A THM STRESS-STRAIN FRAMEWORK FOR MODELLING THE PERFORMANCE OF ARGILLACEOUS MATERIALS IN DEEP REPOSITORIES FOR RADIOACTIVE WASTE

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Introduction

Performance assessment of deep repositories for heat-generating radioactive waste requires the capability of reliably predicting the thermo-hydro-mechanical (THM) behaviour of the clay barriers as well as that of the host rock/clay. This represents an important element of the waste isolation system. In order to provide reasonable assurance that clay barriers and the host material will ensure waste isolation, it is essential to understand their behaviour under a variety of environmental conditions. Due to the complexity of the phenomena that take place in a waste repository, an adequate understanding of the constitutive behaviour of clays and the capability to model their evolution are challenging tasks. The stress-strain material behaviours that need to be understood and modelled include: i. isothermal wetting; ii. saturated heating; iii. non-isothermal suction variations; iv. induced cracks, and v. the role of the material structure and its multi-porosity. The difficulty of some of these tasks is increased by the fact that some effects are coupled.

This lecture mainly focuses on induced thermal disturbance. The basic phenomena of the clay behaviour under non-isothermal conditions are first identified and highlighted in the case of deep repository experiments. A mechanical stress-strain constitutive framework is proposed to model the behaviour of clay barriers as well as that of the host rock/clay. It includes several aspects, such as the thermo-plastic behaviour of saturated and unsaturated materials.

Thermal disturbance in the stress field of clays

High Level Radioactive Waste (HLW) emits heat of variable power depending on the delay time with respect to the discharge from the reactor (temperatures yield 100 to 150°C at the contact of the waste package with the soil). A principal repository design factor is the temperature developing within the soil mass. This determines the spacing of tunnels and/or boreholes. In the commonly accepted concept of multiple barriers (waste package, engineered barrier of backfill and buffer, and clay host formation), the barriers may fail, releasing the radioactive contaminant. In this case, the ultimate containment barrier is the indigenous clay formation itself.

Basic THM stress-strain behaviour of argillaceous materials

Thermo-mechanical behaviour of saturated argillaceous materials

Under normally consolidated conditions (NC), clay contracts when it is heated and a significant part of this deformation is irreversible upon cooling (Figure 1). This behaviour over the whole cycle is representative of thermal hardening. Another important non-isothermal behaviour is the fact that the preconsolidation pressure decreases with increasing temperature, while the isotropic compressibilities don't seem to be significantly affected by temperature changes (Laloui and Cekerevac 2003).

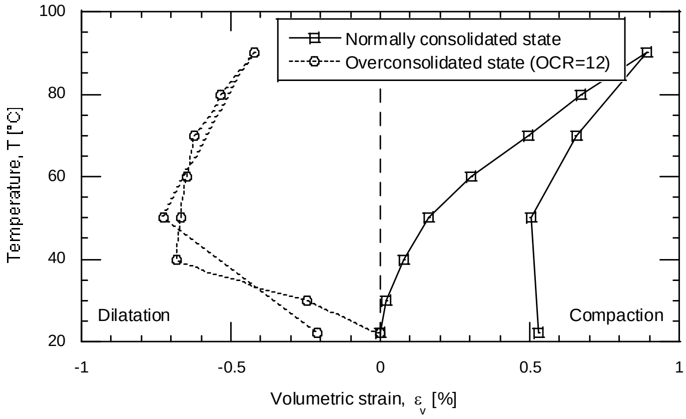

Fig. 1: Typical thermal behaviour of argillaceous materials during a heating-cooling cycle – Kaolin clay (Cekerevac and Laloui 2006)

Thermo-mechanical behaviour of unsaturated argillaceous materials

In addition to the observed features of behaviour of unsaturated soils at constant temperature and of saturated soils under non-isothermal conditions, some coupled effects must be considered. The retention capacity of soils diminishes with temperature increase, mainly because the interfacial tensile between the water and the grains decreases as long as temperature increases (Romero et al. 2001). This thermal effect indirectly influences the mechanical response of the soils by changing the suction value for the same degree of saturation.

ACMEG-TS – A THM stress-strain constitutive framework to model the non-isothermal behaviour of argillaceous materials

Even if natural host clays are different from the engineered clay barriers with respect to mineralogical composition and consolidation history, they both exhibit a close THM stress-strain behaviour. Thus, they could be modelled using the same theoretical framework.

The « generalized » effective stress

The non-saturation state within the soil means that a second fluid phase appears in the inter-particular spaces. The difference of pressure between these two fluid phases (air and water) induces a new stress variable, suction: $s = u_a - u_w$ which modifies the preconsolidation stress values. To take into account this contribution of suction in the thermo-mechanical behaviour of the soil, the generalized Bishop stress approach is used (Bishop 1959) :

$$\sigma'_{ij} = \left(\sigma_{ij} - u_a \delta_{ij}\right) + S_r \left(u_a - u_w\right) \delta_{ij}$$

where σ_{ij}, u_a, u_w, S_r are the mechanical external load, the pore air, the pore water pressures and the degree of saturation, respectively. This effective stress depends here on the thermal, the hydric and the mechanical histories of the material. Indeed, the retention capacity of the soil (e.g. the degree of saturation at a given suction) depends on its dry density, on the suction level and on the temperature. Therefore, this single stress approach converts a complex multi-phase and multi-stress medium in which multi-physics processes occur into a single mechanical state using several coupling equations.

The ACMEG-TS constitutive framework

The concept of the ACMEG-TS model is to consider that the thermal as well as the hydric loads exclusively involve volumetric effects in clayey soils. These considerations are introduced in a thermo-hydro-mechanical (THM) elasto-plastic framework where each T-H-M loading (external mechanical load σ, temperature T and suction s) may induce reversible and irreversible changes of the THM state of the material. Within this elasto-plastic framework, the total strain rate tensor, $\dot{\varepsilon}$, due to the THM loading is split into non-linear thermo-elastic, $\dot{\varepsilon}^e$, and thermo-plastic, $\dot{\varepsilon}^p$, components. The material plasticity is induced by two coupled mechanisms: an isotropic one which may be activated by any mechanical, thermal or hydric loads and a deviatoric mechanism acting only under a mechanical loading having a deviatoric component (Laloui et al. 2005). The yield functions of the two mechanical thermo-plastic mechanisms have the following expressions:

$$f_{iso} = p' - \sigma'_c \, r_{iso} \quad ; \qquad f_{dev} = q - Mp'\left(1 - b \, Log \frac{d \, p'}{\sigma'_c}\right) r_{dev} = 0$$

where the preconsolidation pressure σ'_c depends on the volumetric plastic strain ε_v^p, the temperature T and the suction s:

$$\begin{cases} \sigma'_c = \sigma'_{c0} \exp\left(\beta \; \varepsilon_v^p\right)\left\{1 - \gamma_T \log\left\{\dfrac{T}{T_0}\right\} + \gamma_s \log\left\{\dfrac{s}{s_{e0}}\right\}\right\} & \text{if} \quad s > s_{e0} \\ \sigma'_c = \sigma'_{c0} \exp\left(\beta \; \varepsilon_v^p\right)\left\{1 - \gamma_T \log\left\{\dfrac{T}{T_0}\right\}\right\} & \text{if} \quad s \le s_{e0} \end{cases}$$

r_{iso} and r_{dev} are the degree of mobilization of the isotropic and the deviatoric mechanisms and are hyperbolic functions of the plastic volumetric strain induced by the isotropic mechanism and of the plastic deviatoric strain, respectively. In terms of hydric or thermal response, the desaturation and the heating processes are also seen as yielding phenomena. The yielding mechanisms (deviatoric and isotropic) are coupled through the volumetric plastic strain. With this ACMEG-TS framework, The THM response of the soil is totally described through an elasto-plastic model in the hydric, temperature and mechanical planes (Figure 2).

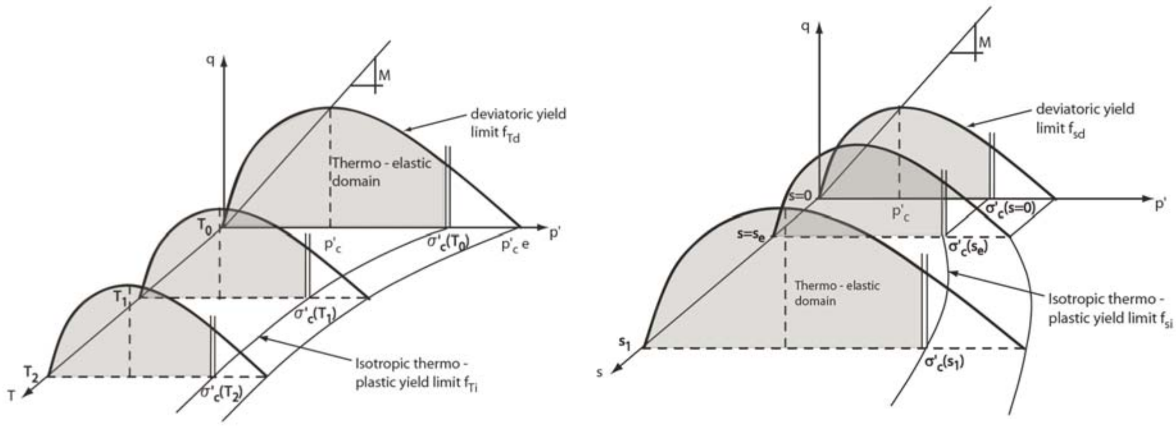

Fig. 2: Yield limits for the THM elasto-plastic framework

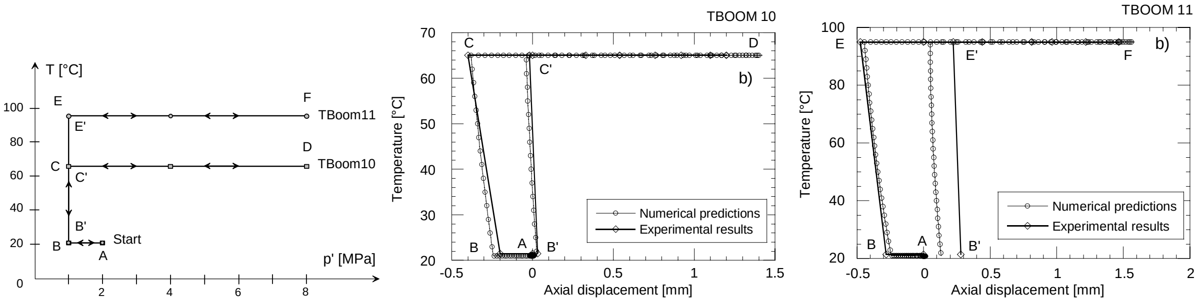

Fig. 3: An example of the numerical prediction of coupled THM paths – Boom Clay Experimental results (Baldi et al., 1991) – Numerical predictions (Laloui, 1993)

Figure 3 shows, as an example of the performance of the THM stress-strain model, the numerical prediction of the coupled drained mechanical-thermal behaviour of Boom clay.

Conclusions

In the scenarios for deep, geological nuclear-waste repositories, clayey soils will be hydrated, heated, cooled and dried. The numerical modelling of these mechanical processes is a key issue. Performance assessment of deep repositories for heat-generating radioactive waste would benefit from improvements in mechanical stress-strain constitutive modelling of the coupled thermo-hydro-mechanical behaviour. The presented ACMEG-TS framework allows progress in understanding the most involved phenomena relevant to nuclear-waste repositories and their coupled nature. It could be used both in the design and in the performance assessment of repositories. It may be applied to disposal in clay formations and to hard-rock repositories where artificially compacted clay is to be used as buffer and backfill. Such a constitutive framework may help in understanding some unexplained or controversial behaviours and in defining experimental programmes to answer key questions.

Acknowledgements

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