The rock-mechanical behavior of Opalinus Clay – synopsis of 20 years of experience at the Mont Terri rock laboratory

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1. Introduction

2. Sampling and rock mechanical testing

3. In-situ stress testing

4. Excavation damaged zone (EDZ)

5. THM-modeling

6. Conclusions
The 16 Partners of the Mont Terri Project

- **Bundesamt für Landestopografie (swisstopo)**
- **Nationale Genossenschaft für die Lagerung von radioaktivem Abfall (NAGRA)**
- **Eidgenössisches Nuklearsicherheitsinspektorat (ENSI)**
- **Agence Nationale pour la Gestion des Déchets Radioactifs (ANDRA)**
- **Institut de Protection et de Sûreté Nucléaire (IRSN)**
- **Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)**
- **Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbh**
- **Empresa Nacional de Residuos Radiactivos, S.A. (ENRESA)**
- **Studiecentrum voor Kernenergie, Mol (SCK•CEN)**
- **Federaal Agentschap voor Nucleaire Controle (FANC)**
- **Japan Atomic Energy Agency (JAEA)**
- **Obayashi Corporation (OBAYASHI)**
- **Central Research Institute of Electric Power Industry (CRIEPI)**
- **Nuclear Waste Management Organisation, Toronto (NWMO)**
- **Department of Energy, Washington DC (U.S. DOE)**
- **Chevron Energy Technology Company, Houston**

**Additional Organizations:**
- **Japan Atomic Energy Agency (JAEA)**
- **Obayashi Corporation (OBAYASHI)**
- **Central Research Institute of Electric Power Industry (CRIEPI)**
- **Nuclear Waste Management Organisation, Toronto (NWMO)**
- **Department of Energy, Washington DC (U.S. DOE)**
- **Chevron Energy Technology Company, Houston**
The Mont Terri rock laboratory – location and situation
138 in-situ experiments since 1996
• Experiments are linked to repository evolution
• Mechanical experiments important for construction and emplacement phase
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Specimen extraction and sampling strategy

**Effects on the clay specimen:**
- Stress relief
- Desiccation
- Increased temperature (frictional)
- Mechanical damage, excess pore water pressure

**Countermeasures:**
- Reduce drilling speed, adapt technique (triple core, air flushing)
- Reduce time of exposure, immediate conditioning
- Use larger diameters

Wild et al. (2015)
Specimen conditioning

Desiccation leads to:
- Increase of strength
- Desiccation cracks + discing

Adapted conditioning:
- Triple core drilling
- Determination of water content on-site
- Immediate sealing in aluminum foil
- Saturation of samples to constant suction in lab

Bossart & Thury (2008)

CT-scan

- Peak strength
- Residual strength

Water content [weight %]

Strength [MPa]
Opalinus Clay shares many similarities with both soils and rocks:

- strong non-linearity (soil)
- micro-acoustic events (brittle rock)
- strong dilatancy for $\sigma_3 < 1\text{MPa}$ (soil)
- CI independent of $\sigma_3$ (brittle rock)

The influence of suction

- Substantial influence of suction on strength
- Similarities with soils: “shrinkage limit” equals the “air-entry value”
- Strength loss due to cyclic variations of relative humidity

Wild et al. (2015)
State-dependent anisotropy

- Effect of orientation to anisotropy higher at higher suction
- UCS versus water content shows steeper slope for s-samples
- Clear influence of anisotropy

Wild et al. (2015)
Impact of facies on rock stiffness

Clear difference between homogeneous **shaly facies** and **sandy facies**

- Scatter of data
- Absolute values
- Slope steeper for sandy facies (P-samples)
Challenges for rock-mechanical testing of Opalinus Clay

- Rock anisotropy
- Significant heterogeneity of sandy facies
- Scale dependency, REV
- Effect of sample size
- Sample extraction and conditioning (suction, damage)
- Few data out of the sandy facies
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## In-situ stress testing at Mont Terri

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<th>Experiment</th>
<th>Borehole</th>
<th>Method</th>
<th>Documentation</th>
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<tbody>
<tr>
<td>Determination of stress</td>
<td>BDS-3</td>
<td>Overcoring</td>
<td>Hesser (2014)</td>
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<td>In situ stress, overcoring</td>
<td>BIS-D1 –</td>
<td>Overcoring</td>
<td>Heusermann et al., (2014)</td>
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<td>Determination of stress</td>
<td>BDS-1 and BDS-2</td>
<td>Hydraulic stimulation</td>
<td>Rummel et al. (2012)</td>
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<td>Determination of stress</td>
<td>BDS-2 and BDS-4</td>
<td>Hydraulic stimulation</td>
<td>Enachescu (2011)</td>
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<tr>
<td>Determination of stress</td>
<td>BDS-1</td>
<td>Laboratory analyses using RACOS®-tests</td>
<td>Jahns (2011)</td>
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<tr>
<td>In situ stress, hydraulic stimulation</td>
<td>BIS-C1 and BIS-C2</td>
<td>Hydraulic stimulation</td>
<td>Evans et al. (1999)</td>
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</table>
In-situ stress measurements methods

- **Hydraulic methods** (provide only direct measure of stress)
  - Hydraulic Testing on Pre-existing Fractures (HTPF)
  - Hydraulic stimulation

- **Borehole failure methods** (useful in high-stress situations)
  - Borehole breakouts
  - Drilling-induced tension fractures

- **Stress relief methods** (measure strain, not stress)
  - Overcoring (various types of gauges)
  - Borehole slotter
  - Under-excavation technique

- Earthquake fault plane solutions (large-scale stress)

(Methods applied at Mont Terri are highlighted in red)
Results from 33 analyzed tests

Orientations of principal stresses

Magnitudes of principal stresses

Properties of tests

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep borehole &gt;20 m</td>
<td>●</td>
<td>△</td>
<td>◆</td>
</tr>
<tr>
<td>Competent rock (limestone)</td>
<td>●</td>
<td>△</td>
<td>◆</td>
</tr>
<tr>
<td>Rock lab, incompetent rock (shale)</td>
<td>●</td>
<td>△</td>
<td>◆</td>
</tr>
</tbody>
</table>

In-situ stress testing across décollement


- BDS-5 drilled across the main décollement
- Opalinus Clay thrust onto upper Jurassic limestones
- Opalinus Clay strongly tectonized

→ Decoupling across décollement?

- 11 hydraulic stimulation tests
- 10 impression packer tests
- pre- and post-frac ABI

Hydraulic stimulation data of BDS-5

Stress components

<table>
<thead>
<tr>
<th>Stress direction (footwall)</th>
<th>Magnitude [MPa]</th>
</tr>
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<tbody>
<tr>
<td>$S_H$</td>
<td>8.3</td>
</tr>
<tr>
<td>$S_h$</td>
<td>4.3</td>
</tr>
<tr>
<td>$S_v$</td>
<td>2.7</td>
</tr>
</tbody>
</table>

$S_H$: Maximum horizontal stress [MPa]

$S_h$: Minimum horizontal stress [MPa]

Not interpreted, since opening of pre-existing features

Trends for the foot wall domain

Main décollement

Mont Terri tunnel BDS-5

0

30

60

90

120

150

180

200

230

260

290

320

350

380

410

440

470

500

530

560

590

620

0

45

90

135

180

Meters above sea level

Sv

Sh

S_H

Depth [m]

Sv

Sh

S_H
Controls on in-situ stress and mechanisms

- Excavation controlled stresses
  - Primary and secondary stress field
  - 2-3 tunnel diameters
- Depth controlled stresses
  - Topography important at shallow levels
  - Tectonic bench-vice at deeper levels
- Lithology controlled stresses
  - Rock competence (UCS, elastic parameters)
  - Backbone and stress transfer in stiff rocks

<table>
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<th>Proposed stress tensor</th>
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<tr>
<td>$\sigma_1$ 6-7 MPa 210/70° subvertical</td>
</tr>
<tr>
<td>$\sigma_{2/3}$ 4-5 MPa 320/10° subhorizontal</td>
</tr>
<tr>
<td>$\sigma_{3/2}$ 2-3 MPa 050/15° subhorizontal</td>
</tr>
</tbody>
</table>

Martin & Lanyon (2003), Bossart & Wermeille (2003) - $\sigma_{2/3}$ in plane but not well defined

| $\sigma_1$ 8.6 MPa 033/0° horizontal |
| $\sigma_2$ 6.7 MPa 123/70° subvertical |
| $\sigma_3$ 3.9 MPa 303/20° subhorizontal |

Enachescu (2011)

| $\sigma_1$ 15 MPa 320/0° subhorizontal |
| $\sigma_2$ 8 MPa 070/0° subhorizontal |
| $\sigma_3$ 4 MPa subvertical |

Shin (2006, 2009)
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Resin impregnation technique for EDZ characterization

Borehole length: 5.0 m, diameter: 42 mm, slightly inclined

Ventilation line
Injection line

Pressure vessel
Resin injection
Scale

N2

Data from Bure rock lab (ANDRA)

Bossart et al. (2002)
EDZ development and observations on various scales

Stress-induced breakouts

Mechanical controlled breakouts

breakouts where bedding plane is tangential to borehole circumference

bedding plane (rock anisotropy)
Temporal evolution of borehole disturbed zone

- Short-term BDZ (within hours)
  - tangential shear fractures
- Extensional fractures and secondary shear fractures
  - interconnected fracture network
- Intermediate-term BDZ (within days)
  - tangential fractures in the opposing direction
  - further bedding parallel fractures, buckling chimney

Kupferschmied et al. (2015)
EDZ - hydraulic properties and self-sealing

- Pneumatic tests / short intervals:
  - Gas permeability high close to tunnel wall
- Self-sealing tests (hydraulic):
  - Swelling closes fractures
- Self-sealing tests (mechanical):
  - Mechanical confinement through buffer
- Cyclic deformations:
  - Humidity variations change properties of EDZ

Bossart et al. (2002)
Conceptual model of EDZ for tunnel towards South (HM-coupling)

Martin & Lanyon (2002)
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## Selection of numerical models applied at Mont Terri

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<th>Experiment</th>
<th>Year</th>
<th>Content</th>
<th>Model type</th>
<th>Constitutive Model</th>
<th>Code</th>
</tr>
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<tbody>
<tr>
<td>HM-A</td>
<td>2015</td>
<td>HM- modeling tunnel of rock lab (collaboration swisstopo, EPFL)</td>
<td>Hydro-Mechanical coupled</td>
<td>Bilinear strain-hardening/softening ubiquitous joints APD (Anisotropy, plasticity, damage)</td>
<td>FLAC 3D, CODE-ASTER</td>
</tr>
<tr>
<td>FE</td>
<td>2012</td>
<td>Predictive modeling of FE</td>
<td>Hydro-Mechanical coupled</td>
<td>Bilinear strain-hardening/softening ubiquitous joints</td>
<td>FLAC 3D</td>
</tr>
<tr>
<td>DR</td>
<td>2010</td>
<td>Modeling of diffusion experiment</td>
<td>Hydro-Chemical</td>
<td>Reactive transport model</td>
<td>PHREEQC</td>
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<tr>
<td>MB</td>
<td>2009</td>
<td>Excavation of MB niche</td>
<td>Hydro-Mechanical coupled</td>
<td>Bilinear strain-hardening/softening ubiquitous joints</td>
<td>FLAC 3D</td>
</tr>
<tr>
<td>EZ-A</td>
<td>2006</td>
<td>Stability of EDZ around EZ-A</td>
<td>Hydro-Mechanical coupled</td>
<td>Elastoplastic, Mohr Coulomb</td>
<td>FLAC 3D</td>
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<tr>
<td>Gallery04</td>
<td>2005</td>
<td>Deformations in EZ-B and HG-A niches</td>
<td>Hydro-Mechanical coupled</td>
<td>Elastoplastic, Mohr Coulomb</td>
<td>FLAC 3D</td>
</tr>
<tr>
<td>VE</td>
<td>2004</td>
<td>Modeling of micro tunnel</td>
<td>Hydro-Mechanical coupled</td>
<td>Elastoplastic model</td>
<td>CODE-BRIGHT</td>
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<tr>
<td>HE-D</td>
<td>2004</td>
<td>Modeling HE-D Experiment</td>
<td>THM</td>
<td>Elastoplastic model Elastoplastic model Isotropic poroelastic model</td>
<td>FLAC 3D, CODE-BRIGHT CODE-ASTER</td>
</tr>
<tr>
<td>HE</td>
<td>2002</td>
<td>Modeling of HE niche excavation</td>
<td>Hydro-Mechanical coupled</td>
<td>Elastoplastic ubiquitous joints</td>
<td>FLAC 3D</td>
</tr>
<tr>
<td>RA</td>
<td>2001</td>
<td>Modeling EDZ behavior</td>
<td>Hydro-Mechanical coupled</td>
<td>Bilinear strain-hardening/softening ubiquitous joints</td>
<td>FLAC 3D</td>
</tr>
<tr>
<td>DM</td>
<td>1999</td>
<td>Deformation mechanisms, new constitutive law</td>
<td>Hydro-Mechanical coupled</td>
<td>Bilinear strain-hardening/softening ubiquitous joints</td>
<td>FLAC 2D</td>
</tr>
<tr>
<td>ED-B</td>
<td>1999</td>
<td>Numerical modeling of the EDZ with PFC</td>
<td>Hydro-Mechanical coupled</td>
<td>Isotropic Mohr Coulomb Isotropic particle flow, incl. damage</td>
<td>FLAC 3D, PFC</td>
</tr>
<tr>
<td>ED-B</td>
<td>1998</td>
<td>Modeling EDZ Gallery 98 section</td>
<td>Hydro-Mechanical coupled</td>
<td>Elastoplastic ubiquitous joints</td>
<td>FLAC 3D</td>
</tr>
</tbody>
</table>
Coupled THM simulation of a heater experiment

- Heater experiment HE-D, THM responses
- Equilibration, 2 phases of heating, cooling
- Benchmarking with 8 modelling teams, different codes
Coupled THM simulation of a heater experiment

- Good agreement for temperature
- Higher differences for pore water pressure (not all aspects of evolution covered)
- General trend for deformation with much more variations

Decovalex, ANDRA, GRS
New constitutive law for Opalinus Clay (APD)

- Anisotropy (calibration through non-linear regression)
- Plastic formulation (Non-linear yield function with bounding surface)
- Damage formulation (Damage coupled with plastic hardening, modification to account for residual value of damage)
- Localization and regularization (Fernandez & Chambon, 2008)

→ Numerical implementation into Code_Aster

Effect of confinement on localization

Vertical displacement field

Parisio et al. (2015)
Conclusions

• Standardized protocols for sampling and conditioning of shale-rock samples are required.

• More data from the heterogeneous sandy facies have to be acquired.

• Magnitude and orientation of in-situ stress tensor depends on local geometry, depth, rock stiffness.

• The EDZ has a large impact on tunnel stability. It exhibits a high complexity in tectonized, anisotropic and heterogeneous rocks.

• Prediction of deformation in Opalinus Clay is still a challenging task due to its post-failure behavior. New tools are available now.
Selected references


