



**HAL**  
open science

# Hydromechanical modelling and numerical simulation of self-sealing phenomena in the Callovo-Oxfordian claystone

Joffrey Bluthé, B. Bary, Éric Lemarchand, Luc Dormieux

► **To cite this version:**

Joffrey Bluthé, B. Bary, Éric Lemarchand, Luc Dormieux. Hydromechanical modelling and numerical simulation of self-sealing phenomena in the Callovo-Oxfordian claystone. EGU General Assembly 2018 ERE5.5 Assessment of Barrier Integrity in Geological Repositories for Nuclear Waste Disposal and Contaminant Isolation, Apr 2018, Vienne, Austria. cea-02339300

**HAL Id: cea-02339300**

**<https://cea.hal.science/cea-02339300v1>**

Submitted on 13 Dec 2019

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Hydromechanical modeling and numerical simulation of self-sealing phenomena in the Callovo-Oxfordian claystone

EGU - Session ERE5.5

Joffrey Bluthé<sup>a,b</sup>, Benoît Bary<sup>a</sup>,  
Eric Lemarchand<sup>b</sup>, Luc Dormieux<sup>b</sup>

April, 13th 2018

<sup>a</sup>CEA, SECR, France

<sup>b</sup>Laboratoire Navier, ENPC, IFSTTAR, CNRS UMR 8205, Marne-La-Vallée, France

- 1 Context and objectives
- 2 Modeling the CDZ experiment
- 3 Conclusions and perspectives

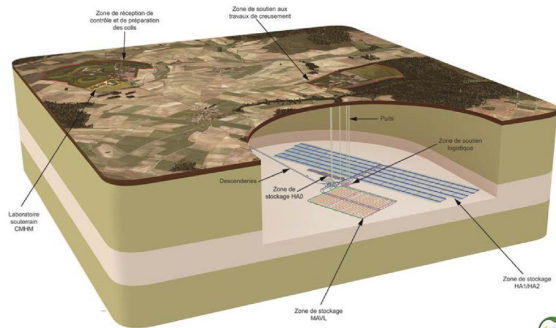
- 1 Context and objectives
- 2 Modeling the CDZ experiment
- 3 Conclusions and perspectives



- Roughly 72% of France's electricity production was nuclear in 2016

- Roughly 72% of France's electricity production was nuclear in 2016
- HLW represented 0.2% of the total volume of French radioactive waste but 94.98% of their total radioactivity in 2007

- Roughly 72% of France's electricity production was nuclear in 2016
- HLW represented 0.2% of the total volume of French radioactive waste but 94.98% of their total radioactivity in 2007
- Project Cigéo : HL/IL-LL waste repository



C.M.OEKS.15.0005.C

Echelle des ouvrages non respectée.  
Pendage des formations géologiques non représenté.

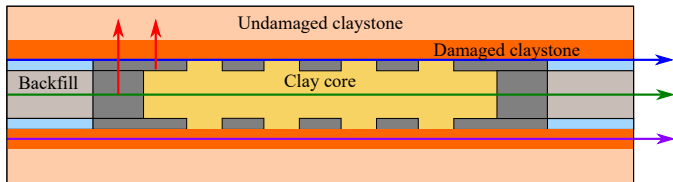






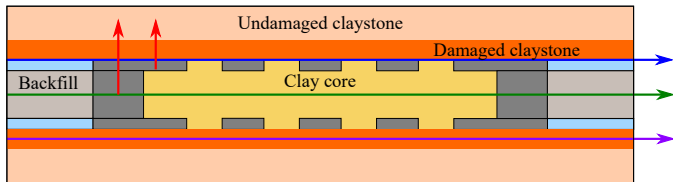
- Excavation process leads to the creation of a high permeability damaged zone along the drifts

- Excavation process leads to the creation of a high permeability damaged zone along the drifts



- Transfer through interface between claystone, clay core and lining
- Transfer through damaged claystone
- Transfer through clay core and drifts
- Transfer through Callovo-Oxfordian

- Excavation process leads to the creation of a high permeability damaged zone along the drifts



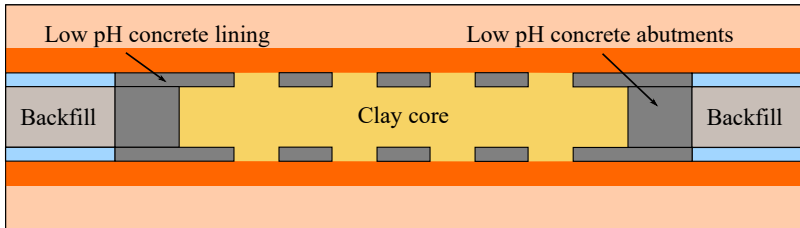
- Transfer through interface between claystone, clay core and lining
- Transfer through clay core and drifts
- Transfer through damaged claystone
- Transfer through Callovo-Oxfordian

- Goal for the overall hydraulic conductivity of the seals + galleries :  $< 10^{-9} \text{ m} \cdot \text{s}^{-1}$  (Bauer et al. [2])

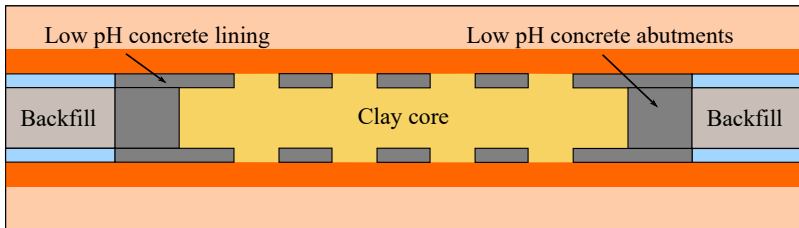


- **Self-sealing** = hydraulic conductivity drops dramatically when the claystone is hydrated

- **Self-sealing** = hydraulic conductivity drops dramatically when the claystone is hydrated
- **Objective** : Predict the evolution of the damaged zone around a horizontal sealing during the resaturation phase



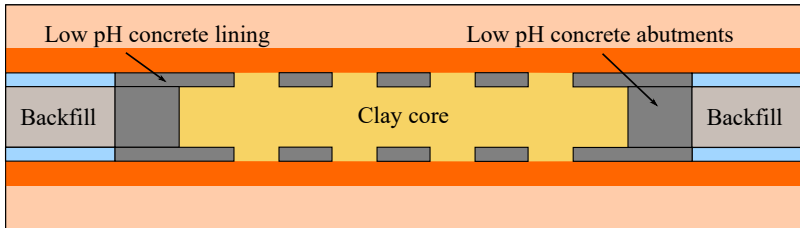
- **Self-sealing** = hydraulic conductivity drops dramatically when the claystone is hydrated
- **Objective** : Predict the evolution of the damaged zone around a horizontal sealing during the resaturation phase



- **Hydromechanical coupling**



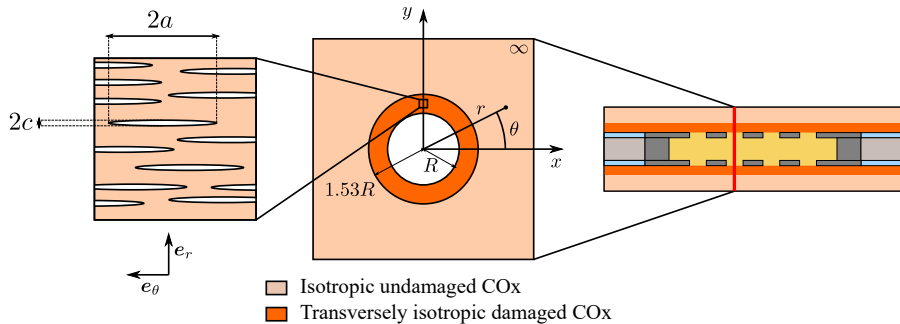
- **Self-sealing** = hydraulic conductivity drops dramatically when the claystone is hydrated
- **Objective** : Predict the evolution of the damaged zone around a horizontal sealing during the resaturation phase

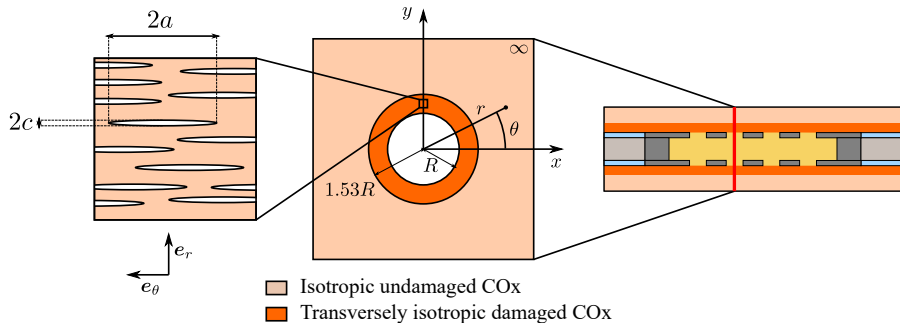


- **Hydromechanical coupling**
- Resaturation takes place over thousands of years  $\Rightarrow$  need to take into account the **viscoplastic** behavior of the claystone (not considered in the following, see perspectives)

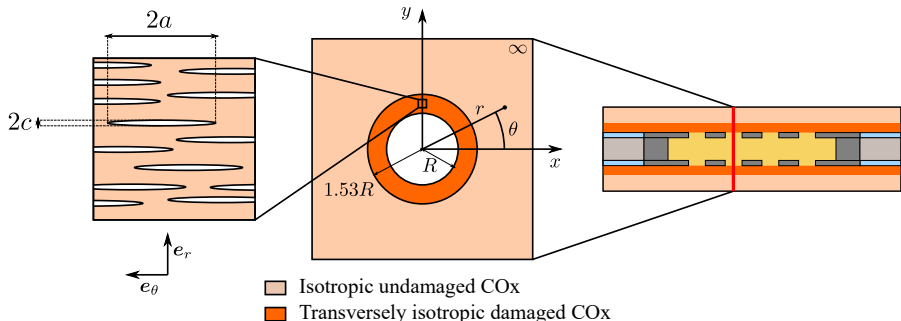
- 1 Context and objectives
- 2 Modeling the CDZ experiment
- 3 Conclusions and perspectives



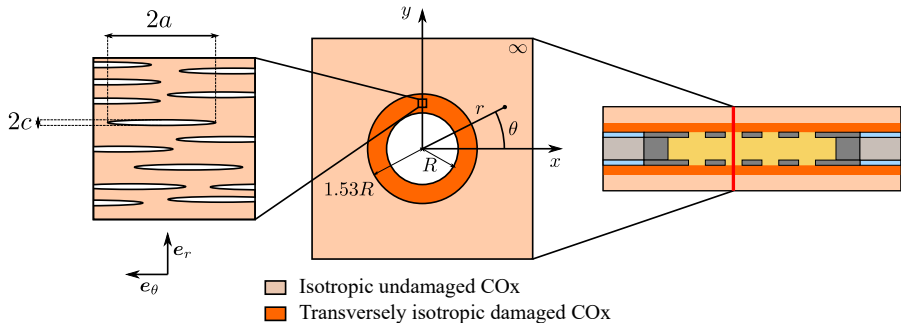


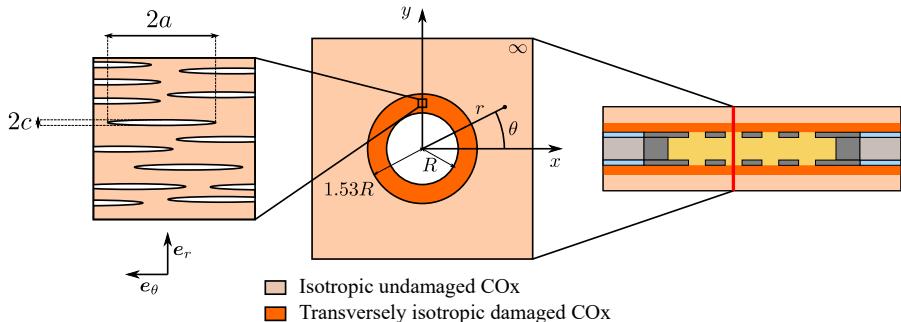


- Circular damaged zone with thickness  $0.53R$  (ensures correct cross-sectional area)



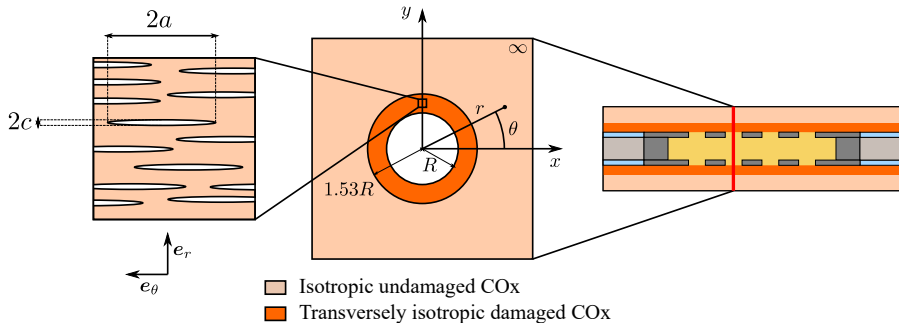
- Circular damaged zone with thickness  $0.53R$  (ensures correct cross-sectional area)
- Mode I cracks parallel to the drift walls (normal =  $e_r$ ), mode II cracks disregarded



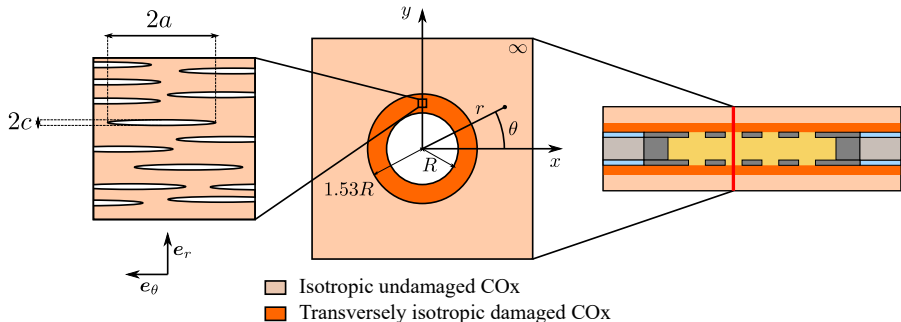


- Linear elastic isotropic behavior of the undamaged claystone

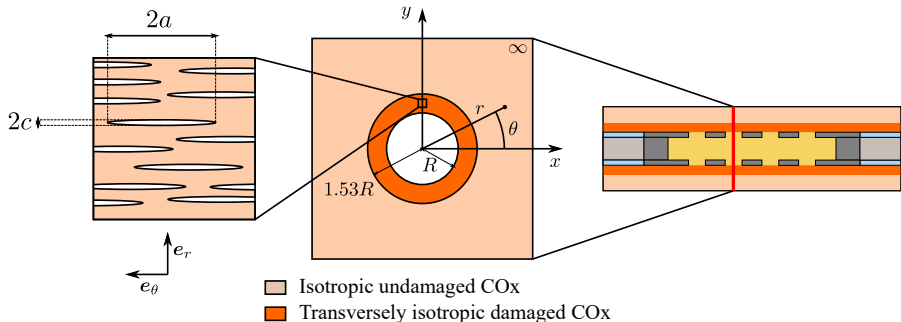




- Linear elastic isotropic behavior of the undamaged claystone
- No prestress



- Linear elastic isotropic behavior of the undamaged claystone
- No prestress
- Plane strain in the plane  $\perp \mathbf{e}_z$

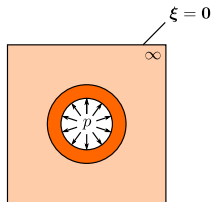


- Linear elastic isotropic behavior of the undamaged claystone
- No prestress
- Plane strain in the plane  $\perp \mathbf{e}_z$
- Cracks remain open during the experiment (ensures linearity)



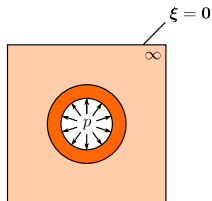
- Two kinds of loading in the CDZ experiment :

- Two kinds of loading in the CDZ experiment :
  - Problem (i) :  $p = 4$  MPa pressure prescribed at  $r = R$

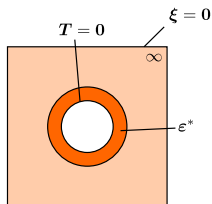


(a) Problem (i).

- Two kinds of loading in the CDZ experiment :
    - Problem (i) :  $p = 4$  MPa pressure prescribed at  $r = R$
    - Problem (ii) : wetting and thus stress-free strain  $\varepsilon^* = g(r)\mathbf{1}$  in the damaged zone, and  $\boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{0}$  at  $r = R$
- NB : Swelling leads to divergence of the drift walls and thus zero displacements at the boundary would lead to unrealistic surface tractions at  $r = R$

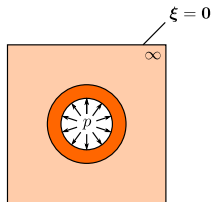


(a) Problem (i).

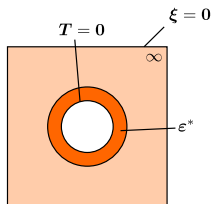


(b) Problem (ii).

- Two kinds of loading in the CDZ experiment :
    - Problem (i) :  $p = 4$  MPa pressure prescribed at  $r = R$
    - Problem (ii) : wetting and thus stress-free strain  $\varepsilon^* = g(r)\mathbf{1}$  in the damaged zone, and  $\boldsymbol{\sigma} \cdot \mathbf{n} = \mathbf{0}$  at  $r = R$
- NB : Swelling leads to divergence of the drift walls and thus zero displacements at the boundary would lead to unrealistic surface tractions at  $r = R$
- Geometry, material behavior, loading  
 $\Rightarrow$  Rotational symmetry around  $\mathbf{e}_z$



(a) Problem (i).



(b) Problem (ii).





- The homogenized behavior of the microcracked damaged zone is investigated in the rate form (ESHELBY based)

- The homogenized behavior of the microcracked damaged zone is investigated in the rate form (ESHELBY based)
- Linear elastic behavior of the intact claystone

$$\dot{\sigma} = \mathbb{C}^{COx} : (\dot{\epsilon} - \dot{\epsilon}^*)$$

- The homogenized behavior of the microcracked damaged zone is investigated in the rate form (ESHELBY based)
- Linear elastic behavior of the intact claystone

$$\dot{\sigma} = \mathbb{C}^{COx} : (\dot{\epsilon} - \dot{\epsilon}^*)$$

- Weak crack interaction : MORI-TANAKA scheme  $\Rightarrow$  nonlinear elastic behavior of the microcracked damaged zone with the same stress-free strain

$$\dot{\Sigma} = \mathbb{C}^{Dam}(\Sigma) : (\dot{E} - \dot{\epsilon}^*)$$

- The homogenized behavior of the microcracked damaged zone is investigated in the rate form (ESHELBY based)
- Linear elastic behavior of the intact claystone

$$\dot{\boldsymbol{\sigma}} = \mathbb{C}^{COx} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^*)$$

- Weak crack interaction : MORI-TANAKA scheme  $\Rightarrow$  nonlinear elastic behavior of the microcracked damaged zone with the same stress-free strain

$$\dot{\boldsymbol{\Sigma}} = \mathbb{C}^{Dam}(\boldsymbol{\Sigma}) : (\dot{\boldsymbol{E}} - \dot{\boldsymbol{\varepsilon}}^*)$$

- The crack opening variation is derived (Deudé [5]) :

$$\dot{c} = c \left( \overline{\dot{\boldsymbol{\varepsilon}}}^c : \mathbf{n} \otimes \mathbf{n} \right) = aX \left( \overline{\dot{\boldsymbol{\varepsilon}}}^c : \mathbf{n} \otimes \mathbf{n} \right)$$



- Cracks  $\rightarrow X = \frac{c}{a} \ll 1$  (same  $X$  for all cracks)

- Cracks  $\rightarrow X = \frac{c}{a} \ll 1$  (same  $X$  for all cracks)
- This leads to

$$\mathbb{C}^{Dam} = \mathbb{C}^{COx} : \left( \mathbb{I} + \frac{4\pi}{3} d\mathbb{T} \right)^{-1} ; \mathbb{T}(\nu^{COx})$$



- Cracks  $\rightarrow X = \frac{c}{a} \ll 1$  (same  $X$  for all cracks)
- This leads to

$$\mathbb{C}^{Dam} = \mathbb{C}^{COx} : \left( \mathbb{I} + \frac{4\pi}{3} d \mathbb{T} \right)^{-1} ; \mathbb{T}(\nu^{COx})$$

- $d = \mathcal{N}a^3$  is the crack density parameter (Budiansky and O'connell [3])

- Cracks  $\rightarrow X = \frac{c}{a} \ll 1$  (same  $X$  for all cracks)
- This leads to

$$\mathbb{C}^{Dam} = \mathbb{C}^{COx} : \left( \mathbb{I} + \frac{4\pi}{3} d \mathbb{T} \right)^{-1} ; \mathbb{T}(\nu^{COx})$$

- $d = \mathcal{N}a^3$  is the crack density parameter (Budiansky and O'connell [3])
- In that limit the problem is linear (as long as the cracks remain open) because  $\mathbb{C}^{Dam}$  is independent of  $c \Rightarrow$  integration with respect to time is possible

- Cracks  $\rightarrow X = \frac{c}{a} \ll 1$  (same  $X$  for all cracks)
- This leads to

$$\mathbb{C}^{Dam} = \mathbb{C}^{COx} : \left( \mathbb{I} + \frac{4\pi}{3} d\mathbb{T} \right)^{-1} ; \mathbb{T}(\nu^{COx})$$

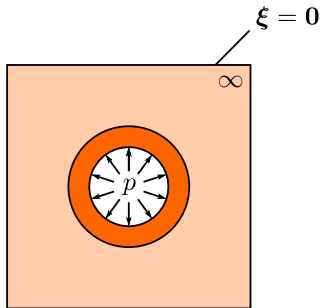
- $d = \mathcal{N}a^3$  is the crack density parameter (Budiansky and O'connell [3])
- In that limit the problem is linear (as long as the cracks remain open) because  $\mathbb{C}^{Dam}$  is independent of  $c \Rightarrow$  integration with respect to time is possible
- Also

$$\begin{aligned} \dot{c} &= \left[ \mathbb{T} : \left( \mathbb{I} + \frac{4\pi}{3} d\mathbb{T} \right)^{-1} : \left( \dot{\mathbf{E}} - \dot{\boldsymbol{\varepsilon}}^* \right) \right] : (\mathbf{an} \otimes \mathbf{n}) \\ &= \left[ \mathbb{T} : \mathbb{C}^{COx-1} : \dot{\boldsymbol{\Sigma}} \right] : (\mathbf{an} \otimes \mathbf{n}) \end{aligned}$$

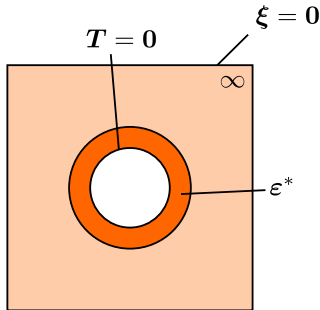


- Integrated equations (no propagation of cracks) :

$$\begin{cases} \Sigma = \mathbb{C}^{Dam} : (\mathbf{E} - \boldsymbol{\varepsilon}^*) \\ \Delta X = \frac{\Delta c}{a} = [\mathbb{T} : \mathbb{C}^{COx-1} : \Sigma] : (\mathbf{n} \otimes \mathbf{n}) \end{cases}$$



(a) Problem (i) : prescribed pressure.



(b) Problem (ii) : prescribed stress-free strain.



- Rotational symmetry  $\Rightarrow$  total displacement looked for in the form  $\xi = f(r)\mathbf{e}_r$

- Rotational symmetry  $\Rightarrow$  total displacement looked for in the form  $\xi = f(r)\mathbf{e}_r$
- Equation of equilibrium yields a second order ordinary differential equation



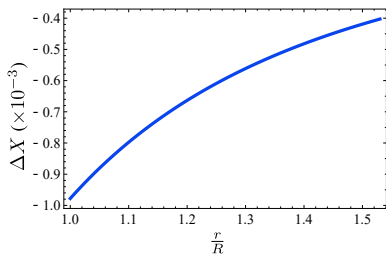
- Rotational symmetry  $\Rightarrow$  total displacement looked for in the form  $\xi = f(r)\mathbf{e}_r$
- Equation of equilibrium yields a second order ordinary differential equation
- Exact analytical solution if  $g(r)$  is a polynomial function of  $r$

- Rotational symmetry  $\Rightarrow$  total displacement looked for in the form  $\xi = f(r)\mathbf{e}_r$
- Equation of equilibrium yields a second order ordinary differential equation
- Exact analytical solution if  $g(r)$  is a polynomial function of  $r$
- If  $g$  is only assumed to be continuous, it can be approximated by a polynomial function  $\Rightarrow$  yields an approximate solution

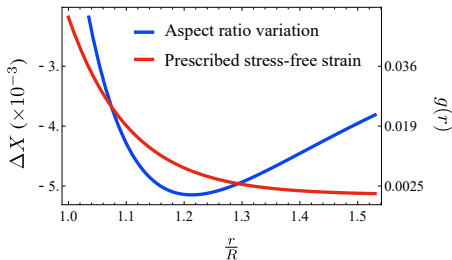
| Parameter            | Value     | Reference          |
|----------------------|-----------|--------------------|
| $E^{COx}$ (MPa)      | 5000      | Pham [7]*          |
| $\nu^{COx}$ (-)      | 0.2       | Pham [7]*          |
| $d$ (-)              | $10^{-3}$ | arbitrary          |
| $\varepsilon^*$ (-)  | $10^{-2}$ | Zhang et al. [8]** |
| $p^{swelling}$ (MPa) | 4         | Andra [1]          |

\*These are averaged values estimated using the measurements before desaturation and after resaturation

\*\*This is the average prescribed strain over the damaged zone. Much higher strains are observed under free swelling conditions and much lower under high triaxial confining stresses so a conservative value of 1% was chosen

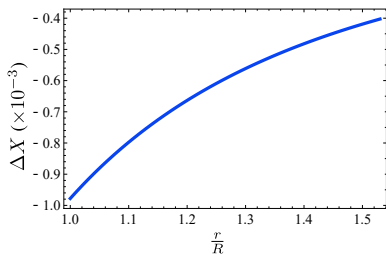


(a) Problem (i).

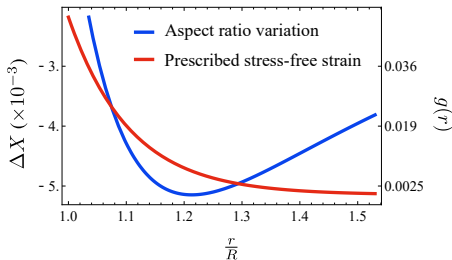


(b) Problem (ii).

FIGURE –  $\Delta X$  as a function of  $\frac{r}{R}$  for problems (i) and (ii).



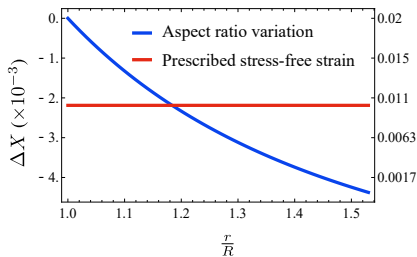
(a) Problem (i).



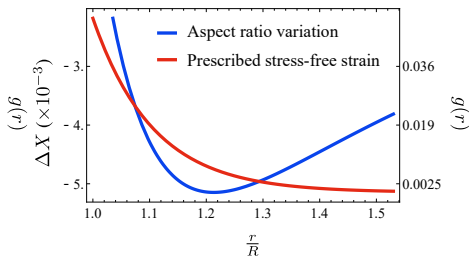
(b) Problem (ii).

FIGURE –  $\Delta X$  as a function of  $\frac{r}{R}$  for problems (i) and (ii).

$|\Delta X|$  max is roughly five times greater for problem (ii) than for problem (i)

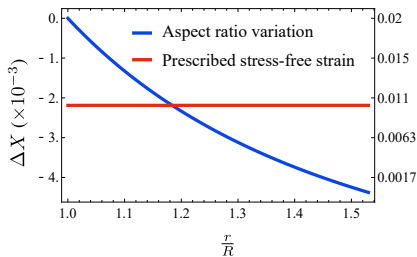


(a) Homogeneous stress-free strain.

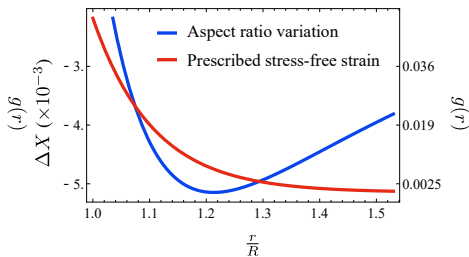


(b) Exponentially decaying stress-free strain.

FIGURE –  $\Delta X$  as a function of  $\frac{r}{R}$  for two different functions  $g(r)$  with the same average value.



(a) Homogeneous stress-free strain.



(b) Exponentially decaying stress-free strain.

FIGURE –  $\Delta X$  as a function of  $\frac{r}{R}$  for two different functions  $g(r)$  with the same average value.

Different monotony but same order of magnitude for  $|\Delta X|$  max





- Note that  $|\Delta X|$  max does not depend much on  $d$  for problem (ii) ( $5.023 \cdot 10^{-3}$  for  $d = 10^{-1}$  and  $5.148 \cdot 10^{-3}$  for  $d = 10^{-6}$ ) and even less for problem (i) ( $9.77848 \cdot 10^{-4}$  in both cases) so a median value of  $10^{-3}$  was chosen arbitrarily

- Note that  $|\Delta X|$  max does not depend much on  $d$  for problem (ii) ( $5.023 \cdot 10^{-3}$  for  $d = 10^{-1}$  and  $5.148 \cdot 10^{-3}$  for  $d = 10^{-6}$ ) and even less for problem (i) ( $9.77848 \cdot 10^{-4}$  in both cases) so a median value of  $10^{-3}$  was chosen arbitrarily
- Taking the value  $a = 250$  mm (Hawkins et al. [6]) for the lateral extent of the cracks yields crack opening variations of  $-0.5$  mm and  $-2.6$  mm for problems (i) and (ii) respectively

- Note that  $|\Delta X|$  max does not depend much on  $d$  for problem (ii) ( $5.023 \cdot 10^{-3}$  for  $d = 10^{-1}$  and  $5.148 \cdot 10^{-3}$  for  $d = 10^{-6}$ ) and even less for problem (i) ( $9.77848 \cdot 10^{-4}$  in both cases) so a median value of  $10^{-3}$  was chosen arbitrarily
- Taking the value  $a = 250$  mm (Hawkins et al. [6]) for the lateral extent of the cracks yields crack opening variations of  $-0.5$  mm and  $-2.6$  mm for problems (i) and (ii) respectively
- This is consistent with *in situ* observations of initial crack openings on the order of the millimeter

- 1 Context and objectives
- 2 Modeling the CDZ experiment
- 3 Conclusions and perspectives**



- Simple model but yields interesting insights into the phenomenon of self-sealing at the scale of the drift

- Simple model but yields interesting insights into the phenomenon of self-sealing at the scale of the drift
- The crack closure was found to be a non-monotonous function of depth for an exponentially decaying stress-free strain

- Simple model but yields interesting insights into the phenomenon of self-sealing at the scale of the drift
- The crack closure was found to be a non-monotonous function of depth for an exponentially decaying stress-free strain
- A mean 1% stress-free strain was found to lead to better self-sealing than the 4 MPa swelling pressure developed by the swelling clay core



- Simple model but yields interesting insights into the phenomenon of self-sealing at the scale of the drift
- The crack closure was found to be a non-monotonous function of depth for an exponentially decaying stress-free strain
- A mean 1% stress-free strain was found to lead to better self-sealing than the 4 MPa swelling pressure developed by the swelling clay core
- Results consistent with *in situ* observation that water injection is more efficient than pure mechanical closure



- The damaged zone was represented by an effective microcracked medium with weak interaction → strong interaction could be dealt with by using a self-consistent scheme, but more importantly the cracks should be introduced explicitly at the scale of the drift

- The damaged zone was represented by an effective microcracked medium with weak interaction → strong interaction could be dealt with by using a self-consistent scheme, but more importantly the cracks should be introduced explicitly at the scale of the drift
- The actual problem is nonlinear due to the closure of different families of cracks

- The damaged zone was represented by an effective microcracked medium with weak interaction → strong interaction could be dealt with by using a self-consistent scheme, but more importantly the cracks should be introduced explicitly at the scale of the drift
- The actual problem is nonlinear due to the closure of different families of cracks
- The stress-free strain was prescribed, when it is in fact the result of a coupled hydromechanical response (the amount of water a sample is able to take in depends on the confining stress which in turn depends on the swelling)

- The damaged zone was represented by an effective microcracked medium with weak interaction → strong interaction could be dealt with by using a self-consistent scheme, but more importantly the cracks should be introduced explicitly at the scale of the drift
- The actual problem is nonlinear due to the closure of different families of cracks
- The stress-free strain was prescribed, when it is in fact the result of a coupled hydromechanical response (the amount of water a sample is able to take in depends on the confining stress which in turn depends on the swelling)
- Time effects have to be included at the scale of the clay particles ( $\simeq 10 - 50$  nm), resulting behavior will be used at the scale of the drift

Thank you for your attention.

- [1] Andra. Dossier d'options de sûreté - Partie après fermeture (DOS-AF), 2016. [50](#)
- [2] C Bauer, G Pépin, and P Lebon. Edz in the performance assessment of the meuse/haute-marne site : conceptual model used and questions addressed to the research. In *Proceedings of the European Commission Cluster conference on Impact of the EDZ on the performance of radioactive waste geological repositories, Luxembourg November*, volume 40, 2003. [8](#), [9](#), [10](#), [11](#)
- [3] Bernard Budiansky and Richard J O'connell. Elastic moduli of a cracked solid. *International journal of Solids and structures*, 12(2) :81–97, 1976. [37](#), [38](#), [39](#), [40](#), [41](#), [42](#)
- [4] Rémi de La Vaissière, Gilles Armand, and Jean Talandier. Gas and water flow in an excavation-induced fracture network around an underground drift : a case study for a radioactive waste repository in clay rock. *Journal of Hydrology*, 521 :141–156, 2015.
- [5] Vincent Deudé. *Non linéarités géométriques et physiques dans les milieux poreux : apport des méthodes de changement d'échelle*. PhD thesis, Ecole des Ponts ParisTech, 2002. [32](#), [33](#), [34](#), [35](#), [36](#)



- [6] IR Hawkins, BT Swift, AR Hoch, and J Wendling. Comparing flows to a tunnel for single porosity, double porosity and discrete fracture representations of the edz. *Physics and Chemistry of the Earth, Parts A/B/C*, 36(17) :1990–2002, 2011. [55](#), [56](#), [57](#), [58](#)
- [7] Quoc Thai Pham. *Effets de la désaturation et de la resaturation sur l'argilite dans les ouvrages souterrains*. PhD thesis, Ecole Polytechnique X, 2006. [50](#)
- [8] CL Zhang, K Wieczorek, and ML Xie. Swelling experiments on mudstones. *Journal of Rock Mechanics and Geotechnical Engineering*, 2(1) :44–51, 2010. [50](#)