanied by a hydrodynamic consolidation process to dissipate the excess pore water pressures caused by the heating phases. It follows that 5 thermal cycles are not sufficient to obtain stabilization in terms of settlements.

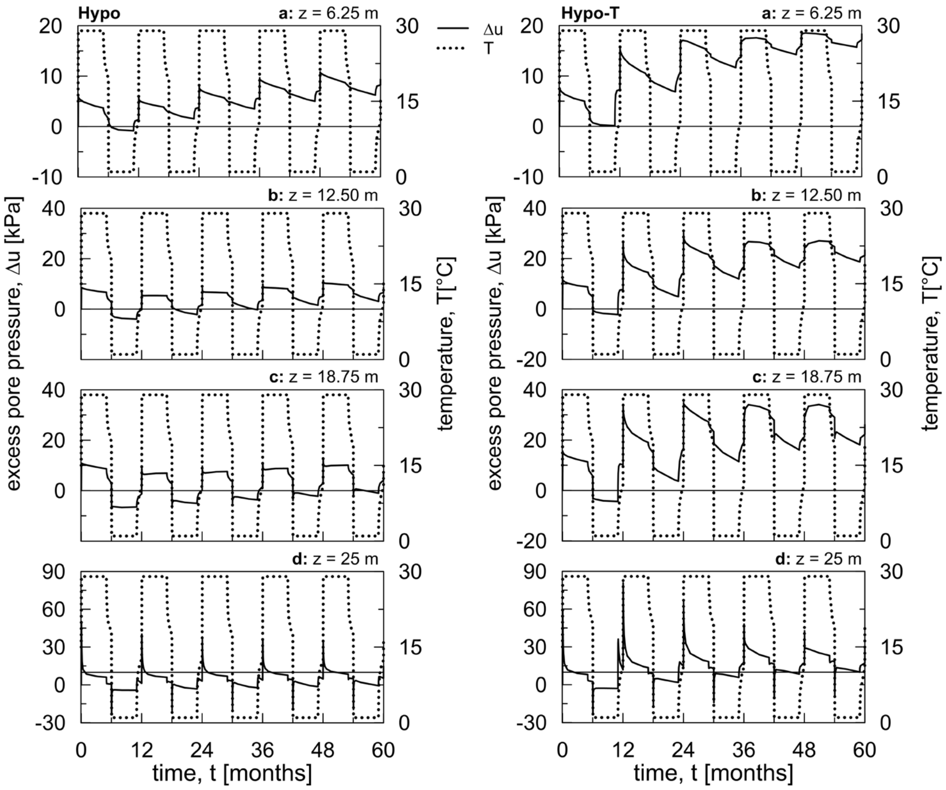

Fig 3. Excess pore pressure developing at pile-soil interface at various depths and at pile base (Q = 30% R_t).

4. Comparison with data available in literature

The results of a very interesting experimental campaign by Wu et al. (2018) are reported in figure 4. The Authors performed a series of tests on small scale floating energy piles (of diameter d = 23 mm and length L = 450 mm) installed in NC saturated clay and subjected to axial mechanical load (around the 40% of the bearing capacity) followed by 5 thermal cycles (14°C and -13°C) under natural gravity. They considered three different testing layouts: (i) energy pile with an adjacent non energy pile without a cap (EP-F), (ii) energy pile with an adjacent non energy pile connected by a cap (EP-R) and (iii) isolated energy pile (EP-S). It is evident that each thermal cycle gives rise to an accumulation of permanent axial displacements which continues even after the end of the fifth thermal cycle. This response is qualitatively very close to the results of the numerical predictions reported in figure 2. The final accumulated displacement at the end of the thermal cyclic loading is about 1.5% of the pile diameter. The accumulation of cyclic settlements is also confirmed by the results of centrifuge tests carried out by Ng et al (2014) for a single pile installed in a lightly overconsolidated clay (OCR=1.7). From the results in the figure, it is also possible to note that the presence of a thermally inactive pile (EP-R test) allows a strong reduction (about 40%) of the accumulated permanent settlement.
From figure 4b, it can be noted that no significant accumulation of excess pore pressure is observed as the number of cycles increases.

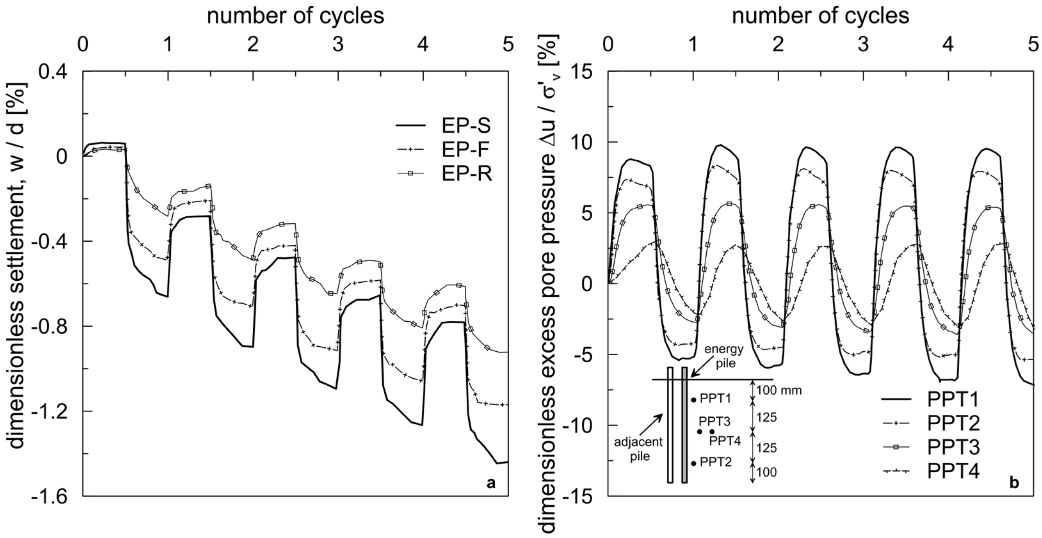

Fig 4. Dimensionless displacement after 5 cycles (a); (b) dimensionless excess pore pressure distribution versus time for EP-F (adapted from Wu et al. 2018).

The different behaviour between numerical analyses and 1-g tests could be due to i) different drainage conditions and ii) temperature-time histories; iii) the presence of thermally inactive pile; iv) the adoption of a constant coefficient of water expansion α_w in the numerical simulations, in place of a more realistic temperature-dependent function, which would allow to better reproduce the hysteretic response. An important role in the development of excess pore water pressures in the soil surrounding the energy pile is played by the combination of soil permeability – which controls the duration of the consolidation process – and the imposed heating rate. In the simulations performed in this work, a heating rate of 14 °C/day has been considered, in a soil with a permeability of 10^{-10} m/s. The results appear in agreement with the that by Salciarini et al. (2017), who analysed the response of an energy piled raft in a clay soil subjected to a heating rate of 0.2 °C/day. On the other hand, when the soil is characterized by a much higher hydraulic permeability (i.e., 10^{-7} m/s) the excess pore water pressures resulting from thermal loading at such low heating rates are almost negligible, and the soil deformation can be considered to occur in drained conditions.

5. Conclusions

The performance of energy piles installed in a soil subjected to heating-induced volumetric collapse has been investigated by means of a numerical study carried out on a free-head energy pile embedded in NC clay. Two advanced hypoplasticity models for fine-grained soils have been considered, one of which capable of reproducing the thermo-mechanical coupling effects experimentally observed. An explicit algorithm with adaptive substepping and error control has been developed for the implementation of this model in the Abaqus Standard FE platform. In the simulations with the Hypo-T model, due to the low soil permeability and the high thermal loading rate adopted, the thermal volumetric collapse of the NC clay is prevented during the heating stages of each cycle; therefore, larger excess pore water pressures are predicted than in the case of standard Hypo model. Both models reproduce accumulation of irreversible displacements without stabilization. This might be attributed to the following two factors. First, excess pore pressure dissipation occurs due to the concurrent consolidation process which, in turns, generates soil deformations and pile head settlements; second, the soil elements are subjected to stress changes generated by the complex soil-pile interaction processes which are much different to those imposed in laboratory tests reported in the literature. The results obtained from the numerical simulations appear qualitatively comparable to the experimental observations made by Wu et al. (2018) on small scale models of energy piles subjected to thermal cyclic loading. It is worth noting that the analyses carried out in the present study refer to a single free-head energy pile whose behaviour is similar to that of a group in which all the piles are thermally activated, while the presence of inactive piles connected to the same cap may significantly reduce the magnitude of the irreversible pile head displacements. As a consequence of the above findings and preceding literature studies, the latter configuration is the only design option when the settlements due to the cyclic temperature variations threaten the serviceability of the supported structure. In this case, a careful design of the foundation is necessary to satisfy safety requirements by technical codes.

References

Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, C. and 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. Géotechnique, 56(2):81–122.

Burghignoli, A., Desideri, A., and Miliziano, S. (2000). A laboratory study on the thermomechanical behaviour of clayey soils. Canadian Geotechnical Journal, 37(4), 764-780.

Campanella, R. G., and Mitchell, J. K. (1968). Influence of temperature variations on soil behaviour. Journal of Soil Mechanics and Foundations Div. Vol. 94(3), pp. 709–734, 1968.

Cekerevac, C., and Laloui, L. (2004). Experimental study of thermal effects on the mechanical behaviour of a clay. International journal for numerical and analytical methods in geomechanics, 28(3), 209-228.

Dassault Systemes (2014). Abaqus Analysis User Guide v6.14. Dassault Systèmes Simulia Corp., Providence, RI, USA.

Iodice, C., Di Laora, R. and Mandolini A. (2020). Analytical solutions for Ultimate Limit State design of thermal piles. Journal of Geotechnical and Geoenvironmental Engineering, ASCE. 146(5), 04020016.

Iodice, C., Di Laora, R. and Mandolini A. (2021). A practical method to design thermally stressed piles. Géotechnique, 1-14.

Kolymbas, D. (1991). An outline of hypoplasticity. Archive of applied mechanics, 61(3), 143-151.

Laloui, L., Nuth, M. and 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.

Ma, Q. J., Ng, C. W. W., Mašín, D. and Zhou, C. (2017). An approach for modelling volume change of fine-grained soil subjected to thermal cycles. Canadian Geotechnical Journal, 54(6), 896–901.

Mašín, D. (2005). A hypoplastic constitutive model for clays. International Journal for Numerical and Analytical Methods in Geomechanics, 29(4), 311-336. Mašín, D.: Hypoplastic Cam-clay model. Géotechnique 62(6), 549–553 (2012).

Mašín, D., and Khalili, N. (2012). A thermo-mechanical model for variably saturated soils based on hypoplasticity. International journal for numerical and analytical methods in geomechanics, 36(12), 1461-1485.

Mašín, D. (2019). Modelling of Soil Behaviour with Hypoplasticity: Another Approach to Soil Constitutive Modelling. Springer.

Ng, C. W. W., Shi, C., Gunawan, A. and Laloui, L. (2014). Centrifuge modelling of energy piles subjected to heating and cooling cycles in clay. Geotechnique letters, 4(4), 310–316.

Niemunis, A., & Herle, I. (1997). Hypoplastic model for cohesionless soils with elastic strain range. Mechanics of Cohesive-Frictional Materials, 2(4), 279-299.

Salciarini, D., Ronchi, F., and Tamagnini, C. (2017). Thermo-hydro-mechanical response of a large piled raft equipped with energy piles: a parametric study. Acta Geotechnica, 12(4), 703-728.

Sutman, M., Olgun, C. G., and Laloui, L. (2019). Cyclic load–transfer approach for the analysis of energy piles. Journal of Geotechnical and Geoenvironmental Engineering, 145(1), 04018101.

Tamagnini, C., Viggiani, G., & Chambon, R. (2000). A review of two different approaches to hypoplasticity. Constitutive modelling of granular materials, 107-145.

Tamagnini, C., Viggiani, G., Chambon, R., and Desrues, J. (2000). Evaluation of different strategies for the integration of hypoplastic constitutive equations: Application to the CLoE model. Mechanics of Cohesive-frictional Materials: An International Journal on Experiments, Modelling and Computation of Materials and Structures, 5(4), 263-289.

Vega, A., and McCartney, J. S. (2014). Cyclic heating effects on thermal volume change of silt. Environmental Geotechnics, 2(5), 257-268.

Wu, D., Liu, H. L., Kong, G. Q., Ng, C. W. W., and Cheng, X. H. (2018). Displacement response of an energy pile in saturated clay. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 171(4), 285-294.