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Thermo-hydro-mechanical behaviour of a deep plastic clay formation

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Several applications which are framed in the energy geotechnics field, particularly the design of energy geo-structures, energy geo-storage, enhanced geothermal energy systems and radioactive waste disposal, require a thorough thermo-hydro-mechanical (THM) characterisation of their host soil/rock formation. The present study comes up from the need to investigate the THM behaviour of deep Ypresian clays (Ycs, 300 to 400 m below ground) since they are one of Belgium's potential host rock formations for deep geological disposal of heat-emitting and long-lived radioactive waste.

The impact of temperature on the hydro-mechanical response of deep clays has been extensively tackled for the last four decades. Nevertheless, to the authors' knowledge, the study of the evolution of radial stresses during drained thermal paths under oedometer conditions has never been addressed. Such information would allow for drawing a better-defined stress state while accurately measuring volume changes. To this aim, the present study used a newly designed and fully instrumented temperature-controlled oedometer cell [3] combined with well-planned test protocols. The local instrumentation consisted of a pore pressure transducer embedded in the soil 3 mm from the bottom boundary, thermocouples at various positions and radial displacement transducers with a localised thin-wall system to estimate radial stress.

Two well-preserved Ycs core samples retrieved at different depths at Kallo (Belgium) and belonging to distinct lithological units were tested (see Table 1). Both slightly overconsolidated samples (Yield Stress Ratios of Ycs between 1.2 and 1.8, [1, 2, 3]) presented high initial matric suctions induced on deep water-undrained sampling. Consequently, the first stage of the well-planned test protocol consisted of loading at constant water content to bring the samples to the large *in situ* stresses and diminish the induced matric suction. The remaining matric suction was then reduced by soaking with synthetic water equivalent to *in situ*. Afterwards, drained loading and unloading paths were followed to attain different vertical effective stresses at varying overconsolidation ratios (*OCRs*) before performing the main research goal of drained thermal paths. The heating-cooling (H-C) cycles consisted of slowly stepwise increase/decrease in temperature (steps of 10ºC) with intermediate stabilising periods of around 15 hours controlled by the embedded pore pressure transducer.

Figure 1 depicts the vertical deformation in terms of the mean effective stress (p') beyond *in situ* stress. Changes in radial stresses ruled the variations in p' during heating-cooling cycles since the vertical effective stress was kept constant during non-isothermal paths. At a slightly overconsolidated (OC) state (Core-48), the drained '1st H-C' cycle showed a quasi-reversible response in volume changes and radial stresses. At OC state (*OCR*=2) on Core-103 ('2nd H-C'), the response was reversible. However, the induced volume change in normally consolidated (NC) states was not reversible with a contractive response dependent on the stress level. Therefore, the nature of the thermal-induced volume changes aligned with the behaviour observed on other plastic clays. Nevertheless, the stress dependence of the contractive response at NC state differed from the observations made by [4] on NC Boom Clay - the other poorly indurated clay considered as potential host rock in Belgium. As observed in '2nd H-C' (NC conditions) on Core-48, a reduction of the radial effective stress was only recorded at temperatures higher than 70°C. In contrast, the radial effective stress systematically increased on heating at values < 70°C, tending the sample to lower deviatoric stress. This phenomenon might be

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associated with some change in the soil structure on heating that tends to a more isotropic stress state despite the oedometer condition. A clear transition between the elastic and elastoplastic domains was detected during the subsequent loading after each H-C cycle at NC states.

Finally, the study included a thermo-mechanical elastoplastic interpretation: thermal expansion coefficients dependent on temperature and mean effective stress in the elastic domain and thermal softening function on post-yield drained heating.

Table 1. Properties and initial state of tested Ycs core samples.

	Core-48 (335 m)	Core-103 (390 m)
Bulk density, ρ (Mg/m^3)	1.96	2.10
Density of solids, ρ_s (Mg/m^3)	2.72	2.73
Water content, w (%)	22.4	18.4
Void ratio, e (-)	0.701	0.540
Degree of saturation, S_r (%)	87.1	92.8
Initial total suction, ψ (MPa)	3.1	4.1
Particle sizes < 40 μm (%)	99.8	97.0
Particle sizes < 2 μm (%)	31.3	55.7
Liquid limit, w_L (%)	134	61.3
Plasticity index, PI (%)	105	38.1

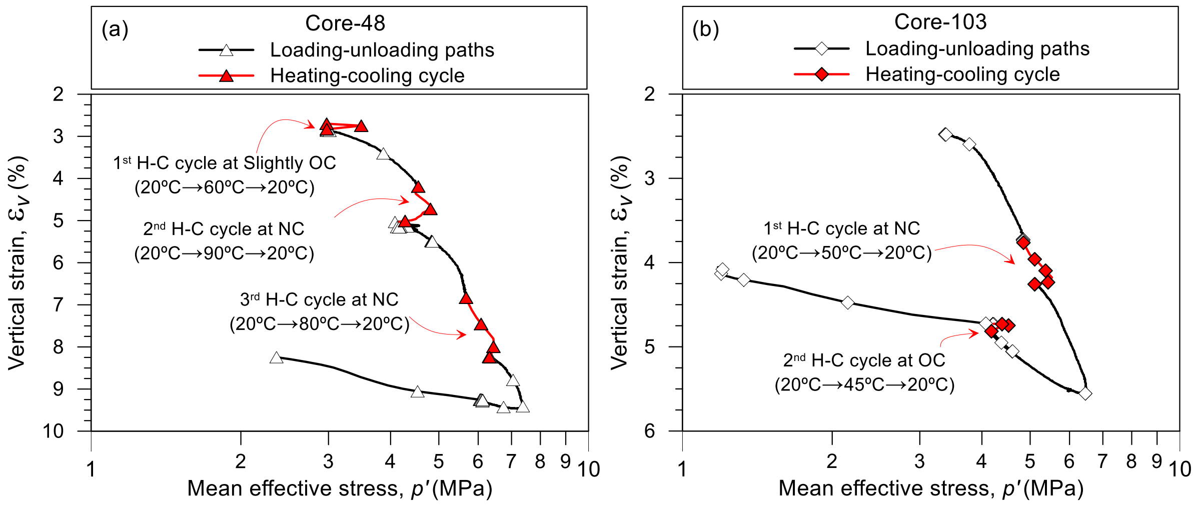

Figure 1: Evolution of vertical strains versus mean effective stress: (a) Core-48, (b) Core-103.

Contributor statement

N. Sau: Conceptualization, Methodology, Experimental work, Formal analysis, Visualization, Writing-Original Draft

E. Romero: Conceptualization, Methodology, Project administration, Resources, Writing-Review & Editing

H. Van Baelen: Conceptualization, Resources, Writing-Review & Editing

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