Modelling clay rock behaviour from macro to micro scales (and back): deformation, rupture, and hydromechanical phenomena

Benoît Pardoen, Frédéric Collin, Pierre Bésuelle, Stefano Dal Pont, Philippe Cosenza, Jacques Desrues.

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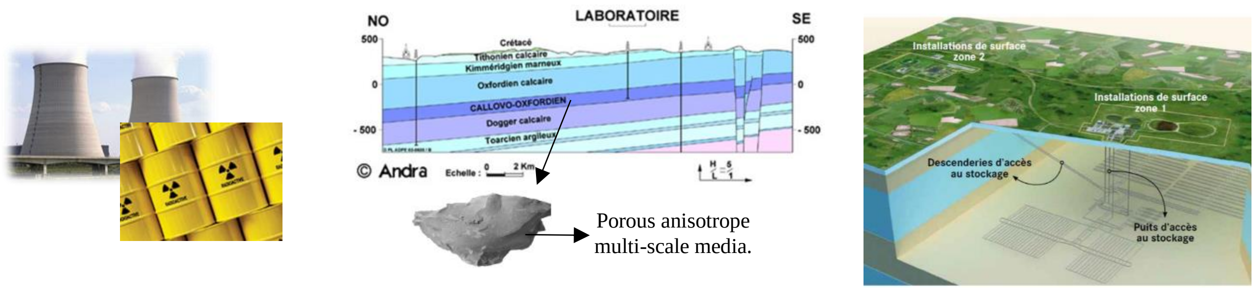
Context

The long-term management of high-level nuclear wastes is envisaged by deep geological repository. In this context, clay rocks are considered as favourable media for deep geological repositories (*Fig. 1*). Due to the safety function of the host formation, the behaviour of the Excavation Damaged Zone (EDZ) that develops around underground galleries during their drilling is of paramount importance (*Fig. 2*). The EDZ is dominated by fracturing process which engenders irreversible modifications of the hydro-mechanical properties of the porous rock. In this zone, a significant hydraulic permeability increase of several orders of magnitude is observed. It may alter the safety function of the host formation by creating preferential flow paths for the migration of radionuclides towards the biosphere. Consequently, the understanding and the prediction of the EDZ hydro-mechanical behaviour are crucial issues for the long-term (safe) management of nuclear wastes. Among the different low-permeability media that are envisaged for the deep repository, the Callovo-Oxfordian claystone is studied.



(a) (b) (c)

Fig. 1 – Long-term management of radioactive wastes in France envisaged: (a) nuclear waste production, (b) the Callovo-Oxfordian claystone as a host material, (c) underground structures (Cigéo project) [1].

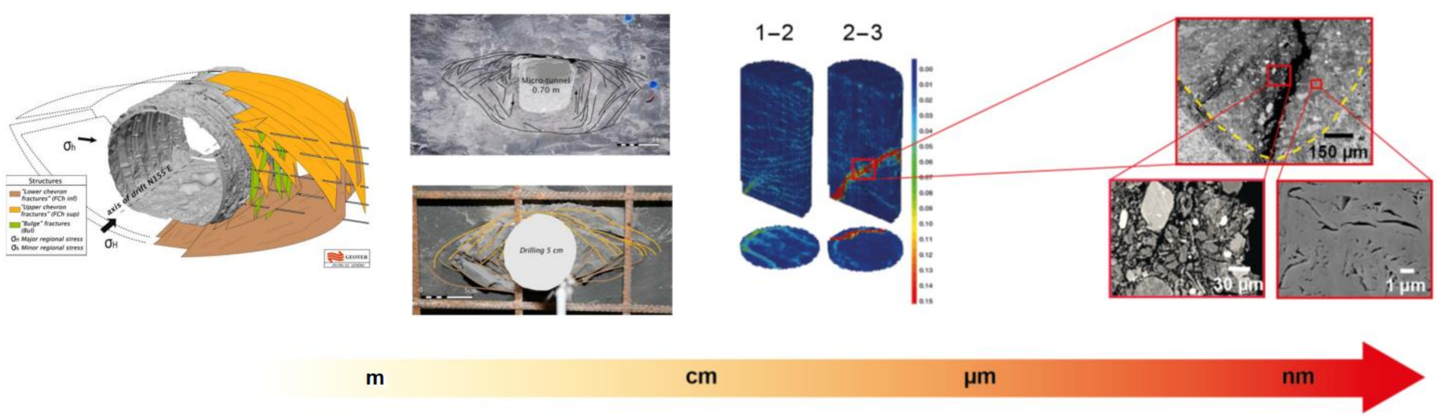


Fig. 2 – Excavation Damaged Zone (EDZ), fractures, and deformation at various scales ([2], [3], [4]).

Moreover, it is well known that large-scale phenomena (deformation, failure, hydromechanical coupling …) take their origin from small scale processes (at grain and pore scale) (*Fig. 2*). Argillites are complex clay rock exhibiting a multi-scale heterogeneous microstructure (*Fig. 3*). Questions have risen on how microstructural characteristics of heterogeneous rocks can enrich the constitutive behaviour at macroscale, in order to predict deformation and failure processes for instance (*Fig. 2*). Consequently, the modelling of the hydro-mechanical behaviour of a clay rock is considered by taking into account its microstructural characteristics and their variabilities.

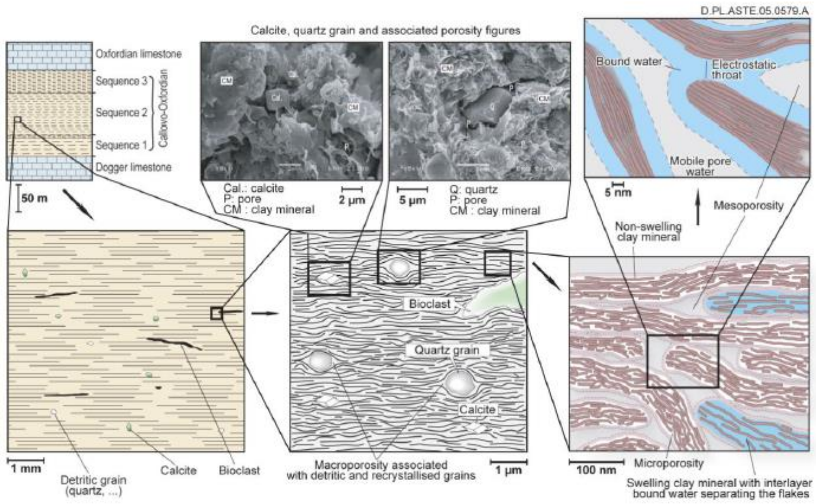


Fig. 3 – Callovo-Oxfordian structure at different scales [5].

Part I – Macroscale

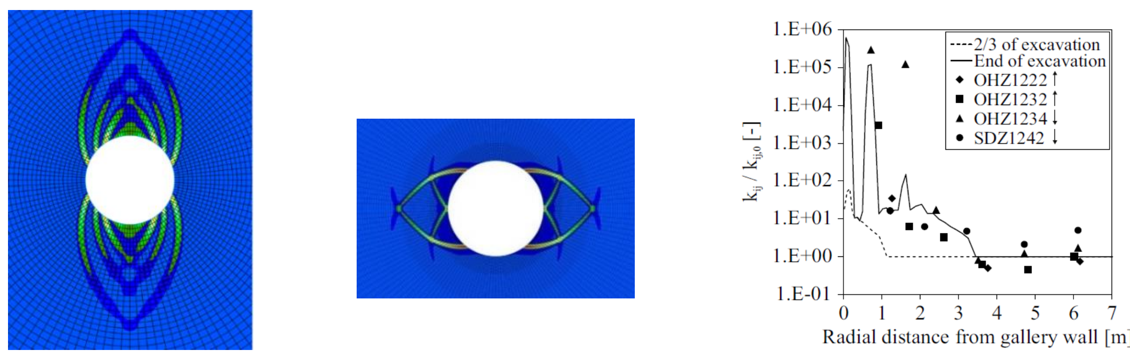
Hydro-mechanical analysis of the fracturing induced by the excavation of nuclear waste repository galleries using shear banding ([6] to [12])

By Benoît Pardoen, Frédéric Collin

The fracturing behaviour, the water transfers, and the coupled processes that occur around the underground galleries are addressed, especially in the EDZ. The fractures induced by the excavation process are reproduced with strain localisation in shear bands. An appropriate model allowing to properly reproduce the strain localisation in geomaterials with finite element methods is used. It is an enhanced model for microstructure media called the coupled local second gradient model and which involves a regularisation method. Its application is extended to unsaturated anisotropic rocks with compressible solid grains. The numerical modelling of the fractured zone with shear banding provides information about its shape, extent, fracturing structure, and behaviour that are in good agreement with in situ measurements (*Fig. 4*, *Fig. 5*). In particular, the shape of the EDZ in the Callovo-Oxfordian claystone is governed by its anisotropy and the gallery convergence strongly depends on the appearance of the shear bands.

The fluid transfers and the coupled processes are investigated in the EDZ. The impact of the rock fracturing on its hydraulic properties is addressed by taking into account strain localisation effects at macroscale. The evolution of the intrinsic water permeability is expressed by a strain-dependent relation which engenders a more pronounced increase of the permeability inside the shear bands (*Fig. 4* (c)). In agreement with experimental measurements, an important increase is reproduced in the excavation damaged zone (*Fig. 4* (c)). After gallery excavation, the hydraulic transfers in the rock surrounding the galleries are investigated by considering the interaction between the rock and the gallery air. These transfers are studied at large-scale during the reproduction of gallery air ventilation. Depending on the air hygrometry, the gallery ventilation implies drainage and desaturation of the surrounding rock which affect the shear banding development. The hydraulic transfers in the rock which depend on the water exchanges at gallery wall are also studied.

The proposed approach aims to highlight the important hydro-mechanical aspects to take into account for the reproduction of the EDZ behaviour in unsaturated biphasic media with shear banding. The focus is resolutely on the large-scale numerical modelling of the EDZ as well as on the reproduction of the mechanical and hydraulic experimental measurements performed around galleries.



(a) (b) (c)

Fig. 4 - EDZ in the Callovo-Oxfordian argillite: shear band representation for galleries parallel to the principal horizontal stress (a) minor σ_h and (b) major σ_H , and (c) reproduction of the argillite intrinsic permeability evolution in the vertical direction around galleries parallel to σ_h ([7] to [10]).

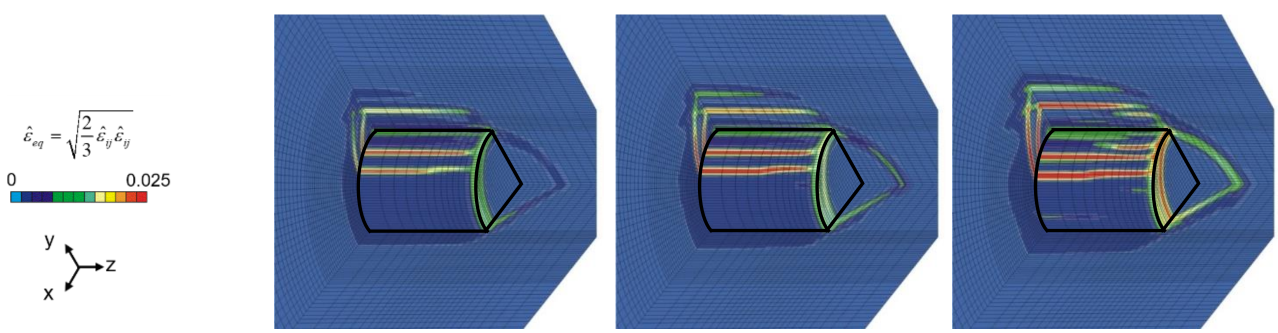


Fig. 5 – 3D modelling of the development of EDZ by shear banding around a gallery.

<u>Part II – Multi-scale</u>

Accounting for microstructural heterogeneity and variability of argillite through a multi-scale numerical approach ([13], [14])

By Benoît Pardoen, Pierre Bésuelle, Stefano Dal Pont, Philippe Cosenza, Jacques Desrues

An approach is investigated for the modelling of the hydro-mechanical coupled behaviour of Callovo-Oxfordian claystone, a potential host rock for repositories in France. The developed numerical approach takes into account the multi-scale heterogeneity and spatial variability with its effects from small to large (engineering) scale ([13], [14],

[15]). It is based on experimental characterisation and the main objectives are: consider microstructures that are more realistic, predict the deformation and damage from micro to macroscale, consider the effect of heterogeneity and variability at both scales. Furthermore, the principle of deep geological repositories relies among others on the low permeability of the host rock. As the permeability is influenced by mechanical damage of the material, the coupling between hydraulic and mechanical behaviour of the host rock is of importance.

The approach presented is a double-scale finite element method (FEMxFEM) using elementary areas (EA) to model the material behaviour at the microscale [15] (*Fig. 6*). The global response of the microscale EA serves as a homogenised numerical constitutive law for the macroscale. At macroscale, a poro-mechanical continuum is defined with fully coupled hydro-mechanical behaviour. At microscale, the microstructure of the material in the EA contains elastic deformable solids separated by damageable cohesive interfaces. Cohesive forces are described by a damage law, allowing softening of the material due to deformation. Additionally, the interfaces form a porous network allowing fluid transport prescribed by the variation in interface opening which leads to a variation of the material permeability. With fluid pressure acting on the solid parts, this gives a coupled hydro-mechanical system at the micro level [15].

The work focuses on the definition of the EA in a clay rock [14], in order to be both a realistic and simple representation of the material (*Fig. 6*). Experimental observations and characterisations of the rock's microstructure are considered to define the material in a realistic manner [16]. The representativeness of the microstructure in the elementary volume depends on its size which is limited due to numerical constrains for double-scale approach. The weakness of the representativeness can be partially solved by the spatial variability of the EA at Gauss points of the macro-FE-model. Moreover, the natural heterogeneity of clay rock at intermediate scales between the macro and micro scales can be taken into account by a spatial variability of the EA. A sensibility analysis on the choice of the EA and consequences on the macro response is investigated [14]. Moreover, double-scale computation results highlight the claystone behaviour at micro and macro scales with comparison to experimental data of compression tests [13]-[14]. An emphasis is put on the prediction of deformation and failure processes (*Fig. 6*) at both scales.

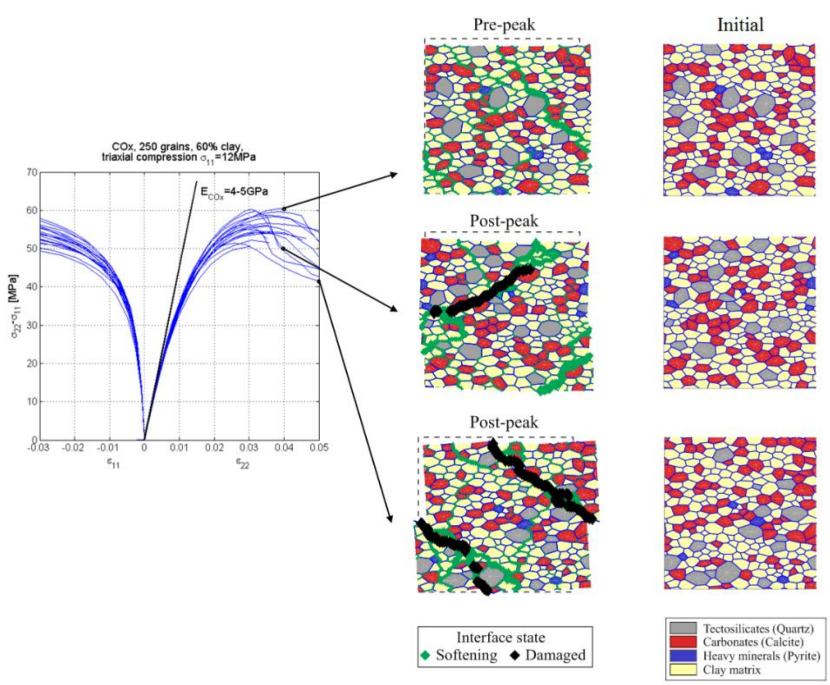


Fig. 6 – Material response at microscale under biaxial compression [14].

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