Symposium on Energy Geotechnics
Accelerating the energy transition
3-5 October 2023, Delft, the Netherlands

Peer-reviewed Conference Contribution

Thermal and mechanical creep of clay in hypoplasticity

Merita Tafili[1,*], Mohammadsadegh Ashrafi[1] and Torsten Wichtmann[1]
[1] Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics, Ruhr-University Bochum, Bochum, Germany
* Corresponding author: merita.tafili@rub.de

Clays and clay soils or shales have attracted a lot of interest in a variety of applications, including the development of geothermal resources [1], energy foundations [2], oil exploration [3], energy storage [4], and the storage of nuclear waste [5]. The continued operation of ground source heat pump installations can lead to considerable long-term settlements, which could negatively affect the adjacent or underlying foundations [1]. Therefore, thermal volume change has been widely experimentally investigated in clays [4, 7, 8, 9]. Especially in [4] the authors studied the thermal and mechanical consolidation of saturated marine clays through laboratory element tests, where excess pore pressures were generated by heating samples at constant water content and then allowed to dissipate. In constant stress creep experiments described in [4] it was documented that thermal creep strains typically increased linearly with log time at rates controlled by the prevailing temperature.

On the other hand, the mechanical time dependency of the stress–strain behaviour of soft soils, especially highly plastic clay, is generally too significant to be ignored [10, 11]. The constitutive modelling of the time-dependent stress–strain behaviour of soils has been an active area of research for five decades and has attracted much attention from the international geotechnical community in recent years as denoted in [12]. In [13] a visco-hypoplastic (VHP) model for normally and overconsolidated clays has been proposed. Probably the most salient feature of hypoplasticity itself is that loading and unloading can be described with only one equation as $\dot{\boldsymbol{\sigma}} = \mathsf{E}:(\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{hp} - \dot{\boldsymbol{\varepsilon}}^{vis}) = \mathsf{E}:\left(\dot{\boldsymbol{\varepsilon}} - Y\boldsymbol{m}\|\dot{\boldsymbol{\varepsilon}}\| - I_v\lambda\left(\frac{1}{OCR}\right)^{\frac{1}{I_v}}\boldsymbol{m}\right)$, with the strain and stress rate denoted as $\dot{\boldsymbol{\varepsilon}}$ and $\dot{\boldsymbol{\sigma}}$, respectively. The elastic stiffness tensor is represented by E; Y is the degree of nonlinearity and $\boldsymbol{m}$ is the flow rule (direction of hypoplastic strain). The last part of the equation expresses the time-dependent strain rate (i.e. viscous) with the material parameters I_v as the viscosity index and λ being the compression index. OCR denotes the overconsolidation ratio. As may be observed, the model is not restricted solely to time-dependent clay materials, because $I_v = 0$ does not represent a singularity for the constitutive equation as in other hypoplastic models. The model has been extended in [14] to account for the small-strain stiffness and the mechanical behaviour under cyclic loading. It follows the critical state theory and incorporates a loading surface for the definition of OCR, see Fig. 1A). Time-dependent one-dimensional behaviour of clays is in most cases explained by the isotache framework, which assumes a unique relation between effective stress, strain, and strain rate in compression, shown as loci of constant strain rate in $e - \log(p')$ space, see Fig. 1B). The creep deformation at constant effective stress ($p_0{}'$; Fig. 1C)) corresponds to a decrease in strain rate of the soil (path A to B′ in Fig. 1C)). Consolidation stress history, represented by swelling along the path A−C′, causes a marked reduction in compressive creep rates at low OCR (C′ −D′), while expansive/dilative creep strains occur at higher OCR (C′ −E′ −E″).

Due to the temperature dependency of the compressibility of clays the isotachs may be considered as temperature dependent as well. As shown in [6] the isotache loci at a given strain rate for normally consolidated states are functions of strain rate and temperature. Increases in temperature cause additional compressive thermal creep strains for NC and lightly OC states (B′ −B″ and D′ −D″ in Fig.1C)) and augment the swelling strains at higher OCR (E′ −E″).

DOI: https://doi.org/10.59490/seg23.2023.625

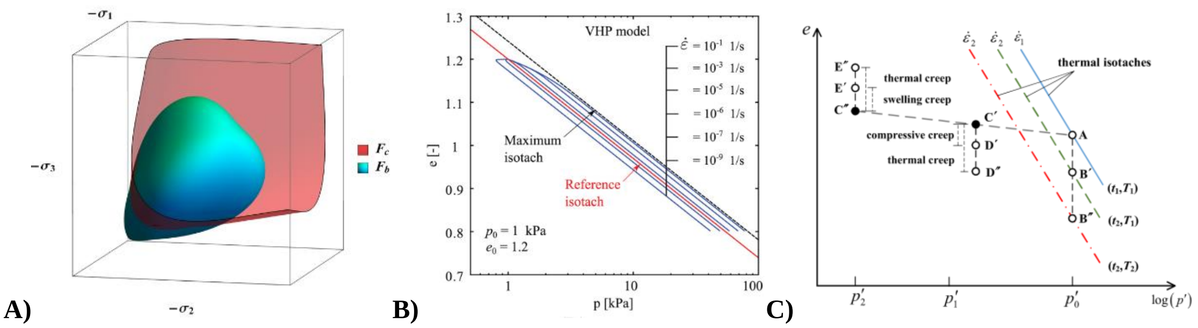

Figure 1: A) Critical state and loading surface; B) Oedometer simulations with different strain rates (isotachs); C) Unification of thermal and mechanical creep in 1D compression tests through isotache framework from [6].

In the framework of hypoplasticity, the non-isothermal behaviour has not gained much attention [15]. This work is devoted to the extension of the VHP model formulation to present a unified model for both thermal and viscous strains in clays. The model predictions are assessed through comparisons with existing laboratory experiments from [7] on two clays with measurements of both isothermal/mechanical creep and thermally induced creep strains, providing a thorough calibration scheme as well.

Contributor statement

M. Tafili (Data curation, Conceptualization, Funding acquisition, Formal analysis, Investigation), M. Ashrafi (Data curation, Formal analysis), T. Wichtmann (Conceptualization, Funding acquisition)

Acknowledgments

The presented study has been performed within the project "Experimental and numerical investigation of coupled thermo-hydro-mechanical behaviour of clay with focus to cyclic processes" funded by the German Research Council (DFG, project No. WI 3180/11-1). The authors are grateful to DFG for the financial support.

References

[1] D. M. Zymnis, and A. J. Whittle. "Geotechnical considerations in the design of borehole heat exchangers in clay." Can. Geotech. J., vol. 58, no. 9, pp. 1247–1262, 2020. Available: https://doi.org/10.1139/cgj-2020-0118. [Accessed Jan. 31, 2023].

[2] H. Brandl. "Energy foundations and other thermo-active ground structures." Géotechnique, vol 56, no. 2, pp. 81–122, 2006. Available: https://doi.org/10.1680/geot.2006.56.2.81. [Accessed Jan. 31, 2023].

[3] T. Hueckel, and M. Borsetto. "Thermoplasticity of saturated soil sand shales: Constitutive equations." J. Geotech. Geoenviron. Eng., vol. 116, no. 12, pp. 1765–1777, 1990. Available: https://doi.org/10.1061/(ASCE)0733-9410(1990)116:12(1765). [Accessed Jan. 31, 2023].

[4] L. Laloui, and C. Cekerevac. "Thermo-plasticity of clays: Anisotropic yield mechanism." Comput. Geotech., vol. 30, no. 8, pp. 649–660, 2003. Available: https://doi.org/10.1016/j.compgeo.2003.09.001. [Accessed Jan. 31, 2023].

[5] Y. J. Cui, T. T. Le, and A. M. Tang. "Investigating the time-dependent behaviour of Boom clay under thermo-mechanical loading." Géotechnique, vol. 59, no. 4, pp. 319–329, 2009. Available: https://doi.org/10.1680/geot.2009.59.4.319. [Accessed Jan. 31, 2023].

[6] N. Zhao, X. Cheng, and A. J. Whittle. "Extended TTS Model for Thermal and Mechanical Creep of Clay and Sand". Journal of Geotechnical and Geoenvironmental Engineering, vol, 148, no. 6, pp. 04022044, 2022.

[7] A. Burghignoli, A. Desideri, and S. Miliziano. "A laboratory study on the thermomechnical behavior of clayey soils." Can. Geotech. J., vol. 37, no. 4, pp. 764–780, 2000. Available: https://doi.org/10.1139/t00-010.

[8] N. Sultan, P. Delage, and Y. J. Cui. "Temperature effects on the volume change behaviour of Boom clay." Eng. Geol., vol. 64, no. 2–3, pp. 135–145, 2002. Available: https://doi.org/10.1016/S0013-7952(01)00143-0.

[9] A. Di Donna, and L. Laloui. "Response of soil subjected to thermal cyclic loading: Experimental and constitutive study." Eng. Geol., vol. 190, no. 14, pp. 65–76, 2015. Available: https://doi.org/10.1016/j.enggeo.2015.03.003

[10] L. Bjerrum. "Engineering geology of Norwegian normally consolidated marine clays as related to the settlements of buildings". Géotechnique., vol. 17, no. 2, pp. 83–11, 1967.

[11] R. I. Borja, and Kavazanjian, E. "A constitutive model for the stress-strain-time behaviour of 'wet' clays". Géotechnique., vol. 35, no. 3, pp. 283–298, 1985.

[12] M. Tafili, W. Fuentes, and T. Triantafyllidis. "A comparative study of different model families for the constitutive simulation of viscous clays." International Journal for Numerical and Analytical Methods in Geomechanics, vol. 44, no. 5, pp. 633-667, 2020.

[13] M. Tafili, and T. Triantafyllidis. "A simple hypoplastic model with loading surface accounting for viscous and fabric effects of clays." International Journal for Numerical and Analytical Methods in Geomechanics, vol. 44, no. 16, pp. 2189-2215, 2020.

[14] M. Tafili, and T. Triantafyllidis. "AVISA: anisotropic visco-ISA model and its performance at cyclic loading." Acta Geotechnica, vol. 15, pp. 2395-2413, 2020.

[15] D. Mašín, and N. Khalili. "A thermo-mechanical model for variably saturated soils based on hypoplasticity." International journal for numerical and analytical methods in geomechanics, vol. 36, no. 12, pp. 1461-1485, 2012.