Boundary value level simulation of monotonic and cyclic thermal oedometer tests on natural sensitive clay

Yanling Li[1 *], Mats Karlsson[1], Jelke Dijkstra[1], Minna Karstunen[1]

[1] Chalmers University of Technology, Gothenburg, Sweden
* yanling.li@chalmers.se

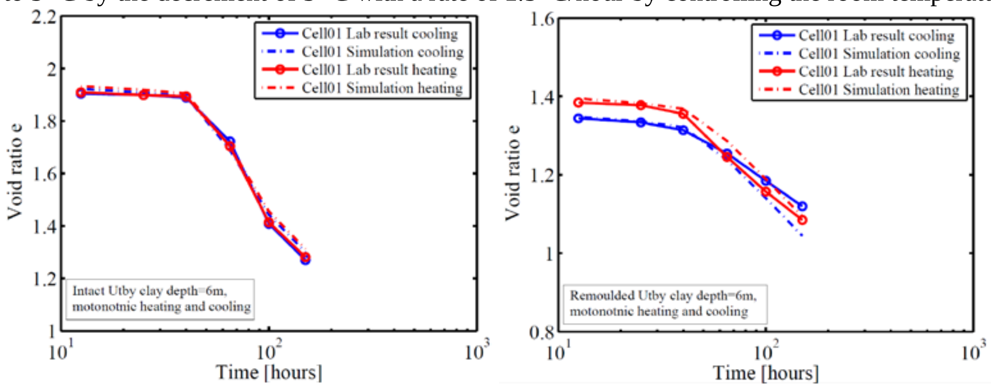
Introduction

The mechanical behaviour of the soil surrounding Energy piles, especially in soft sensitive clay, is susceptible to mechanical loading during pile installation, followed by subsequent mechanical and thermal loading (Akrouch et al., 2014). This is a complex boundary value problem. Similarly, the interpretation of thermo-hydro-mechanical laboratory tests need to be done at boundary value level. The latter requires fully coupled modelling of the mechanical, hydraulic and thermal components.

Thermal constitutive models are usually used as an effective tool in predicting the soil behaviour under thermo-mechanical loads (Hueckel & Baldi, 1990, Cui et al., 2000, Abuel-Naga et al., 2007). Most of these models are rate-independent or aimed at soil under extreme temperature changes. As a result, these models are less suitable for modelling the soils around Energy piles in Scandinavia, where soft sensitive soils are common and the temperature varies slowly in a rather limited range (5 ºC to 25 ºC). The thermal load that the soils around Energy piles are usually subjected to changes seasonally, hence only a limited number of thermal loading cycles will be endured during the life-span of an Energy pile. Therefore, the first reasonable approach adopted here is to use an advanced creep model (Creep-SCLAY1S) in a fully coupled numerical framework (flow and heat equations), without explicitly modelling thermal softening. First, the model is calibrated at boundary value level on unique monotonic test data gathered on saturated intact and remoulded Swedish sensitive clays. Then the long-term response of the sensitive soils under repetitive temperature changes will be predicted using COMSOL Multiphysics.

Monotonic test simulation and calibration

Temperature controlled oedometer tests were conducted on sensitive clay from the Utby area in Gothenburg. In the laboratory tests, combined thermal and mechanical loads were designed and applied to both intact and remoulded samples from the depth of 6 meters. The apparent preconsolidation pressure σ'_{pc} for the intact samples from 6 meters was 54 kPa in CRS (Constant Rate of Strain) tests. Three remoulded samples were created from the soil from the same depth as the intact samples, by remoulding and reconsolidated to the in-situ stress σ'_{v0}, 45 kPa. Monotonic heating was proceeded from 5 ºC to 25 ºC by increment of 5 ºC whilst monotonic cooling was from 25 ºC to 5 ºC by the decrement of 5 ºC with a rate of 1.5 ºC/hour by controlling the room temperature.



(a) Intact sample (b) Remoulded sample

Fig. 1: Simulation on monotonic heating and cooling tests on Utby clay from the depth of 6 meters

An axisymmetric model (18mm in height and 25mm in diameter) of the soil sample was built in COMSOL Multiphysics for fully coupled analysis. The rate-dependent constitutive model Creep-SCLAY1S (Sivasithamparam et al., 2015, Gras et al 2015, 2017) for sensitive soil was implemented by Olsson (2013) in COMSOL Multiphysics. Coupled with fluid flow, as well as heat transfer, the model is used to simulate and predict the mechanical response of saturated soil upon temperature change when following the test procedure described in Li (2018). The sample in the model is heated and cooled from the outside boundaries with open drainage on the top.

The parameters for the Creep-SCLAY1S were obtained from the compression curves and displacement-time curves from both intact and remoulded samples by curve fitting. The stress strain relationship can be well captured by the model with the acquired data as plotted in Fig.1. For remoulded samples, the intrinsic compression index λ is higher in heating tests than in cooling tests as shown in Fig. 1(b) and the average value is used in simulations.

Simulation of oedometer tests under cyclic thermal loading

The clay close to a driven Energy pile is usually disturbed (remoulded) during pile installation, whilst also subjected to the largest temperature change when compared to the intact soil further away from the pile. Therefore, the oedometer tests under drained cyclic thermal loading were first carried out on saturated remoulded clays. Subsequently, the results are further generalised for more load cycles and more realistic loading conditions using the numerical simulations. In the tests on the remoulded clay the samples were first consolidated to three distinct effective vertical stress levels (40 kPa, 65 kPa & 100 kPa) for 48 hours before the cyclic thermal loading. The temperature for cyclic thermal loading was regulated by following Equation 1 using extra heater with PID control. The amplitude of temperature variation was 10 ºC and the average temperature was 15ºC. The period of this cyclic thermal loading was four hours. The thermal and mechanical parameters calibrated against monotonic heating and cooling tests were used in the simulation on oedometer tests under cyclic thermal loading. The simulation results are plotted together with laboratory tests in Fig.2.

$$T = 10 \cdot \sin\left(\frac{t}{4} + w_0\right) + 15 \quad (1)$$

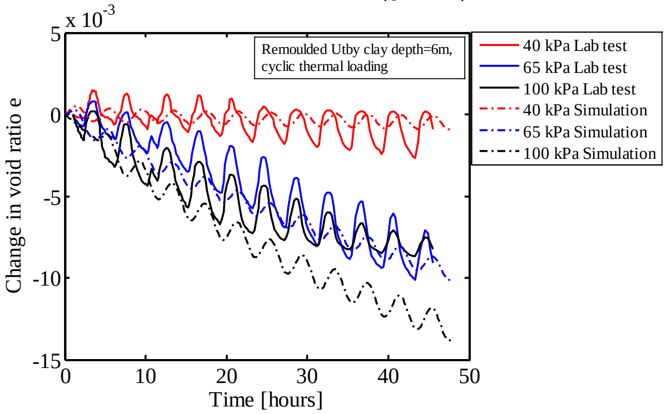


Fig. 2: Simulation on cyclic thermal loading test on remoulded Utby clay

The trend of the changes in void ratio under cyclic thermal loading was well captured by the temperature independent constitutive model as shown in Fig.2, except for the stress level of 100 kPa where the creep rate was higher in the simulation than that in the laboratory tests. The amplitude of the soil expansion and contraction under temperature change was underestimated in the simulation. This could be caused by the underestimation on the thermal expansion coefficient of water, soil particles or the oedometer setup upon temperature change.

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