A CONSTITUTIVE APPROACH TO ADDRESS THE THERMAL AND HYDRIC IMPACTS IN THE CONCEPT OF DEEP RADIOACTIVE WASTE REPOSITORIES

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INTRODUCTION

Performance assessment of deep repositories for heat-generating radioactive waste (e.g. vitrified high-level radioactive waste - HLW) requires the capability of predicting reliably the thermo-hydro-mechanical behaviour of both clay barrier and host rock/clay. Due to the complexity and highly coupled nature of phenomena taking place in a waste repository, an adequate understanding of the constitutive behaviour of clays and the capability to model their evolutions are challenging tasks. Within this context, a mechanical stress-strain constitutive framework taking into consideration the non-isothermal and unsaturated conditions is proposed to model the behaviour of the aforementioned confining materials. Thermo-plasticity of saturated and unsaturated materials is featured within the framework which also takes advantage of a convenient generalized effective stress (Nuth & Laloui, 2007). The proposed constitutive context allows a performing prediction of experimental features of behaviour by comprehending complex thermo-hydro-mechanical coupling effects.

THERMO-HYDRO-MECHANICAL PROCESSES

In the years following the construction of the underground disposal, the near-field which can be defined as the zone altered by the presence of radioactive waste undergoes complex mechanical, hydric and thermal interdependent loads (THM couplings). Indeed, between the times of excavation and HLW placing, drainage and consolidation processes occur in the surrounding host rock so that a decrease in effective stress is assorted with swelling of the host rock and likely initiates desaturation. Once the canister and engineered (initially unsaturated) barrier are in place, the heating from the canister and the hydration from the surrounding rock become the two principal environmental loads. According to the stress state in the clayey barrier, the soil may be subject to thermal and hydric swelling or undesired plastic shrinkage due to thermo-plasticity and wetting collapse.

ACMEG-TS: A CONSTITUTIVE FRAMEWORK

Based on experimental evidence on the relevant THM features of behaviour of fine grain soils, a new unified thermo-mechanical constitutive model for unsaturated soils (ACMEG-TS, for Advanced Constitutive Model in Environmental Geomechanics – Thermal and Suction effects) has been developed in the framework of elasto-thermoplasticity of unsaturated soils. The model uses the concept of generalized effective stress adapted from Bishop (1959):

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

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

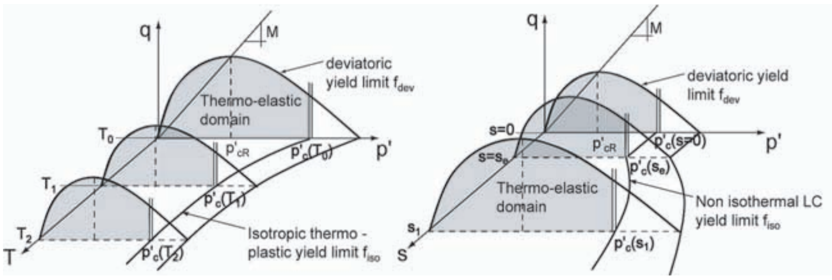

Figure 1: Yield limits for the THM elasto-plastic framework.

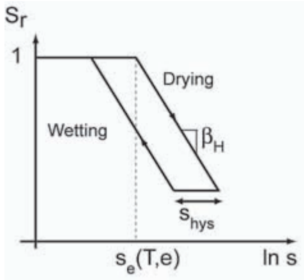

Figure 2: Schematic representation of the water retention curve model.

In the context of elasto-plasticity, the total strain increment tensor, due to THM loading is decomposed into non-linear thermo-elastic and thermo-plastic components. Material plasticity is induced by two coupled hardening processes: an isotropic and a deviatoric mechanism. The yield functions of the two mechanical thermo-plastic mechanisms have the following expressions (Figure 1) (François and Laloui, 2007), r_{iso}, r_{dev}, d and b being material parameters:

$$f_{iso} = p' - p'_c(\mathrm{s,T})\; r_{iso} = 0 \quad ; \quad f_{dev} = q - Mp'\left(1 - b\; Log \frac{d\; p'}{p'_c(\mathrm{s,T})}\right) r_{dev} = 0$$

Preconsolidation pressure, p'_c is known to depend on temperature and suction conditions so that it is not only the hardening variable during mechanical loading but also the one variable piloting the shape of the yield limit enabling to model thermal and hydric collapse.

In terms of hydric response, desaturation is also believed to raise elasto-plastic phenomena. Upon a drying process, suction increase is associated with a reduction in the degree of saturation S_r that falls significantly once the air entry suction s_e is overpassed. Figure 2 gives a qualitative representation of this temperature and material dry density dependent hydric limit. Under re-wetting, an hysteretic hydric phenomenon occurs which is also represented by a yielding process (Figure 2). Further wetting-drying cycles activate successively two hydric yield limits (François et al., 2007).

NUMERICAL SIMULATIONS

Finally, the presented advanced constitutive model has been implemented in the LAGAMINE finite element code (Collin 2003), providing a performing numerical tool to address, to model and most of all to understand the highly coupled mechanical, hydric and thermal effects governing the THM behaviour of geological and engineered barriers in a HLW deep repository.

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