Influence Mechanism of Temperature Gradient on Consolidation of Soft Clay Foundation in PVTD Technology (Postprint)

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Abstract

This study establishes a fully coupled thermo-hydro-mechanical (THM) finite element model based on non-equilibrium thermodynamics theory. The model innovatively introduces bound water temperature and particle temperature parameters to characterize microscopic thermal effects, systematically revealing the influence mechanism of temperature gradients on PVTD consolidation behavior. By comparing with the Bangkok clay test data from Abuel-Naga et al. (2006), the model demonstrates good accuracy in predicting temperature field distribution, temperature-induced deformation, and consolidation settlement in thermal PVD systems. The research results indicate: (1) Temperature-driven hydraulic property optimization: temperature increase (20–90°C) significantly reduces pore water dynamic viscosity (to 1/3), thereby substantially enhancing hydraulic conductivity; (2) Thermal creep-dominated consolidation acceleration mechanism: temperature cycles induce irreversible volume contraction, with its microscopic contribution ratio being—thermal creep caused by bound water migration to free water (77.7%), isothermal mechanical creep (17.7%), and particle packing effect (4.6%); (3) Critical influence of temperature gradients: simulations of different heat source locations indicate that consolidation efficiency is highest when the heat source is concentrated around the PVD drain. At this time, thermal effects can maximally act on critical drainage areas such as the smear zone, consistent with the experimental conclusions of Abuel-Naga et al. (2006). Non-uniform temperature distribution will induce non-uniform settlement; if the heat source is fixed on the drain board, it will lead to reduced porosity in the surrounding area and inhibit drainage; (4) Thermally induced excess pore pressure and settlement effects: the superposition of thermal expansion of particles and water with thermal contraction promotes the generation of thermally induced excess pore water pressure, thereby significantly increasing soil settlement magnitude. These findings provide solid theoretical support for the engineering optimization design of PVTD technology, and profoundly

elucidate the physical mechanism by which temperature gradients effectively suppress smear effects and significantly accelerate consolidation by regulating microscopic thermo-hydro-mechanical processes.

Full Text

Mechanisms of Thermal Gradient Effects on Soft Clay Consolidation in PVTD Systems

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Abstract

This study develops a fully coupled thermo-hydro-mechanical (THM) finite element model based on non-equilibrium thermodynamics theory. The model innovatively introduces bound water temperature and particle temperature parameters to characterize microscopic thermal effects, systematically revealing the influence mechanisms of temperature gradients on PVTD consolidation behavior. Through comparison with experimental data from Bangkok clay reported by Abuel-Naga et al. (2006), the model demonstrates good accuracy in predicting temperature field distribution, thermally induced deformation, and consolidation settlement in thermal PVD systems.

The results reveal several key mechanisms. Temperature-driven optimization of hydraulic properties occurs as temperature increase (20–90°C) significantly reduces pore water dynamic viscosity (to one-third), substantially enhancing hydraulic conductivity. Consolidation acceleration is dominated by thermal creep, with temperature cycles inducing irreversible volumetric contraction. Microscopic contributions to this process include bound water migrating to free water (77.7%), isothermal mechanical creep (17.7%), and particle packing effects (4.6%). Regarding temperature gradients, simulations demonstrate that consolidation efficiency is maximized when the heat source is concentrated around the PVD drain, allowing thermal effects to act most effectively upon the smear zone and other critical drainage areas—consistent with findings from Abuel-Naga et al. (2006). However, non-uniform temperature distribution induces differential settlement, while fixing the heat source at the drain board reduces surrounding porosity and inhibits drainage. Finally, thermally induced excess pore pressure and settlement effects arise from the superposition of thermal expansion and contraction of particles and water, promoting generation of thermally induced excess pore water pressure and significantly increasing soil settlement.

These findings provide solid theoretical support for the engineering optimization design of PVTD technology. The study elucidates the physical mechanisms through which temperature gradients effectively suppress smear effects and significantly accelerate consolidation by regulating microscopic thermo-hydro-mechanical processes.

Keywords: Prefabricated Vertical Thermal Drain (PVTD); temperature gradient; thermo-hydro-mechanical coupling (THM); soft ground consolidation; smear effect; thermal creep; particle temperature

Note: Figure translations are in progress. See original paper for figures.

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