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Thermo-Hydro-Mechanical Analysis of Geothermal Piles: Implications for Shaft Bearing Capacity

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Summary

Undrained heating of clays under a non-isotropic stress state represents a worst-case scenario for the stress evolution under field conditions near an embedded heat source, such as in the heating phase in geothermal piles, where the temperature increase may raise pore pressure significantly. Indeed, the increase in pore pressure may be very large and approach shaft friction reduction at the pile–soil interface. To address this, we enhanced a viscoplastic model that was originally developed for rock joints to incorporate non-isothermal conditions to be employed in the THM simulation of shaft bearing capacity of geothermal piles. The developed framework was applied to a full-scale in situ geothermal piles test. The research indicates that with low permeability combined with elevated temperatures, effective stress is significantly reduced in pile-soil interface due to developed excess porewater pressures (pwp).

1 Introduction

Thermal loading induces volumetric changes in both the solid and fluid phases, generating excess pwp when drainage is constrained [1, 2]. In low-permeability clays, this process can lead to significant reductions in effective stress and, consequently, in shaft resistance at the pile–soil interface [3]. Prior studies have emphasized the role of permeability and compressibility in controlling pore pressure response during thermal loading [3, 4], identifying critical thresholds below which pressure buildup becomes dominant. Field observations confirm that these pressures are not only transient but may persist over the timescales of geothermal operation, particularly under repeated thermal cycles [5].

This paper advances a coupled thermo-hydro-mechanical (THM) framework for simulating the response of geothermal piles under non-isothermal conditions. The proposed approach enhances a viscoplastic constitutive model originally developed for rock joints [6], extending it to incorporate temperature-dependent yielding and time-dependent deformation under finite strain [7, 8]. A parametric analysis is conducted to examine the role of soil permeability and heating intensity on excess pore water pressure generation in soil-pile interface and shaft resistance degradation. The framework is then applied to reproduce the results of a full-scale geothermal pile test at EPFL [9].

2 Numerical simulation and Discussion

The full theoretical development and numerical implementation are detailed in [7]. This model is implemented in the finite element code `CODE_BRIGHT` [10], and applied to simulate a full-scale geothermal pile test conducted at EPFL [9]. The model domain, the finite element mesh and boundary condition used are depicted in Fig. 1.

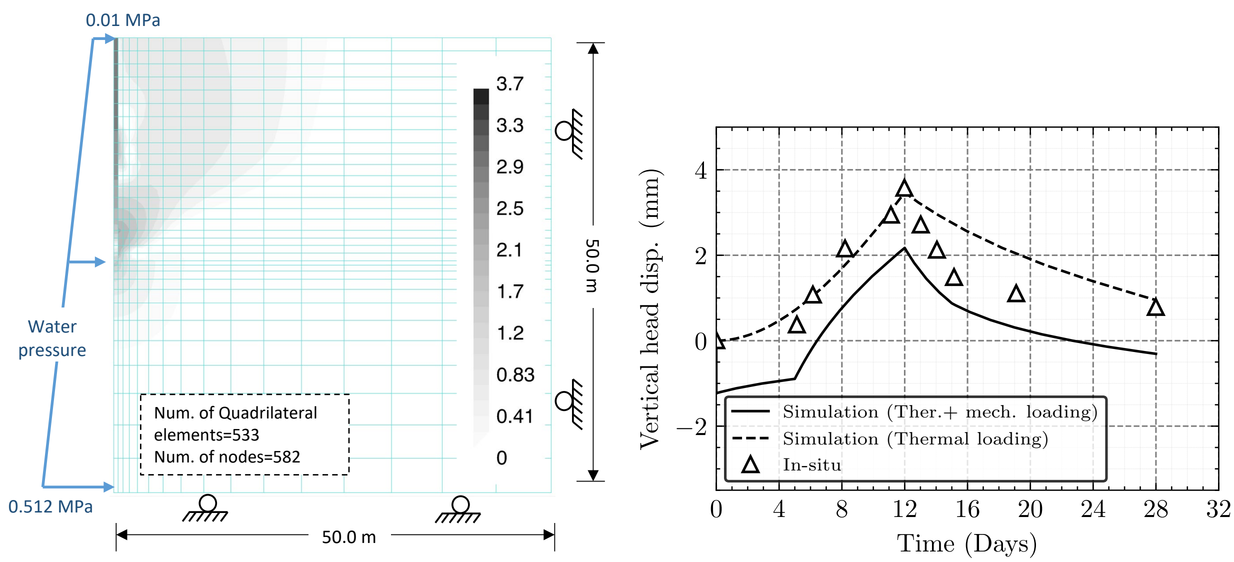

Figure 1: (Left) Domain, finite element mesh and boundary conditions and computed contours of pile vertical displacement (mm); (Right) Pile head vertical displacement.

To evaluate the impact of hydraulic and thermal conditions on pore pressure generation, excess pwp at the pile–soil interface were computed for varying permeability values (10^{-6}–10^{-14} m^2) and fluid temperatures (21–50°C). The simulations show a pronounced increase in excess porewater pressure with decreasing permeability, as lower permeability values inhibit dissipation and favour pressure accumulation during heating. In addition, for a given permeability, higher fluid temperatures result in consistently greater excess pore pressures due to enhanced thermal expansion of pore fluid and solid matrix. These results, presented in Fig. 2 (Left), confirm the coupled influence of permeability and temperature on transient pore pressure behaviour.

To analysis the effect of excess pwp generated by thermal loading on the shaft resistance, a depth-wise reduction factor is defined as:

$$\alpha(z) = \max\left[0,\ 1 - \frac{\Delta u(z)}{\sigma'_v(z)}\right], \quad f_{s,\mathrm{red}}(z) = \alpha(z) f_{s,0}, \tag{1}$$

where $\Delta u(z)$ is the excess porewater pressure, $\sigma'_v(z) = \gamma' z$ is the initial vertical effective stress, and $f_{s,0}$ denotes the reference unit shaft resistance in the absence of excess pore pressure.

Parametric simulations across a range of permeability and temperature values Fig. (2, right) confirm that reductions in f_s become more severe with increasing permeability and fluid temperature. These trends are consistent with the growth of excess pwp under undrained thermal conditions, particularly in soils with limited drainage capacity.

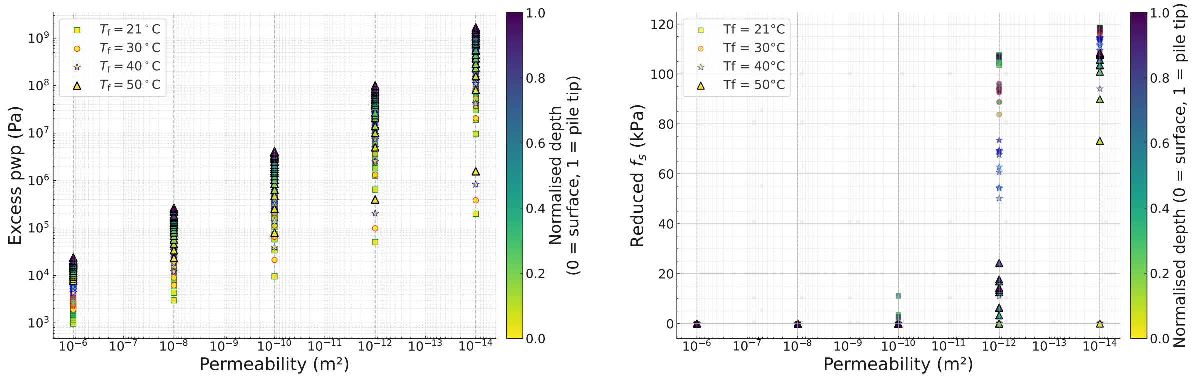

Figure 2: (Left) Excess pwp vs. permeability; (Right) Shaft resistance reduction ratio vs. permeability.

2.1 Application to In-situ Test

The model applied to EPFL geothermal pile data [9] reproduces both the time-history of pile head displacement and the spatial displacement field around the pile. As shown in Fig. 1 (Right), the simulated vertical displacement curve tracks the field measurements with a peak of about 3.6 mm at day 12. Fig. 1 (Right) presents the computed contours of vertical displacement at day 20 on a log scale, illustrating how the maximum pile displacement localizes near the pile head and decays rapidly with depth and radial distance.

3 Conclusions

In this work, we extend a numerical framework—originally developed to rock joint—to the context of geothermal energy piles. The non-isothermal viscoplastic interface model, previously validated for temperature-dependent degradation in clay-rich materials, is applied here to evaluate the evolution of excess porewater pressure of interface elements and its impact on shaft resistance at the pile–soil interface. The simulations reveal that under undrained thermal loading, excess pore pressures can rise significantly, particularly in low-permeability soils, leading to a substantial reduction in effective stress and interface shear strength. A simple yet effective reduction formulation is introduced to quantify the degradation in shaft resistance as a function of permeability, temperature, and depth. Application of the model to a full-scale geothermal pile test confirms its capacity to reproduce observed trends in thermal displacement and pore pressure evolution.

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