Horizontal bentonite backfilling and concrete plug for the Full-Scale Emplacement (FE) Experiment at the Mont Terri URL: requirements, design, instrumentation and emplacement

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- Project initiation
- Construction of FE cavern (Oct. 2010 - June 2011)
- Participation in LU COEX
- Instrumentation of rock in the far-field (Nov. 2011 - March 2012)
- Instrumentation during tunnel construction
- Construction of FE tunnel (April - Sept. 2012)
- Ventilation period
- Instrumentation of EDZ & tunnel wall
- Installation of crane & rails
- Construction of emplacement machine
- 1:1 off-site pre- & mock-up tests (May & August 2014)
- Filling of interjacent sealing section (ISS)
- Emplacement of heaters & instrumentation of bentonite
- Backfilling of heaters with granulated bentonite mixture
- Construction of plug (Feb. & March 2015)
- Start heating (15th of Dec. 2014)

Monitoring (from Dec. 2011)

Monitoring (from Dec. 2011)
Outline

- Granulated bentonite mixture (GBM) backfill
  - Requirements
  - Pretests: development of backfilling technique and QC methodology
  - FE tunnel: backfilling and applied QC

- Concrete plug
  - Targets
  - Plug implementation and observations
Requirements

- Important buffer parameters (hydraulic/gas conductivity, swelling pressure and microbiological activity) depend on:
  - The smectite content (see previous presentation)
  - The **emplacement dry density**

- In the FE experiment, a minimum emplacement dry density of **1.45 t/m³** was targeted. Hereby importance was also given to **homogeneous** emplacement (Homobento).

- Aim of this presentation is to show how dry density was checked.
## Pre-tests and history

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Engineered Barrier (&quot;EB&quot;) Experiment backfilling at Mont Terri</td>
</tr>
<tr>
<td>2006</td>
<td><strong>ESDRED</strong> Backfilling Test</td>
</tr>
<tr>
<td>2009 - 2012</td>
<td><strong>FE / LUCOEX</strong>: Concept development, pre-testing and refinement. <strong>HE-E</strong> experiment (<strong>PEBS</strong>)</td>
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<tr>
<td>2013</td>
<td><strong>FE / LUCOEX</strong>: Detailed planning</td>
</tr>
<tr>
<td>2014</td>
<td><strong>FE / LUCOEX</strong>: Fabrication &amp; Testing (Mock-up Test)</td>
</tr>
<tr>
<td>2014 – 2015</td>
<td><strong>FE / LUCOEX</strong>: Commissioning and operation at Mont Terri Rock Laboratory</td>
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Backfilling system must have **brakes** that are capable of handling the horizontal forces from auger backpressure.

Screw pitch and the auger tube's end cutting angle influence the direction of forces.
Local dry density estimation with dielectric measurement tools

Average dry density:
- PR2 average: 1.52 Mg/m³
- Mass balance: 1.51 Mg/m³
The prototype backfilling machine for the FE Experiment

Feeding unit

Backfilling unit

Bentonite big bags

Heater

Material distribution

Bentonite Block Pedestal

Designed and manufactured by Rowa Tunnelling Logistics, Switzerland

16 m

9.7 m
Mock-up tests in a surface industrial facility

Aims of the mock-up tests

1. **Technology approval** of the backfilling process with the backfilling machine
   a) Check and optimise the functionality of the entire system "backfilling technology" under realistic conditions
   b) Check and optimise the control parameters of the backfilling technology incl. calibration of the braking forces
   c) Check and optimise process related interfaces such as bentonite pedestal as well as sensors' and cables' positions for instrumentation, heater elements etc.

2. **Check the process sequences** incl. their duration for the assessment of a work programme for the implementation at Mont Terri

3. **Quality control (QC)** of the backfill: global and local assessment of the bulk dry density backfilled into the dummy-tunnel
Mock-up tunnel rig with installations for local density measurement

- **Sectional density measurement** by mass control and geodetic surveying of the slope
- **Local density assessment** by
  - Dielectric measurement
  - Gamma-gamma measurement
  - Horizontal cone penetration measurements
- **Observation windows**
Dielectric measurements: dry density profiles (1)

Section A, a (with heater)

Higher density near augers

Data assessed by Toshihiro Sakaki
Moist* density profiles by gamma-gamma measurements

* Average water content of the bentonite was 5.6%.

Data assessed by BLM Gesellschaft für Bohrlochmessungen mbH, Germany
Horizontal Cone Penetration Testing

Selected profiles of calculated* dry density

\[ \rho_d = \rho_d = \left( \frac{\sqrt{0.5}}{\sqrt{t}} \right)^{0.1} \cdot 1.61 \cdot q_c^{0.06} \]

\( \rho_d \) = dry density  
\( t \) = depth below surface  
\( q_c \) = measured cone resistance

Data assessed by Geoprofile GmbH, Switzerland

### Roof area

<table>
<thead>
<tr>
<th>Location</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPTU10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPTU01</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CPTU02</td>
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### Floor area

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<tr>
<td>CPTU14</td>
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<td></td>
<td></td>
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<tr>
<td>CPTU05</td>
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</tbody>
</table>

Dry Density values derived from dielectric measurements
Mock-up sectional dry density results from mass-volume measurements

<table>
<thead>
<tr>
<th>Values in [t/m³]</th>
<th>Mock-up 1</th>
<th>Mock-up 2 gap</th>
<th>Mock-up 2 around canister</th>
<th>Mock-up 2 total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average dry density</td>
<td>1.498</td>
<td>1.490</td>
<td>1.525</td>
<td>1.502</td>
</tr>
<tr>
<td>Deviation</td>
<td>±0.023</td>
<td>±0.013</td>
<td>±0.022</td>
<td>±0.009</td>
</tr>
</tbody>
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Dry density results in [t/m³] calculated from mass-volume measurements.

Values for deviation result from conservative assumption of
- 0.35% due to weighing inaccuracy and 2.5 kg material loss per big bag.
- standard deviation in water content measurements (5.54 ±0.16% for Mock-up 1 and 5.60 ±0.09% for Mock-up 2)
- inaccuracy in volume estimation (1% for Mock-up 1 and 0.2% for Mock-up 2)
- inaccuracy in positioning of the survey (±0.01 m³)
Backfilling machine operation at Mont Terri

Backfilling machine passing under the gantry crane in the FE-A niche at Mont Terri

Backfilling machine with screw conveyors driving over the heater and its pedestal (left) and during backfilling operation (right)

Front view of the backfilling machine in the FE emplacement tunnel
Operation at Mont Terri

Loading Big Bags onto the feeding wagon

Rear end of the feeding wagon with control unit visible and brakes attached to the rails

Geodetic survey of slopes (left) and sample-shapes (right) for differential volume and subsequent density calculations

© Comet
Dry density results from the FE tunnel

<table>
<thead>
<tr>
<th>Section</th>
<th>Wall TM 15</th>
<th>Slope 11</th>
<th>Slope 10</th>
<th>Slope 9</th>
<th>Slope 8</th>
<th>Slope 7</th>
<th>Slope 6</th>
<th>Slope 5</th>
<th>Slope 4</th>
<th>Slope 3</th>
<th>Slope 2</th>
<th>Slope 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local dry density [t/m³]</td>
<td>1.403</td>
<td>1.477</td>
<td>1.444</td>
<td>1.555</td>
<td>1.530</td>
<td>1.496</td>
<td>1.519</td>
<td>1.494</td>
<td>1.487</td>
<td>1.474</td>
<td>1.495</td>
<td>1.496</td>
</tr>
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- Average dry density results in [t/m³] per section calculated from mass-volume measurements.
- Deviation is estimated 0.007 t/m³ resulting from the assumption of 0.35% material loss and weighing inaccuracy plus 0.1% volume estimation inaccuracy.
- However, local heterogeneity could not be recorded but is expected to be similar to the mock-up tests.
Outline

- Granulated bentonite mixture (GBM) backfill
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  - FE tunnel: backfilling and applied QC

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  - Targets
  - Plug implementation and observations
FE retaining wall and plug construction

- Backfilling segment by segment
- Retaining wall sealed since 12th of Feb. 2015
- Re-routing of approx. 700 cables
- Plug concreting on 17th of March 2015

No demonstration character
Requirements: air and water tight + mechanically stable

- **Q₁**: flow through plug. Limited by water penetration depth (according to SIA 272)
- **Q₂**: Interface flow. Reduced by:
  - Low shrinkage concrete (<0.5‰)
  - Resin injection
- **Q₃**: EDZ flow. Reduced by:
  - Resin injection
- **M**: Increased friction plug
- **Qₓ**: Instrumentation related flow. Resin filled syphon.
Requirements: limit temperature and use highly flowable self-compacting concrete

- Slump flow test: Only direct no go QC on-site
- 3D temperature modelling
- Empty space detected by: TDR lines
- Injection lines
- Measurements
O₂ and gas pressure measurements

Monitoring sections:
- FE-O2_083
- FE-O2_084
- FE-O2_085
- FE-O2_081
- FE-O2_082
- FE-O2_080

O₂ Concentration (% v/v)

01Nov14 01Jan15 01Mar15 01May15 01Jul15 01Sep15 01Nov15 01Jan16

FE-O2_080
FE-O2_081
FE-O2_082
FE-O2_083
FE-O2_084
FE-O2_085

nagra
Conclusions

- The FE tunnel was **successfully backfilled** with approximately 255 tons of granulated bentonite mixture. The measured emplacement dry density is 1.5t/m³, **overachieving the target**.

- A number of **indirect dry density measurement techniques** were developed.
  - Support the direct mass volume measurement
  - Give an estimation of the dry density **heterogeneity**

- **Braking system, optimization of auger tips and sticking augers** were found necessary to:
  - Improve in situ compaction
  - Improve the filling of the top space
  - Limit the dust production

- After backfilling 350 tons, **signs of wear** on screw were observed.

- System will be **optimized** (also against auger wear) and **automatized** in the decades to come.
International cooperation

- Experimental partners within the FE @ Mont Terri:
  - ANDRA (France)
  - BGR (Germany)
  - DOE (U.S.A.)
  - GRS (Germany)
  - NWMO (Canada)

- For selected tasks (such as tunnel construction, bentonite production & backfilling) the FE Experiment is Nagra’s participation in the EU-project **Large Underground Concept Experiments (LUCOEX)**

- Partner organisations within **LUCOEX**:
  - ANDRA (France)
  - POSIVA (Finland)
  - SKB (Sweden)
Empty tunnel (2012)

- Instrumentation
Porous concrete (July 2014)

- 3.5m; instrumentation (at each step)
Bentonite block wall (September 2014)

- 2m
Bentonite block wall

- 2m
Backfilling Interjacent Sealing Section
Construction pedestal 1
Construction pedestal 1 (October 2014)
Emplacing heater 1 (October 2014)
Emplacing heater 1 (October 2014)
Emplacing heater 1 (October 2014)
Backfilling H1 (October 2014, 3 days)
Backfilling H1
Backfilling H1
Construction pedestal 2 (November 2014)
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