Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190365

Thermo-Mechanics of Soils: Historical Advances and Current Challenges

Alessandro F. ROTTA LORIA[a,1] and Jibril B. COULIBALY[a]
[a] *Northwestern University, Department of Civil and Environmental Engineering, Mechanics and Energy Laboratory*

Abstract. The mechanical response of soils under non-isothermal conditions determines the behavior and performance of a large number of engineering applications with more or less notable consequences for the daily life of people. Over the past fifty years, a substantial amount of research has been devoted to investigate such a response for applications including shallow and deep geothermal systems, nuclear waste repositories, and underground thermal energy storage systems. Despite the previous investigations and the accumulated knowledge about this subject, various challenges currently remain to be addressed. Looking at such challenges, the aim of this paper is twofold: (i) to provide an introduction about unresolved challenges related to the thermo-mechanics of soils from a perspective that considers their solution as a means to establish engineered earth materials; and (ii) to expand the fundamental analysis of the previous challenges that aims at pushing the boundaries of the current knowledge on the thermo-mechanics of soils.

Keywords. Soils, thermo-mechanics, temperature, volumetric response.

1. Introduction

Over the past fifty years, a substantial amount of research has been carried out to address the mechanical response of soils under non-isothermal conditions, given its importance in the analysis and design of shallow and deep geothermal systems, nuclear waste repositories and other applications at the interface between geomechanics and energy. In this context, particular attention has been devoted to fine-grained soils because of the higher sensitivity of their response to temperature variations compared to coarse-grained soils [1]. However, temperature variations can affect the deformation and strength of all types of soils [2]. These phenomena can be reversible or irreversible and may induce, for example, volumetric deformations that are associated with changes in the material porosity, and thus, density. As a consequence, the stiffness, hydraulic conductivity and thermal conductivity of the material can change, with a potentially significant impact on the related behavior (e.g., thermo-hydro-mechanical).

Based on the previous considerations, addressing the perturbation of soils caused by temperature variations is paramount for ensuring an adequate behavior, performance and resilience of structures that are constructed on, in or with such materials. In particular, understanding the physical variables that govern the mechanical response of soils under non-isothermal conditions across scales and being capable to control them appears paramount to achieve earth materials that may be tailored for any engineering application.

[1] Corresponding Author, E-mail: af-rottaloria@northwestern.edu.

Currently, various experimental and theoretical investigations offer an understanding of the mechanical response of soils under non-isothermal conditions (see, e.g., [3, 4]). Despite the available knowledge, various fundamental aspects of the mechanical response of soils under non-isothermal conditions remain poorly understood and challenges that govern both fundamental and applied problems in science and engineering remain to be addressed. In regard to those lasting problems, this paper provides (i) an introductory description of unresolved challenges related to the thermo-mechanics of soils and (ii) a summary of a fundamental analysis of those challenges for pushing the boundaries of the current knowledge about this subject.

2. Thermally induced volumetric response of soils

Among the aspects of the thermo-mechanics of soils whose understanding is currently limited, the volumetric response of such materials appears to be characterized by unresolved and sometimes conflicting features. In fact, heating and cooling respectively induces an expansion and contraction of all of the soil constituents, proportional to their thermal expansion coefficient and to the applied temperature variation. However, during drained heating paths, both expansive and contractive strains of soil matrices can be observed. Historically, this evidence has been shown experimentally for fine-grained soils to depend on the stress history, e.g., measured in terms of the overconsolidation ratio, OCR [5]. Nevertheless, more recent experimental evidence suggests that the same phenomenon can characterize coarse-grained soils depending on both the stress history and stress state, e.g., measured in terms of the relative density, D_R [6].

Two bounding responses can characterize soils: (i) expansion upon heating and reversible contraction upon cooling for overconsolidated fine-grained soils and very dense coarse-grained soils; and (ii) contraction upon heating (i.e., leading to the so-called thermal collapse phenomenon) and partly irreversible contraction upon cooling for normally consolidated fine-grained soils and loose coarse-grained soils. In between the two bounding responses, opposite responses have been shown to characterize slightly overconsolidated fine-grained soils and dense coarse-grained soils: while the former initially expand and then contract upon drained heating, the latter initially contract and then expand upon drained heating (in both cases, contraction is observed upon cooling). A summary of the aforementioned phenomena is depicted in Figure 1.

3. A novel approach to address the thermo-mechanics of soils across scales

While well-established constitutive models and theoretical frameworks are available to describe at the continuum scale the two bounding volumetric responses of soils to temperature changes [1], the interpretation of the phenomena governing these responses remain phenomenological and the understanding of the fundamental processes and variables controlling them appear to be missing. Moreover, the response of soils to temperature changes in intermediate conditions cannot be interpreted in a unified framework with current constitutive models.

The understanding of the fundamental physical variables that control the different mechanical responses of soils subjected to temperature variations is expected to lie at the scale of the solid particles that constitute the material structure. That is because the response of soil matrices at the continuum scale and their equilibrium are governed by the physical and/or chemical interactions that develop at the scale of the particles.

In this context, analyses addressing microscopic phenomena such as the topological reorganization of the material structure under the application of temperature changes are underway to exhaustively address the volumetric mechanical response of soils under non-isothermal conditions. The goal of these investigations is threefold: (i) to provide additional insights into the thermo-mechanics of soils, (ii) to offer novel information for the microscopically-informed enrichment of constitutive models, and (iii) to develop comprehensive multi-scale and multi-physical analyses of problems involving soils.

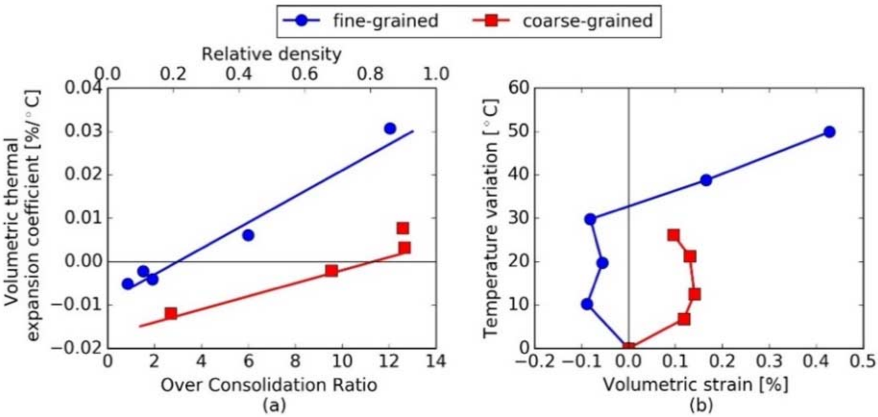

Figure 1. (a) Volumetric thermal expansion coefficient of soils for different values of OCR and D_R (data from [6-8]); and (b) Volumetric strain-temperature change relationship for slightly overconsolidated fine grained soils and dense coarse-grained soils (data from [9] and [6]). Expansion is negative.

References

[1] L. Laloui, "Thermo-mechanical behaviour of soils," *Revue Française de Génie Civil,* vol. 5, pp. 809-843, 9 2001.

[2] T. Hueckel and G. Baldi, "Thermoplasticity of Saturated Clays: Experimental Constitutive Study," *Journal of Geotechnical Engineering,* vol. 116, pp. 1778-1796, 12 1990

[3] W. L. Vargas and J. J. McCarthy, "Thermal expansion effects and heat conduction in granular materials," *Physical Review E,* vol. 76, 10 2007.

[4] S. Zhao, T. M. Evans, X. Zhou and S. Zhou, "Discrete element method investigation on thermally-induced shakedown of granular materials," *Granular Matter,* vol. 19, 12 2016.

[5] G. Baldi, T. Hueckel and R. Pellegrini, "Thermal volume changes of the mineral–water system in low-porosity clay soils," *Canadian Geotechnical Journal,* vol. 25, pp. 807-825, 11 1988.

[6] C. W. W. Ng, S. H. Wang and C. Zhou, "Volume change behaviour of saturated sand under thermal cycles," *Géotechnique Letters,* vol. 6, pp. 124-131, 6 2016.

[7] H. Liu, H. Liu, Y. Xiao and J. S. McCartney, "Influence of Temperature on the Volume Change Behavior of Saturated Sand," *Geotechnical Testing Journal,* vol. 41, p. 20160308, 4 2018.

[8] C. Cekerevac and L. Laloui, "Experimental study of thermal effects on the mechanical behaviour of a clay," *International Journal for Numerical and Analytical Methods in Geomechanics,* vol. 28, pp. 209-228, 2 2004.

[9] H. M. Abuel-Naga, D. T. Bergado and A. Bouazza, "Thermally induced volume change and excess pore water pressure of soft Bangkok clay," *Engineering Geology,* vol. 89, pp. 144-154, 1 2007.