Excavation damaged zone modelling with shear strain localisation in claystone

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**In situ evidences:**

Observations and measurements (ANDRA URL, GED Gallery, Armand *et al.* 2013, Cruchaudet *et al.* 2010b).

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**Excavation damaged zone**

**Front of the section GED1002**

**Major issues:** prediction of the extension and fracturing structure.

- damaged zone development with shear strain localisation
- influence of the gallery ventilation and permeability variation.
1. CONSTITUTIVE MODELS

2. NUMERICAL RESULTS FOR GALLERY EXCAVATION

3. CONCLUSIONS AND OUTLOOKS
1. CONSTITUTIVE MODELS

2. NUMERICAL RESULTS FOR GALLERY EXCAVATION

3. CONCLUSIONS AND OUTLOOKS
1. Constitutive models

Modelling of strain localisation – coupled 2d gradient model: (Chambon et al., 1998 and 2001)

Classical FE → mesh dependency → enriched model: 2d gradient

Porous media, multiphasic: solid + fluid

The continuum is enriched with microstructure effects. The kinematics include the classical one (macro) and the microkinematics (Toupin 1962, Mindlin 1964, Germain 1973, Collin et al., 2006).

Balance equations:

\[ \int_{\Omega} \left( \sigma_{ij} \frac{\partial u_i^*}{\partial x_j} + \Sigma_{ijk} \frac{\partial^2 u_i^*}{\partial x_j \partial x_k} \right) d\Omega = \int_{\Omega} G_i u_i^* d\Omega + \int_{\Gamma_p} \left( t_i u_i^* + T_i Du_i^* \right) d\Gamma \]

\[ \int_{\Omega} \left( \frac{\partial M}{\partial t} p_w^* - m_i \frac{\partial p_w^*}{\partial x_i} \right) d\Omega = \int_{\Omega} Q p_w^* d\Omega + \int_{\Gamma_q} \bar{q} p_w^* d\Gamma \]

\( \Sigma_{ijk} \) is the double stress, which needs an additional constitutive law.
1. Constitutive models

Modelling of strain localisation – coupled 2d gradient model:

- Solid and fluid phases behaviour:

Multiphasic medium under unsaturated condition ($p_g = \text{cst}$)

Compressibility of the solid grain skeleton.

Permeability: anisotropy and evolution with mechanical parameter

\[ \sigma_{ij} = \sigma'_{ij} - b S_{r,w} p_w \delta_{ij} \]

\[ b = 1 - \frac{K_0}{K_s} \]

Fluid mass flow (advection, Darcy):

\[ m_{w,i} = -\rho_w \frac{k_{ij} k_{r,w}}{\mu_w} \left( \frac{\partial p_w}{\partial x_j} + \rho_w g_j \right) \]
1. Constitutive models

Modelling of strain localisation – coupled 2\textsuperscript{nd} gradient model:

- Solid and fluid phases behaviour:

Multiphasic medium under \textit{unsaturated condition} ($p_g$=cst)

\textbf{Compressibility} of the solid grain skeleton.

\textbf{Permeability}: anisotropy and evolution with mechanical parameter

\[ \sigma_{ij} = \sigma'_{ij} - b S_{r,w} p_w \delta_{ij} \]

Bishop’s stress definition:

\[ b = 1 - \frac{K_0}{K_s} \]

Biot’s coefficient:

Fluid mass flow (advection, Darcy):

\[ m_{w,i} = -\rho_w \frac{k_{ij} k_{r,w}}{\mu_w} \left( \frac{\partial p_w}{\partial x_j} + \rho_w g_j \right) \]

- Stiffness matrix:

\[
\begin{bmatrix}
E_{14 \times 4} & 0_{4 \times 2} & K_{WM4 \times 3}^t & 0_{4 \times 8} & 0_{4 \times 4} & -I_{4 \times 4} \\
G_{12 \times 4}^t & 0_{2 \times 2} & G_{22 \times 3}^t & 0_{2 \times 8} & 0_{2 \times 4} & 0_{2 \times 4} \\
K_{MW3 \times 4}^t & 0_{3 \times 2} & K_{WW3 \times 3}^t & 0_{3 \times 8} & 0_{3 \times 4} & 0_{3 \times 4} \\
E_{8 \times 4}^t & 0_{8 \times 2} & 0_{8 \times 3} & D_{8 \times 8}^t & 0_{8 \times 4} & 0_{8 \times 4} \\
E_{3 \times 4}^t & 0_{4 \times 2} & 0_{4 \times 3} & 0_{4 \times 8} & 0_{4 \times 4} & I_{4 \times 4} \\
E_{4 \times 4}^t & 0_{4 \times 2} & 0_{4 \times 3} & 0_{4 \times 8} & -I_{4 \times 4} & 0_{4 \times 4} \\
\end{bmatrix}
\]
1. Constitutive models

Mechanical model – 1st gradient model:

Non-associated elasto-plastic internal friction model, with a Drucker-Prager yield surface:

\[ F \equiv II_{\sigma} - m \left( I_{\sigma} + \frac{3c}{\tan \phi_c} \right) = 0 \]

Hardening of \( \phi \) and softening \( c \) as a function of the Von Mises equivalent plastic strain \( \varepsilon_{eq}^p \):

\[ \varepsilon_{eq}^p = \sqrt{\frac{2}{3}} \hat{\varepsilon}_{ij}^p \hat{\varepsilon}_{ij}^p \]

\[ \phi_C = \phi_{C0} + \frac{(\phi_{Cf} - \phi_{C0}) \varepsilon_{eq}^p}{B_{\phi} + \varepsilon_{eq}^p} \]
1. Constitutive models

**Mechanical model – 2\textsuperscript{d} gradient model:** (Chambon \textit{et al.}, 1998 and 2001)

Double stress $\Sigma_{ijk}$ additional constitutive law: linear elastic law (Mindlin, 1964) function of the (micro) second gradient of displacement field $u_i$, \( h_{ijk} = \frac{\partial v_{ij}}{\partial x_k} = \frac{\partial^2 u_i}{\partial x_j \partial x_k} : \\

\begin{bmatrix}
\Sigma_{111} \\
\Sigma_{112} \\
\Sigma_{121} \\
\Sigma_{122} \\
\Sigma_{211} \\
\Sigma_{212} \\
\Sigma_{221} \\
\Sigma_{222}
\end{bmatrix} = \mathbf{D} \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & \frac{1}{2} & \frac{1}{2} & 0 \\
0 & \frac{1}{3} & \frac{1}{3} & 0 & -\frac{1}{3} & 0 & 0 & \frac{1}{3} \\
0 & \frac{1}{2} & \frac{1}{2} & 0 & -\frac{1}{2} & 0 & 0 & \frac{1}{2} \\
0 & 0 & 0 & 1 & 0 & -\frac{1}{2} & -\frac{1}{2} & 0 \\
0 & -\frac{1}{2} & -\frac{1}{2} & 0 & 1 & 0 & 0 & 0 \\
\frac{1}{2} & 0 & 0 & -\frac{1}{2} & 0 & \frac{1}{2} & \frac{1}{2} & 0 \\
\frac{1}{2} & 0 & 0 & -\frac{1}{2} & 0 & \frac{1}{2} & \frac{1}{2} & 0 \\
0 & \frac{1}{2} & \frac{1}{2} & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
\frac{\partial v_{11}}{\partial x_1} \\
\frac{\partial v_{11}}{\partial x_2} \\
\frac{\partial v_{12}}{\partial x_1} \\
\frac{\partial v_{12}}{\partial x_2} \\
\frac{\partial v_{21}}{\partial x_1} \\
\frac{\partial v_{21}}{\partial x_2} \\
\frac{\partial v_{22}}{\partial x_1} \\
\frac{\partial v_{22}}{\partial x_2}
\end{bmatrix}

It depends only on one elastic parameter \( D \). The shear band width is proportional to this parameter. (Chambon \textit{et al.}, 1998, Kotronis \textit{et al.}, 2007).
1. Constitutive models

**Fluid phase:**

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

\[ S_{r,w} = S_{res} + (S_{max} - S_{res}) \left[1 + \left(\frac{P_c}{P_r}\right)^N\right]^{-M} \]

\[ k_{r,w} = \sqrt{S_{r,w}} \left[1 - \left(1 - S_{r,w}^{1/M}\right)^M\right]^2 \]
1. CONSTITUTIVE MODELS

2. NUMERICAL RESULTS FOR GALLERY EXCAVATION
   - 2D: ventilation, permeability variation
   - 3D

3. CONCLUSIONS AND OUTLOOKS
2. Numerical results for gallery excavation – 2D

**Full gallery:**

Modelling of a full gallery to avoid symmetry assumption.

HM modelling in 2D plane strain state. Gallery radius = 2.3 m.

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
  - \( p_{w,0} = 4.5 \text{ [Mpa]} \)
  - \( \sigma_{y,0} = \sigma_{z,0} = 12 \text{ [Mpa]} \)
  - \( \sigma_{x,0} = 15.6 \text{ [MPa]} \)

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**Diagram:**

- Constant pore water pressure \( (p_{w,0}) \)
- Constant total stress \( (\sigma_{y,0} / \sigma_{x,0}) \)
- Constrained displacement
2. Numerical results for gallery excavation – 2D

Localisation zone:

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

End of excavation

Total deviatoric strain

Plasticity

3 days  4 days  5 days  100 days  1000 days
Localisation zone:

Chevron fracture:
- pattern corresponding to *in situ* observations (Armand et al. 2013).
- concentrated above the gallery because of the anisotropic stress state.

The extension of the excavation damaged zone obtained numerically corresponds fairly well to the *in situ* experimental measurements of shear fractures.
2. Numerical results for gallery excavation – 2D

**Quarter of gallery:**

By symmetry: quarter of the gallery

Second gradient boundary condition (Zervos et al. 2001)

Gradient terms in the equilibrium equations

→ Higher order constrains

→ Radial displacement must be symmetric on both sides of the symmetry axes

→ Normal derivative cancel

\[
\frac{\partial u_x}{\partial y} = 0 \quad \text{along the x-axis}
\]

\[
\frac{\partial u_y}{\partial x} = 0 \quad \text{along the y-axis}
\]
2. Numerical results for gallery excavation – 2D

**Influence of second gradient boundary condition:**

End of the calculation
2. Numerical results for gallery excavation – 2D

**Gallery ventilation:**

Pressure at gallery wall:

→ gallery excavation: $\sigma_x$ and $\sigma_y$ decrease

→ gallery ventilation: water phases equilibrium (Kelvin's law)

\[
RH = \frac{p_v}{p_{v,0}} = \exp\left(\frac{-p_c M_v}{RT \rho_w}\right)
\]

<table>
<thead>
<tr>
<th>RH</th>
<th>$p_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>$0.1$ [MPa]</td>
</tr>
<tr>
<td>80%</td>
<td>$-30.7$ [MPa]</td>
</tr>
</tbody>
</table>
Influence of gallery ventilation:

End of excavation

No ventilation

3 days
4 days
5 days
100 days
1000 days

Total deviatoric strain

Plasticity

σ/σ₀ = 0.40
σ/σ₀ = 0.20
σ/σ₀ = 0.00
σ/σ₀ = 0.00
σ/σ₀ = 0.00

0 0.184
2. Numerical results for gallery excavation – 2D

**Influence of gallery ventilation:**

- **3 days**
- **4 days**
- **5 days**
- **100 days**
- **1000 days**

**Total deviatoric strain**

- 0
- 0.184

**Plasticity**

- End of excavation
- Ventilation
2. Numerical results for gallery excavation – 2D

Influence of gallery ventilation:

Cross-section

No ventilation

Pore water pressure

Context
Constitutive models
Numerical results
Conclusions
Influence of gallery ventilation:

Cross-section

Pore water pressure

Degree of saturation

No ventilation
2. Numerical results for gallery excavation – 2D

**Influence of gallery ventilation:**

- **Cross-section**
- **Pore water pressure**
- **Degree of saturation**

**No ventilation**

**Ventilation**
Influence of gallery ventilation:

Convergence

Vertical

Horizontal

Important during the excavation and keeps increasing afterwards.

Anisotropic convergence because of the shear strain localisation bands located above the gallery.
Influence of gallery ventilation:

Convergence

- Vertical
- Horizontal

Important during the excavation and keeps increasing afterwards.

Anisotropic convergence because of the shear strain localisation bands located above the gallery.

Influence of the ventilation.
Influence of gallery ventilation:

Convergence

Important during the excavation and keeps increasing afterwards.

Anisotropic convergence because of the shear strain localisation bands located above the gallery.

Influence of the ventilation.

Experimental results from a gallery of the Andra URL (Armand et al. 2013, Cruchaudet et al., 2010b).

Good matching in the vertical direction for the modelling without ventilation.
2. Numerical results for gallery excavation – 2D

Permeability variation:

Hydraulic properties is not homogeneous in the damaged zone.

Influence of rock fracturing on intrinsic permeability.

Permeability increase in Opalinus clay (Bossart et al., 2002)

In situ permeability and fractures in Callovo-Oxfordian claystone (Armand et al. 2013, Cruchaudet et al. 2010b)
2. Numerical results for gallery excavation – 2D

**Permeability variation:**

Cubic evolution of $k$ with **porosity**:

$$\frac{k_{ij}}{k_{ij,0}} = 1 + \alpha(n - n_0)^\beta$$

$\alpha = 2 \times 10^{12}$, $\beta = 3$

End of excavation
2. Numerical results for gallery excavation – 2D

Permeability variation:

Cubic evolution of $k$ with total equivalent strain:

$$\frac{k_{ij}}{k_{ij,0}} = 1 + \alpha (\varepsilon_{eq} - 0.01)\beta \quad \text{if} \quad \varepsilon_{eq} > 0.01$$

$$\varepsilon_{eq} = \sqrt{\frac{3}{2}} \hat{\varepsilon}_{ij} \hat{\varepsilon}_{ij} \quad \hat{\varepsilon}_{ij} = \varepsilon_{ij} - \varepsilon_{m} \delta_{ij}$$

End of excavation

Vertical cross-section

Horizontal cross-section
2. Numerical results for gallery excavation – 2D

**Permeability variation:**

- 5 days
- End of excavation

**Pore water pressure, influence of ventilation**

- 1000 days
- End of calculation

**Context**

- No ventilation (RH=100%)

**Constitutive models**

- Ventilation (RH=80%)

**Numerical results**

- End of calculation
2. Numerical results for gallery excavation – 2D

**Permeability variation:**
- 5 days
- End of excavation

**Pore water pressure, influence of ventilation**
- 1000 days
- End of calculation

**No ventilation (RH=100%)**

**Ventilation (RH=80%)**

**Vertical cross-section**

![Images of permeability variation and pore water pressure graphs for different time periods and ventilation conditions.](Images)
2. Numerical results for gallery excavation – 2D

Permeability variation:

Pore water pressure, influence of ventilation and permeability variation

No ventilation (RH=100%)

Ventilation (RH=80%)

Vertical cross-section

\[ k = \text{cst} \]

Vertical cross-section

\[ k = f(\varepsilon_{eq}) \]
1. CONSTITUTIVE MODELS

2. NUMERICAL RESULTS FOR GALLERY EXCAVATION
   - 2D: ventilation, permeability variation
   - 3D

3. CONCLUSIONS AND OUTLOOKS
2. Numerical results for gallery excavation – 3D

**Numerical modelling (LAGAMINE-ULg):**

Mechanical modelling in 3D state. Classical FE, no second gradient!
2. Numerical results for gallery excavation – 3D

**Numerical modelling (LAGAMINE-ULg):**

Mechanical modelling in 3D state.
Classical FE, no second gradient!
2. Numerical results for gallery excavation – 3D

**Numerical modelling (LAGAMINE-ULg):**
Mechanical modelling in 3D state.
Classical FE, no second gradient!

**Localisation zone:**
Equivalent deformation $\varepsilon_{eq}$ - during boring

<table>
<thead>
<tr>
<th>Days</th>
<th>$\sigma/\sigma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 days</td>
<td>0.40</td>
</tr>
<tr>
<td>3.25 days</td>
<td>0.35</td>
</tr>
<tr>
<td>3.5 days</td>
<td>0.30</td>
</tr>
<tr>
<td>3.75 days</td>
<td>0.25</td>
</tr>
<tr>
<td>4 days</td>
<td>0.20</td>
</tr>
<tr>
<td>4.25 days</td>
<td>0.15</td>
</tr>
</tbody>
</table>
2. Numerical results for gallery excavation – 3D

**Numerical modelling (LAGAMINE-ULg):**

Mechanical modelling in 3D state.
Classical FE, no second gradient!

**Localisation zone:**

Equivalent deformation $\varepsilon_{eq}$ - during boring

<table>
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<th>$\sigma/\sigma_0$</th>
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<tbody>
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<td>3 days</td>
<td>0.40</td>
</tr>
<tr>
<td>3.25 days</td>
<td>0.35</td>
</tr>
<tr>
<td>3.5 days</td>
<td>0.30</td>
</tr>
<tr>
<td>3.75 days</td>
<td>0.25</td>
</tr>
<tr>
<td>4 days</td>
<td>0.20</td>
</tr>
<tr>
<td>4.25 days</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Localisation zone: Equivalent deformation $\varepsilon_{eq}$ - for 4.25 days of excavation ($\sigma/\sigma_0 = 0.15$):

- $z<0$: excavation zone
- $z=0$: gallery front
- $z>0$: rock mass
Localisation zone: Equivalent deformation $\varepsilon_{eq}$ for 4.25 days of excavation ($\sigma/\sigma_0 = 0.15$):
1. CONSTITUTIVE MODELS

2. NUMERICAL RESULTS FOR GALLERY EXCAVATION

3. CONCLUSIONS AND OUTLOOKS
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*.

→ need for a better definition of:
  - the rock anisotropy
  - the properties changes
  - the hydromechanical coupling
References


1. Constitutive models

Mechanical and hydraulic parameters:

Synthesis of Callovo-Oxfordian claystone parameters from (Charlier et al. 2013 in press)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Young’s modulus</td>
<td>4000</td>
<td>MPa</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson’s ratio</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>Biot’s coefficient</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>ρₕ</td>
<td>Specific mass</td>
<td>2300</td>
<td>kg/m³</td>
</tr>
<tr>
<td>ψ</td>
<td>Dilatancy angle</td>
<td>0.5</td>
<td>°</td>
</tr>
<tr>
<td>φ₀</td>
<td>Initial friction angle</td>
<td>10</td>
<td>°</td>
</tr>
<tr>
<td>φ₉</td>
<td>Final friction angle</td>
<td>20</td>
<td>°</td>
</tr>
<tr>
<td>Bₗφ</td>
<td>Friction angle hardening coefficient</td>
<td>0.002</td>
<td>-</td>
</tr>
<tr>
<td>c₀</td>
<td>Initial cohesion</td>
<td>3</td>
<td>MPa</td>
</tr>
<tr>
<td>c₉</td>
<td>Final cohesion</td>
<td>0.3</td>
<td>MPa</td>
</tr>
<tr>
<td>Bₗc</td>
<td>Cohesion softening coefficient</td>
<td>0.003</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>Second gradient elastic parameter</td>
<td>5000</td>
<td>N</td>
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</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>kₗₜₒ_r</td>
<td>Horizontal intrinsic water permeability</td>
<td>4 x 10⁻²⁰</td>
<td>m²</td>
</tr>
<tr>
<td>kₗᵥᵉ_r_t</td>
<td>Vertical intrinsic water permeability</td>
<td>1.33 x 10⁻²⁰</td>
<td>m²</td>
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<tr>
<td>n₀</td>
<td>Porosity</td>
<td>0.18</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>Van Genuchten coefficient</td>
<td>0.33</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>Van Genuchten coefficient</td>
<td>1.49</td>
<td>MPa</td>
</tr>
<tr>
<td>Pₑ</td>
<td>Van Genuchten parameter</td>
<td>15</td>
<td>Pa⁻¹</td>
</tr>
</tbody>
</table>

Permeability anisotropy

Friction angle hardening

Cohesion softening