INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 10th European Conference on Numerical Methods in Geotechnical Engineering and was edited by Lidija Zdravkovic, Stavroula Kontoe, Aikaterini Tsiampousi and David Taborda. The conference was held from June 26th to June 28th 2023 at the Imperial College London, United Kingdom.

To see the complete list of papers in the proceedings visit the link below:

https://issmge.org/files/NUMGE2023-Preface.pdf

Proceedings 10th NUMGE 2023
10th European Conference on Numerical Methods in Geotechnical Engineering
Zdravkovic L, Kontoe S, Taborda DMG, Tsiampousi A (eds)

https://doi.org/10.53243/NUMGE2023-441

Coupled thermo-hydro-mechanical behaviour of soils and applications in energy geotechnics

J.M. Pereira

Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France

ABSTRACT: With the rise of energy geo-engineering, the temperature effects on the behaviour of geomaterials have gained a strong attention in geotechnical research and engineering applications in the past couple of decades. Many applications are concerned, ranging from thermo-active geostructures, radioactive waste disposals, gas and energy storage in geological reservoirs, landscape evolution studies, etc. In this paper, we present a brief overview of thermo-hydro-mechanical behaviour features of geomaterials, mainly focusing on the mechanical behaviour at the material scale or at the soil-structure interface scale, on the hydraulic behaviour and on the thermal behaviour of geomaterials. We also discuss key issues regarding the thermo-hydro-mechanical constitutive modelling of soils and considerations about the modelling of this coupled behaviour as opposed to simplified approaches usually considered in geotechnical engineering. We finally brush an overview of recent advances in some engineering applications where the thermo-hydro-mechanical behaviour of geomaterials plays a fundamental role.

Keywords: Geomaterials; Multiphysics couplings; Constitutive modelling; Thermo-active geostructures; Geological storage

1 INTRODUCTION

The effects of temperature changes have gained a strong attention in geotechnical research and engineering applications in the past couple of decades. As an illustration, Figure 1 shows the evolution of the number of research papers mentioning temperature or thermal issues in their title, abstract or keywords and published in scientific journals covering the geotechnical engineering field. Interestingly, the first paper returned by the query given in Figure 1 has been published in *Géotechnique* and discusses insulating solutions to protect the soil from thermal effects of industrial plants (Ward and Sewell, 1950). Then, a slow increase of the annual publishing rate is observed before a fast increase starting around the year 2000. Actually, preliminary signals of this increase appear in the 1990s with publications related to research on radioactive waste disposals. Another hot topic having significantly increased the number of papers since 2000 is the study of thermo-active research structures. For instance, the most cited paper returned by the same query is a paper on this specific application (Brandl, 2006), also published in *Géotechnique*.

However, a variety of geotechnical applications involve thermal effects, and a proper understanding of the fundamental mechanisms at the origin of the coupled thermo-hydro-mechanical (THM) behaviour of geomaterials is required to satisfactorily predict the behaviour of the concerned geostructures. Among these applications, one can cite landscape evolution phenomena such as rapid landslides (Pinyol and Alonso, 2010; Veveakis et al., 2007) or rock cliff stability (Gasc-Barbier et al., 2021) where thermal effects might play a major role, offshore geotechnics with pipe-soil interactions (Dingle et al., 2008), thermo-active geostructures (Laloui and Di Donna, 2013), radioactive waste disposals (Delage et al., 2010), carbon dioxide geological storage (Pijaudier-Cabot and Pereira, 2013), gas storage in porous reservoirs (Zhu et al., 2017), deep geothermal energy production, etc. to name but a few. As can be seen, many of these applications are directly or indirectly connected to energy geotechnics (Santamarina et al., 2022).

In this paper, we first present a brief overview of thermo-hydro-mechanical behaviour features of geomaterials, mainly focusing on the mechanical behaviour at the material scale or at the soil-structure interface scale, on the hydraulic behaviour and on the thermal behaviour of soils. Then, we discuss a few key issues regarding the THM constitutive modelling of soils covering mechanical, hydraulic and thermal aspects. A few considerations about the modelling of this coupled behaviour as opposed to simplified approaches usually sought for in geotechnical engineering will be presented. We finally brush an overview of recent developments in some engineering applications where the THM behaviour of geomaterials plays a fundamental role.

It is worth noting that we will consider mainly soils either in saturated or unsaturated states (but not rocks) and relatively small temperature changes, typically comprised between 0 and 100 °C, so that phase changes of the pore water will not be discussed in detail in this work.

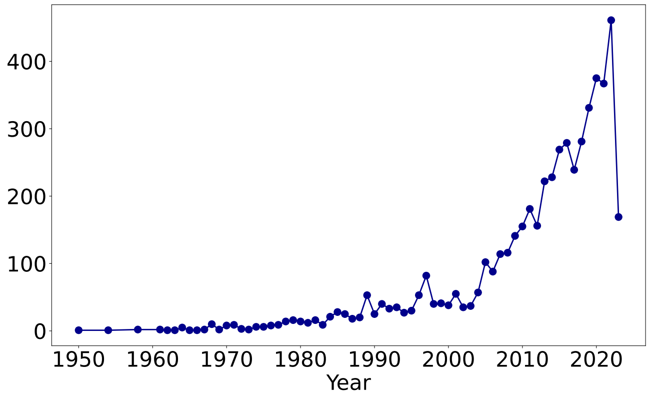

Figure 1. Evolution of articles published in geotechnical engineering journals mentioning temperature or thermal issues in their title, abstract or keywords. Scopus query, performed on 2023/04/15: ((TITLE-ABS-KEY(therm OR temperature*) AND SRCTITLE(geotech* OR geomech* OR ""soil mech*"" OR ""soil* foundation*"")) AND (LIMIT-TO (DOCTYPE,""ar"") OR LIMIT-TO (DOCTYPE,""re"") OR LIMIT-TO (DOCTYPE,""no"") OR LIMIT-TO (DOCTYPE,""er"") OR LIMIT-TO (DOCTYPE,""le""))).*

2 THM BEHAVIOUR

2.1 What we know: a brief review

2.1.1 Mechanical behaviour

In this section, we will review the effects of temperature on the hydromechanical behaviour of geomaterials. Many studies have been dedicated to thermal effects on mechanical properties of soils. It is generally acknowledged that coarse grained soils are slightly affected by temperature changes encountered in conventional geotechnics, that is at least when not involving phase changes of the pore water. However, this slight influence of temperature on the behaviour of granular soils is not a general statement, and some effects have been reported in specific conditions. For instance, Blanc and Géminard (2013) observed what they called *intrinsic creep* in a granular column made of glass beads subjected to thermal cycles.

When considering fine soils, several aspects can be mentioned. Firstly, in terms of volumetric behaviour, significant differences have been reported between over-consolidated soils and normally or poorly consolidated soils (Cekerevac and Laloui, 2004; Hueckel and Baldi, 1990; Sultan et al., 2002). Indeed, it appears that the volumetric response of over-consolidated soils subjected to a temperature cycle is quite reversible, while irreversible deformations are observed when a normally consolidated specimen is subjected to such a cycle. These irreversible deformations induce the so-called thermal-consolidation of clays. This terminology refers to the fact that a normally consolidated specimen would appear as over-consolidated once sufficiently heated before being cooled down again. This behaviour could be exploited to improve the mechanical properties of soft clays (Huancollo et al., 2023). In any case, it is a specificity that (macroscopic) thermo-mechanical constitutive models for clays have to account for (see §2.2).

Secondly, temperature effects on the shear strength of soils have been thoroughly studied. Contradicting conclusions have been reported in the literature, with strength hardening or softening induced by temperature changes, or no appreciable effect at all. A recent work summarises the conclusions on the influence of temperature on shear strength of clays (Huancollo et al., 2023).

The *intrinsic creep* reported by Blanc and Géminard (2013) is related to the propagation of the temperature profile along the tested column leading to non-homogeneous compaction of the material. This phenomenon is strengthened when rapid temperature cycles are applied. This type of behaviour might have consequences on the long-term design of geothermal structures. The effects of thermal cycles on the settlement of thermal piles has been studied using a small scale pile under 1-g conditions in dry sand (e.g. Nguyen et al., 2017b; Yavari et al., 2014a) and in saturated clay (Nguyen et al., 2020; Nouri et al., 2023), and using centrifuge modelling of thermal piles or thermal pile groups (Ng et al., 2021, 2014). The results generally show an accumulation of irreversible settlement of the pile with the number of cycles (ratcheting effect, see § 2.2), with a significant part of this irreversible settlement occurring during the first cycle. The magnitude of this irreversible settlement increases with the mechanical load to which the pile is subjected. It was shown that irreversible settlements (i.e. per cycle) tend to vanish when the supported load is far from the pile bearing capacity. When the thermally-induced pile deformation can be accommodated by an increase of the shear stress mobilised along the pile shaft, then the deformation will remain reversible (Pasten and Santamarina, 2014). We will come back to this discussion in the applications part of this paper (see §4.2).

The above discussion, and the observation of irreversible settlements in some experiments on thermal piles raise the question of the thermal behaviour of the soil-structure interface. Yavari and co-authors (Yavari et al., 2016) tested sand, clay, and clay–concrete interfaces at various temperatures (ranging between 5 and 40 °C) in the direct shear box. They concluded that, in that range of temperatures, temperature had negligible effects on the interface properties.

Apart from the effects of thermal cycles on the long-term behaviour of geothermal structures discussed above, the time dependent behaviour of soils, including strain rate dependency and creep, is also temperature dependent, as reported by Leroueil and Marques (1996). We have also seen that, as reported by Blanc and Géminard (2013), the rate of temperature change has consequences on the overall behaviour of soils. In that particular case, the rate effects are related to structural effects because heat has to diffuse through the soil, leading to non-homogeneous deformations. It will be seen later on that, through more complex couplings, the effects of the rate of change of temperature may also be observed at the material point.

2.1.2 *Hydraulic behaviour*

Effects of temperature on the hydraulic properties of soils are now discussed. Indirect effects, such as effects due to porosity changes induced by temperature changes, are to be distinguished from direct effects.

Direct temperature effects on the permeability of soils can easily be accounted for working with the intrinsic permeability (dimension $[L]^2$) rather than the hydraulic conductivity ($[L][T]^{-1}$). This is simply explained by the fact that temperature has negligible direct effects on the intrinsic permeability while the hydraulic conductivity is fluid dependent, and notably through the viscosity of the fluid, this latter being quite sensitive to temperature. Thus, in practice, it is recommended to use the intrinsic permeability and a temperature dependent viscosity of the fluid, which is generally well known. In numerical simulators, this is the choice that is generally made at the implementation stage. If it were not the case, and one would solely need to model water flow at non-standard temperatures using the hydraulic conductivity, then the numerical values to employ for this quantity are relatively simple to deduce. Indeed, intrinsic permeability and hydraulic conductivity are related as follows:

$$K = \frac{\rho_f\, g}{\mu_f} k \qquad (1)$$

where K is the hydraulic conductivity, ρ_f and μ_f are the density and viscosity of the fluid and k is the intrinsic permeability of the porous material.

The permeability of unsaturated geomaterials has been studied for a long time, and the effects of temperature on this particular property have been studied for decades, notably in oil engineering (Esmaeili et al., 2020). As in the saturated case, and even when relatively large temperature ranges are considered (between approximately 20 and 200 °C), Esmaeili and co-authors concluded that the temperature does not play any role on the oil/water relative permeability in consolidated sand packs. This observation is confirmed by Ye et al. (2012) who attribute temperature-induced changes of unsaturated hydraulic conductivity of bentonite solely to water viscosity changes in the high suction range but to a combined effect of water viscosity and temperature-induced microstructural changes in the low suction range. This observation in the low suction range, where the clay is softer, arises from both direct (thermo-hydraulic couplings) and indirect (induced by thermo-mechanical couplings) effects.

Finally, we close this part with the effects of temperature on the water retention properties of geomaterials. In the capillary dominated regime, these effects mainly arise from interfacial tension which is temperature dependent. Osmotic and adsorptive contributions to the water content in soils are also temperature dependent, through the physico-chemical interactions occurring between the water phase, its solutes and the solid particles. However, in usual ranges of temperatures (typically below 100 °C), these effects only slightly affect the water retention curve of geomaterials (Olchitzky, 2002). However, in (Pham et al., 2023), the authors explored a larger range of temperatures and report appreciable effects of temperature on the water retention curves.

Regarding indirect effects, temperature induced deformations translate into changes in the soil microstructure, which lead in turn to changes in the hydraulic properties (water flow and retention properties).

2.1.3 *Thermal behaviour*

Heat transport in geomaterials can be quite complex, when involving various modes of heat transfer. However, it is usually assumed that conduction is the main mode of heat transfer, together with heat advection (i.e. transported by the fluid flow). Convective phenomena are generally neglected because of the hindering effects of the pore network. Radiative effects are also generally neglected.

An emblematic phenomenon of THM couplings in soils is the so-called thermal pressurisation. This phenomenon is related to the mismatch between the thermal expansion coefficients of liquid water and mineral constituents of the soil. Indeed, the water phase expands almost ten times more than usual solid constituents of soils. In laboratory conditions, these effects are usually observed during undrained experiments (Baldi et al., 1991; Braun et al., 2021) and might lead to the tensile failure of the material (Braun et al., 2022). In field conditions, thermal pressurisation might be significant in fast moving landslides and accounting for it appears to be of primary importance (Pinyol and Alonso, 2010; Sulem and Famin, 2009; Veveakis et al., 2007). In these cases, an interplay happens between water flow (driven by pore pressure gradients and ruled by permeability) and rate of temperature increase.

2.2 *Constitutive modelling*

2.2.1 *THM constitutive models*

Many constitutive models have been proposed to render the THM behaviour of soils. The first model, based on an extension of the Modified Cam clay model, is due to Hueckel and co-authors (Hueckel and Baldi, 1990; Hueckel and Borsetto, 1990). A number of other models have been proposed afterwards, also adopting an elasto-plastic framework with a temperature dependant yield surface (Abuel-Naga et al., 2009; Cui et al., 2000; Graham et al., 2001; Laloui and François, 2009), to cite but a few. Interested readers are referred to the following review articles (Hong et al., 2013; Seneviratne et al., 1993). Adaptations of the conventional elastoplastic framework have been proposed with two-surface plasticity (similar to bounding surface plasticity) or kinematic hardening for cyclic behaviour in Hong et al. (2016, 2014).

These models are essentially empirical and focus on the modelling of the thermal consolidation phenomenon mentioned in §2.1.1. An interesting approach based on molecular simulations and its upscaling towards the macroscopic scale has been proposed by Brochard et al. (2017) to explain from an energetic viewpoint at the molecular scale how irreversible deformation might be triggered by temperature changes.

Among the phenomena described previously in §2.1, creep and strain rate effects have been considered in a constitutive model developed by Laloui et al. (2008). Additionally, the indirect couplings between thermally induced changes of hydraulic properties through changes of microstructure can, for instance, be modelled using the well-known Kozeny-Carman model for permeability changes (Carman, 1937; Kozeny, 1925) and/or micro-macro approaches to assess permeability and retention properties from microstructural changes (Arson and Pereira, 2013; Pereira and Arson, 2013).

2.2.2 *Thermal properties*

Thermal properties (heat capacity, thermal conductivity, thermal expansion) are obviously key properties when evaluating the thermo-hydro-mechanical behaviour of geostructures. When performing numerical simulations, it is convenient to be able to update these properties from the current state of the material, essentially in terms of porosity and water content (or degree of saturation). This can be done quite straightforwardly for the heat capacity but no simple while rigorous approach exists for the thermal conductivity, at least without enough information about the soil microstructure.

Neglecting the contribution of the gas phase, the volumetric heat capacity C of an unsaturated soil is given by:

$$C = (1-n)\rho_s c_s + n S_w \rho_w c_w \qquad (2)$$

where ρ_s and ρ_w are the solid and water densities, c_s and c_w are specific heat capacities of the solid phase and liquid water, respectively and n is the soil porosity.

Several models have been proposed for the thermal conductivity of soils. A basic arithmetic weighted average similar to Equation (2) is used in several studies. In other works, Johansen's model, based on a weighted geometric average, is used (Johansen, 1975):

$$\lambda = \prod_{\alpha=1}^{N} {\lambda_\alpha}^{f_\alpha} \qquad (3)$$

where α represents the phase (one out of *N* phases), λ is the thermal conductivity of the soil, λ_α is the thermal conductivity of the phase α and f_α is a weighting parameter. In the case of unsaturated soils, Johansen proposed an alternative approach to track the influence of the degree of saturation of water instead of using Equation (3):

$$\lambda(S_r) = \left(\lambda_{sat} - \lambda_{dry}\right) k(S_r) + \lambda_{dry} \qquad (4)$$

where λ_{sat} and λ_{dry} are the thermal conductivity values at saturated and dry states, respectively and $k(S_r)$ is a function of the degree of saturation. The latter should be fitted based on experimental data. As an illustration of experimental data that could be used to fit Equation (4), Figure 2 shows the thermal conductivity of an intact loess from northern France as a function of the degree of saturation (see (Muñoz-Castelblanco et al., 2012) for more details on this loess). The data shows that the various drying/wetting paths collapse on a master curve, meaning that the water content is the variable controlling the thermal conductivity in the unsaturated range. Interestingly, in the explored range of water contents, the variation of the thermal conductivity is approximately linear.

Additionally, Géminard and Gayvallet (2001) have shown that for granular media (spherical glass beads and crushed glass beads), the addition of water is much more efficient in increasing soil thermal conductivity at low water contents, i.e. below a critical value above which the increase in thermal conductivity is much slower. In the low water content range, added water forms menisci at the contacts between grains, significantly improving heat transfer, with this dominantly occurring within the solid particles (as opposed to the gas phase).

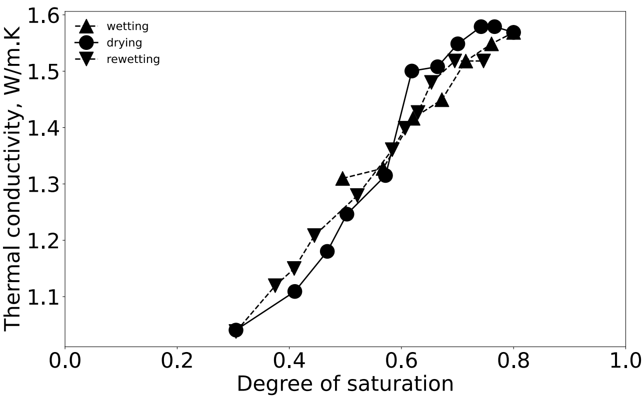

Figure 2. Thermal conductivity of loess from northern France as a function of the degree of saturation of water (after Nguyen et al., 2017a).

The choice between thermal conductivity models such as those given in Equations (3) and (4) thus relies on assumptions on how heat flows within the soil constituents (in series, in parallel, mixed). These assumptions depend on the soil microstructure, including how the liquid phase is distributed within the porosity. As an illustration, Gruescu et al. (2007) propose another approach based on two-scale homogenisation to determine the thermal conductivity of claystone accounting for its complex microstructure.

It is worth noting that the use of Equations (3) and (4) and any similar equation based on microstructural features has the advantage to readily account for porosity changes or other deformation induced changes of the microstructure, facilitating the modelling of coupled effects on thermal properties (similar to Kozeny-Carman or micro-macro approaches mentioned previously for hydraulic properties). Readers interested in modelling the thermal conductivity of soils are referred to (Dong et al., 2015), where a critical review is presented.

3 COUPLED BEHAVIOUR VS SIMPLIFIED STRATEGIES

In an academic context, these advanced approaches have been developed for specific problems such as the study of nuclear waste disposals or CO_2 geological storage. However, in engineering practice, numerical approaches to THM problems rarely account for a fully coupled (monolithic) resolution of the governing equations and advanced constitutive models.

It has been demonstrated that simplified approaches can be considered in specific conditions when geotechnical analysis software do not propose thermal analyses. For instance, Yavari et al. (2014b) simulated the mechanical behaviour of thermal piles by simply imposing the thermally induced volumetric strain to the pile body as a boundary condition. Using this basic decoupling method, the authors obtained satisfactory results in terms of pile head displacement and distribution of axial load along the pile length. Of course, this simplified approach conveys strong limitations as no temperature change is calculated within the pile or the soil. In particular, the good performance of this approach means that the volumetric expansion of the soil around the pile does not play a significant role on the pile behaviour (and that the radial expansion of the pile might be sufficient to approximate the behaviour of the pile-soil interface). It is also recalled that decoupling strategies might lead to significant errors in numerical results (see e.g. Preisig and Prévost, 2011) in the case of THM simulation of CO_2 injection in a geological reservoir.

Simplified engineering tools based on the extension of the load-transfer approach to thermal problems have been developed (e.g. Laloui et al., 2006; Ravera et al., 2020; Song and Pei, 2022) and prove to constitute efficient tools for the thermo-mechanical analysis of thermoactive piles and pile groups. In terms of constitutive models for the cyclic behaviour of thermal piles, simplified models avoiding the explicit modelling of every cycles have been developed to predict their long-term behaviour (Pastén et al., 2019; Pasten and Santamarina, 2014). These simplified strategies are quite interesting in practice but will not be further discussed in this paper.

4 APPLICATIONS IN ENERGY GEOTECHNICS

Engineering applications involving THM behaviour of geomaterials are numerous and varied (Santamarina et al., 2022). In this part, we will briefly review some of them.

4.1 *Soil-atmosphere interaction*

Even if not directly related to energy geotechnics, modelling of soil-atmosphere interactions is mentioned in this paper because the numerical tools and models used to model them have often been developed in the context of energy geotechnics.

Soil-atmosphere interaction stands for humidity and heat exchanges between the soil surface and the environment of the studied geo-structures. Such interactions have been considered for a couple of decades in applications related to slope stability (Tagarelli and Cotecchia, 2020), dyke and embankment design (Cui, 2022), effects of drought on structures built on expansive clays (Hemmati et al., 2012), etc. (Elia et al., 2017) presents a relatively recent review.

Numerical modelling of these interactions is generally quite complex since the tools have to account for coupled THM balance equations, vapour-liquid phase change of water, hydromechanical effects of vegetation (Boldrin et al., 2021), non-trivial and time-varying boundary conditions, difficulties in the establishment of an equilibrated and representative initial state, etc. On this last point, interested readers are referred to *spin-up* strategies discussed in Ross et al. (2021) and Tagarelli and Cotecchia (2020), among others.

4.2 *Geothermal structures*

Thermo-active geostructures have been used for decades (with first installation of thermal piles in Austria in the 1980s) but a significant acceleration in the use of this technology dates back to the beginning of the 2000s (Bourne-Webb et al., 2009; Laloui et al., 2003). Nowadays, several other types of structures are thermo-active like diaphragm walls or tunnel linings (Barla et al., 2016; Dong et al., 2019).

In terms of numerical modelling, various degrees of complexity are usually accounted for in terms of thermal boundary conditions imposed to the thermal piles. The simplest approaches consider a uniform temperature field imposed to the pile with temperature values corresponding to the average between ingoing and outgoing temperatures of the heat carrier fluid. More sophisticated and realistic approaches consider explicitly the fluid flow within the exchanger tubes embedded within the piles, at the cost of much increased computational cost. It is worth noting that this computational cost could be overcome in practice by introducing machine learning techniques, as shown in Makasis et al. (2018)

for the thermal design of thermo-active piles. It is worth noting that, in many cases, the thermal design of piles and other geostructures constitutes the main practical interest, with little attention paid to the mechanical problem.

Constitutive models used in the analysis of geothermal structures are often relatively simple since the relevant temperature range at which thermal structures operate is not large (typically between 0 and 50 °C). The consequence is that thermal consolidation of normally consolidated clays is rather unlikely in this context.

As mentioned previously, the question of the cyclic behaviour of the soil-structure interface might be important in the long-term assessment of these structures. Bourne-Webb et al. (2022) have discussed the important role played by the available shaft resistance and the ratio of mobilised friction on the accumulation of settlement, which is mainly occurring during the first cooling and induced by the thermal shrinkage of the pile radius. Incremental settlement (i.e. per cycle) then tends to vanish as the cycle number increases. This observation was obtained from thermo-mechanical simulations using the finite element method and agrees with the experimental results reported in §2.1.1.

4.3 Radioactive waste disposals

Accounting for THM behaviour in the analysis of radioactive waste disposals is of primary importance. The literature is abundant on this topic, and covers many physical aspects, including two phase flow in swelling clays, thermal pressurisation, plastic and/or damage mechanics for the host rock, etc. This application has been studied for decades and many experimental data, from laboratory elementary tests, small scale experiments and full-scale field experiments are available. This data is highly valuable to validate numerical tools for THM modelling of geomaterials (Schäfers et al., 2020) and the THM constitutive models accounting for non-trivial couplings.

4.4 CO_2 storage and deep geothermal energy

CO_2 geological storage and deep geothermal energy production require geomechanics solvers working efficiently at the reservoir scale. These applications might necessitate specific developments to simulate multiphasic flow in reservoirs that may be fractured at various scales. Obvious in deep geothermal energy production, thermal effects are also significant in carbon dioxide geo-storage (Vilarrasa and Rutqvist, 2017). Other couplings might even be necessary in some cases, such as chemical couplings in CO_2 storage. These couplings are not necessarily implemented in THM codes and the recourse to low coupling strategies (sequential coupling, for instance) between geomechanical codes and reactive transport software is common.

5 CONCLUSIONS

Thermo-hydro-mechanical couplings are present in many applications of geotechnical engineering. In the context of the energy transition, such applications involving energy geo-engineering, they are gaining more and more importance.

In this paper, we have presented on overview of the thermo-hydro-mechanical couplings observed in geomaterials and the way these effects could be included in constitutive models for geomaterials. We also discussed the numerical modelling of typical geotechnical applications where THM behaviour of geomaterials plays an important role. Finally, it is recognised that accounting for these multiphysics couplings might be relatively complex and simplified approaches more specifically suited for engineering applications have been evoked.

6 REFERENCES

Abuel-Naga, H.M., Bergado, D.T., Bouazza, A., Pender, M., 2009. Thermomechanical model for saturated clays. *Géotechnique* **59**, 273.

Arson, C., Pereira, J.M., 2013. Influence of damage on pore size distribution and permeability of rocks. *Int. J. Numer. Anal. Methods Geomech.* **37**, 810–831.

Baldi, G., Hueckel, T., Peano, A., Pellegrini, R., 1991. *Developments in modelling of thermo-hydro-mechanical behaviour of Boom clay and clay-based buffer materials, Vol. 1 and 2, EUR 13365/1 and 13365/2, Luxembourg: Commission of the European Communities*. Nuclear Science and Technology, Commission of the European Communities.

Barla, M., Di Donna, A., Perino, A., 2016. Application of energy tunnels to an urban environment. *Geothermics* **61**, 104–113.

Blanc, B., Géminard, J.-C., 2013. Intrinsic creep of a granular column subjected to temperature changes. *Phys Rev E* **88**, 22201.

Boldrin, D., Leung, A.K., Bengough, A.G., 2021. Hydro-mechanical reinforcement of contrasting woody species: a full-scale investigation of a field slope. *Géotechnique* **71**, 970–984.

Bourne-Webb, P.J., Amatya, B., Soga, K., Amis, T., Davidson, C., Payne, P., 2009. Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles. *Géotechnique* **59**, 237–248.

Bourne-Webb, P.J., Lupattelli, A., Bodas Freitas, T.M., Salciarini, D., 2022. The influence of initial shaft resistance mobilisation in the response of seasonally, thermally-activated pile foundations in granular media. *Geomech. Energy Environ.* **32**, 100299.

Brandl, H., 2006. Energy foundations and other thermo-active ground structures. *Géotechnique* **56**, 81–122.

Braun, P., Delage, P., Ghabezloo, S., Chabot, B., Conil, N., Vu, M.-N., 2022. Inducing Tensile Failure of Claystone Through Thermal Pressurization in a Novel Triaxial Device. *Rock Mech. Rock Eng.* **55**, 3881–3899.

Braun, P., Ghabezloo, S., Delage, P., Sulem, J., Conil, N., 2021. Thermo-Poro-Elastic Behaviour of a Transversely Isotropic Shale: Thermal Expansion and Pressurization. *Rock Mech. Rock Eng.* **54**, 359–375.

Brochard, L., Honório, T., Vandamme, M., Bornert, M., Peigney, M., 2017. Nanoscale origin of the thermo-mechanical behavior of clays. *Acta Geotech.* **12**, 1261–1279.

Carman, P.C., 1937. Fluid flow through granular beds. *Trans.-Inst. Chem. Eng.* **15**, 150–166.

Cekerevac, C., Laloui, L., 2004. Experimental study of thermal effects on the mechanical behaviour of a clay. *Int. J. Numer. Anal. Methods Geomech.* **28**, 209–228.

Cui, Y., 2022. Soil–atmosphere interaction in earth structures. *J. Rock Mech. Geotech. Eng.* **14**, 35–49.

Cui, Y.J., Sultan, N., Delage, P., 2000. A thermomechanical model for saturated clays. *Can. Geotech. J.* **37**, 607–620.

Delage, P., Cui, Y.J., Tang, A.M., 2010. Clays in radioactive waste disposal. *J. Rock Mech. Geotech. Eng.* **2**, 111–123.

Dingle, H.R.C., White, D.J., Gaudin, C., 2008. Mechanisms of pipe embedment and lateral breakout on soft clay. *Can. Geotech. J.* **45**, 636–652.

Dong, S., Li, X., Tang, A.M., Pereira, J.M., Nguyen, V.T., Che, P., Xiong, Z., 2019. Thermo-mechanical behavior of energy diaphragm wall: Physical and numerical modelling. *Appl. Therm. Eng.* **146**, 243–251.

Dong, Y., McCartney, J.S., Lu, N., 2015. Critical Review of Thermal Conductivity Models for Unsaturated Soils. *Geotech. Geol. Eng.* **33**, 207–221.

Elia, G., Cotecchia, F., Pedone, G., Vaunat, J., Vardon, P.J., Pereira, C., Springman, S.M., Rouainia, M., Van Esch, J., Koda, E., Josifovski, J., Nocilla, A., Askarinejad, A., Stirling, R., Helm, P., Lollino, P., Osinski, P., 2017. Numerical modelling of slope–vegetation–atmosphere interaction: an overview. *Q. J. Eng. Geol. Hydrogeol.* **50**, 249–270.

Esmaeili, S., Modaresghazani, J., Sarma, H., Harding, T., Maini, B., 2020. Effect of temperature on relative permeability – Role of viscosity ratio. *Fuel* **278**, 118318.

Gasc-Barbier, M., Merrien-Soukatchoff, V., Virely, D., 2021. The role of natural thermal cycles on a limestone cliff mechanical behaviour. *Eng. Geol.* **293**, 106293.

Géminard, J.-C., Gayvallet, H., 2001. Thermal conductivity of a partially wet granular material. *Phys. Rev. E* **64**, 041301.

Graham, J., Tanaka, N., Crilly, T., Alfaro, M., 2001. Modified Cam-Clay modelling of temperature effects in clays. *Can. Geotech. J.* **38**, 608–621.

Gruescu, C., Giraud, A., Homand, F., Kondo, D., Do, D.P., 2007. Effective thermal conductivity of partially saturated porous rocks. *Int. J. Solids Struct.* **44**, 811–833.

Hemmati, S., Gatmiri, B., Cui, Y.-J., Vincent, M., 2012. Thermo-hydro-mechanical modelling of soil settlements induced by soil-vegetation-atmosphere interactions. *Eng. Geol.* **139–140**, 1–16.

Hong, P.Y., Pereira, J.M., Cui, Y.J., Tang, A.M., Collin, F., Li, X.L., 2014. An elastoplastic model with combined isotropic–kinematic hardening to predict the cyclic behavior of stiff clays. *Comput. Geotech.* **62**, 193–202.

Hong, P.Y., Pereira, J.M., Tang, A.M., Cui, Y.J., 2016. A two-surface plasticity model for stiff clay. *Acta Geotech.* **11**, 871–885.

Hong, P.Y., Pereira, J.M., Tang, A.M., Cui, Y.J., 2013. On some advanced thermo-mechanical models for saturated clays. *Int. J. Numer. Anal. Methods Geomech.* **37**, 2952–2971.

Huancollo, H.J.M., Saboya, F., Tibana, S., McCartney, J.S., Garske Borges, R., 2023. Thermal Triaxial Tests to Evaluate Improvement of Soft Marine Clay through Thermal Consolidation. *Geotech. Test. J.* **46**, 20220154.

Hueckel, T., Baldi, G., 1990. Thermoplasticity of saturated clays: experimental constitutive study. *J. Geotech. Eng.* **116**, 1778–1796.

Hueckel, T., Borsetto, M., 1990. Thermoplasticity of saturated soils and shales: constitutive equations. *J. Geotech. Eng.* **116**, 1765–1777.

Johansen, O., 1975. *Varmeledningsevne av jordarter (Thermal conductivity of soils)* (US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H. CRREL draft English Translation 637). University of Trondheim, Trondheim, Norway.

Kozeny, J., 1925. Über turbulentes Fließen bei glatten Wänden. *Z. Für Angew. Math. Mech.* **5**, 244–250.

Laloui, L., Di Donna, A., 2013. *Energy Geostructures: innovation in underground engineering*. John Wiley & Sons.

Laloui, L., François, B., 2009. ACMEG-T: Soil Thermoplasticity Model. *J. Eng. Mech.* **135**, 932–944.

Laloui, L., Leroueil, S., Chalindar, S., 2008. Modelling the combined effect of strain rate and temperature on one-dimensional compression of soils. *Can. Geotech. J.* **45**, 1765–1777.

Laloui, L., Moreni, M., Vulliet, L., 2003. Comportement d'un pieu bi-fonction, fondation et échangeur de chaleur. *Can. Geotech. J.* **40**, 388–402.

Laloui, L., Nuth, M., Vulliet, L., 2006. Experimental and numerical investigations of the behaviour of a heat exchanger pile. *Int. J. Numer. Anal. Methods Geomech.* **30**, 763–778.

Leroueil, S., Marques, M.E.S., 1996. Importance of strain rate and temperature effects in geotechnical engineering, in: Measuring and Modeling Time Dependent Soil Behaviour, Proc. of the ASCE Convention. Washington, DC, USA, pp. 1–60.

Makasis, N., Narsilio, G.A., Bidarmaghz, A., 2018. A machine learning approach to energy pile design. *Comput. Geotech.* **97**, 189–203.

Muñoz-Castelblanco, J.A., Pereira, J.M., Delage, P., Cui, Y.J., 2012. The water retention properties of a natural unsaturated loess from northern France. *Géotechnique* **62**, 95–106.

Ng, C.W.W., Farivar, A., Gomaa, S.M.M.H., Jafarzadeh, F., 2021. Centrifuge Modeling of Cyclic Nonsymmetrical Thermally Loaded Energy Pile Groups in Clay. *J. Geotech. Geoenvironmental Eng.* **147**, 04021146.

Ng, C.W.W., Shi, C., Gunawan, A., Laloui, L., 2014. Centrifuge modelling of energy piles subjected to heating and cooling cycles in clay. *Géotechnique Lett.* **4**, 310–316.

Nguyen, V.T., Heindl, H., Pereira, J.M., Tang, A.M., Frost, J.D., 2017a. Water retention and thermal conductivity of a natural unsaturated loess. *Géotechnique Lett.* **7**, 286–291.

Nguyen, V.T., Tang, A.M., Pereira, J.M., 2017b. Long-term thermo-mechanical behavior of energy pile in dry sand. *Acta Geotech.* **12**, 729–737.

Nguyen, V.T., Wu, N., Gan, Y., Pereira, J.-M., Tang, A.M., 2020. Long-term thermo-mechanical behaviour of energy piles in clay. *Environ. Geotech.* **7**, 237–248.

Nouri, A., Noorzad, A., Pereira, J.-M., Tang, A.M., 2023. Cyclically thermally-activated pile under combined axial/horizontal loads in clay. *Géotechnique Lett.* **13**, 41–47.

Olchitzky, E., 2002. *Couplage hydromécanique et perméabilité d'une argile gonflante non saturée sous sollicitations hydriques et thermiques : courbe de sorption et perméabilité à l'eau* (PhD thesis). Ecole des Ponts ParisTech.

Pastén, C., Castillo, E., Chong, S.-H., 2019. Thermo-mechanical ratcheting in soil–structure interfaces. *Acta Geotech.* **14**, 1561–1569.

Pasten, C., Santamarina, J.C., 2014. Thermally induced long-term displacement of thermoactive piles. *J. Geotech. Geoenvironmental Eng.* **140**, 1–5.

Pereira, J.M., Arson, C., 2013. Retention and permeability properties of damaged porous rocks. *Comput. Geotech.* **48**, 272–282.

Pham, T.A., Hashemi, A., Sutman, M., Medero, G.M., 2023. Effect of temperature on the soil–water retention characteristics in unsaturated soils: Analytical and experimental approaches. *Soils Found.* **63**, 101301.

Pijaudier-Cabot, G., Pereira, J.M. (Eds.), 2013. *Geomechanics in CO2 Storage Facilities*, *Storage Facilities*. ISTE-Wiley.

Pinyol, N.M., Alonso, E.E., 2010. Criteria for rapid sliding II. Thermo-hydro-mechanical and scale effects in Vaiont case. *Eng. Geol.* **114**, 211–227.

Preisig, M., Prévost, J.H., 2011. Coupled multi-phase thermo-poromechanical effects. Case study: CO2 injection at In Salah, Algeria. *Int. J. Greenh. Gas Control* **5**, 1055–1064.

Ravera, E., Sutman, M., Laloui, L., 2020. Load Transfer Method for Energy Piles in a Group with Pile–Soil–Slab–Pile Interaction. *J. Geotech. Geoenvironmental Eng.* **146**, 04020042.

Ross, C., Siemens, G., Beddoe, R., 2021. Initialization of thermal models in cold and warm permafrost. *Arct. Sci.* 1–33.

Santamarina, J., Aftab, A., Espinoza, D.N., Dusseault, M., Gens, A., Hoteit, H., Kim, S., Lee, J.Y., Lei, L., Narsilio, G., Pereira, J.M., Sanchez, M., Soga, K., Villar, M.V., Violay, M., 2022. Energy geo-engineering, in: Proceedings of Twentieth International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2022): A Geotechnical Discovery down under, Sydney, New South Wales, Australia, 1-5 May 2022. pp. 95–117.

Schäfers, A., Gens, A., Rodriguez-Dono, A., Baxter, S., Tsitsopoulos, V., Holton, D., Malmberg, D., Sawada, M., Yafei, Q., Ferrari, A., Laloui, L., Sjöland, A., 2020. Increasing understanding and confidence in THM simulations of Engineered Barrier Systems. *Environ. Geotech.* **7**, 59–71.

Seneviratne, H.N., Carter, J.P., Airey, D.W., Booker, J.R., 1993. A review of models for predicting the thermomechanical behaviour of soft clays. *Int. J. Numer. Anal. Methods Geomech.* **17**, 715–733.

Song, H., Pei, H., 2022. A Nonlinear Softening Load-Transfer Approach for the Thermomechanical Analysis of Energy Piles. *Int. J. Geomech.* **22**, 04022044.

Sulem, J., Famin, V., 2009. Thermal decomposition of carbonates in fault zones: Slip-weakening and temperature-limiting effects. *J. Geophys. Res.* **114**, B03309.

Sultan, N., Delage, P., Cui, Y.J., 2002. Temperature effects on the volume change behaviour of Boom clay. *Eng. Geol.* **64**, 135–145.

Tagarelli, V., Cotecchia, F., 2020. The Effects of Slope Initialization on the Numerical Model Predictions of the Slope-Vegetation-Atmosphere Interaction. *Geosciences* **10**, 85.

Veveakis, E., Vardoulakis, I., Di Toro, G., 2007. Thermoporomechanics of creeping landslides: The 1963 Vaiont slide, northern Italy. *J. Geophys. Res.* **112**, F03026.

Vilarrasa, V., Rutqvist, J., 2017. Thermal effects on geologic carbon storage. *Earth-Sci. Rev.* **165**, 245–256.

Ward, W.H., Sewell, E.C., 1950. Protection of the Ground from Thermal Effects of Industrial Plant. *Géotechnique* **2**, 64–81.

Yavari, N., Tang, A.M., Pereira, J.M., Hassen, G., 2016. Effect of temperature on the shear strength of soils and the soil–structure interface. *Can. Geotech. J.* **53**, 1186–1194.

Yavari, N., Tang, A.M., Pereira, J.M., Hassen, G., 2014a. Experimental study on the mechanical behaviour of a heat exchanger pile using physical modelling. *Acta Geotech.* **9**, 385–398.

Yavari, N., Tang, A.M., Pereira, J.M., Hassen, G., 2014b. A simple method for numerical modelling of mechanical behaviour of an energy pile. *Géotechnique Lett.* **4**, 119–124.

Ye, W.M., Wan, M., Chen, B., Chen, Y.G., Cui, Y.J., Wang, J., 2012. Temperature effects on the unsaturated permeability of the densely compacted GMZ01 bentonite under confined conditions. *Eng. Geol.* **126**, 1–7.

Zhu, C., Shen, X., Arson, C., Pouya, A., 2017. Numerical study of thermo-mechanical effects on the viscous damage behavior of rock salt caverns, in: 51st US Rock Mechanics/Geomechanics Symposium.