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Thermomechanical behaviour of soils and soil-structure interfaces in thermo-active geo-structures

Ali Golchin [1,*], Michael A. Hicks [1] and Philip J. Vardon [1]

[1]Section of Geo-engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands. A.Golchin@tudelft.nl, M.A.Hicks@tudelft.nl, P.J.Vardon@tudelft.nl
* Corresponding author:

In recent years, the demand for sustainable, low carbon-emission energy solutions has risen, leading to an increased interest in shallow geothermal energy systems. These systems, such as ground source heat pump (GSHP) systems, harness the Earth's stable temperature at shallow depths as a heat sink and source of energy. Energy piles are a type of GSHP system that performs both structural and thermal energy-exchange functions [e.g. 1]. Despite the technological advantages of these systems, understanding the thermomechanical behavior of soils and soil-structure interfaces remains a challenge, limiting safe, efficient, and cost-effective designs. This research aimed to address these challenges by developing thermomechanical constitutive models for soils, implementing these models in boundary-value solvers, and analyzing the experimental results from direct shear tests performed on soils to understand their thermomechanical behavior at the soil-structure interface. By comprehensively examining the complex interactions between energy piles and surrounding soils, the research results offer a foundation for improved design standards and implementation.

The methodology followed the following three main directions:

Development of thermomechanical constitutive models for soils: A thermomechanical constitutive model based on the thermodynamic framework of Hyperelasticity-Hyperplasticity was developed to capture the major thermomechanical behaviors of fine-grained soils when subjected to temperature variations [2]. By utilizing a flexible yield surface within the framework, a more precise representation of soil behavior can be simulated. This framework was extended to develop a dual-surface thermomechanical model with an additional yield surface and a temperature-dependent kinematic rule to capture the shakedown behavior of soils subjected to heating-cooling cycles more accurately [3], as illustrated in Figure 1 (left) where two triaxial tests are simulated. The enhanced model addresses the need for improved representation of diverse soil behaviors and their implications for the performance of energy pile systems.

Numerical aspects to improve simulation capability: A new flexible yield function was introduced that addresses the common issue of undesired elastic domains and erratic or divergent gradients in the numerical implementation of constitutive models with flexible yield surfaces and plastic potentials for use in implicit stress integration schemes [4]. By providing a robust and efficient framework for return mapping algorithms, this new yield function supports more precise simulations of soil behavior. An advanced numerical algorithm was devised to implement the thermomechanical constitutive model within a boundary-value solver such as the finite-element method [5]. The algorithm incorporates Gibbs energy potential, Lode angle dependency, and additional features to ensure accuracy, robustness, effectiveness, and convergence during simulations.

Experimental analysis of the soil-structure interface including the impact of initial shear stress and thermal cycles: Laboratory-scale direct shear tests were conducted on fine- and coarse-grained soils to investigate their thermomechanical behavior at the interface with a concrete structure [6, 7]. A focus here was on the impact of thermal cycles; in particular, under realistic working stress conditions. Figure 1 (right) presents example results, where thermal cycles are applied in a temperature controlled shear box, with a clay-concrete interface which had a constant shear stress. Thermal creep is observed, which also has a hardening effect on

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future shear loading. By exploring the variations in soil behavior under differing temperature and loading conditions, the research deepens the understanding of the complexity inherent in soil-pile interactions for energy pile applications.

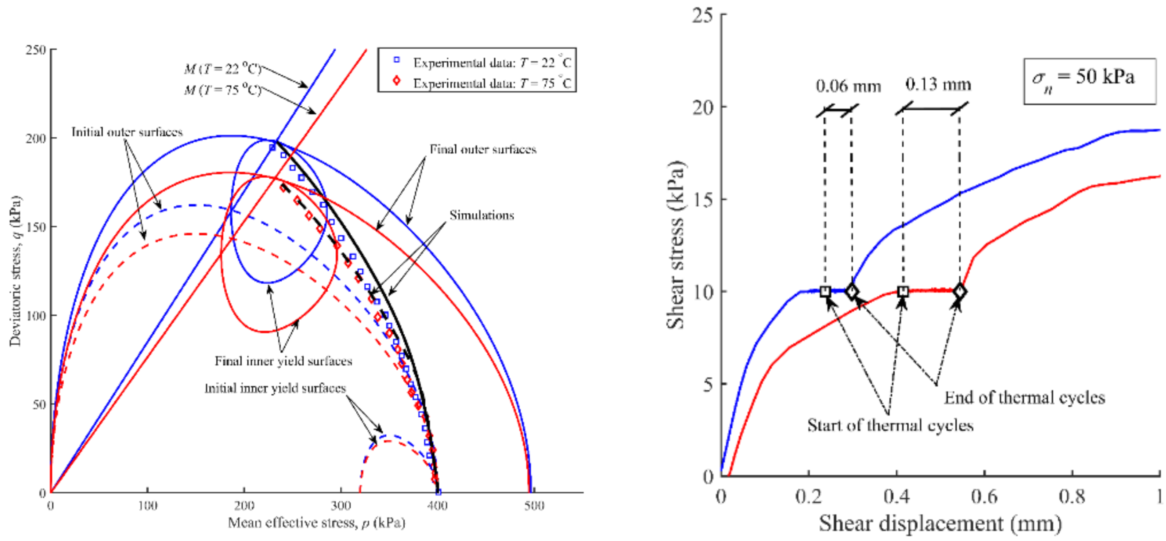

Figure 1: left: simulated undrained triaxial tests at different temperatures using the bubble model [3], right: example results of thermal creep from a clay-concrete interface with fixed thermal cycles applied during a fixed shear stress [6].

This comprehensive investigation of the thermomechanical behavior of soils and soil-structure interfaces in the context of thermo-active geo-structures represents an essential step forward in optimizing energy pile systems for diverse applications. The developed constitutive models, numerical algorithms, and experimental analyses contribute valuable insights for improving energy pile design, ultimately leading to more efficient, safe, and cost-effective solutions.

Future research should continue refining our understanding of the complex processes governing soil behavior in energy pile systems, with emphasis on consolidating the developed models and their implementation for a range of soil types and conditions. Additionally, further experimental studies should focus on elucidating the interactions between soils, piles, and the broader environment to identify potential opportunities for maximizing the performance of energy pile systems through innovative design and implementation.

Contributor statement

Ali Golchin: Methodology development, conceptualization, experimental design, modeling and simulation, writing, reviewing; Philip J. Vardon: Methodology development, conceptualization, reviewing; Michael A. Hicks: Methodology development, conceptualization, reviewing.

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