Thermomechanical behaviour of silty sandy clays: An experimental and numerical investigation

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Thermomechanical behaviour of silty sandy clays: An experimental and numerical investigation

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ABSTRACT: This paper is devoted to the experimental and numerical investigation of the effect of temperature on the volumetric behaviour of silty sandy clay. A temperature-controlled oedometer is developed to study thermally induced volume change. In this system, an electrical ring heater is placed around the conventional oedometer cell, which accommodates the sample. A very low temperature increase rate was achieved by the thermal controller unit to ensure reasonable saturation durations. The interpretation of the test is assisted by the performance of a numerical analysis based on a coupled formulation incorporating the relevant THM phenomena. Heating and cooling at constant isotropic stress show that the thermal volumetric behaviour of clay samples depends on various factors, such as recent stress history prior to the heating and cooling test. The performance and analysis of the thermal consolidation tests have significantly enhanced the understanding of the thermal volumetric behaviour of tested clay and have proved the capability of the numerical formulation to provide adequate modelling capacity.

Keywords: Clay; thermal consolidation; numerical modelling; THM behaviour; oedometer test

1 INTRODUCTION

Emerging sustainable subsurface activities have made it crucial to investigate the hydromechanical behaviour of soils in non-isothermal conditions. Examples of such applications are nuclear waste disposal (Bumbieler et al., 2020; Tourchi et al., 2020), energy geostructures (Adinolfi et al., 2021; Di Donna and Laloui, 2015) and landslides (Loche et al., 2022; Scaringi et al., 2022; Tourchi et al., 2023).

Several laboratory tests have been performed to study thermal volumetric responses of various soils (Baldi et al., 1988; Cekerevac and Laloui, 2004; Romero et al., 2005). Stress history, i.e., over consolidation ratio (OCR), has been highlighted to control the volumetric response of soils during drained heating. Normally consolidated soils exhibit elastoplastic contraction after exposure to drained heating and cooling cycle. The magnitude of plastic contraction will decrease by an increase in OCR value where elastic expansion is observed for highly over consolidated samples.

In their pioneering study, (Campanella and Mitchell, 1968) explained that the thermal consolidation phenomenon occurs due to differential thermal expansion between soil solids and pore water. This discrepancy leads to excess pore water pressure, which is the primary cause of thermal consolidation. However recent studies have highlighted importance of other factors to be considered in order to fully understand the thermal volumetric response of fine-grained soils such recent stress path, physio-chemical interactions, and natural structure. Reconstitution of samples could have impact on volumetric thermal behaviour of fine-grained soils and few studies could be found where intact samples were used, and the natural structure of samples was considered (Hoseinimighani and Szendefy, 2021, 2022).

Hueckel and Borsetto, 1990 developed one of the first thermomechanical model by extending the well-known Modified Cam-Clay (MCC) model to consider thermo-elastoplastic behaviour. The proposed model accounts for the shrinking of the elastic domain during heating (thermal softening) and expansion during cooling when the stress state is within the yield surface. Adopting similar assumptions, subsequent models accounting for temperature effects are based on the same principle (Di Donna and Laloui, 2015; Hamidi et al., 2017; Robinet et al., 1996). In this context, this paper aims to investigate the thermal volumetric response of undisturbed samples of Silty Sandy Clay through experimental and numerical analysis.

2 NUMERICAL MODELLING

The theoretical THM formulation used herein is a particular case of the general formulation presented in Olivella et al., (1994) for saturated and unsaturated media. For space reasons, the formulation is only outlined in this section. The equation of equilibrium of forces (or stresses), the equation of mass balance of water and the equation of mass balance of energy were solved simultaneously to obtain displacements, pressure and temperature at each point and time of the model. Stress and strain invariants follow the soil mechanics notation (positive for compression).

$$\frac{\partial}{\partial t}[\rho_\mathrm{s}(1-\phi)]+\nabla\cdot(\mathbf{j}_\mathrm{s})=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_l\phi)+\nabla\cdot(\mathbf{j}_l)=f^\mathrm{w} \tag{2}$$

$$\frac{\partial}{\partial t}[E_\mathrm{s}\rho_\mathrm{s}(1-\phi)+E_\mathrm{l}\rho_\mathrm{l}S_\mathrm{l}\phi]+ \\ \nabla\cdot(\mathbf{i}_\mathrm{c}+\mathbf{j}_\mathrm{Es}+\mathbf{j}_\mathrm{El})=f^\mathrm{Q} \tag{3}$$

$$\nabla\cdot\boldsymbol{\sigma}+\mathbf{b}=\mathbf{0} \tag{4}$$

where ϕ is porosity; ρ is density, j is total mass flux; σ is the stress tensor; b is the body forces vector; E is the specific internal energy; $\mathrm{i_c}$ is the conductive heat flux; $\mathrm{j_E}$ is the energy flux due to mass motion; f^w is external supply of water; S_l is liquid saturation; and f^Q is energy source term. The solid mass balance (Equation 1) can be eliminated by introducing it into the water mass balance relationship (Equation 2). Making use of the material derivative definition, the following equation results:

$$\phi\frac{\mathrm{D_s}\rho_\mathrm{w}}{\mathrm{D}t}+\frac{\rho_\mathrm{w}}{\rho_\mathrm{s}}(1-\phi)\frac{\mathrm{D_s}\rho_\mathrm{s}}{\mathrm{D}t}+ \\ \rho_\mathrm{w}\nabla\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t}+\nabla(\rho_\mathrm{w}q_l)=0 \tag{5}$$

u is the solid displacement vector; q_l is volumetric flux of liquid; and t is time. The first two derivatives of this expression can be developed further, taking into account the dependences of the liquid and solid densities on temperature, solid pressure and pore pressure:

$$[\phi b_\mathrm{w}+(1-\phi)3b_\mathrm{s}]\frac{\mathrm{D_s}T}{\mathrm{D}t}+\phi\beta_\mathrm{w}\frac{\mathrm{D_s}p_\mathrm{w}}{\mathrm{D}t} \\ +(1-\phi)\beta_\mathrm{s}\frac{D_\mathrm{s}p_\mathrm{s}}{\mathrm{D}t}+\nabla\frac{\mathrm{du}}{\mathrm{d}t}+\frac{\nabla(\rho_\mathrm{w}q_\mathrm{l})}{\rho_\mathrm{w}}=0 \tag{6}$$

Where T is temperature; β_w and β_s are the water and solid compressibilities, respectively, and b_w and b_s are the volumetric and linear thermal expansion coefficients for water and the solid grain, respectively. Equation (6) contains the THM couplings that explain the pore pressure variation when a temperature change is applied to the clay. The first term expresses the differential thermal expansion of the solid and liquid phases. The second and third terms are the volume changes of water and solid phase water associated with a pore pressure change; the fourth term is the volume change of the material skeleton (includes contributions from stresses, pore pressures and temperature); and the fifth term is the volume change associated with the flow of water in or out of the element considered.

2.1 Thermomechanical constitutive model

The numerical simulation of the thermal consolidation of silty sandy clay is performed using the non-isothermal extension of Barcelona Basic Model (BBM) (Alonso et al., 1990). The model captures the important aspects of the thermomechanical behaviour of clays and can well describe the thermal consolidation behaviour under different temperature paths and confining pressures. Although the model is proposed for unsaturated soils, it can be used for saturated soil after modification. This model is briefly described here. Elastic, isotropic, non-isothermal volumetric strains are defined by:

$$\mathrm{d}\varepsilon_\mathrm{v}^\mathrm{e}=\frac{\kappa_i}{1+e}\frac{\mathrm{d}p'}{p'}+\frac{\kappa_s}{1+e}\frac{\mathrm{d}s}{s+0.1}+\alpha\mathrm{d}T \tag{7}$$

where e is the void ratio, κ_i and κ_s are initial elastic slope for specific volume-mean stress and specific volume-suction, respectively, α is elastic thermal strain parameter, p' is net mean stress, s is suction and T is temperature. For deviatoric elastic strains, a constant Poisson ratio is used. Plasticity is accounted for using a Modified Cam-Clay yield surface (and plastic potential) with the following equation:

$$F=q^2-M^2(p'+p_\mathrm{s})(p_0-p')=0 \tag{8}$$

where p_s and p_0 correspond to the intersection of the ellipse with the p'-axis, q is the equivalent shear stress, and M is parameters. The apparent unsaturated preconsolidation pressure (p_o) is a function of suction and temperature in the non-isothermal BBM with the following form:

$$p_\mathrm{o}(s)=p^\mathrm{c}\left(\frac{p_\mathrm{o}^*(T)}{p^\mathrm{c}}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \tag{9}$$

where p^c is reference stress in BBM model, $p_0^*(T)$ is the preconsolidation pressure at a given temperature and staruated condition, $\lambda(0)$ is the slope of the virgin elastoplastic compressibility for saturated soil conditions, and κ is the slope of the unload-reload line (elastic response). The function $\lambda(s)$ is the slope of the virgin elastoplastic compressibility for a given suction (volumetric compressibility index), written as:

$$\lambda(s)=\lambda(0)[(1-r)\exp(-\beta s)+r] \tag{10}$$

where r and β are parameters. The function $p_0^*(T)$ is written as:

$$p_o^*(T) = p_o^* + 2(\alpha_1 \Delta T + \alpha_3 \Delta T|\Delta T|) \tag{11}$$

$$\Delta T = T - T_{ref} \tag{12}$$

where α_1 and α_3 are plastic thermal strain parameters; p_0^* is the precosnoldiation pressure at reference temperature T_{ref} and satruated condition. Finally, considering satruated condition, hardening law for the non-isothermal BBM is given as:

$$\mathrm{d}p_0^* = \frac{1+e}{\lambda(0)-\kappa_i} p_0^* \mathrm{d}\varepsilon_\mathrm{v}^\mathrm{p} \tag{13}$$

where $\mathrm{d}\varepsilon_\mathrm{v}^\mathrm{p}$ is the plastic volumetric strain increment.

2.2 Hydraulic and thermal constitutive models

The fluid flow is governed by Darcy's law, given as:

$$\mathbf{q}_l = -\frac{\mathbf{k}k_\mathrm{rl}}{\mu_1}(\nabla P_l - \rho_l \mathbf{g}) \tag{14}$$

where $\mathbf{q}_\mathrm{l}$ is the volumetric flux of liquid, $\mathbf{k}$ is the intrinsic permeability tensor, k_rl is the phase relative permeability, μ_1 is the viscosity of the fluid, P_l is the pressure of the fluid and ρ_l is the density of the fluid. The degree of saturation for the liquid phase is calculated using the retention curve with the relationship of Van Genuchten; this is written as:

$$S_\mathrm{e} = \frac{S_l - S_\mathrm{rl}}{S_\mathrm{ls} - S_\mathrm{rl}} = \left[1 + \left(\frac{P_\mathrm{g} - P_l}{P}\right)^{1/(1-\lambda)}\right]^{-\lambda} \tag{15}$$

where S_e is the effective degree of saturation of porous media, S_l is the degree of saturation of liquid, S_rl is the residual degree of saturation, S_ls is the maximum degree of saturation, P_g is the gas pressure, P_l is the liquid pressure, λ is the shape function coefficient for the retention curve and P is a parameter that can be interpreted as the pressure of air entrance. The heat transfer process is governed by Fourier´s law, given as the heat flux vector:

$$\mathbf{i}_\mathrm{c} = -\lambda \nabla T \tag{16}$$

where thermal conductivity depends on the degree of saturation in the following way:

$$\lambda = \lambda_\mathrm{sat} S_l + \lambda_\mathrm{dry}(1 - S_l) \tag{17}$$

where $\mathbf{i}_\mathrm{c}$ is the conductive flux vector of heat, T is the temperature, λ is the thermal conductivity, λ_sat is the thermal conductivity of the water-saturated porous medium, λ_dry is the thermal conductivity of the dry porous medium and S_l is the degree of saturation. For the thermal analysis, the required parameters for the materials are the thermal conductivity (λ), the specific heat (c_s) and the solid density (ρ_s).

3 SAMPLES AND EXPERIMENTAL SETUP

A thermal consolidometer is developed exclusively as a part of PhD thesis of first author and presented for the first time in this paper. The conventional consolidation cell was modified with new equipment to perform thermal consolidation tests (Figure 1). The consolidation cell accommodated the soil sample (75 mm in diameter and 20 mm in height) submerged in water and sandwiched between the top and bottom porous stone and a loading cap on top of them. Specimen temperature is controlled by placing a ring electrical heater around the outer face of the consolidation cell connected to a computer-programmed unit capable of imposing thermal gradients with various rates. Ring heater is fully covered by insulation material inside metal box to minimize heat loss and guarantee more even distribution of heat. Temperature of specimen is recorded by data acquisition and placing thermocouples type K (with an accuracy of 0.1°C) in submerging water to prevent disturbance of sample during experiment. A system for water supply consisting of a water reservoir, electrical valve, and water sensor is used to compensate for water evaporation, especially at high temperatures and to ensure saturated conditions during tests. Vertical displacement of the specimen is measured and logged with the help of a linear variable displacement transducer (LVDT) with an accuracy of 0.1 μm. The entire setup is calibrated by conducting non-isothermal tests with blank specimen to take in to account possible thermal fluctuation of different parts of the consolidation cells and they are subtracted from final LVDT measurement to obtain the actual displacement undergone by the specimen.

The tested material is undisturbed satruated silty sandy clay from Budapest in Hungary. Table 1 summarizes the initial properties of the tested soil.

Various mechanical stress paths are performed on samples to study the thermal volumetric response of silty sandy clays under different vertical effective stress and stress history (i.e., over consolidation ratio). Details of the experimental program are provided in Table 2. The preconsolidation pressure of the tested soil is around 100 kPa. Samples are first loaded up to 1200 kPa for tests T1, T2 and T3 beyond preconsolidation pressure. Then unloading is performed to 600 kPa and 200 kPa for tests T2 and T3, respectively, to create over-consolidated samples. Test T4 is performed under no vertical stress except for the loading cap and porous stone (5 kPa). After reaching the target effective stress and allowing sufficient time to ensure full dissipation of excess pore pressure, a heating-cooling cycle is performed on the specimens starting from room temperature to the maximum temperature of 82°C with the heating rate of 0.3°C/h and cooling rate 2.5°C/h. Such a low rate of temperature increase is essential to ensure drained conditions during heating and cooling and to prevent thermally induced pore pressure due to different thermal expansions of water and soil.

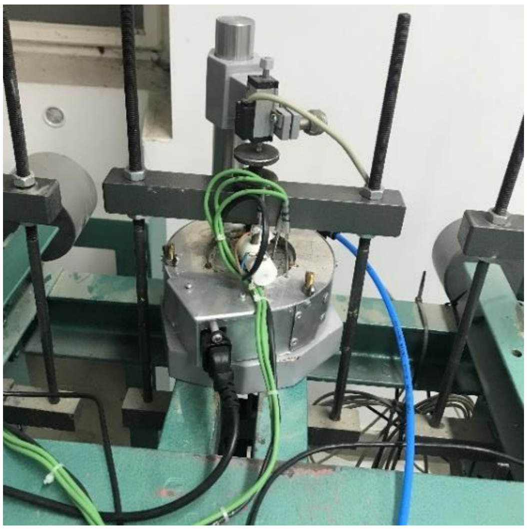

Figure 1. Consolidation cell modified for controlled-temperature testing.

Table 1. Summary of specimen properties.

Parameter	Value
Density, ρ (g cm^{-3})	1.99-2.06
Water content, ω (%)	17-20
Liquid limit, LL (%)	40-49
Plastic limit, PL (%)	25-27
USCS	CL

Table 2. experimental program

Test number	Effective stress path (kPa)	OCR	Temperature
T1	5-1200	1	23-82-23
T2	5-1200-600	2	
T3	5-1200-200	6	
T4	5	20	

4 RESULTS AND DISCUSSION

The volumetric thermal strain of the examined specimens, subjected to varying stress levels and histories, is depicted in Figure 2. Upon exposure to a temperature increment ($\Delta T \approx 65$ °C), all samples demonstrated contraction, as indicated by positive strain values. The most pronounced contraction was observed in the normally consolidated sample (T1), with the magnitude of contraction diminishing as the over-consolidation ratio increased. These findings are consistent with previous studies, as illustrated in Figure 3 where the logarithmic trendline provides a better visual representation of the over-conolidation ratio on thermal volumetric strain.

Figure 2 further reveals an irreversible volume change in the normally consolidated sample (T1). As the over-consolidation ratio increases, the irreversible contraction observed at the conclusion of the heating-cooling cycle diminishes. Notably, the highly over-consolidated sample (T3) exhibits reversible (elastic) thermal volumetric strain, indicating a distinct response to temperature changes compared to its less over-consolidated counterparts. The thermal volumetric response of silty sandy clay is in line with results from literature (Baldi et al., 1988; Sultan et al., 2002) where the over-consolidation ratio was highlighted to be controlling volume change of fine-grained soils during drained heating and cooling cycle.

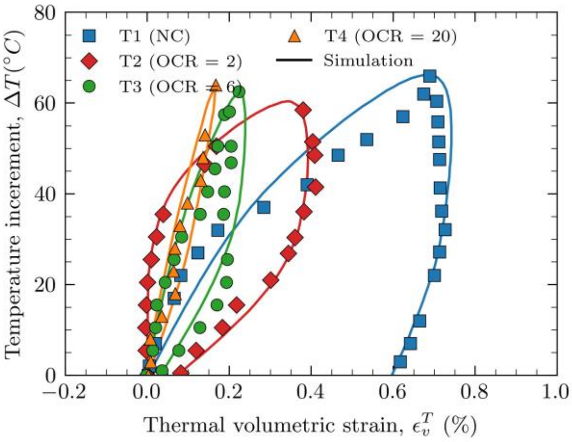

Figure 2. The volumetric strain of silty sandy clay exposed to the drained heating-cooling cycle.

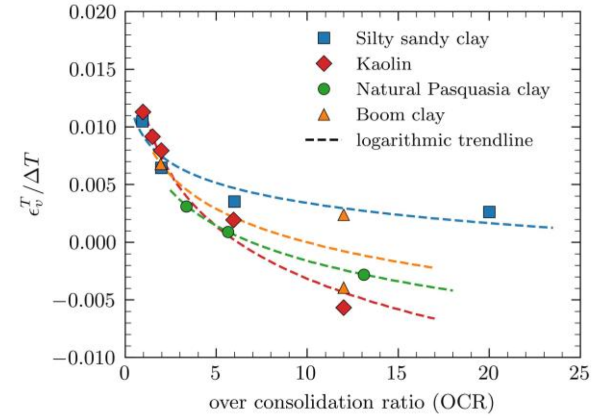

Figure 3. Evolution of normalized thermal volumetric strain with OCR for Kaolin (Cekerevac and Laloui, 2004)*, Natural Pasquasia clay* (Hueckel and Baldi, 1990) *and Boom clay* (Sultan et al., 2002).

The thermal irreversible contraction observed during drained heating can be attributed to other factors. Firstly, the dissipation of thermally induced excess pore pressure has been identified as a significant contributor (Campanella and Mitchell, 1968). Additionally, the increase in temperature influences physio-chemical interactions and structural collapse (Baldi et al., 1988; Romero et al., 2005).

Figure 3 also shows that samples with OCR (over consolidation ratio) higher than 10 resulted in expansion at elevated temperatures, which is not the case for sample T4. Due to less clay content and expansive material in tested samples, they are expected to have higher permeability leading of faster dissipation of thermally induced pore pressure and, subsequently, less expansion potential during heating (Campanella and Mitchell, 1968; Robinet et al., 1996).

On the other hand, results for silty sandy clay sample could also be linked to recent stress changes prior to heating. highly over consolidated samples, reloaded prior to heating, exhibited contraction once exposed to drained heating. Therefore, the expansion potential of unloaded samples could contribute to thermal expansion during drained heating test (Burghignoli et al., 2000; Towhata et al., 1993). This behaviour is in line with the thermal volume response of sample T4, which was not unloaded prior to the heating test (table 2). Hence, reconstitution of the test sample structure in the laboratory could also influence the results of drained heating-cooling cycles.

4.1 Simulation of test results

The numerical simulation was carried out using the finite element code Code_Bright (Olivella et al., 1996), which incorporates the non-isothermal Barcelona Basic Model (BBM). The simulation was conducted under axisymmetric two-dimensional coupled thermo-hydro-mechanical (THM) conditions, taking into account the effects of temperature on both the mechanical and hydraulic properties of the silty sandy clay.

The preceding oedometer test results for evolution of volumetric strain with heating-cooling cycles are used to verify the ability of the model to describe the thermal consolidation behaviour of saturated test soil. These tests provided valuable information on the consolidation characteristics and compressibility of the test soil under varying temperature and stress conditions.

The model parameters were calibrated using the experimental data and are listed in Table 3 and 4. Table 3 presents the BBM parameters for the silty sandy clay and Table 4 provides the hydraulic and thermal parameters for the silty sandy clay. The calibrated model was then implemented in the Code_Bright to simulate the response of the silty sandy clay under various loading and temperature conditions. The results of the numerical analysis were compared with the experimental data obtained from the oedometer tests to assess the model's ability to accurately predict the thermal consolidation behavior of the saturated test soil. Figure 2 presents a comparison of the numerical results (represented by solid lines) and the experimental measurements (represented by symbols) for various test conditions, including temperature and over-consolidation ratio.

In general, the numerical results show good agreement with the experimental data, demonstrating the model's ability to capture the essential features of the thermomechanical behavior of silty sandy clays. It is important to note that the numerical analysis accounts for various factors such as temperature changes, hydraulic conditions, and mechanical interactions, making it a comprehensive representation of the coupled THM processes occurring within the saturated soil. This holistic approach enhances the accuracy and reliability of the model's predictions.

The numerical simulation using the Code_Bright and the non-isothermal BBM has proven to be a valuable tool for investigating the thermomechanical behavior of silty sandy clays. By calibrating the model using experimental data from oedometer tests and comparing the numerical results with the test measurements, we can gain confidence in the model's ability to describe the complex interactions between thermal and mechanical processes in these soils, ultimately informing the design of geotechnical structures subjected to varying temperature and stress conditions.

Table 3. Non-isothermal BBM parameters for Silty sandy clay.

Parameter	**Symbol**	**Value**
Poisson ratio	v	0.3
Minimum bulk module (MPa)	$K_{\min}$	10
Elastic stiffness parameter for changes in net mean stress	κ_{i0}	0.03
Slope of void ratio – mean net stress curve	$\lambda(0)$	0.1
Reference pressure for the P_0 function (MPa)	p^c	0.1
Preconsolidation mean stress for saturated soil (MPa)	P_0^*	1.2
Critical state line	M	1.0

Table 4. Hydraulic and thermal parameters for Silty sandy clay.

Hydraulic parameters	**Value**	**Thermal parameters**	**Value**
$P(\mathrm{MPa})$	25	$\rho_s(\mathrm{kgm^{-3}})$	2000
$\lambda\,(-)$	0.4	ϕ_o	0.35
$a\,(-)$	-	$c_s\ (\mathrm{Jkg^{-1}\ K^{-1}})$	784
$k(\mathrm{m}^2)$	1.6×10^{-20}	$\lambda_{dry}\ (\mathrm{Wm^{-1}\ K^{-1}})$	0.32
$m\,(-)$	3	$\lambda_{sat}\ (\mathrm{Wm^{-1}\ K^{-1}})$	1.32
$\tau(-)$	0.4	$\alpha_T\ (\mathrm{K^{-1}})$	1.4×10^{-5}

5 CONCLUSION

The influence of temperature on silty sandy clays behaviour was experimentally investigated. It is believed that this is an important issue in geo-energy applications. The conventional consolidation cell was modified with new equipment to perform thermal consolidation tests. Main modifications included the addition of thermocouples and a data acquisition system.

The temperature-controlled oedometer test results indicate that all samples exhibit contraction upon exposure to a temperature increment, with the most pronounced contraction observed in the normally consolidated sample. The magnitude of contraction decreases as the over-consolidation ratio increases. The highly over-consolidated sample shows reversible (elastic) thermal volumetric strain, indicating a distinct response to temperature changes compared to less over-consolidated samples. Recent stress changes, minerals, and natural structure of fine-grained soils are important to be considered alongside over-consolidated ratio to better understand thermal volumetrci behavioure.

Numerical simulation was performed using a finite element code called Code_Bright incorporating coupled THM formulation capable of modelling pore pressure variations with temperature increase. A non-isothermal extension of the Barcelona Basic Model (BBM) was introduced as a constitutive law in Code_Bright. The experimental features of the silty sandy caly tested are satisfactorily captured by the numerical simulation performed. The numerical modeling approach and experimental setup presented here can serve as a basis for further research on the thermal behavior of clayey soils and contribute to the development of more accurate and reliable models for sustanble subsurface geo-energy develpements.

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