Numerical analysis of coupled hydro-mechanical and thermo-hydro-mechanical behaviour in buffer materials at a geological repository for nuclear waste: Simulation of EB experiment at Mont Terri URL and FEBEX at Grimsel test site using Barcelona basic model

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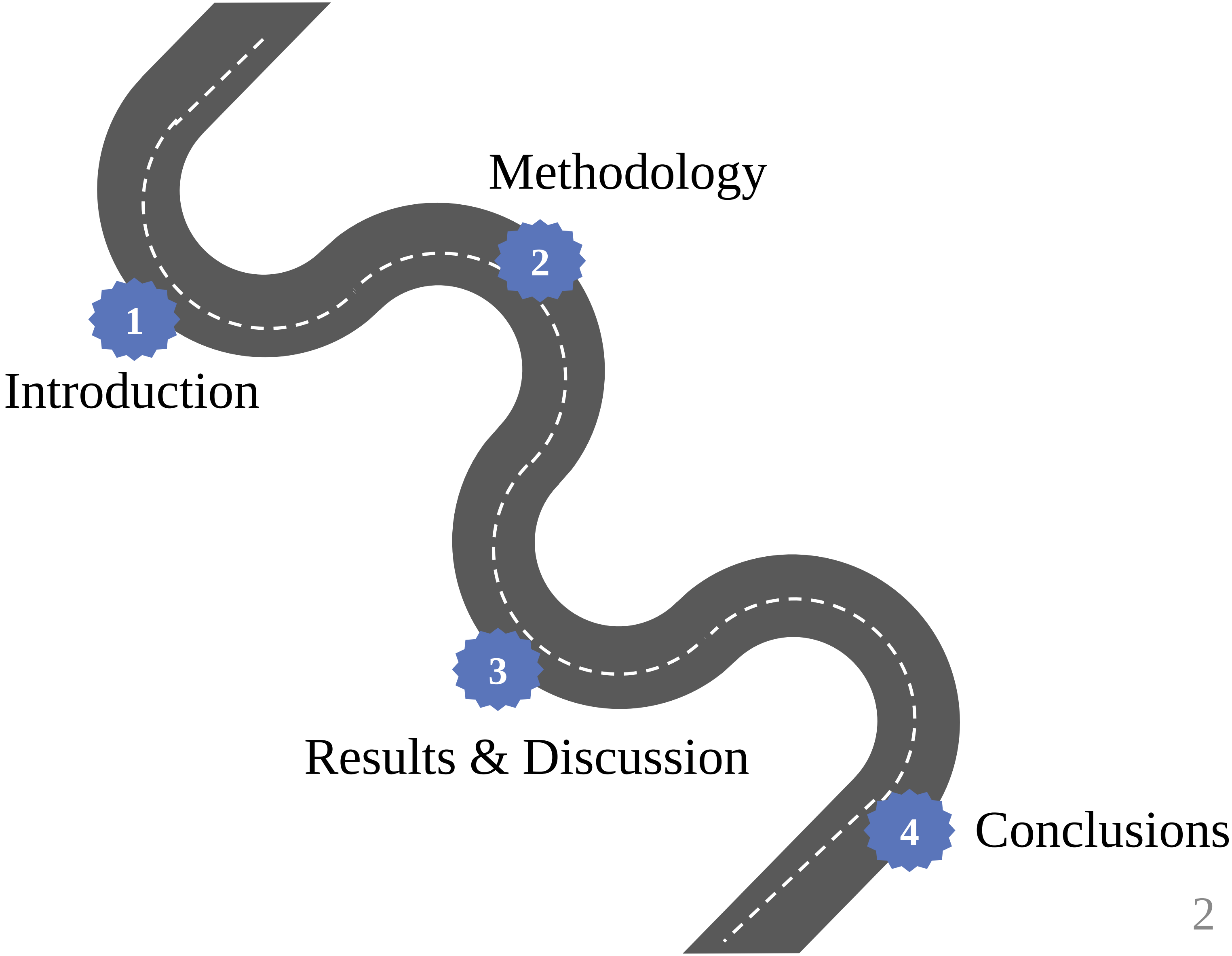
Outline



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Introduction

Deep Geological Disposal

- Spent nuclear fuel has high level of radioactivity and a long half-life. This type of radioactive wastes is called high-level radioactive waste(HLW).
- Seeking appropriate environmental disposal to isolate HLW from the biosphere.
- The concept of multiple barriers, the spent nuclear fuel is buried in the geology below 300~1000 meters, and then the canister and buffer materials are used to cover and place.

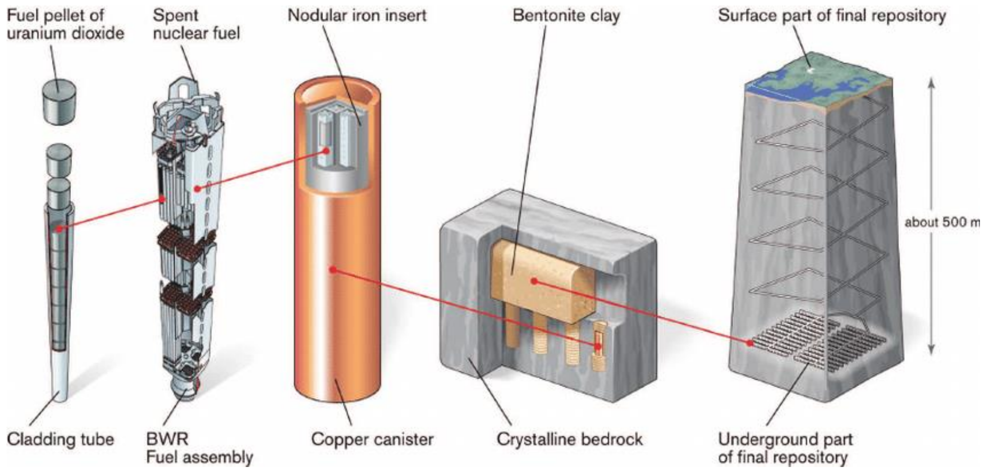
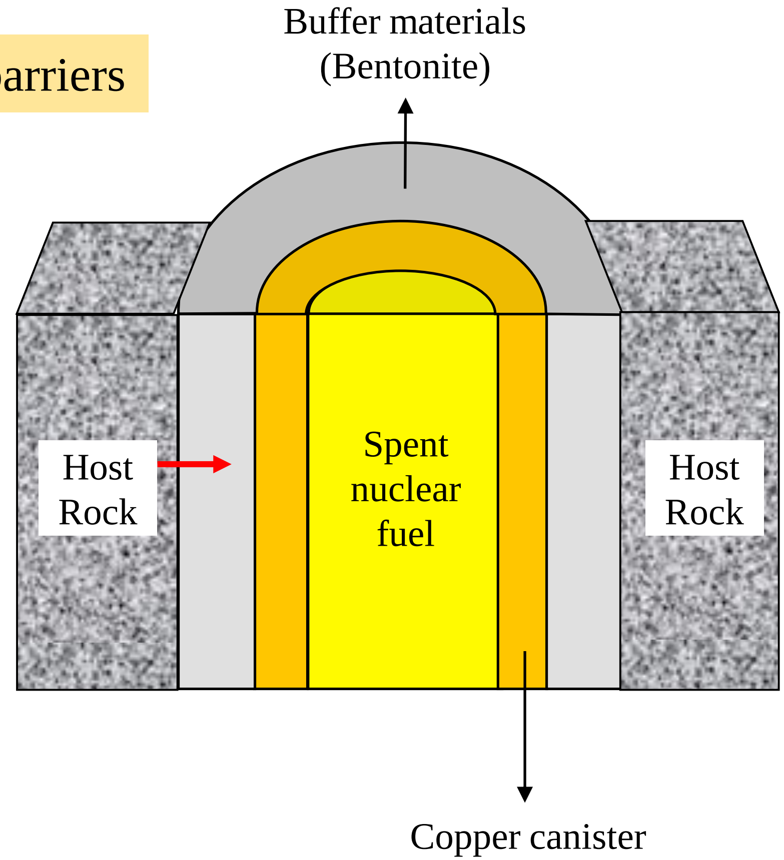


Fig. 1. Design Concept for the Deep Geological Disposal (Swedish KBS-3 method)

Coupled THMC process

(Thermo-hydro-mechanical-chemical)

Multiple barriers



Coupled THMC process
(Thermo-hydro-mechanical-chemical)

M The rise temperature produces water evaporation and condenses in cooler areas, so the buffer material is shrinking and swelling.

T The radioactive wastes emits heat by radiation decay ➔ cause temperature rise

H Buffer materials is unsaturated, under suction, groundwater flows from the host rock to the buffer.

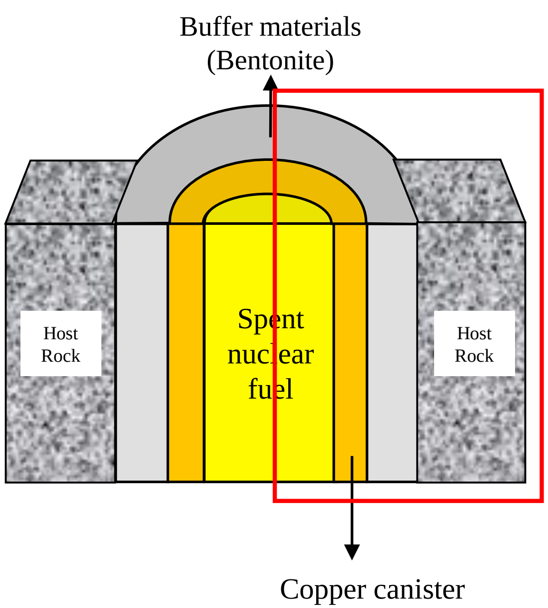


Fig. 2-1. Schematic cross-section (reference from Rebecca Lunn)

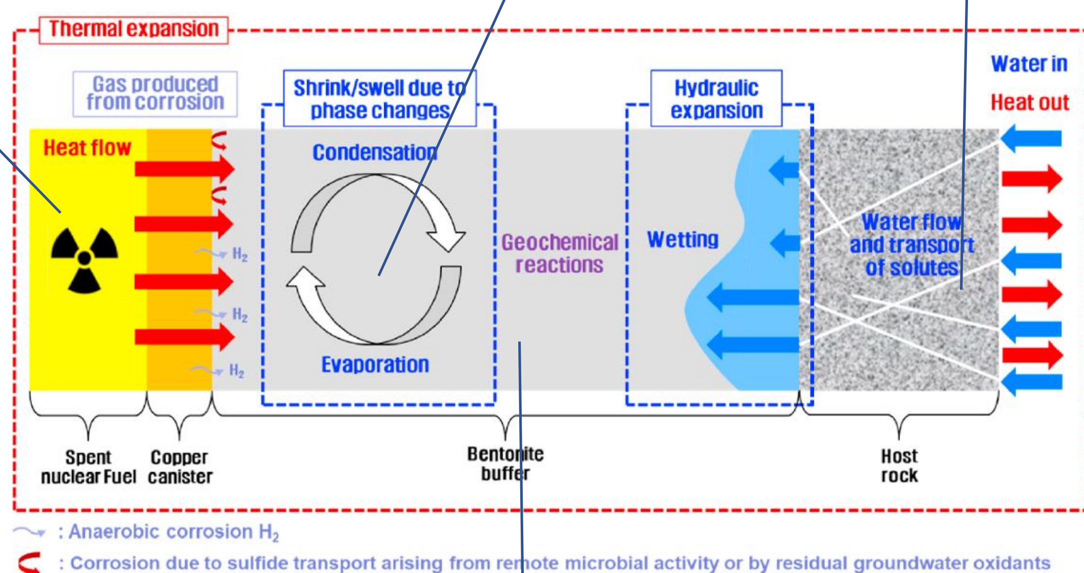


Fig. 2-2. Schematic of the coupled THMC processes in the HLW disposal system.

C Colloids are carried into the groundwater and cause progressive erosion of the buffer material.

Coupled THMC process

(Thermo-hydro-mechanical-chemical)

- The coupled THMC processes play important roles in the design, construction, and operation of a repository in deep geological formations.
- However, it is difficult to combine the complex coupled THMC processes into efficient models and develop numerical techniques to simulate them.

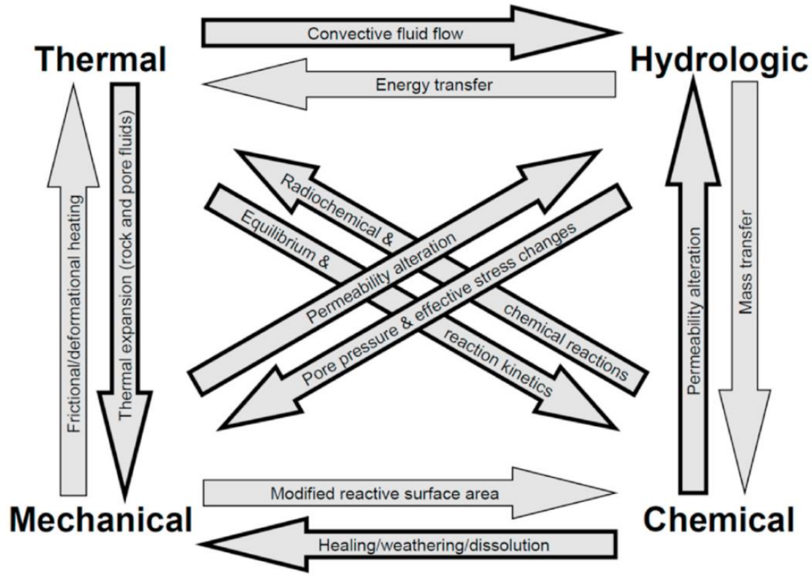


Fig.3. Coupled THMC processes in the repository for HLW.

Objective

- To solve these problems, an international cooperative project called DECOVALEX is to study HM and THM interactions. Special attention was paid to the evolution of barrier heterogeneity under transient conditions and the final state of the barrier.

Two in-situ experiments

The EB (Engineered barrier) test

Site	▶	Mont Terri URL
Rock mass	▶	Opalinus clay
Barrier type	▶	Granular bentonite(GBM) and bentonite blocks.
Hydration	▶	Artificial hydration
Total duration	▶	10.7 years
Observe	▶	coupled HM behavior

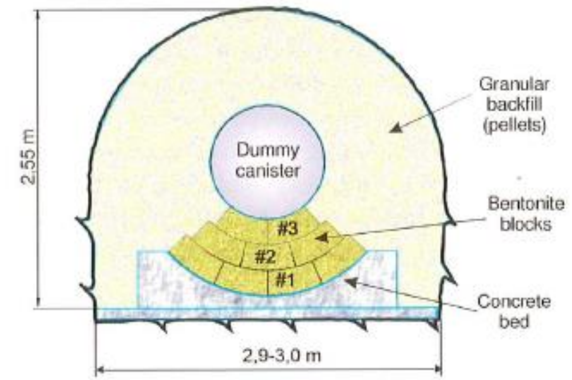


Fig.3-1. EB experimental layout

Fig.3-2. Canister sitting on a bed of compacted bentonite blocks.

Two in-situ experiments

The FEBEX (Full-scale Engineered Barrier EXperiment) test

Site	▶ Grimsel Test Site
Rock mass	▶ crystalline rock (Granite)
Heater	▶ Non-isothermal test
Barrier type	▶ Bentonite blocks
Hydration	▶ Natural hydration
Total duration	▶ 18.4 years
Observe	▶ coupled THM behavior

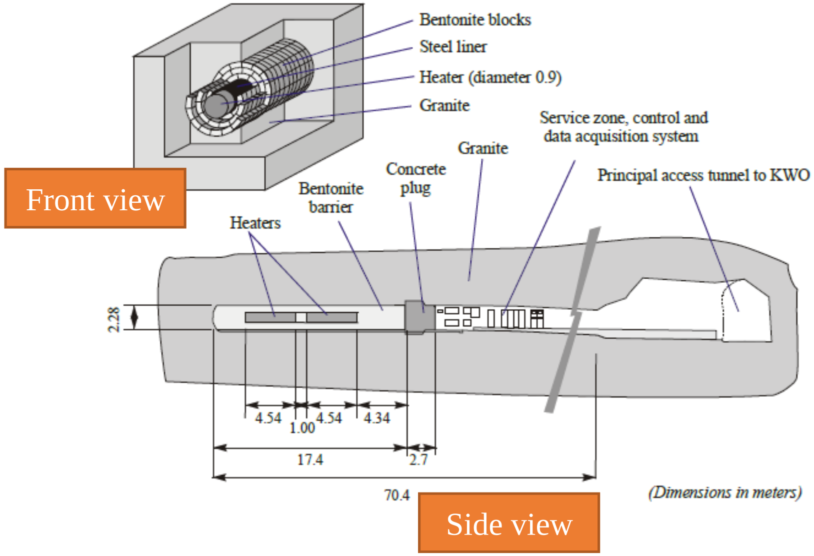


Fig.3-2. FEBEB experimental layout

Methodology

Numerical simulator

- Using a TOUGH2-MP/FLAC3D simulator to represent the coupled behaviour in bentonite buffer materials at the two long-term in situ experiments.
- TOUGH2-MP (**T**ransport **O**f **U**nsaturated **G**roundwater and **H**eat) is a numerical simulation program for nonisothermal flows of multicomponent, multiphase fluids in porous and fractured media.
- FLAC3D (**F**ast **L**agrangian **A**nalysis of **C**ontinua in 3D) is to solve complex geotechnical problems for three-dimensional analyses of soil, rock, concrete, structural ground support, and groundwater flow.

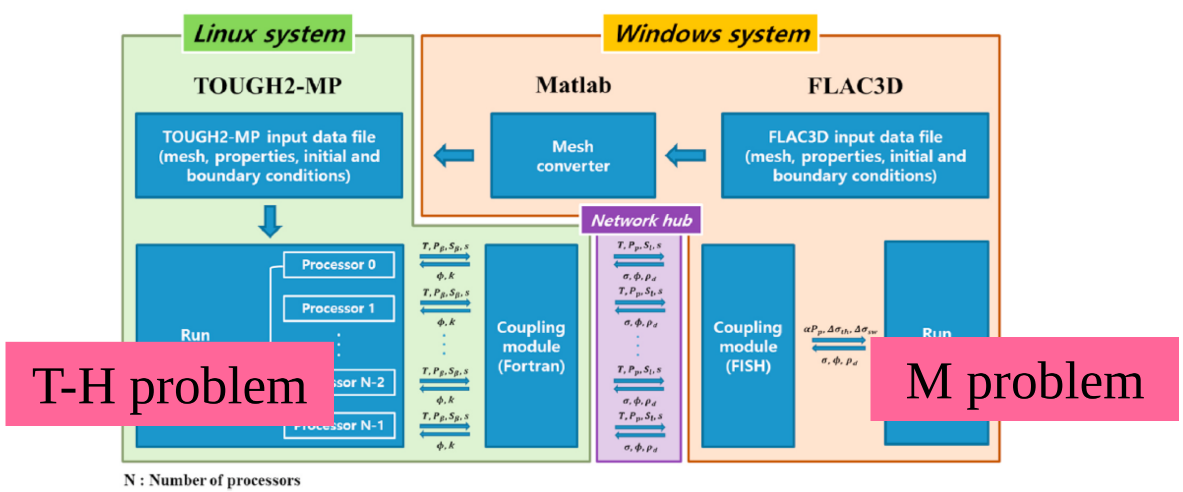


Fig. 4. TOUGH2-MP/FLAC3D coupling algorithm

Mathematical formulations

- Balance equations

(a.) The total mass balance equation of the fluid

$$\frac{d}{dt}\varphi\sum_{\beta}S_{\beta}\,\rho_{\beta}X_{\beta}^{k}+\nabla\cdot\left(\sum_{\beta}X_{\beta}^{k}\rho_{\beta}u_{\beta}-\sum_{\beta}\overline{D}_{\beta}^{k}\rho_{\beta}\nabla X_{\beta}^{k}\right)=Q_{\beta}$$

k is component (air or water)
β is phase (gas or liquid)
φ is porosity
S_{β} is the saturation of phase β
ρ_{β} is the density of phase β
X_{β}^{k} is the mass fraction of component k
u_{β} is the Darcy velocity in phase β
$\overline{D}_{\beta}^{k}$ is the hydrodynamic dispersion tensor of k *in* phase β
Q_{β} is the fluid source or the sink term in phase β

Mathematical formulations

- Balance equations

(b.) The heat transfer

$$\frac{d}{dt}\left((1-\varphi)\rho_R C_R T + \varphi \sum_{\beta} S_\beta \, \rho_\beta u_\beta\right) + \nabla \cdot \left(-\lambda \nabla T + \sum_{\beta} h_\beta F_\beta\right) = Q$$

φ is porosity
ρ_R is the grain density of the matrix
C_R is the specific heat of the matrix
S_β is the saturation of phase β
ρ_β is the density of phase β
u_β is the specific internal energy in phase β
λ is the effective thermal conductivity
h_β is the specific enthalpy in phase β
F_β is the phase flux
Q is the energy source or sink term

(c.) The momentum balance equation

$$\nabla \cdot \sigma + b = 0$$

σ is a stress tensor
b is a vector of body forces

Numerical modelling

The EB test

- The domain was 20 m wide, 40 m high, and 0.1 m thick with a central plane of symmetry. The mesh contains 16,534 elements and 17,050 grid points.

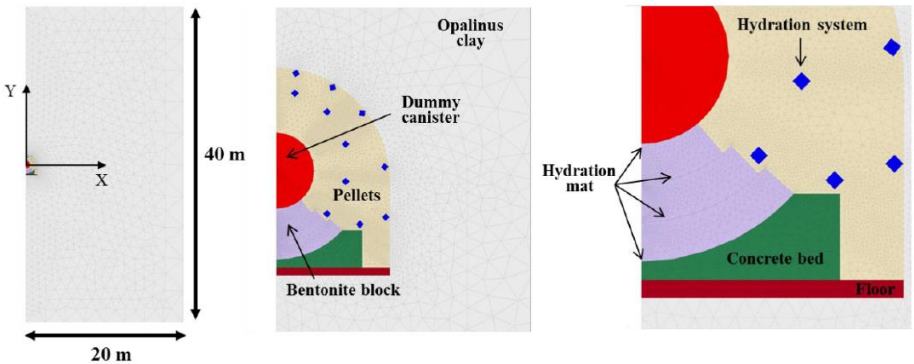


Fig.5-1. Plane strain domain for EB test

Table 1. Stages of the EB test

Stage No.	Description	Start time (day)	Duration (days)
1	Excavation and tunnel ventilation	-160	160
2	Installation	0	5
3	1st artificial hydration	5	2
4	Natural hydration only	7	125
5	2nd artificial hydration	132	324
6	3rd artificial hydration	456	1003
7	4th artificial hydration	1459	416
8	Natural hydration only	1872	2036

Numerical modelling

The FEBEX test

- The domain was 120 m length (X) and 50 m radius (Y) with 6966 elements and 14,277 grid points.

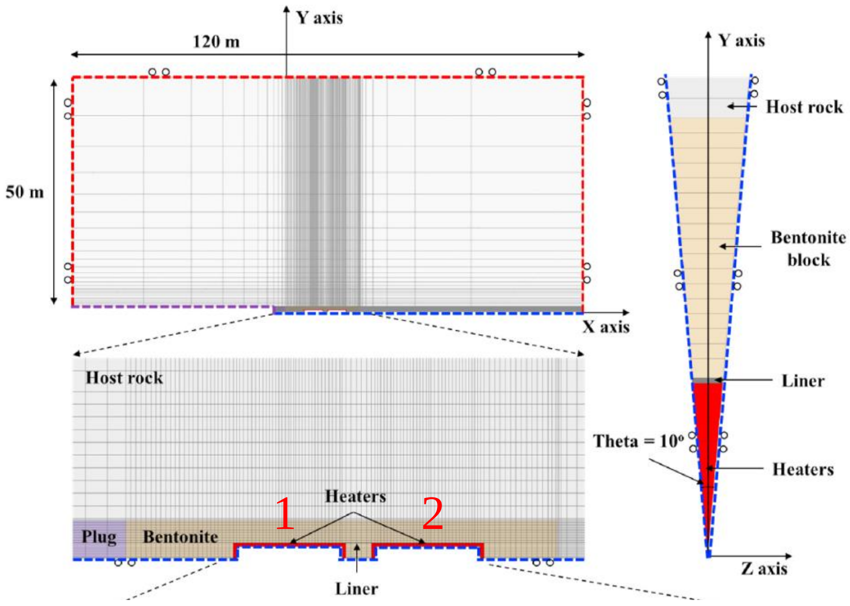


Fig.5-2. Plane strain domain for FEBEX test

Table 2. Stages of the FEBEX test

Stage No.	Description	Start time (day)
1	Tunnel excavation and ventilation	-385
2	Installation of the experiment	-135
3	1200 W applied by each heater	0
4	2000 W applied by each heater	20
5	Controlled temperature of the heaters: 100˚C	53
6	Heater #1 switched off and first dismantling	1827
7	Construction of the shotcrete plug	1966
8	Controlled temperature of heater #2: 100˚C	1974
9	Heater #2 switched off	6630
10	Final dismantling	6758

Results& Discussion

EB test

relative humidity sensor on GBM

relative humidity sensor on bentonite blocks

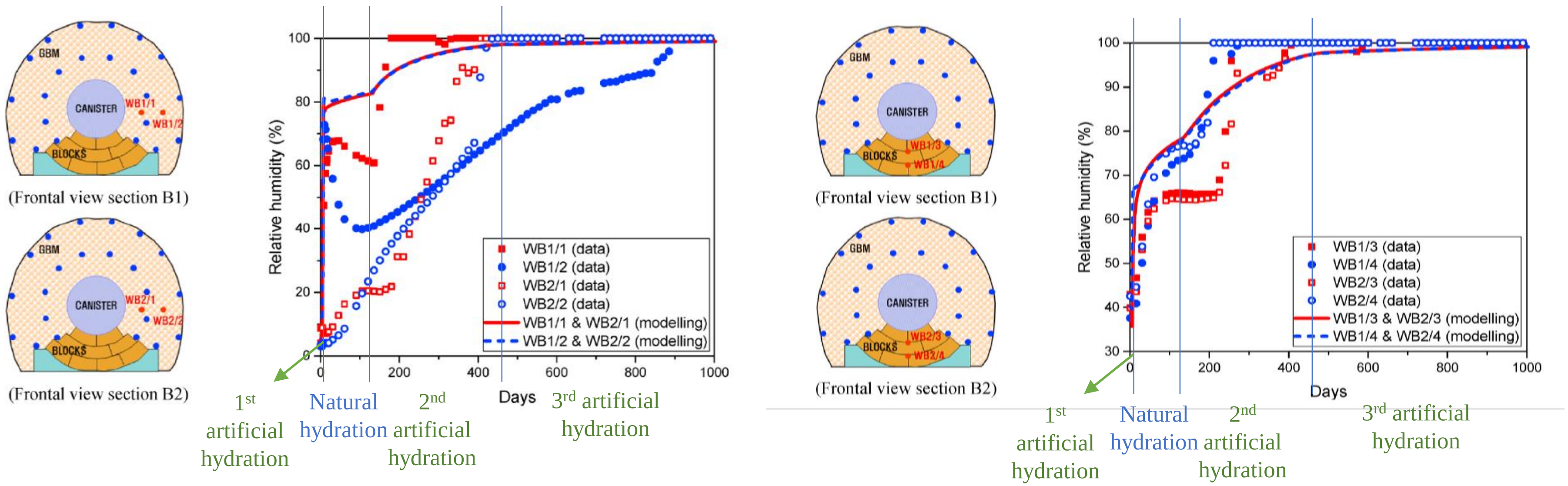


Fig.6-1. Evolution of relative humidity at Sections B1 and B2

The modelling result of bentonite blocks is more satisfy with in-situ data than GBM.

- On GBM found that leakages through the Opalinus Clay formation and the concrete plug.
- The amount of water losses could not be quantified in the in-situ experiment.

EB test

Dry density

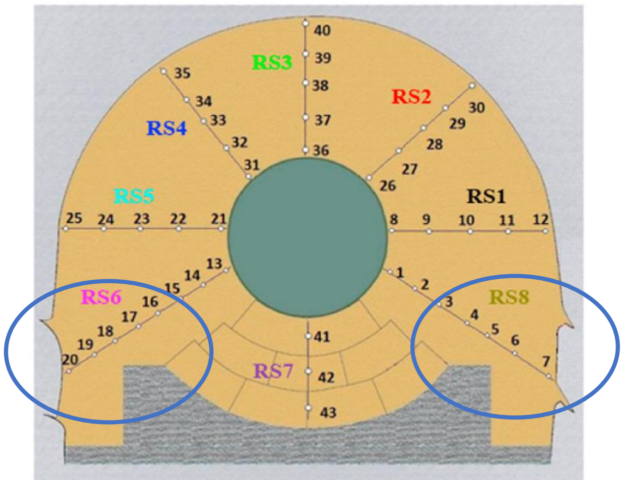


Fig. Divided into eight radial segments at Sections B2

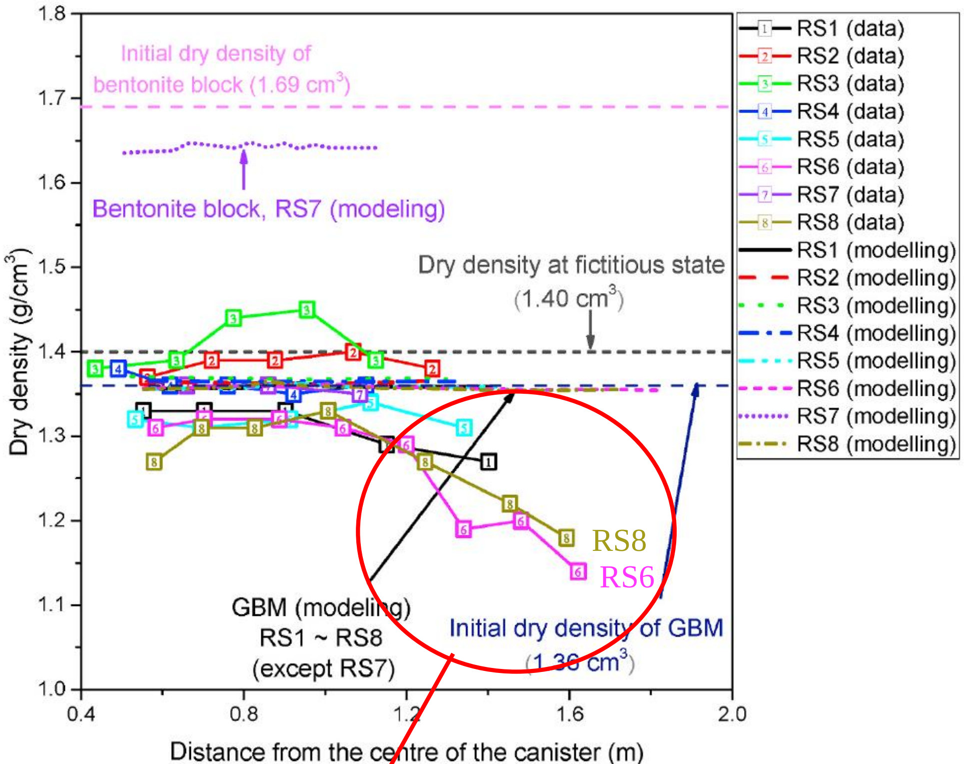
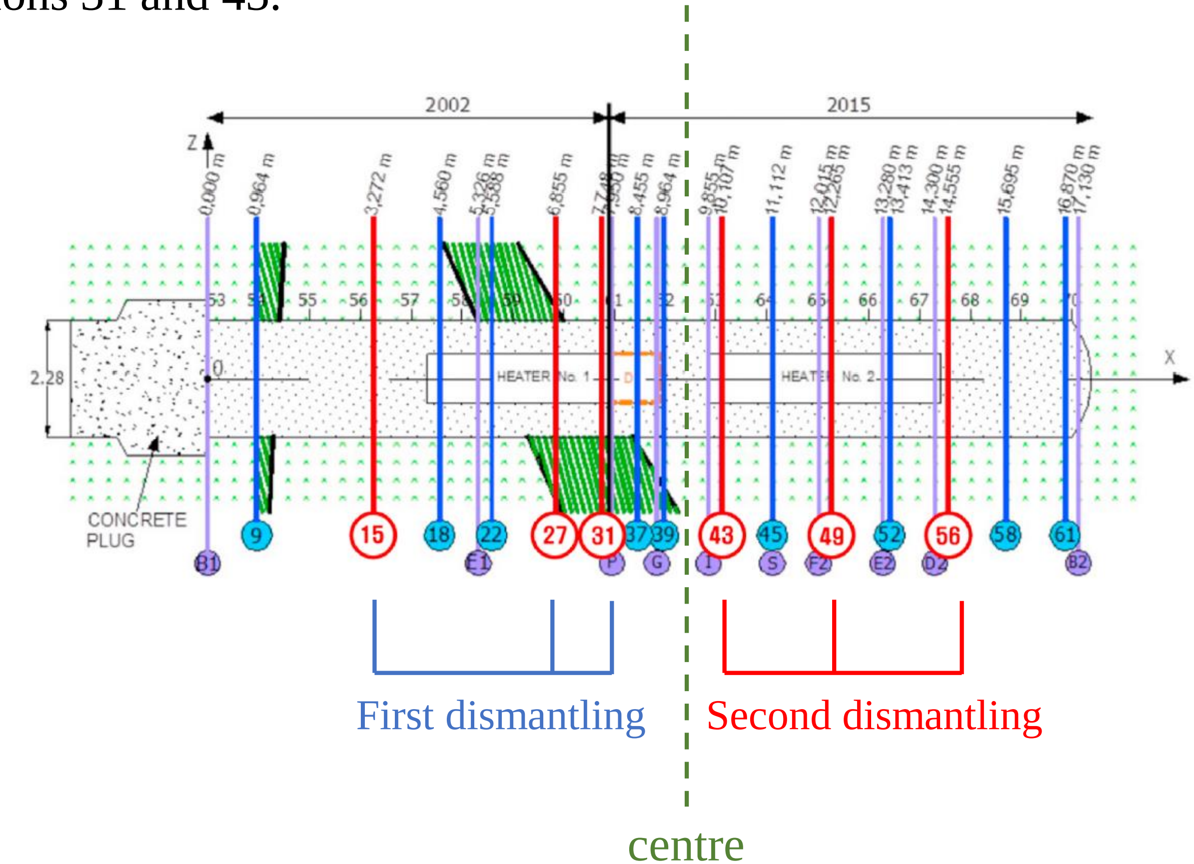


Fig. Distribution of dry density

There are damage zone with high permeability at the corner due to the stress concentration, so most of water may have leaked through the corners.

FEBEX test

- Base on the distance from the centre of the two heaters, it investigate the difference between the observations after the first and second dismantling.
- The six sections were divided into three groups, sections 15 and 56, sections 27 and 49, and sections 31 and 43.



FEBEX test

Heater power

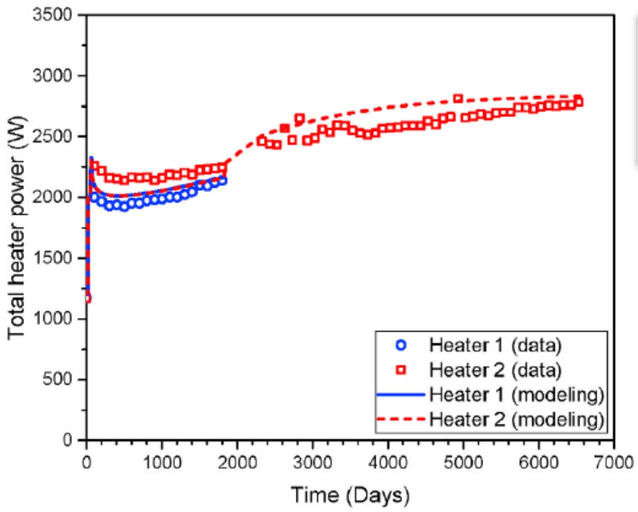


Fig.8. Total heater power of heaters #1 and #2

approximately 10% of the difference between the power values could not be reproduced in the numerical simulations

1. Because all bentonite blocks were assumed to have been simultaneously installed in the numerical simulations.

2. The rock mass was assumed to be a homogeneous medium without considering the presence of lamprophyre with low thermal conductivity.

FEBEX test

Water content

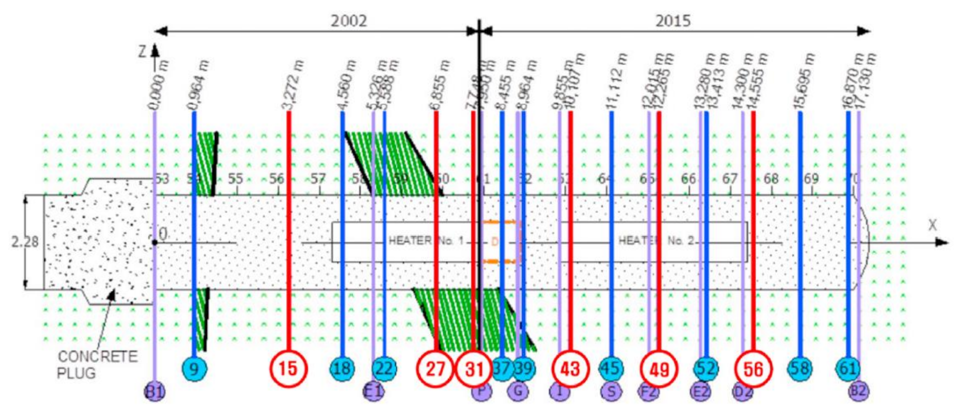
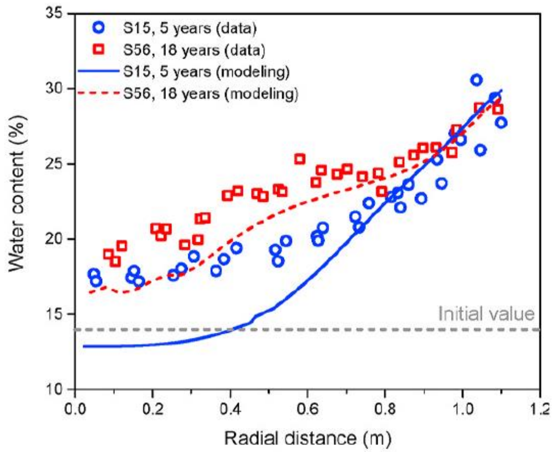
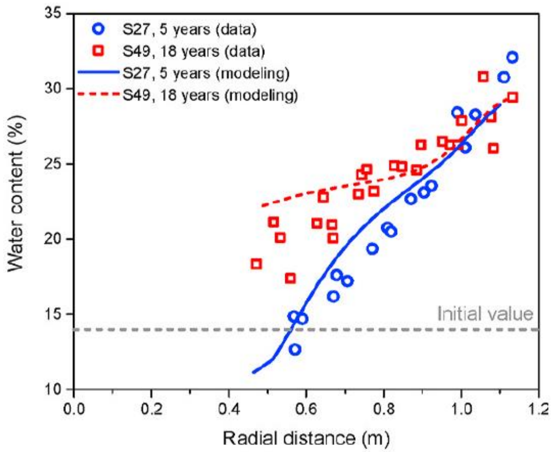


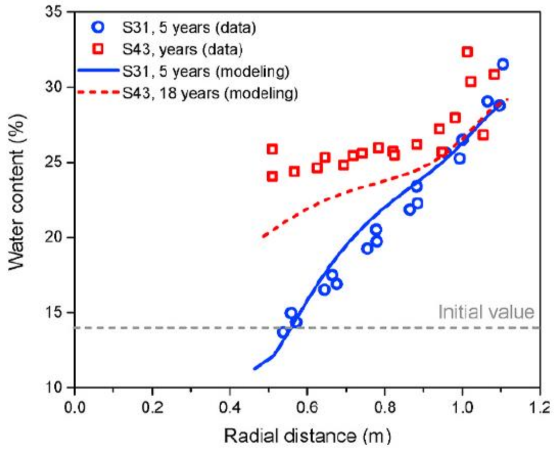
Fig.9. Location of sampling after dismantling sections



(a). Sections 15 and 56



(b). Sections 27 and 49



(c). Sections 31 and 43

FEBEX test

Dry density

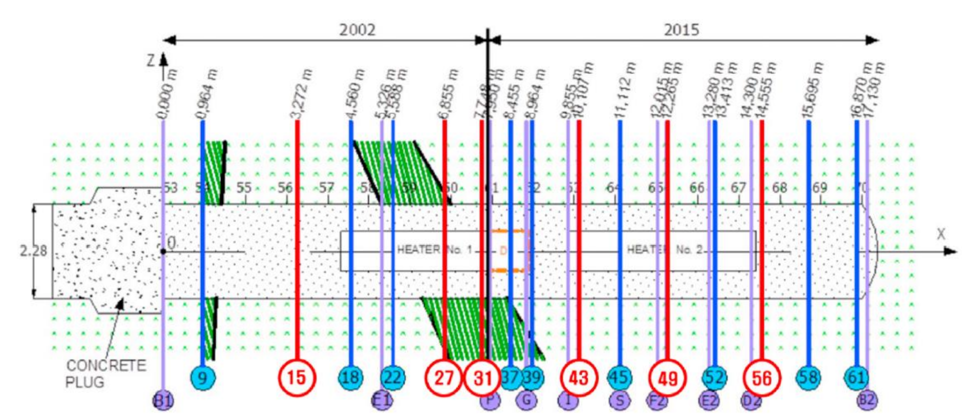
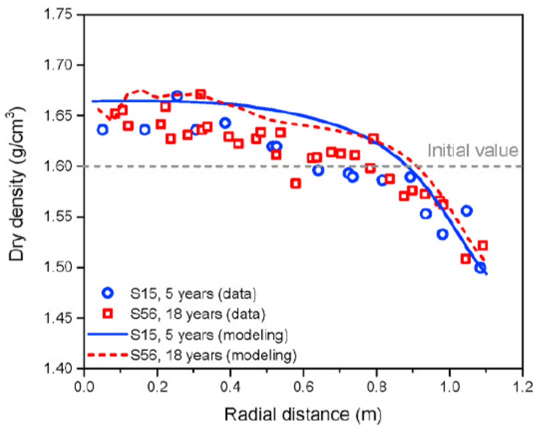
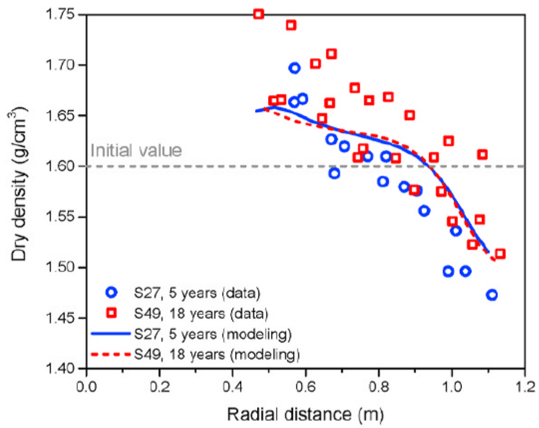


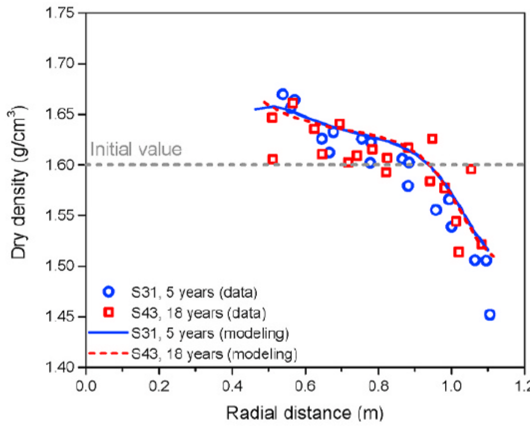
Fig.9. Location of sampling after dismantling sections



(a). Sections 15 and 56



(b). Sections 27 and 49



(c). Sections 31 and 43

Conclusions

Conclusions

- The numerical models in TOUGH2-MP/FLAC3D were able to reproduce the coupled HM and THM behavior at two in-situ experiments.
- The low dry density at the lower corner was not numerically observed, may be required to enhance and improve the models for better predictions.
- The difference between the power values measured in two heaters could not be simulated, taking into account the installation process at FEBEX and at least two types of rock masses, granite and lamprophyre.

Thank you for your attention.