Modelling the excavation damaged zone in Callovo-Oxfordian claystone using shear strain localisation

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Excavation damaged zone

Long-term management of radioactive wastes

Intermediate (long-lived) & high activity wastes

Deep geological disposal

Repository in deep geological media with good confining properties (Low permeability $K<10^{-12}$ m/s)

Underground structures
= network of galleries

Disposal facility of Cigéo project in France (Labalette et al., 2013)
Excavation damaged zone

Repository phases

- Construction
  - Excavation
- Maintenance
  - Ventilation

Repository
- Sealing

Long term
- Corrosion, heat generation

Type C wastes (Andra, 2005)
Excavation Damaged Zone (EDZ)

Fracturing & permeability increase
(several orders of magnitude)
Opalinus clay in Switzerland
(Bossart et al., 2002)
Excavation damaged zone

**Callovo-Oxfordian claystone (COx)**

Sedimentary clay rock (France).

- Underground research laboratory

Feasibility of a safe repository

France (Meuse / Haute-Marne, Bure)
**In situ evidences (Andra):** (Armand et al. 2014)

Anisotropy: - stress: $\sigma_H > \sigma_h \sim \sigma_v$
- material: cross-anisotropy

Major issues: prediction of the extension, fracturing structure and properties modifications.

Study:
- fractures modelling with **shear strain localisation**
- influence of permeability variation
Outline

1. CONSTITUTIVE MODELS

2. FRACTURES MODELLING
   - GALLERY // TO $\sigma_h$
   - GALLERY // TO $\sigma_H$

3. PERMEABILITY EVOLUTION
1. Constitutive models

1.1 Strain localisation with regularization - Coupled 2d gradient model: (Chambon et al., 1998 and 2001)

The continuum is enriched with microstructure effects. The kinematics include the classical one (macro) and the microkinematics (Toupin 1962, Mindlin 1964, Germain 1973).

Biphasic porous media: solid + fluid (Collin et al., 2006)

Balance equations for biphasic porous media:

\[
\int_{\Omega} \left( \sigma_{ij} \frac{\partial u^*_i}{\partial x_j} + \sum_{ijk} \frac{\partial^2 u^*_i}{\partial x_j \partial x_k} \right) d\Omega = \int_{\Omega} G_i u^*_i d\Omega + \int_{r^*_u} \left( \tilde{t} u^*_i + \tilde{T} D u^*_i \right) d\Gamma
\]

\[
\int_{\Omega} \left( \frac{\partial M}{\partial t} p^*_w - m_{w,j} \frac{\partial p^*_w}{\partial x_i} \right) d\Omega = \int_{\Omega} Q p^*_w d\Omega + \int_{r^*_u} \bar{q} p^*_w d\Gamma
\]

Bishop’s effective stress:

\[
\sigma_{ij} = \sigma'_{ij} - b_{ij} S_{rw} p_w \delta_{ij}
\]

Double stress:

\[
\tilde{\Sigma}_{ijk} = f \left( B, \frac{\partial^2 u^*_i}{\partial x_j \partial x_k} \right)
\]
1. Constitutive models

1.2 Mechanical model:

Linear elasticity: Cross-anisotropic (5 param.) + Biot's coefficient

\[ d\varepsilon_{ij}^e = D_{ijkl}^e d\sigma_{kl}^t \]

\[ b_{ij} = \delta_{ij} - \frac{C_{ijkl}^e}{3K_s} \]

Plasticity:

Van Eeckelen yield surface
Hardening/softening of \( \varphi/c \):

\[ F = \Pi_\sigma - m \left( I_{\sigma'} + \frac{3c}{\tan \phi_C} \right) = 0 \]

Cohesion anisotropy:

\[ c = a_{ij} l_i l_j = \bar{c} \left( 1 + A_{11}(1 - 3l_3^2) + b_1 A_{11}^2 (1 - 3l_3^2)^2 + \ldots \right) \]

\[ l_i = \sqrt{\frac{\sigma_{i1}^2 + \sigma_{i2}^2 + \sigma_{i3}^2}{\sigma_{ij} \sigma_{ij}}} \]
1. Constitutive models

1.3 Flow model:

Advection of liquid phase (Darcy’s flow):

\[ m_{w,i} = -\rho_w \frac{k_{ij} k_{r,w}}{\mu_w} \frac{\partial p_w}{\partial x_j} \]

Water retention and permeability curves (Van Genuchten’s model):

\[ S_{r,w} = S_{res} + \left( S_{max} - S_{res} \right) \left[ 1 + \left( \frac{p_c}{P_r} \right)^n \right]^{-m} \]

\[ k_{r,w} = \sqrt{S_{r,w}} \left[ 1 - \left( 1 - S_{r,w}^{1/m} \right)^m \right]^2 \]
2.1 Gallery // to $\sigma_h$:

Anisotropic stress state, isotropic model

HM modelling in 2D plane strain state (LAGAMINE-Ulg):

Anisotropy (Andra URL):

- hydraulic permeability anisotropy
  $k_{\text{hor/vert}} = 4 \times 10^{-20} / 1.33 \times 10^{-20} [\text{m}^2]$  

- initial anisotropic stress state
  $p_{w,0} = 4.5 \text{ [MPa]}$
  $\sigma_{v,0} = \sigma_{h,0} = 12 \text{ [MPa]}$
  $\sigma_{H,0} = 1.3 \sigma_{v,0} = 15.6 \text{ [MPa]}$

Excavation:
2. Fractures modelling

Total deviatoric strain
\[ \varepsilon_{eq} = \sqrt{\frac{2}{3} \hat{\varepsilon}_{ij} \hat{\varepsilon}_{ij}} \]

Plasticity

End of excavation
\[ \sigma/\sigma_0 = 0.0 \]
σ anisotropy is the predominant factor leading to strain localisation and to the elliptical shape of the damaged zone.
2. Fractures modelling

2.2 **Gallery // to $\sigma_H$** :

Isotropic stress state ($\sigma=12$ MPa), anisotropic model

HM modelling in 2D plane strain state

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End of excavation

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Fractures modelling
2. Fractures modelling

Cohesion evolution:

Anisotropy: \[ c = a_i l_i l_j = \bar{c} \left( 1 + A_{11}(1-3l_2^2) + b_1 A_{12}^2(1-3l_2^2)^2 + \ldots \right) \]

Initially: isotropic \( \sigma_{ij} \rightarrow c = \bar{c} \quad l_2 = \sqrt{3} / 3 = 0.58 \)

Excavation: \( \sigma_r \downarrow \) and \( \sigma_{ort} \uparrow \)
2. Fractures modelling

Anisotropic stress state, anisotropic model

\[ \sigma_{H,0} = 1.3 \sigma_{v,0} > \sigma_{v,0} = \sigma_{h,0} = 12 \text{ [MPa]} \]

Fractures

Total deviatoric strain

Convergence

Isotropic stress state in the gallery section does not lead to shear strain localisation unless the material anisotropy is considered.

Material anisotropy seems to be the predominant factor leading to strain localisation and to the elliptical shape of the damaged zone.
3. Permeability evolution

3.1 Large-scale experiment of gallery ventilation (SDZ)

Characterise the effect of gallery ventilation on the hydraulic transfer around it.

→ drainage / desaturation
→ exchange at gallery wall
3. Permeability evolution

Permeability variation in fractured zone

HM coupling in the EDZ.

Saturated permeability in boreholes

Fracture and rock matrix permeabilities

→ Capture $k_w$ evolution
→ Relation to fractures
3. Permeability evolution

Evolution of intrinsic water permeability

Various approaches: deformation, damage, cracks…

- Relation to deformation

Volumetric effects = increase of porous space
(Kozeny-Carman)

\[ k_w = k_{w,0} \frac{(1 - \phi_0) \bar{\varepsilon}_i}{\phi_0 \varepsilon_i} \frac{\phi \varepsilon_i}{(1 - \phi)^n} \quad \varepsilon_v = \frac{\varepsilon_{ii}}{3} \]

- Fracture permeability

Cubic law for parallel-plate approach
(Witherspoon 1980; Snow 1969, Olivella and Alonso 2008)

\[ k_w = \frac{b^3}{12B} \]

\[ b = b_0 + B \left( \varepsilon^n - \varepsilon^n_0 \right) \]

Localised deformation
Fracture initiation

- Empirical law

Related to strain localisation effect
Permeability variation threshold

\[ k_{w,ij} = k_{w,ij,0} \left( 1 + \beta_{per} \left( YI - YI^{thr} \right) \hat{\varepsilon}_e^3 \right) \]

\[ YI = \frac{II_A}{II_\sigma} \]
3. Permeability evolution

Modelling of excavation and SDZ experiment

**HM coupling in EDZ**

- Gallery excavation

\[
\text{SDZ} \rightarrow \text{GED gallery} \parallel \sigma_h
\]

Anisotropic \( \sigma_{ij,0} \) and material

\[ \Rightarrow \text{Localisation zone dominated by stress anisotropy} \]

- Intrinsic permeability evolution

\[
\frac{k_{w,ij}}{k_{w,ij,0}} = \left(1 + \beta \left( YI - YI^{thr} \right) \hat{e}_{eq}^3 \right)
\]

\( YI^{thr} = 0.95 \)

Cross-sections

Plastic strain and a part of the elastic one

\[ \Rightarrow \text{EDZ extension} + k_w \text{ increase} \]
Modelling of the SDZ experiment

- Water pressure in the cavity air

\[ p_{w}^\text{air} = \frac{\rho_w RT}{M_v} \ln(RH) + p_{atm} \quad \rho_v^\text{air} = RH \rho_v^0 \]

Imposed at gallery wall through hydraulic boundary condition.

Excavation (RH=100%) → Initiation phase → Ventilation
3. Permeability evolution

- Drainage / $p_w$ reproduction

**Oblique 45°**

- Experimental
- Numerical

**Horizontal**

$\alpha_v = 10^{-3} \text{ m/s}$
3. Permeability evolution

- Desaturation EDZ / w reproduction

→ Desaturation: overestimation in long term
→ Vapour transfer ($\alpha_v = 10^{-3}$ m/s)

→ Good reproduction at gallery wall
Damaged zone → strain localisation zone similar to *in situ* measurements

→ modelling provide information about the rock structure and evolution within this zone, as observed *in situ*.

→ rock anisotropy and properties modification