Experimental study of the hydromechanical coupling in argillaceous rocks: the example of Boom clay

Cécile Coll (GeomaC, Liège)
Jacques Desrues (L3S, Grenoble)
Pierre Bésuelle (L3S, Grenoble)
Cino Viggiani (L3S, Grenoble)
Pascal Charrier (L3S, Grenoble)

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Outline

• Framework
• HM coupling in argillaceous rocks
• Boom clay: main properties
• Experimental techniques
• Experimental results
• Conclusions & Perspectives
General framework

Storage of nuclear waste

in deep geological formations

Safety condition: to preserve environment of internal radioactivity
Natural barrier
(clay, crystalline rock, salt)

Properties:
• high dimensions (100\text{a\text{ine}} meters)
• homogeneous
• no seismic activity
• very low permeability

Function: avoid fluid circulation (radionuclides) from the waste disposal to the natural medium

Issue: excavation of underground structures

EDZ (Excavated Disturbed Zone)
• state of stress changes
• fissuration
• temperature and moisture changes
Natural Barrier Performance?

Characterisation of the EDZ

C-T-H-M coupling processes

H-M coupling

Argillaceous formation: Boom Clay
(Mol, Belgium)

Permeability evolution with time due to damaging

UE project SELFRAC (Self Healing of Fractures, 2001-2004)
HM coupling in argillaceous rocks

great complexity

- low to very low permeability (<$10^{-12}$ m/s)
  - saturation
  - drainage/pore pressure homogenisation
- clay particles/fluid: strong interactions
- clay particles arrangement
- multiscale porosity (infra → macro)

- consolidation
- swelling
- flows
- ...

(kinetics, amplitude)
**Boom clay (soil type)**

- Clay fraction > 55%
- w_N = 25%
- n = 39% (aggregates)
- ū = 2 = 2 × 10^{-4} \text{mm}^2
- Highly plastic
- Prone to swelling
- Self healing/sealing
- Not cemented
- q_c = 2 \text{ MPa}
- c < 300 \text{ kPa}
- \(\phi = 18-24^\circ\)

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HADIES Underground Research Lab. (Mol, Belgium)

Connecting gallery

First shaft

Second shaft

Test Drift

URL

(z = 223 m)

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Bastiaens W., Euridice report 03-294, 2003

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W(H)YDOC 05 (23-25 Nov. 2005)
Experimental Objectives

- HM behaviour
- Isotropic / Deviatoric stress – permeability
- Strain localisation - permeability

Experimental study on natural, “intact” & saturated specimens

CD Triaxial tests (detection of strain localisation) + Permeability measurement
Experimental techniques

- Experimental installation
  - triaxial apparatus: HP cell + pressure generators
  - local measurements of axial & radial displacements (LVDTs)
  - system of temperature control

- Permeability measurement procedure
Experimental set up (1/4)

- Triaxial high pressure cell

- Confining cell ($\sigma_{3\text{max}} = 60 \text{ MPa}$)
- Force gauge
- Pore pressure line (bottom, $U_{\text{max}} = 60 \text{ MPa}$)
- Pore pressure line (top, $U_{\text{max}} = 60 \text{ MPa}$)

Axial piston ($q_{\text{max}} = 270 \text{ MPa}$)

U and $\Delta V/V_0$ controlled at both ends of the specimen
Experimental set up (2/4)

- Global view of the installation

- Temperature regulator
  (2 niveaux de régulation)

- Pressure Regulators
  $p_c$, $q$, $U_t$, $U_p$

- 4 pressure generators
  (jacks, water or oil)

- Data acquisition and control
experimental set up (3/4)

- technical improvement: temperature control

\[ T = 25 \, ^\circ\text{C} (\pm 0.025 \, ^\circ\text{C}) \]

- negligible influence of \( \Delta T \):
  - pore pressure
  - volume change
Experimental set up (4/4)

- On-specimen local axial/radial strain measurements

- Detection of strain localisation
- Volumetric strain measurement

4 radial + 3 axial LVDTs
 (+/- 0.005 mm)
Permeability measurement:
Motivation for an improved method

➤ Steady state method (direct method)

\[ \frac{\mu}{m^2} \]

\[ \begin{align*}
|Q_e| &= |Q_s| \\
\frac{H}{S} \frac{\Delta U}{Q} &\approx k \quad (m^2)
\end{align*} \]

- volumetric strains (consolidation/swelling, dilatancy, creep, adsorption)
- leakages
- ….

« Parasite » flows
Influence on \( Q_e \) and \( Q_s \)
\[ y = -1.136x - 7.1442 \]
\[ R^2 = 0.9833 \]
\[ y = 3.3539x + 1.1652 \]
\[ R^2 = 0.9998 \]

\[ Q_{\text{in}}^1 \approx 3.40 \text{ mm}^3/\text{hr} \]
\[ Q_{\text{out}}^1 \approx 1.15 \text{ mm}^3/\text{hr} \]
\[ p'_{0} = 2.3 \text{ MPa} \]
\[ Q_g = 0.5 \text{ mm}^3/\text{hr} \]

**Phase 1:**
- \[ Q_{\text{in}}^1 \approx 3.40 \text{ mm}^3/\text{hr} \]
- \[ Q_{\text{out}}^1 \approx 1.15 \text{ mm}^3/\text{hr} \]

- **Volume (mm\(^3\))**
- **Time (hr)**
**Improved steady state method**

**Phase 1**  
$Q_{in}^1 \approx 3.40 \text{ mm}^3/\text{hr}$  
(top)  
$y = 3.3539x + 1.1652$  
$R^2 = 0.9998$

$Q_{out}^1 \approx 1.15 \text{ mm}^3/\text{hr}$

**Phase 2**  
$Q_{in}^2 \approx 3.80 \text{ mm}^3/\text{hr}$  
(bottom)  
$y = 3.8312x + 10.982$  
$R^2 = 0.9978$

$Q_{out}^2 \approx 1.15 \text{ mm}^3/\text{hr}$

- hydraulic gradient $\Rightarrow$
  
  $Q_d = \frac{1}{4} \left[ (Q_{out}^1 - Q_{in}^1) - (Q_{out}^2 - Q_{in}^2) \right]$

- others (consolidation, leakage, …) $\Rightarrow$
  
  $Q_c = (Q_{out}^1 + Q_{in}^1) + (Q_{out}^2 + Q_{in}^2)$
Experimental study of HM behaviour of Boom Clay: Results

• Testing program
• Results
  – volumetric behaviour under isotropic load
  – behaviour under deviatoric load
  – permeability evolution with $p'_0$ and $q$
Testing program

• specimen: h=d=40 mm
• uniaxial compression test ($\sigma_3=0$)
• triaxial compression (axisym.)
  » $p'_0 = p_0 - u = 0.4; 2; 2.3; 5$ MPa
  » $u = 2.2$ MPa (synthetic fluid)
• triaxial extension (axisym.)
  » $p'_0 = 2$ MPa
  » $u = 2.2$ MPa
• drained consolidated tests
  » $v = 0.25$ $\mu$m/min ($6,25 \times 10^{-6}$ min$^{-1}$)
  » $v = 25$ $\mu$m/min (1 test)
• permeability: axial direction ($\perp$ strati.)
Isotropic consolidation

- consolidation (stress changes)
- swelling (physico-chemical processes)
Deviatoric stage ($p'_0=0.4$ MPa, $v=0.25\mu m/min$)

« destructuration »
during the swelling phase

(BC19 : strain localisation detected but no discontinuity observed)
Deviatoric stage ($p'_0 = 2.3$ MPa)

<table>
<thead>
<tr>
<th>Test</th>
<th>Displ. rate (um/min)</th>
<th>Stain rate (min$^{-1}$)</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC07</td>
<td>0.25</td>
<td>$6,25 \times 10^{-6}$</td>
<td>Non localised</td>
</tr>
<tr>
<td>BC20</td>
<td>0.25</td>
<td>$6,25 \times 10^{-6}$</td>
<td>localised</td>
</tr>
<tr>
<td>BC12</td>
<td>25</td>
<td>$6,25 \times 10^{-4}$</td>
<td>localised</td>
</tr>
</tbody>
</table>
$p'_0 - k$ relation

$k \approx 2 \times 10^{-19} \text{ m}^2$

0.4 < $p'_0$ < 32 MPa

6.3 $\times 10^{-19}$ < $k$ < 1.2 $\times 10^{-20}$ m$^2$
Relation $e - k$

- $k$ – stress history
- several macroporosities?

Perform more tests at high $p'_0$

Isotropic compression test
0-32 MPa

$p'_c \approx 5$ MPa
q – k relation

\[ p'_0 = 0.4 \text{ MPa} \]

\[ p'_0 = 5 \text{ MPa} \]

- no significant evolution of the permeability
- contractancy \( \rightarrow \) \( k \) decreases
Conclusions

- A long experimental campaign: CD tests with permeability measurements
  - $k$-measurement procedure developed

- Under isotropic loading
  - swelling/consolidation coexisting
  - physico-chemical swelling
  - $k$ decreases $\leftrightarrow$ macroporosity reduction
  - $k$ influenced by stress history (more tests needed)
Conclusions

- **HM behaviour influenced**
  - mean effective stress \( p'_0 \) : ductile-contractant
  - water content *loss of strength*
  - strain rate

- **Permeability not influenced by \( q \) and strain localisation?**
  - \( \rightarrow \) Global axial measurement / localised discontinuities?
Perspectives

- physico-chemical behaviour
- $k$ evolution

Studies at the microscale level

- Swelling
- influence of strain rate
- self-healing evidence

Visco-élasto-plastic behaviour
Thank you for your attention!
Multi scale porosity

- fluid flows: interconnected macropores i.e. inter-aggregate porosity (free water)
- consolidation/swelling concerns also smallest pores (microporosity)
- adsorption: interlayer porosity +…
- chemical reactions: infra → macro porosity

SEM images of undisturbed Boom Clay: section perpendicular to the bedding with interstitial pores (p) (Dehandschutter et al., 2004).
reduced section for drainage

- limit friction
- drainage at both ends

zone with less friction

specimen

porous HEA discs
d=16 mm

flow lines not // between each other

non homogeneous gradient

k is underestimate

total drainage

Modelling : correction of k
Overview of CD tests on Boom clay

• mean effective stress \( p'_{0} \) ↑: ductile-contractant

• water content

• strain rate

\( \sigma_1 - \sigma_3 \) (MPa)

Axial strain

Volumetric strain

HM behaviour

loss of strength

Déformation axiale externe

Déformation Volumique

\( \varepsilon_1 \) externe

BC11 - 0,4

BC12 - 2,3

BC07 - 2,3

BC08 - 0,4

BC09 - 5

BC19 - 0,4

BC20 - 2,3

BC18 - 2

BC10 - 2

-0,06 -0,04 -0,02 0 0,02 0,04 0,06 0,08 0,1

-0,04 -0,03 -0,02 -0,01 0 0,01 0,02 0,03

-0,05 -0,03 -0,01 0,01 0,03 0,05

-0,06 -0,04 -0,02 0 0,02 0,04 0,06 0,08 0,1