Multiphysical Behaviour of Shales

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The involvement of shales in new energy-related fields such as the extraction of gas shale and shales oil, the deep geothermal energy capture, the sequestration of CO2 and the nuclear waste geological storage, has raised a new and growing interest in the geomechanical behaviour of the material. In this context, fundamental issues come along with the complex multiphysical conditions in which the geomaterial is found where temperature, chemistry and unsaturated conditions play a major role. As a consequence the study of the coupled thermo-hydro-chemo-mechanical (THCM) behaviour of shales is strongly sought.
This lecture introduces the most recent advances in the experimental testing and modelling of the THCM behaviour of shales. Such testing under complex multiphysical conditions come along with the need to develop advanced experimental tools and techniques to reproduce the extreme multiphysical conditions experienced by shales in the context of the latest engineering developments. The lecture addresses the devices developed and methodologies established to study the water retention properties of shales and gas shales, the water and gas transport properties, the 1D volumetric behaviour, the thermo-mechanical couplings, the impact of the pore water composition on the mechanical response and the unsaturated behaviour of shales.

A workflow established for the analysis of the water retention behaviour of shales in non-isochoric conditions is introduced; the method allows for the determination of the main drying and wetting paths and of the volume change response upon total suction variations (Ferrari et al. 2014).

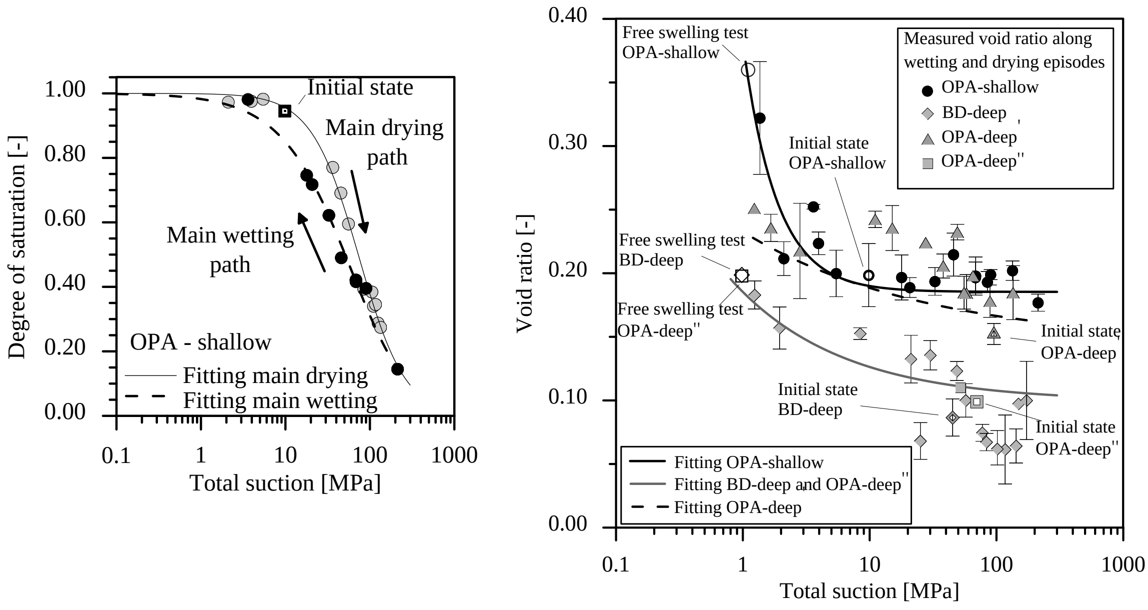

Figure 1: Water retention behaviour of Opalinus Clay shale in terms of degree of saturation as a function of the total suction (left); void ratio evolution as a function of the total suction for various Swiss shale samples (Ferrari et al. 2014).

With particular regards to gas shales, advanced testing set-ups and experimental methodologies are presented to specifically investigate their behaviour in partially saturated conditions. When dealing with gas shales, significant additional challenges have to be taken into account due to their extreme-low porosity and higher stiffness with respect to conventional shales. A comprehensive analysis of the hydro-mechanical behaviour of gas shales involves the definition of the water retention properties and the impact of suction/water saturation on the mechanical properties. The lecture highlights the ad-hoc laboratory procedure adopted for the determination of the water retention behaviour of gas shales. The methodology allows the investigation of wetting and drying processes, by giving a strong focus on the impact of anisotropy on the volumetric behaviour due to suction change in unstressed conditions. A high pressure testing device is also introduced to perform uniaxial compression tests and highlight the coupling between the hydraulic and mechanical behaviour. Experimental analyses allow the investigation of the dependence on suction of both elastic and strength properties along with the volumetric behaviour in stressed conditions.
A high-pressure oedometric cell is also presented; the apparatus allows for the analysis of the transition from the pre-yield behaviour to the normally consolidated state (Ferrari and Laloui 2013). The analysis of the settlement versus time curves yields information on the consolidation, the permeability and the creep of the material as a function of the void ratio. The device has being equipped with additional tools to study the volumetric behaviour of shales in non-isothermal conditions and with different pore fluid chemical compositions. An advance thermo-hydro-mechanical triaxial apparatus is also introduced; the cell allows to study the THM behaviour of shales at high stresses, high temperatures and in unsaturated conditions. The test results are illustrated for three Mesozoic shales.

The last part of the lecture is devoted to the theoretical framework developed for reproducing and predicting the mechanical behaviour of Shales. From the constitutive point of view shale can be generally seen as a quasi-brittle material, a class of behaviour that includes for example rocks, concrete and cemented soils. The dissipation process takes places with two distinct mechanisms of irreversible strains formation and degradation of the elastic properties. At low values of confinement, elasticity can be considered to be linear. Before reaching the peak stress, accumulated irreversible strains are in the order of the elastic ones. After the stress peak is reached, the accumulation of inelastic strains caused principally by debonding and decohesion mechanisms, as well as by microcracks growth, leads the material to exhibit softening behaviour. The end of the softening phase is followed by a residual state in which the deformation processes is purely plastic, no elastic strains are produced and the deviatoric stress remains at constant values. In order to be able to reproduce such behaviour a constitutive model that couples plasticity and damage was developed (Parisio et al. 2015). The isotropic damage evolution is of the Marigo type, i.e. is based on the elastic energy density. The phenomenological expression is of the exponential type and is taken from the Weibull probabilistic theory that describes the failure process of brittle materials. The plastic yield surface, formulated in the damage effective stress space, is non-linear and based on a second order formulation. The dependency of the yield locus with mean stress is properly accounted for. The hardening process is based on a bounding surface theory, so that when plasticity reaches saturation and no hardening takes place anymore, the damage evolution is stopped (elastic strain increments are null in this phase). Both plastic yield and damage surfaces are postulated and thermodynamic consistency is later investigated. The constitutive model is integrated with an implicit stress return algorithm for what concerns plasticity, while damage can be integrated implicitly once the plastic strain tensor is known. Numerical analyses at Gauss point level are compared against experimental results from two shales: Opalinus Clay (OPA) from Mont Terri URL and La Biche shale from Canada. Figure 2 comparison between numerical back-calculations and experimental results of a triaxial test at 3 MPa of confinement on OPA.

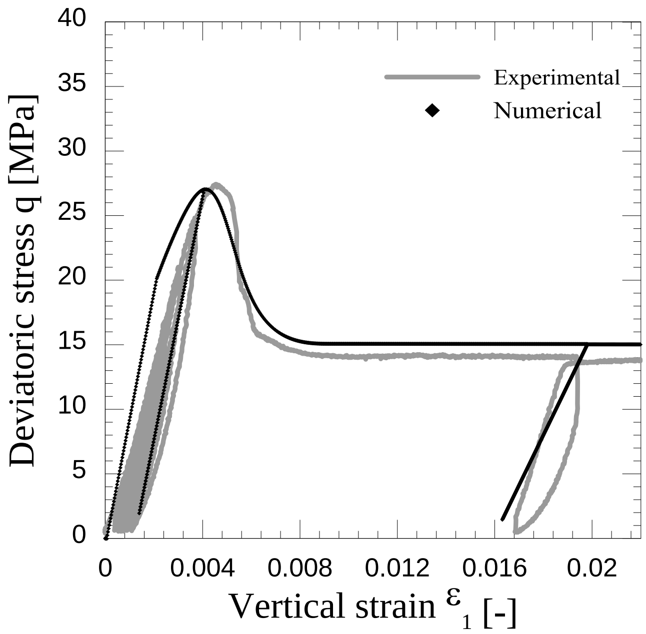

Figure 2: Deviatoric stress vs vertical strain experimental results compared against numerical results of a triaxial test at 3 MPa of confinement stress in Opalinus Clay (experimental data from Gräsle et al. 2011).

References

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