Load-Transfer Approach for Modelling the Cyclic Thermo-Mechanical Behaviour of Energy Piles

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Introduction

Energy piles are subjected to short- and long-term cyclic thermal loads due to their unique role as heat exchangers. Their response to monotonic temperature change has been investigated by various researchers from both experimental and numerical points of view. Yet, their behaviour during cyclic temperature changes remained to be an obscure area to this date. To investigate this knowledge gap, a two-dimensional finite elements model has been developed employing the load-transfer approach coupled with Masing's Rule. The model has been validated by the results of an in-situ test which involved application of multiple temperature cycles to a full-scale energy pile.

Methodology

A two-dimensional (2D), axisymmetric finite elements model was developed using COMSOL Multiphysics Software (Comsol 2014) to simulate the response of energy piles to cyclic thermo-mechanical loads. The top of the pile is either free or partially restricted by a spring on top, depending on the presence of the mechanical load during temperature cycles. The soil-pile interaction at the pile shaft is represented by springs, acting between the soil and the pile, having both tangential and normal components. The soil-pile interaction at the toe of the pile has only a normal component represented by a spring. The algorithm for both shaft and toe resistance has been developed by coupling the load-transfer approach with Masing's rule (Masing 1926). The model presented herein allows the implementation of various approaches to define the soil-energy pile interaction. For the present study, three approaches have been implemented: (1) experimental approach (direct input from pile load test), (2) analytical approach (Randolph and Wroth 1978), (3) empirical approach (Frank and Zhao 1982). The same pile and soil properties, as well as soil resistance limits were used for all three approaches. Therefore, the only difference between the three approaches is the stiffness of the load-transfer curves.

The model has been validated using the results of a full-scale field test where five heating-cooling cycles with a maximum of 43°C and minimum of 8°C were applied to an energy pile, Test Pile-1 (TP-1), over a period of 6-weeks. For this purpose, the model is employed for 37 temperature changes, extracted from vibrating wire strain gages (VWSG), for each day of the field test without being interrupted, so that the mobilized shaft resistance, axial stress and axial displacement during each temperature change constitute the initial condition for the subsequent step. More information on the field test setup, soil profile, test pile and test procedure can be found on Sutman et al (2013).

Results

Thermally induced axial stresses and mobilized shaft resistance during the first heating-cooling episode for the three different load-transfer approaches are presented in Fig. 1 (a,b,e,f representing the heating episode and c,d,g,h representing the subsequent cooling episode). Full-scale field test results are presented in the figures as well, which are calculated using the strain data recorded by VWSGs.

A weaker agreement between the numerical and experimental results is observed in Fig. 1, during the first day of heating period, which can be attributed to not considering the residual stresses from the installation of TP-1 and the application of pile load test prior to thermal cycles. Both numerical and experimental results, in terms of thermally induced axial stresses, are very close to zero on top of TP-1, which is due to the absence of a structural load during thermal cycles. It can be observed from the field test results, as well as the model outputs, that the thermally induced axial stress has a transition from being compressive to tensile in nature, during the shift from the heating to cooling episode. Moreover, after the heating episode, the magnitude of the thermally mobilized shaft resistance decreases along the entire length of the pile on the first day of cooling and eventually changes direction as the pile was cooled further.

Comparison of the numerical and field test results points out a better consistency when the experimental approach was employed, which might be expected as the load-transfer curves were determined directly from the pile load test data. Furthermore, it is observed that the empirical approach yields similar results to the experimental one since the two approaches have comparable soil-pile stiffness, particularly along the initial parts of the load-transfer curves. On the other hand, the results of the analytical approach show lower thermally induced axial stresses which can be attributed to the significantly lower stiffness of the load-transfer curve, which has two main consequences: (i) less restriction to the thermal elongation/contraction, which is the reason behind significantly lower thermally induced axial stresses; (ii) lower shaft resistance mobilization per unit axial displacement of the pile. Although (i) points out higher thermal axial displacement along TP-1 due to lower restriction, (ii) overcomes this effect, yielding an overall lower shaft resistance mobilization in comparison with the field test results.

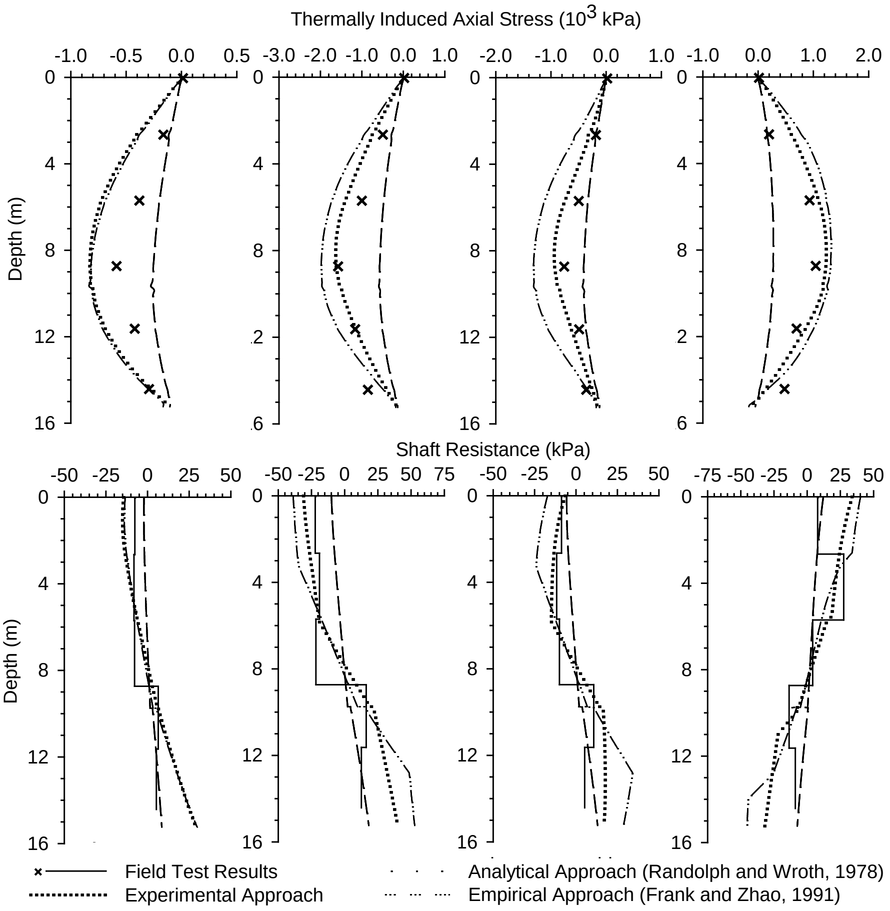

Fig. 1: Thermally induced axial stress and shaft resistance during the first heating-cooling episode

Conclusion

This investigation shows that coupling of load-transfer approach with the Masing's Rule is competent in modelling the cyclic thermo-mechanical behaviour of energy piles, yet, the choice of a proper load-transfer relationship for the soil-energy pile interaction is of paramount importance. Comparison of the three different load-transfer approaches shows that although the same resistance limits were assigned, along with the identical soil and pile properties, three load transfer approaches yielded disparate results, revealing the significance of assigning proper load-transfer curve stiffness during analysis.

References

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