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FIFTH INTERNATIONAL ITASCA SYMPOSIUM 2020 VIENNA, AUSTRIA

CIGEO radioactive waste repository project

An observation-based model of claystone behavior for thermomechanical FLAC3D simulations

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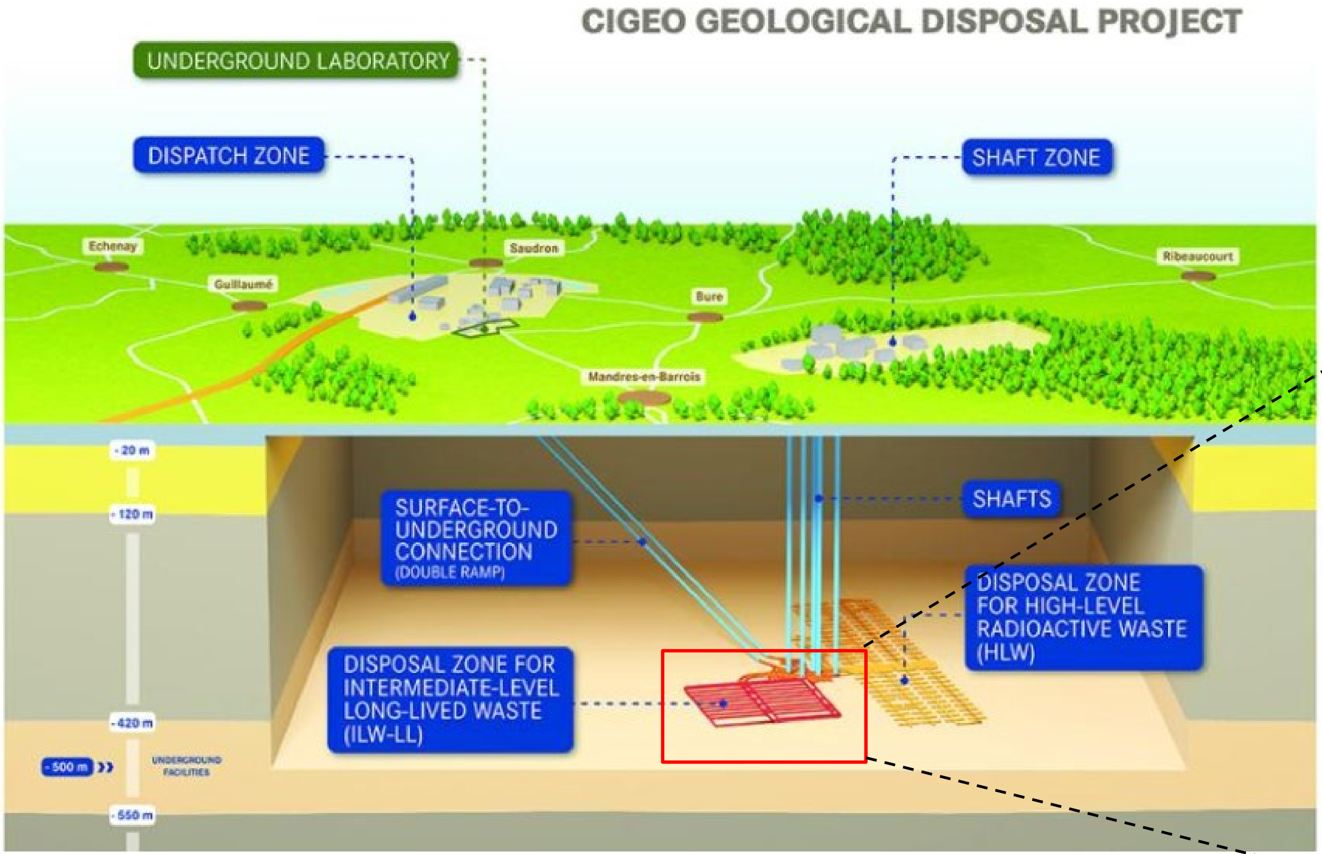
Outline

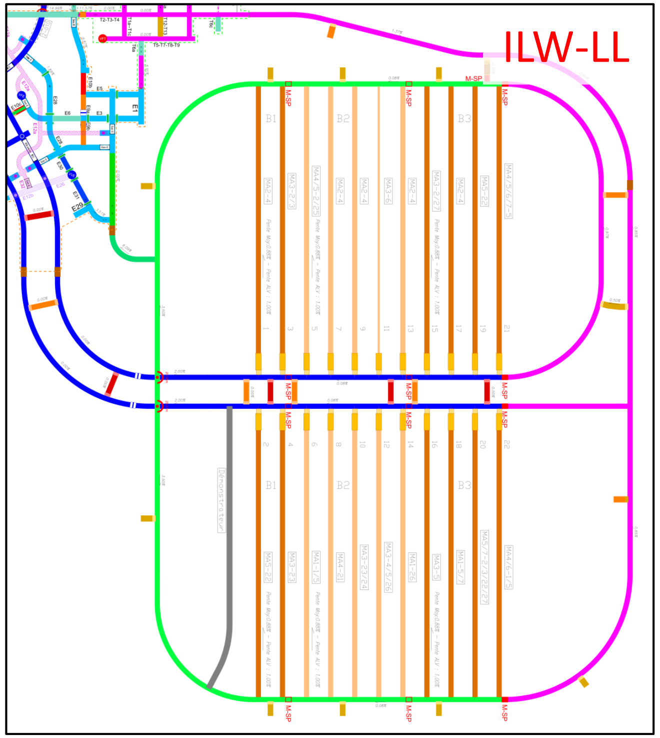
- Study context
- Modelling considerations:
  1. Claystone behavior
  2. Tunnel components
- Setting of the thermo-mechanical coupling approach
- Results of the sensibility study on thermal and creep effects
- Conclusions

Context of the study

The CIGEO project

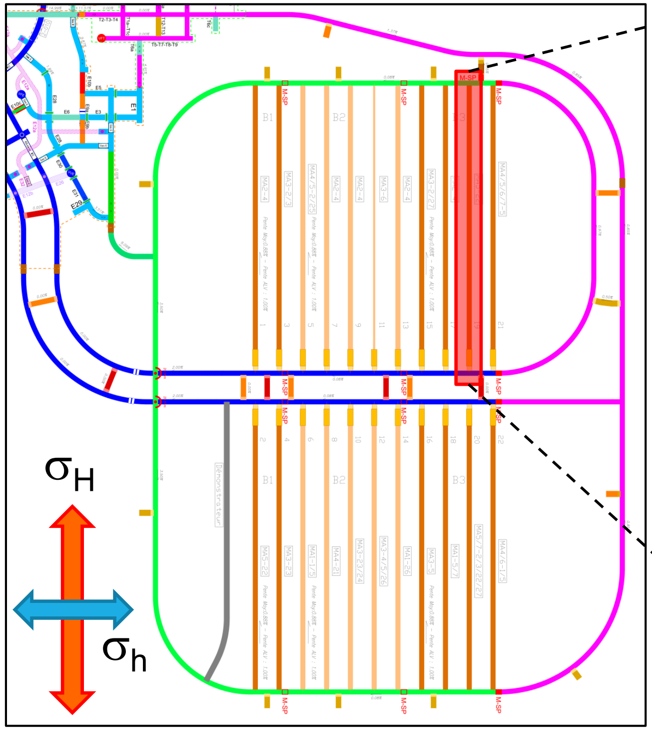


- Geological layer: Callovo-Oxfordian claystone, homogeneous across a wide surface area and very thick (>=140 meters)
- Depth: ~500 meters

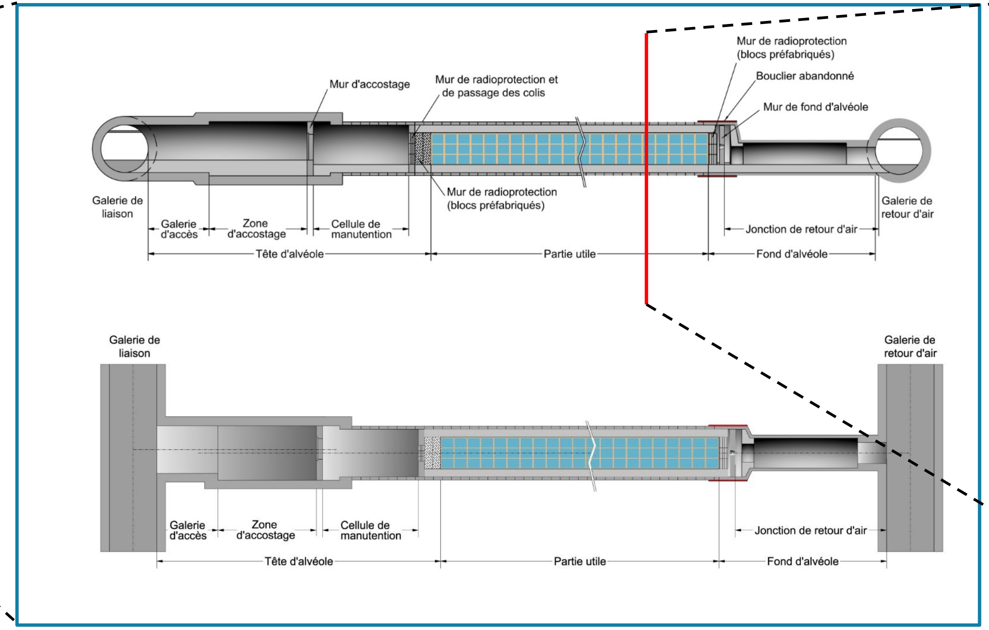


- Waste type: **HLW** and **ILW-LL**
- ~100 years of operation

The CIGEO project

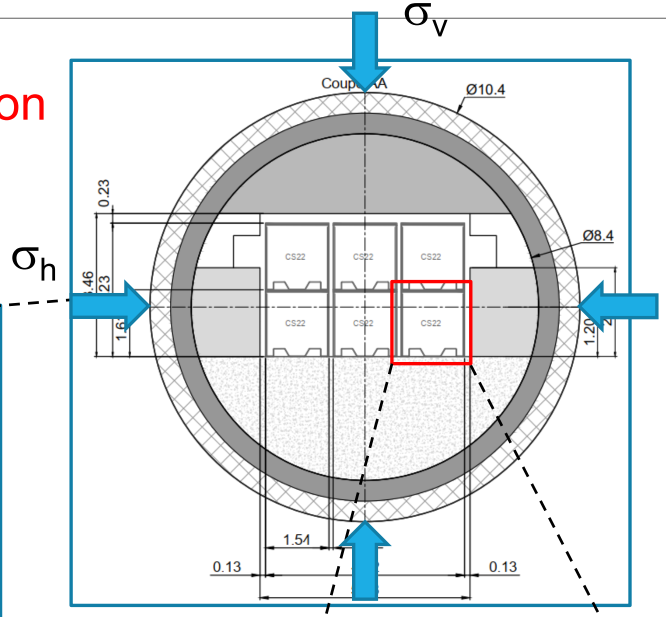


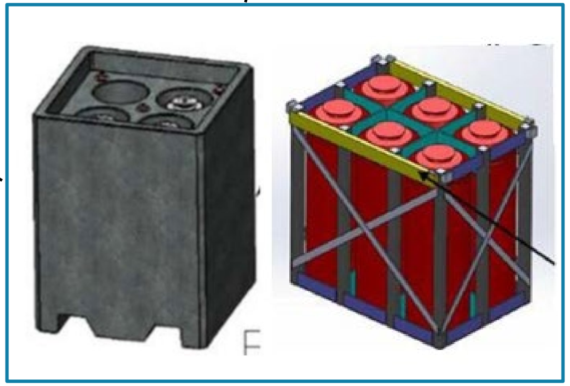
ILW-LL zone



Repository drift

Drift section

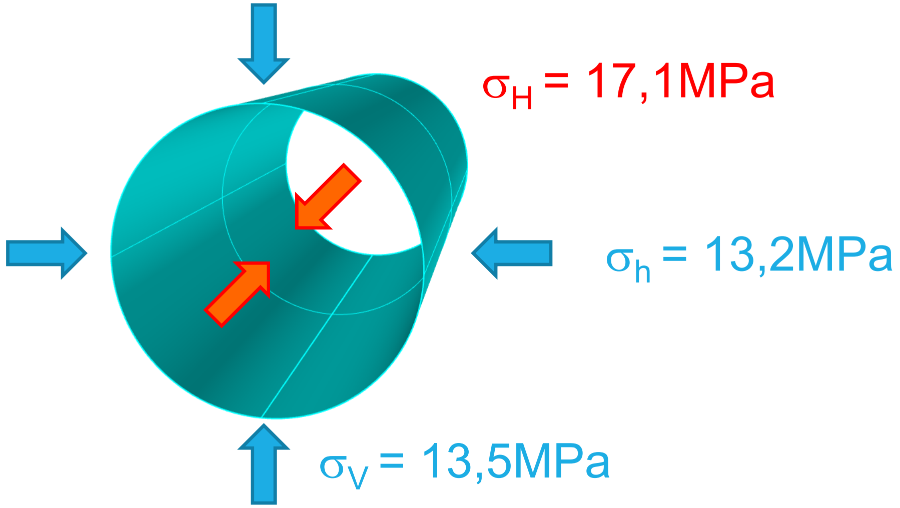


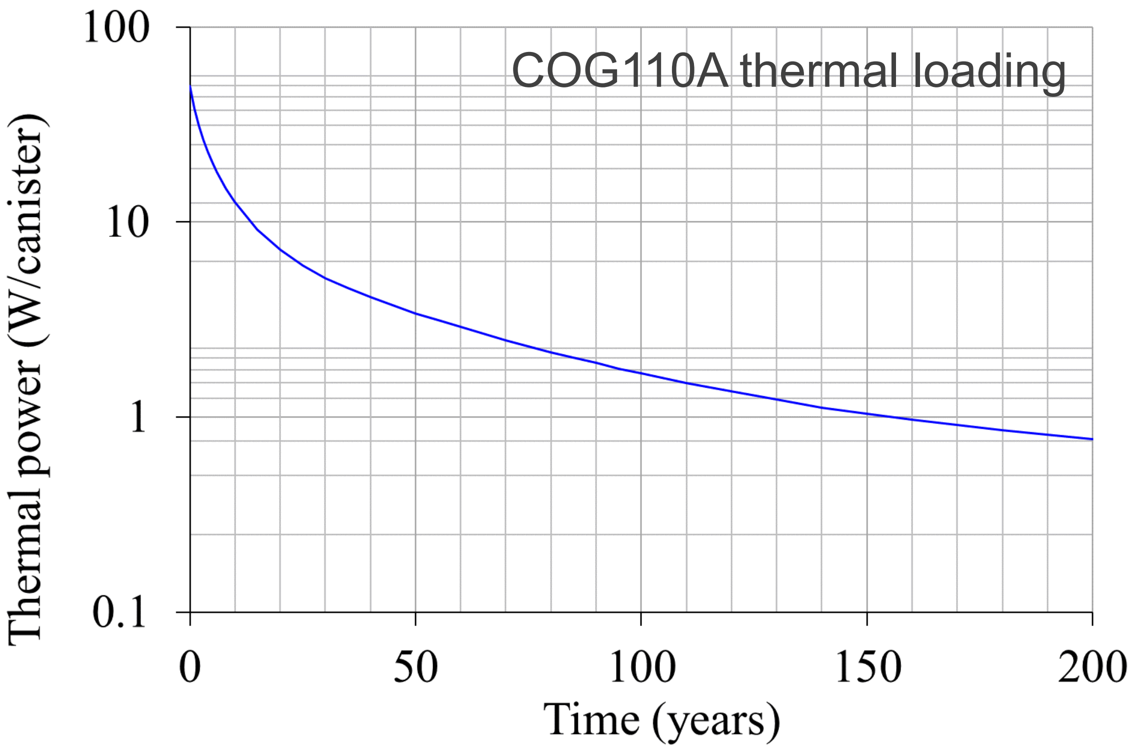


Study purpose

- Design of segmental lining to withstand with creep and thermal loading over the repository reversal period (~100 years)

- Study conditions:
  - Tunnel oriented along σ_H
  - Excavation diameter ~10m
  - Support: concrete lining / compressible material
  - 2D modelling conditions





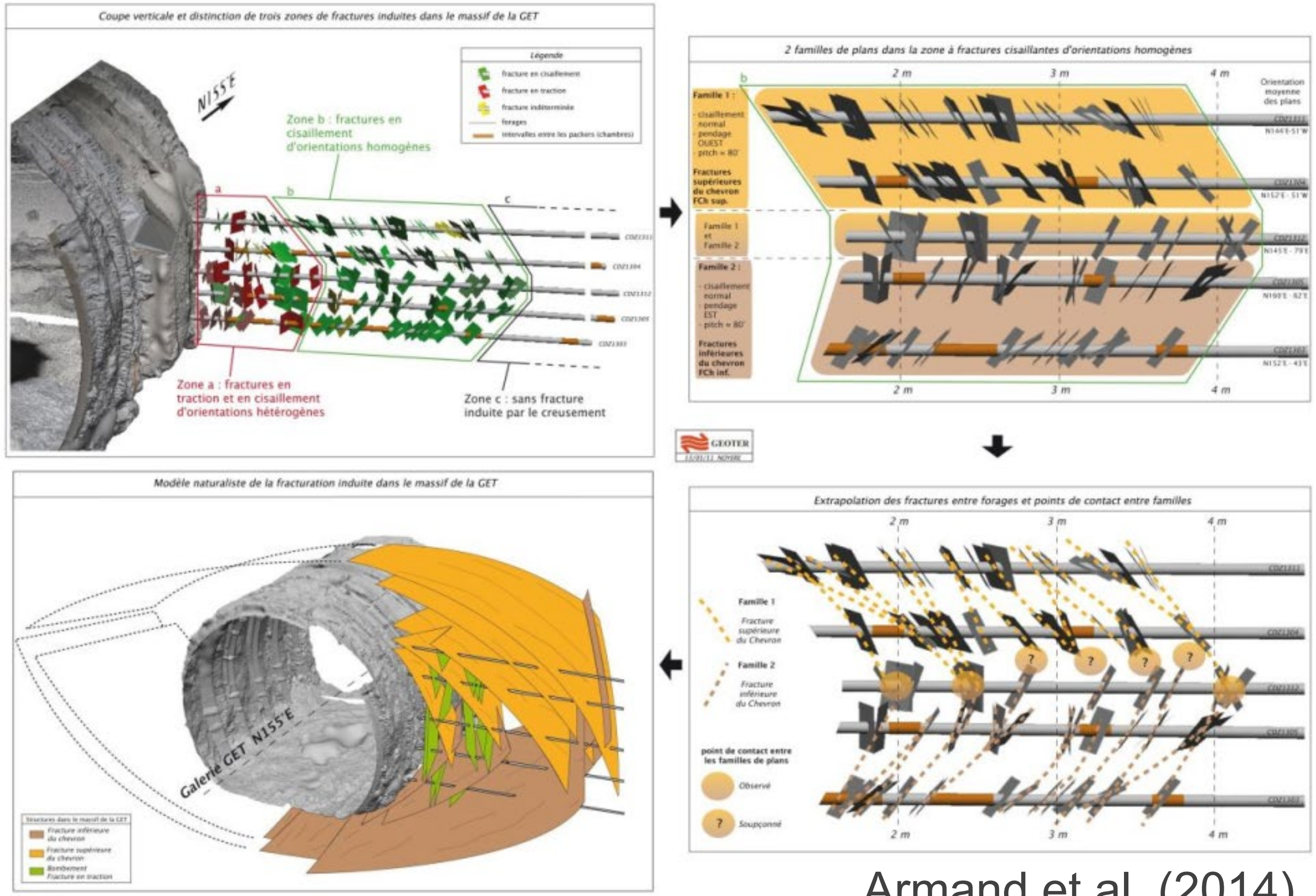
Modelling considerations

The claystone behavior

- Characteristics to be accounted for: the EDZ region and the claystone creep behavior
- Extensive data available from in situ tests and monitoring performed at the near-by Meuse/Haute-Marne URL:
  - ❖ Structure and stress anisotropy
  - ❖ Rock properties from laboratory tests

    (elastic moduli, UCS, TX, …)
  - ❖ EDZ obtained from borehole data
  - ❖ Tunnel convergences

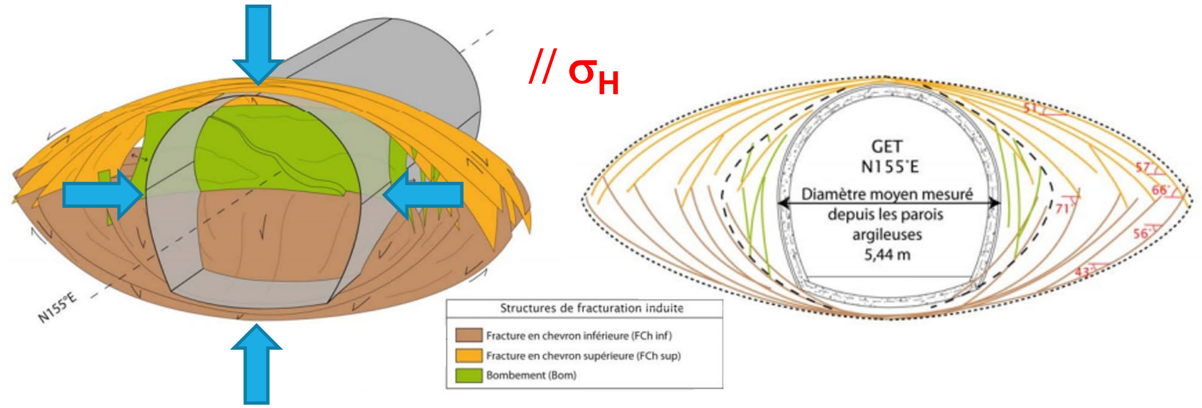
Influenced by the orientation of the tunnel relative to the major and minor horizontal stresses

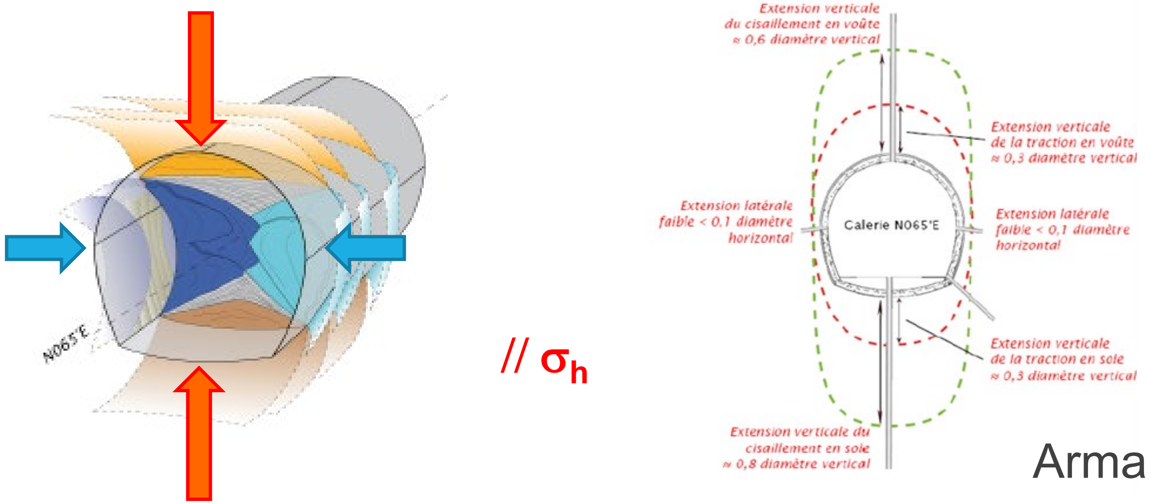


Armand et al. (2014)

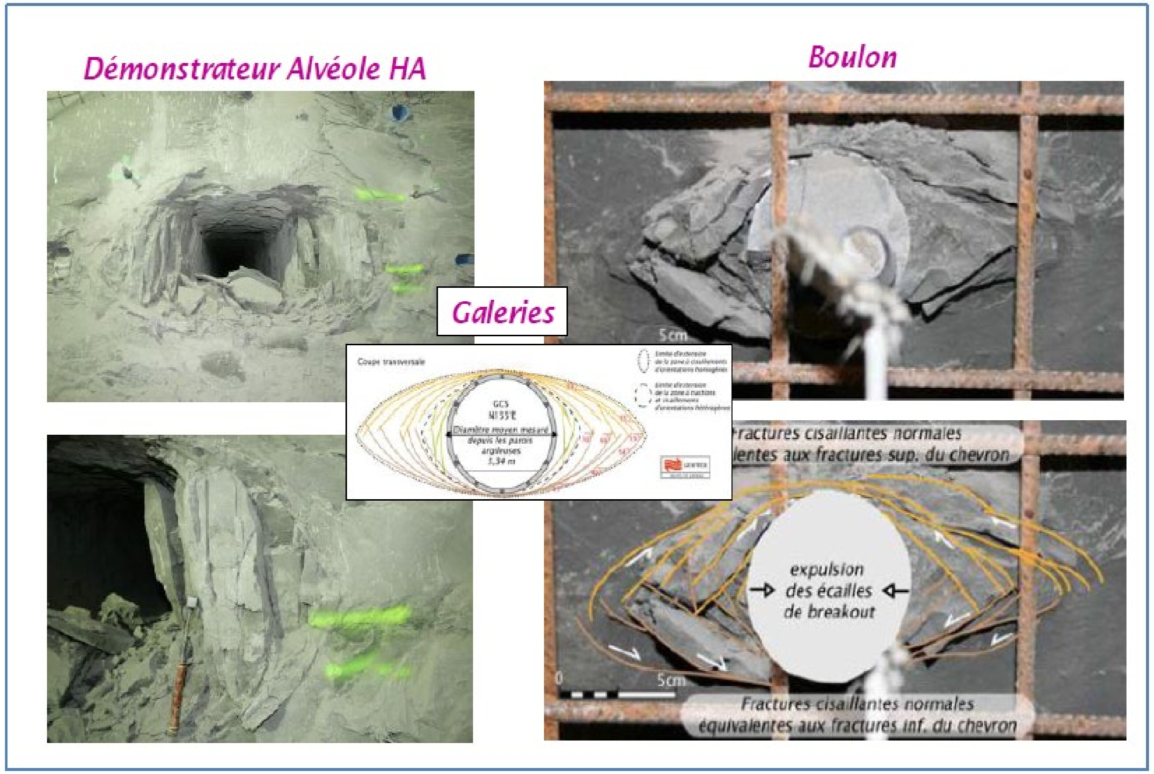
Excavation Damaged Zone

Geometry mainly depends on the tunnel orientation…





… but the structure is similar independently on the excavation size



Armand et al. (2014)

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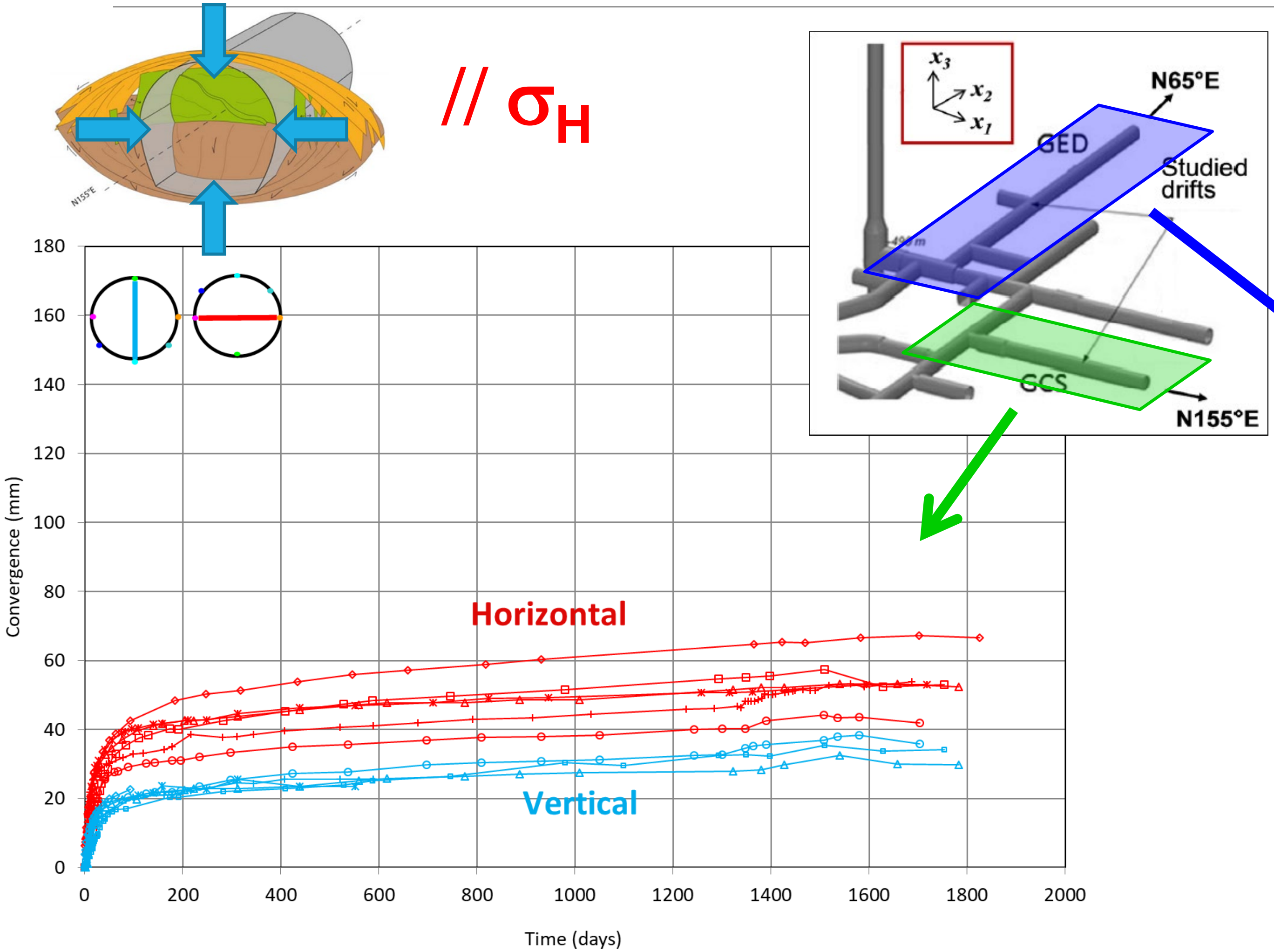
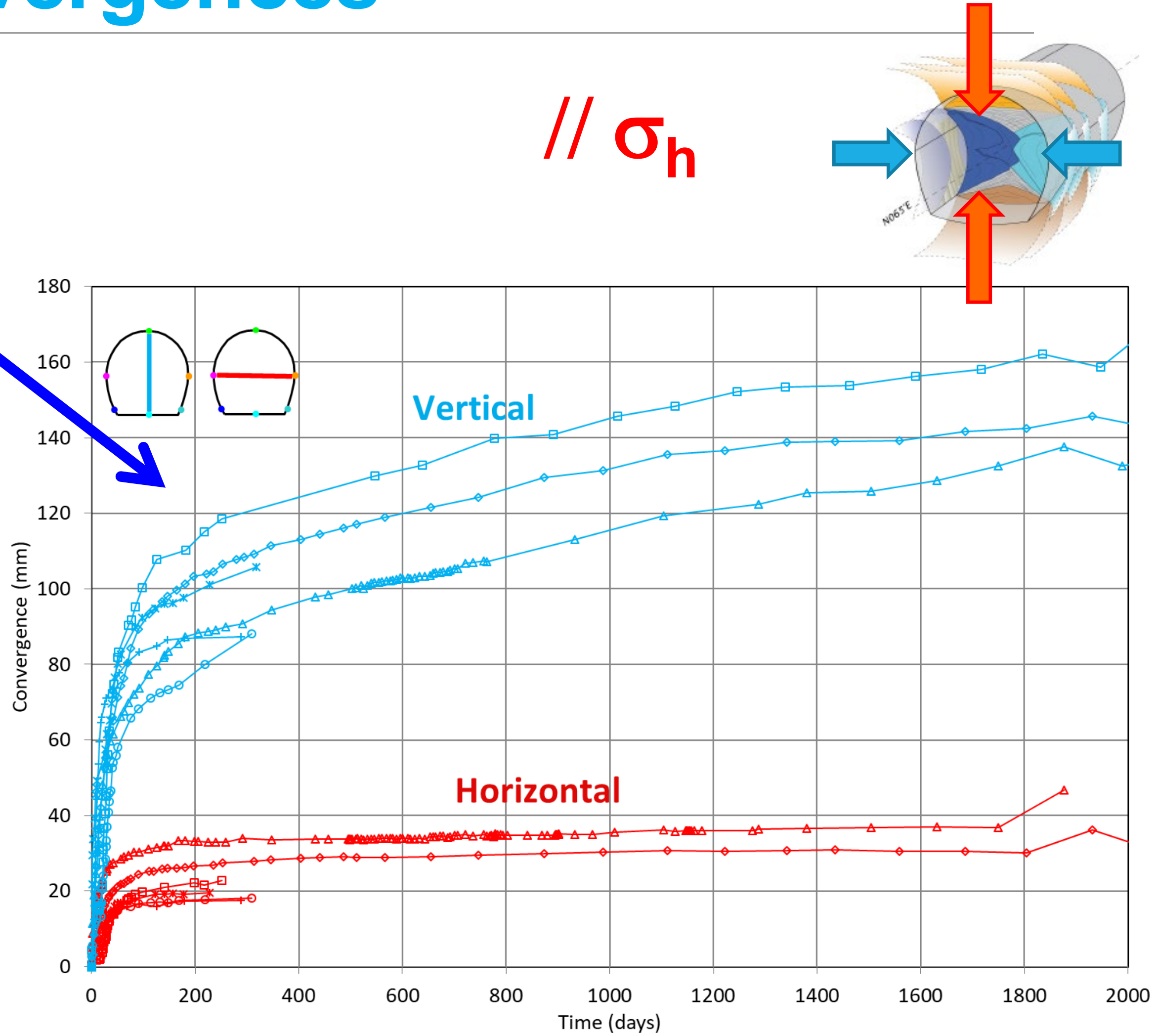
Influence of EDZ on tunnel convergences

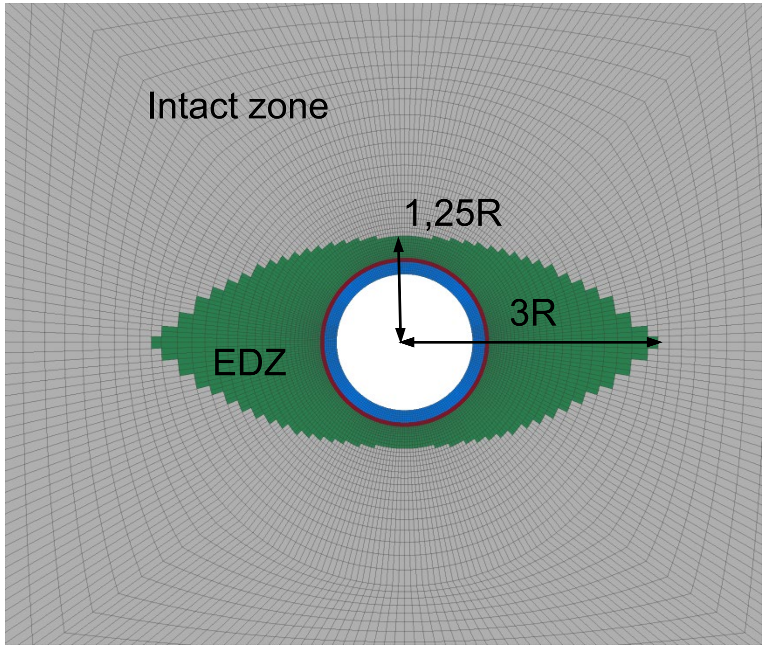


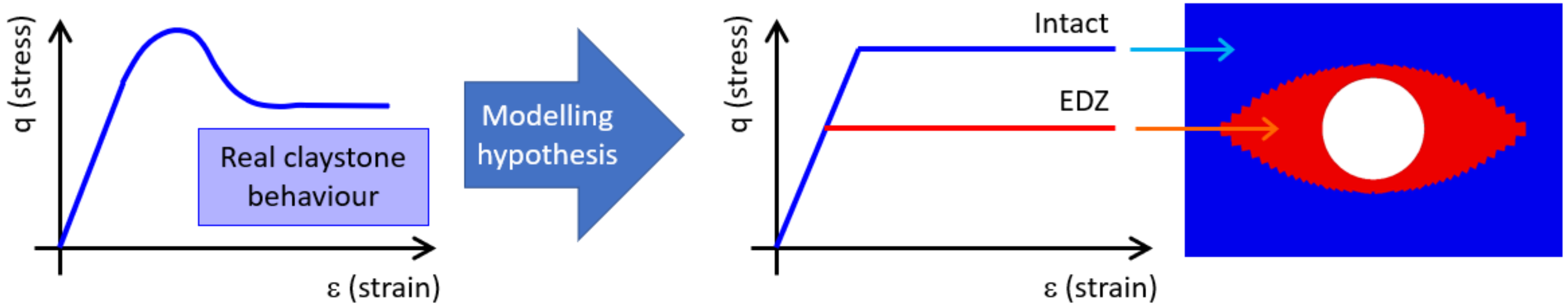


Armand et al. (2013)

Modelling of claystone behavior

- Modelling hypotheses based on a previous work (Saitta et al., 2017) in which the Mohr-Coulomb/Power Law (**POWER-MOHR**) constitutive model has been calibrated to reproduce displacement developed around tunnels of the near-by URL of Bure
- Residual strength parameters are considered for volumetric elements included in the EDZ region





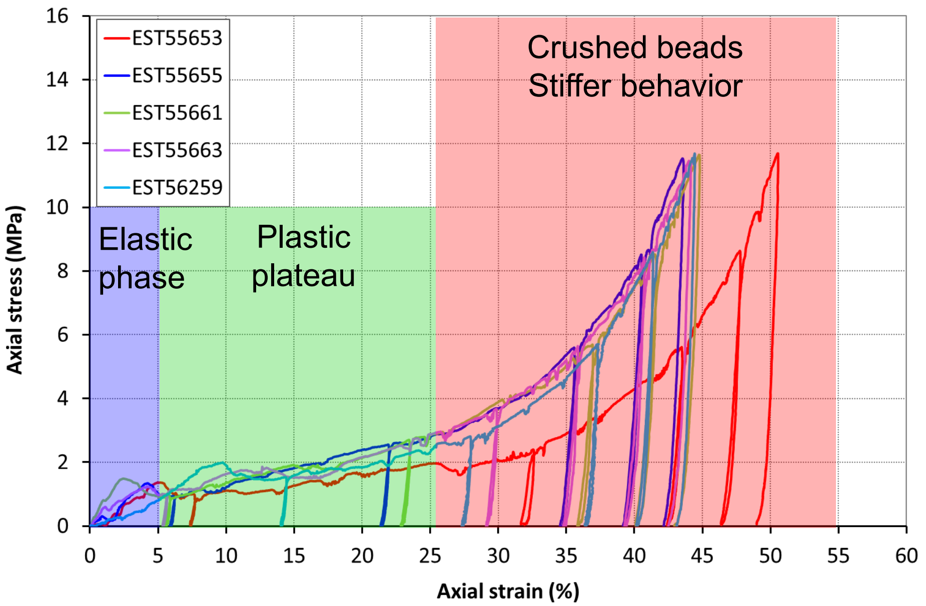
Initial deviatoric stress considered as creep threshold

Property		Intact zone	EDZ
Young modulus	E (GPa)	4	
Poisson ratio	ν (-)	0.3	
Cohesion	c (MPa)	6.4	0.1
Friction angle	φ (°)	20	30
Dilatancy angle	ψ (°)	0	9.5
Tensile strength	σ_t (MPa)	0.9	0
Norton coefficient	A (-)	$2.5\ 10^{-59}$	
Norton coefficient	n (-)	6.8	

Tunnel components

Segmental concrete lining including a compressible layer

ANDRA / CMC patent



Elastic model

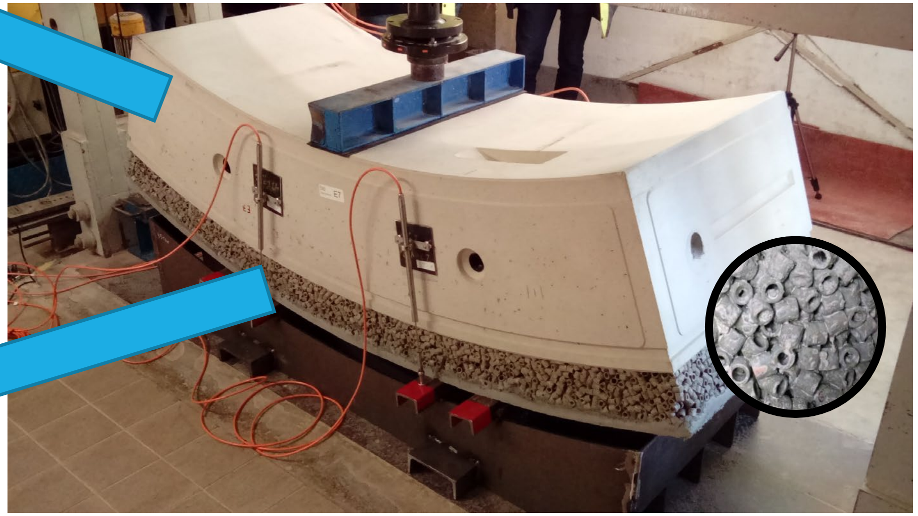
Concrete part (50cm)
f_{ck}=60MPa

Double Yield model
(only volumetric criterion)

Compressible layer (20cm)

Integrated on concrete outer surface

Assembly of crushable clay/cement mixture beads



Calibration of compressible material properties (DY)

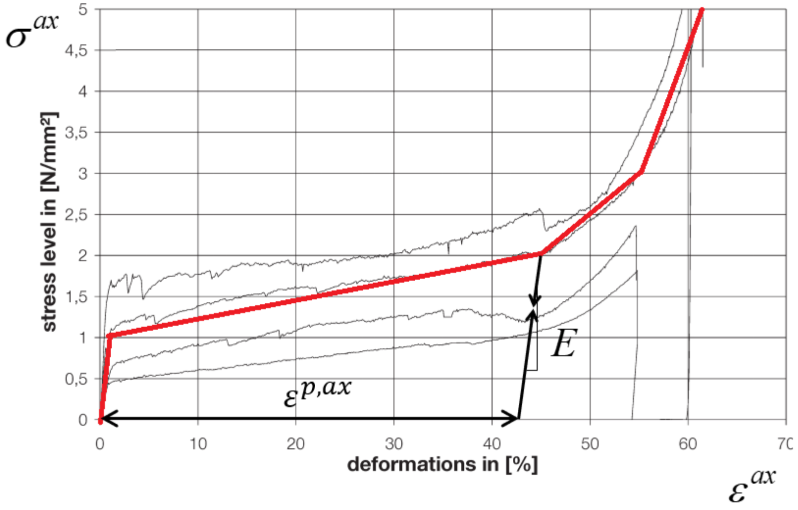
Calibration of the hardening curve p-e_v^{pl} to reproduce oedometer results

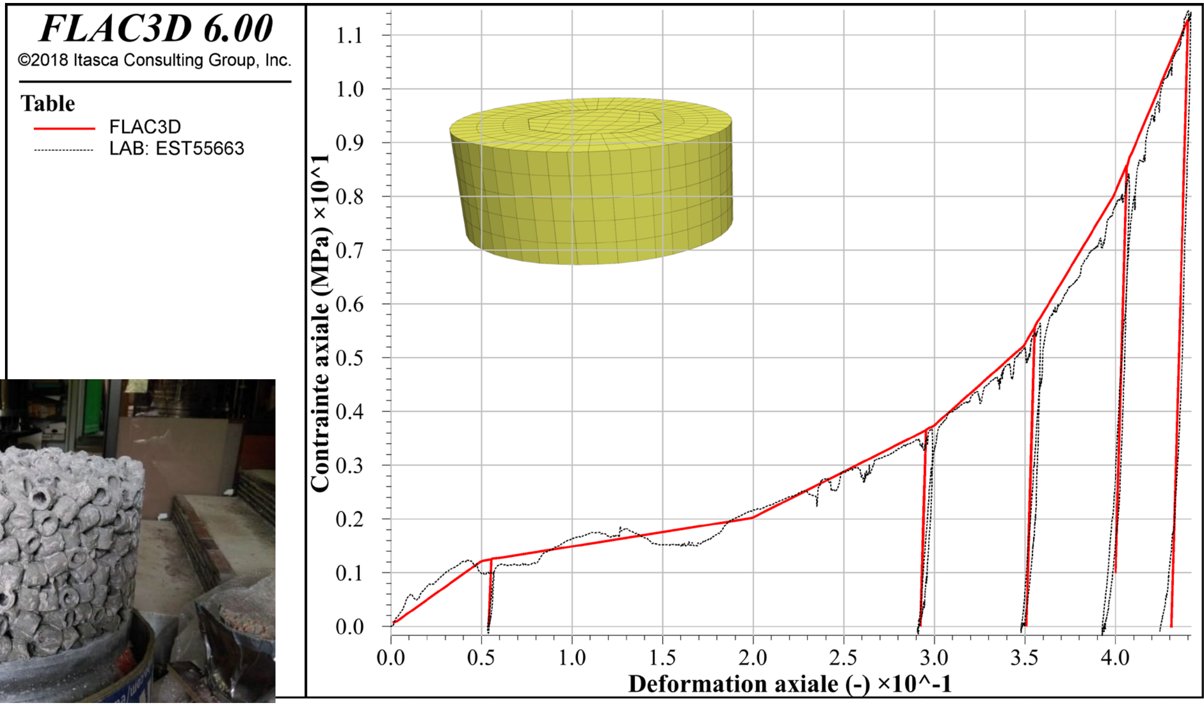
$$p = \frac{\sigma^{ax}}{3}$$

No expansion in direction perpendicular to loading direction

$$e^{pv} = 3\varepsilon^{p,ax} = 3(\varepsilon^{ax} - \varepsilon^{e,ax}) = 3\left(\varepsilon - \frac{\sigma^{ax}}{E}\right)$$

$$\boxed{\Delta e^{pv} = \Delta e_1^{pv} + \Delta e_2^{pv} + \Delta e_3^{pv} = 3\left(\tfrac{1}{3}\lambda^v\right)}$$





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Thermo-mechanical coupling approach

Coupling approach

- Different needs associated with thermal and mechanical process simulation

Model size

Thermal simulation requires for large model to limit the influence of boundary conditions on diffusion processes

In mechanical simulations, the distance of the boundaries can be reduced to 5D

Thermal

Mechanical

Discretization

Mechanical simulation requires for finer elements for a reliable estimation of lining stresses

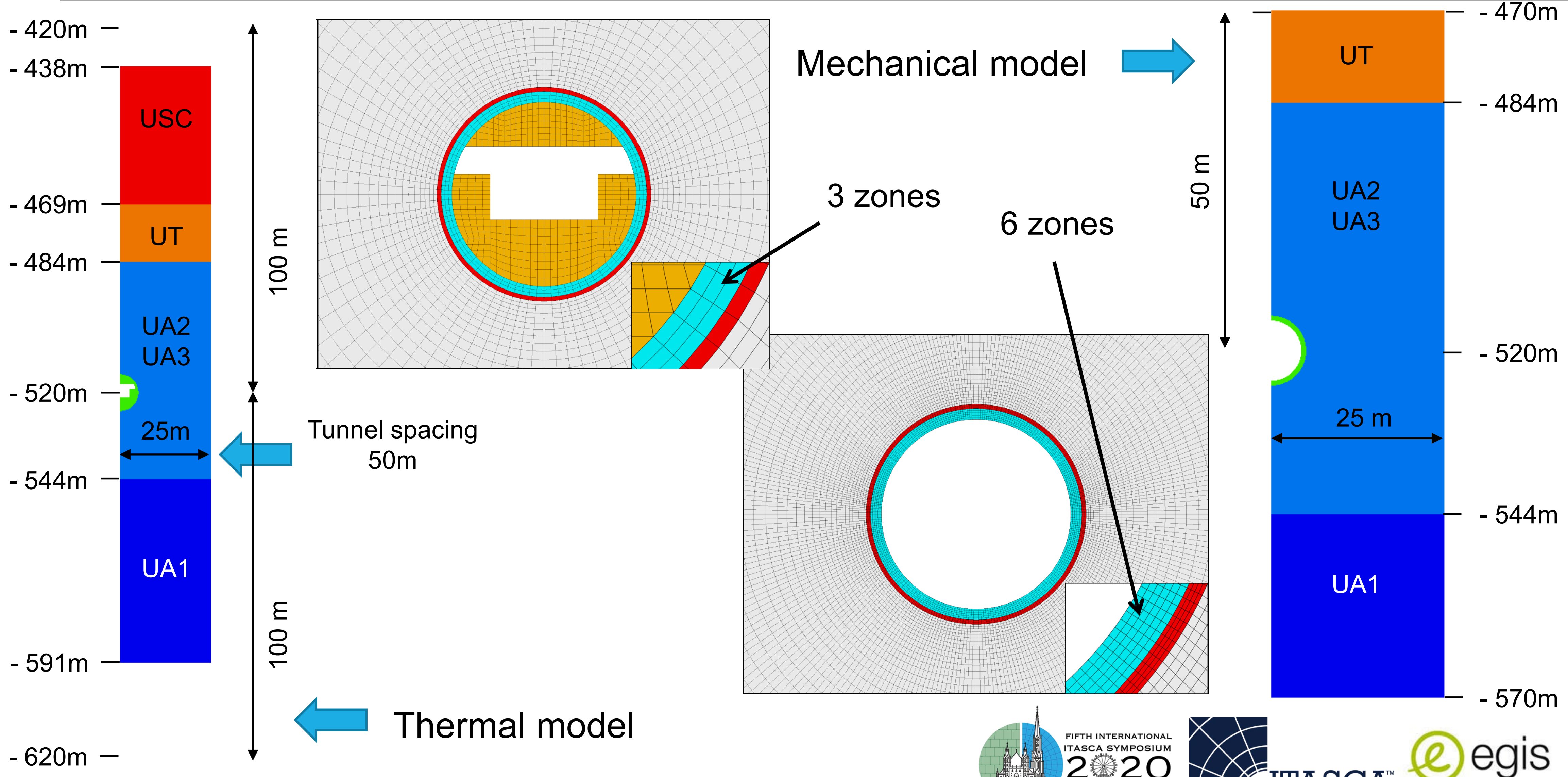
Thermal simulations are less sensitive to the element sizes. Also, smaller sizes imply smaller thermal timesteps

- Solution: use of two different meshes for the thermal and mechanical calculations with different **extensions** and **discretization**

- Practically…a thermal calculation is first performed and obtained temperature maps are then injected into the mechanical model as the creep simulation proceeds

- Possible because of the unidirectional coupling (low kinetic energy associated with mechanical deformations)

Model meshes



Thermal calculation

Model initialization

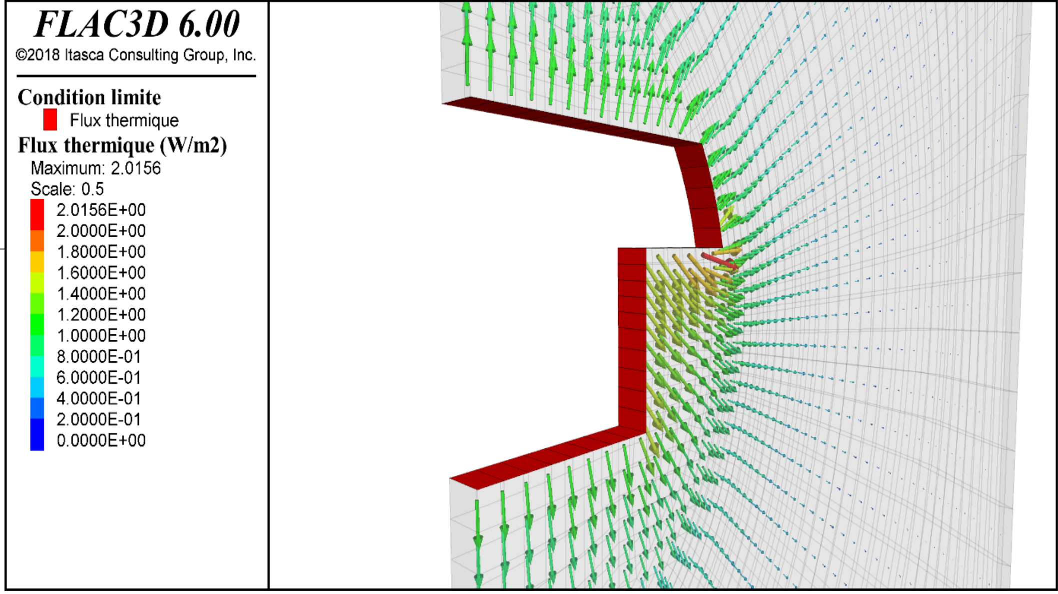
Initialization of gridpoint temperature and zone thermal properties depending on the depth

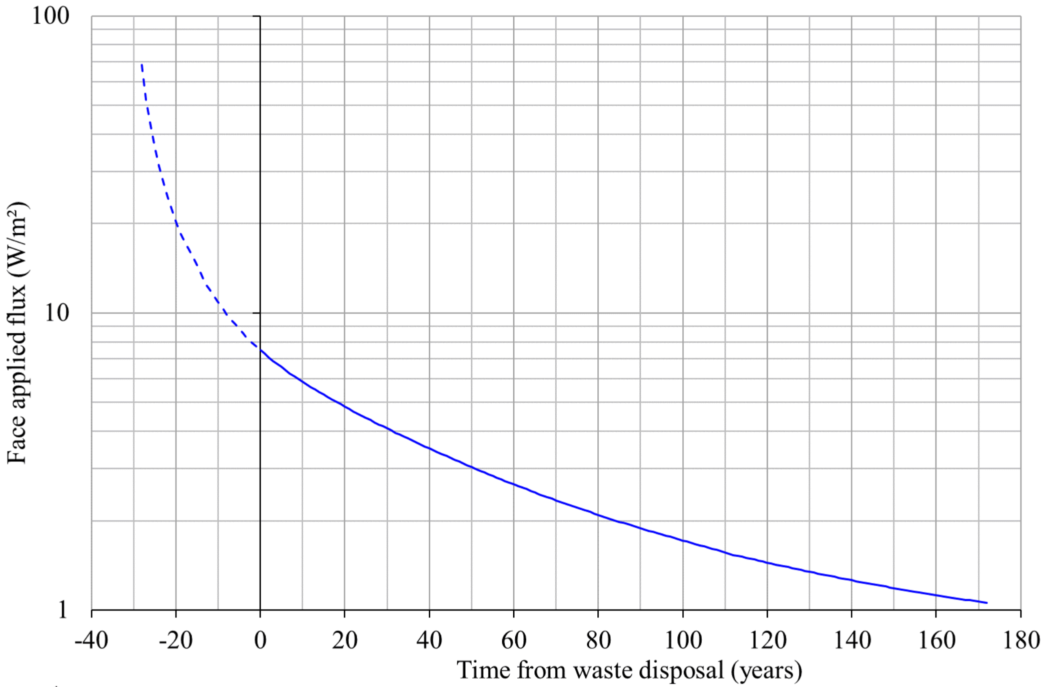
Application of the thermal flux

A time dependent thermal flux condition (W/m²) is applied on internal faces of the disposal chamber, according to the thermal power curve of the waste. Time from waste conditioning to disposal is also considered

Simulation over 100 years

… and dumping of temperature maps over the time (higher dump frequency at the beginning when change in temperature are higher)





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Simulation over 100 years

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Model initialization

Initialization of zone mechanical properties and stress field

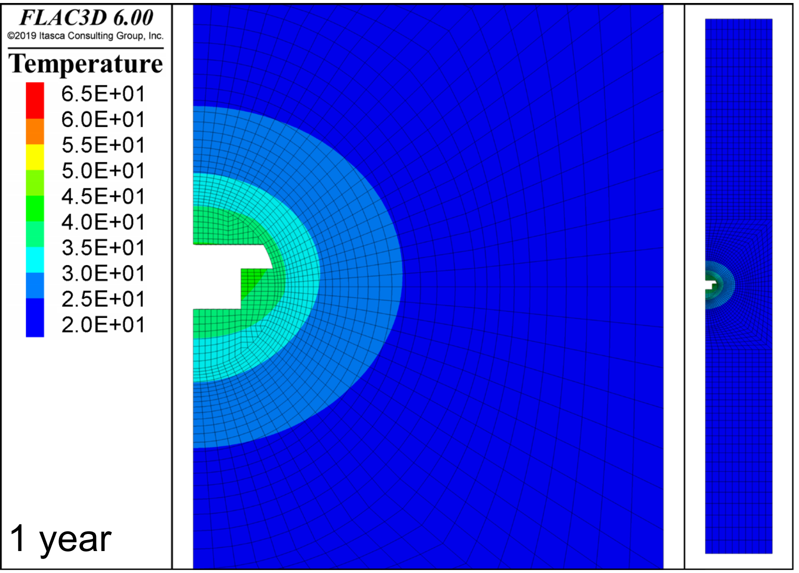
Simulation of the excavation

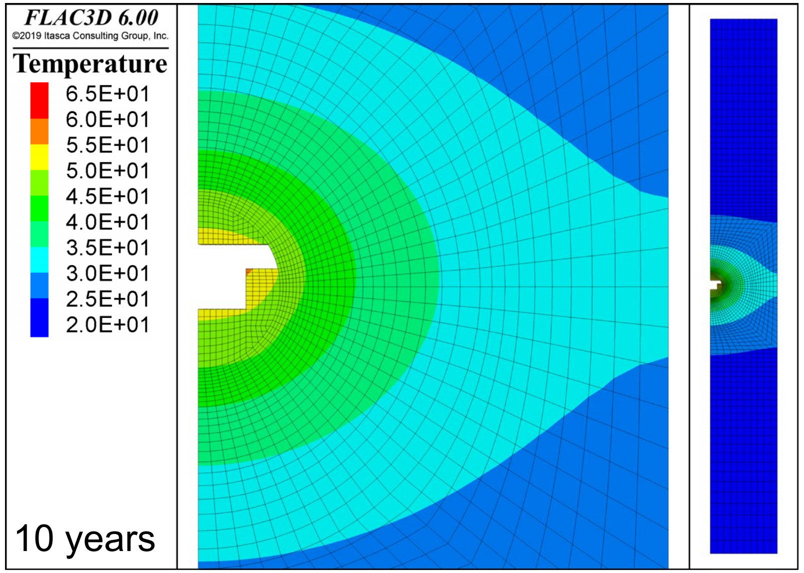
- Relaxation of tunnel boundary forces until 90% (Saitta et al.,2017)
- Lining installation
- Complete relaxation of tunnel boundaries

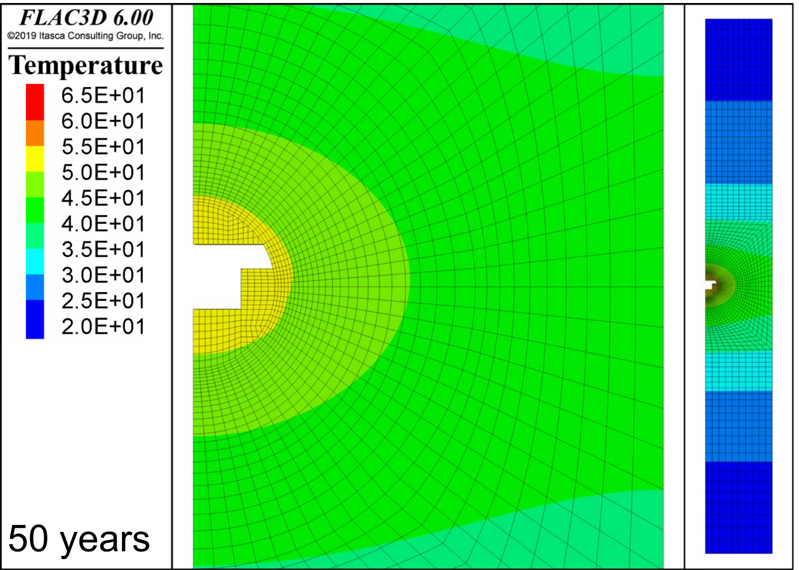
Simulation over 100 year

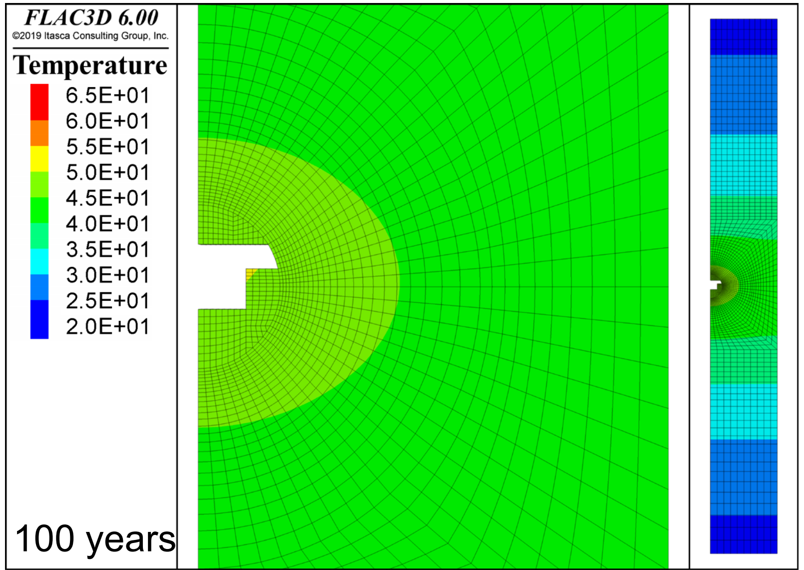
- Creep over 4 years, i.e. the time before the introduction of waste into the drift
- Thermo-mechanical simulation over 100 year with a continuous update of the gridpoint temperature according to thermal simulation results

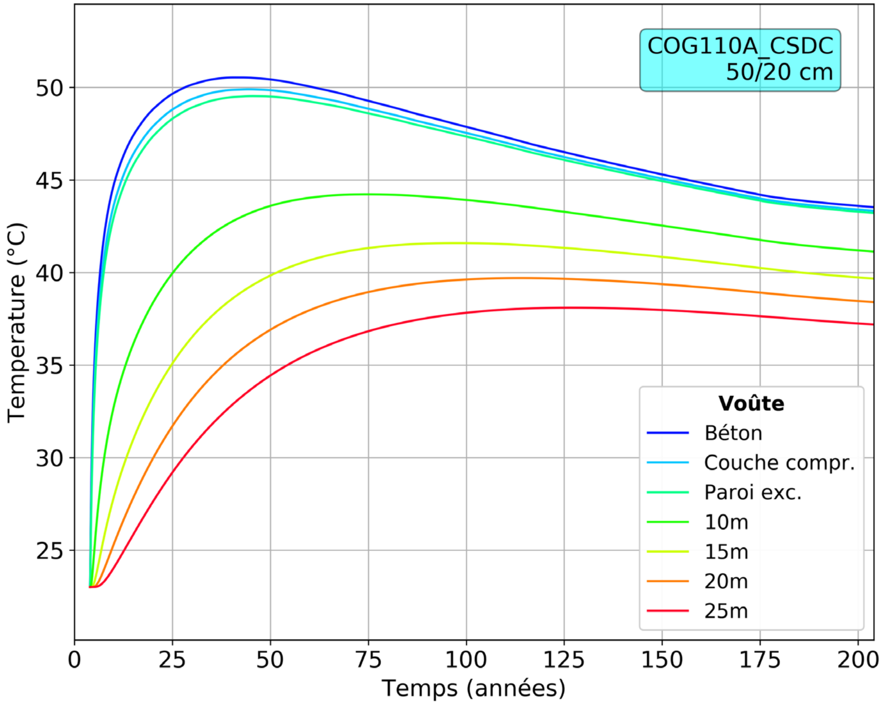
Thermal model results

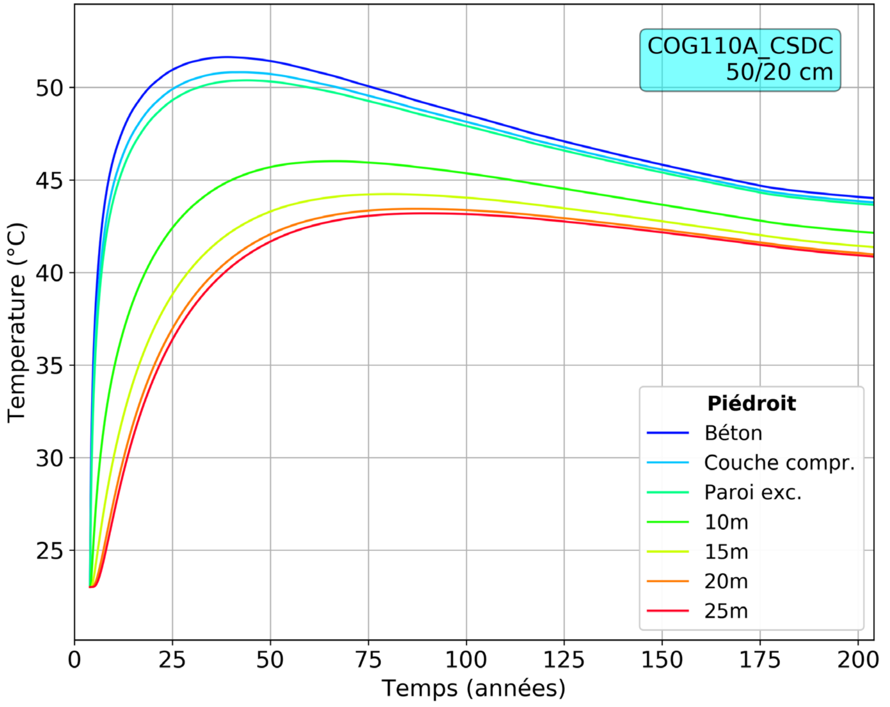












Thermal-mechanical modelling

- Main purpose: Design of compressible lining to withstand with thermal and mechanical loading with time
- Analysis of thermal and creep contributions on the long-term behavior

Analysis	Active processes			$\dot{\varepsilon} = A\bar{\sigma}^n$
	M	C	T	
TM – A=0	✓	✗	✓	A = 0
M	✓	✓	✗	Const = A_{23}
TM - A=A23	✓	✓	✓	Const = A_{23}
TM - A=f(T) - A_{80}/A_{23}=3	✓	✓	✓	f(T) – A_{80}/A_{23}=3

« A » calibrated from convergence measures of Bure URL tunnels, where T=23°

$$A(T) = A_0\,exp\left(-\frac{B}{RT}\right)$$

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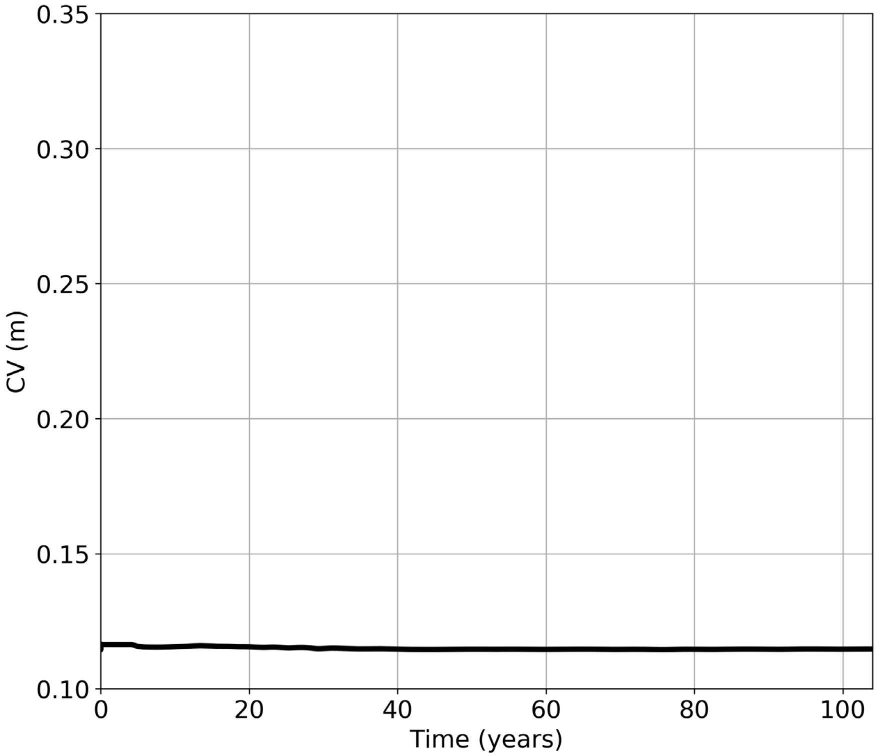
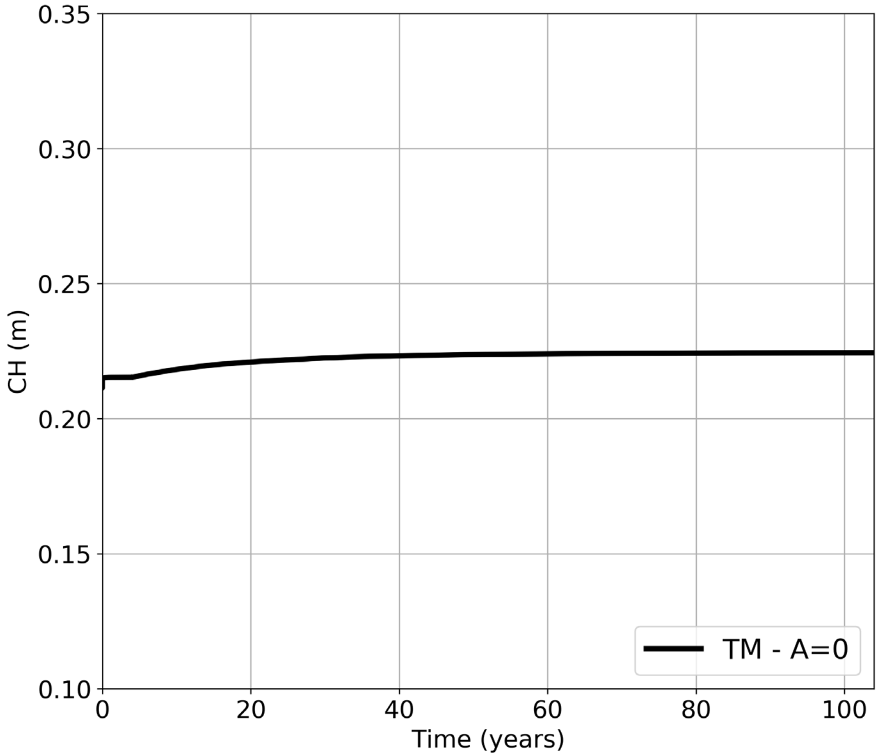
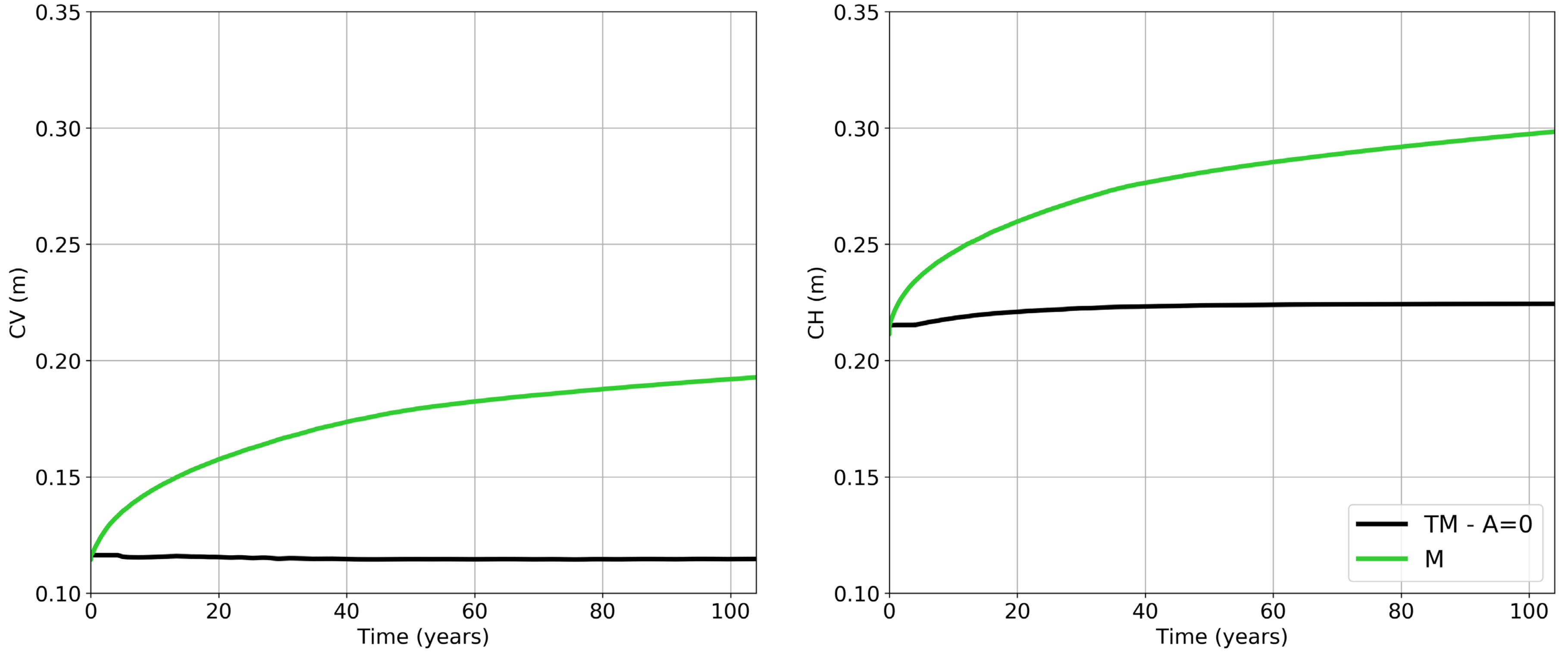
Thermal-mechanical modelling – Tunnel convergence





TM – A=0 (only thermal expansion)

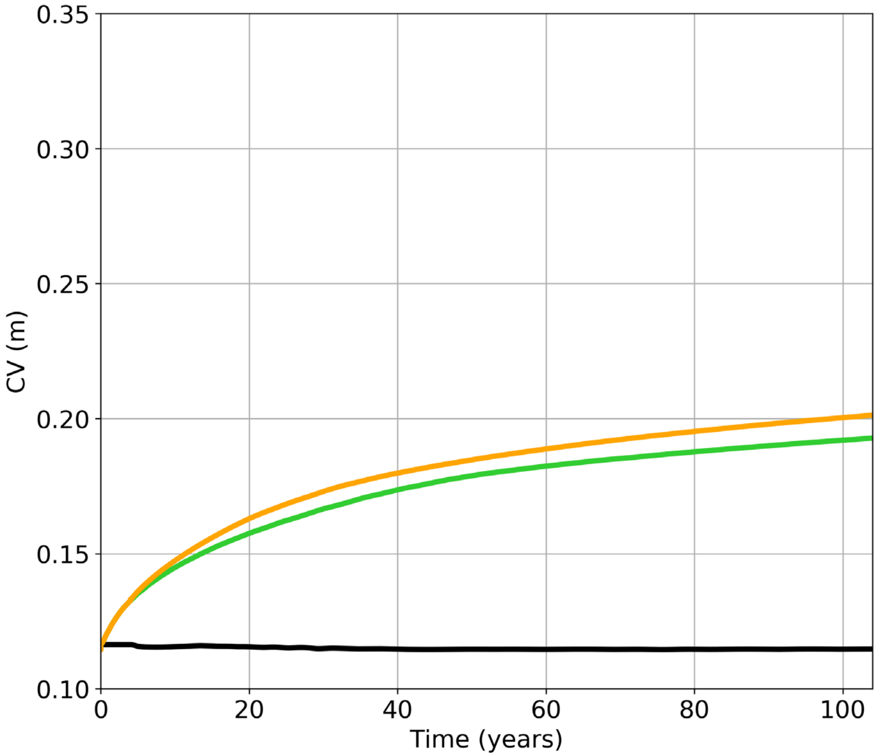
Thermal-mechanical modelling – Tunnel convergence

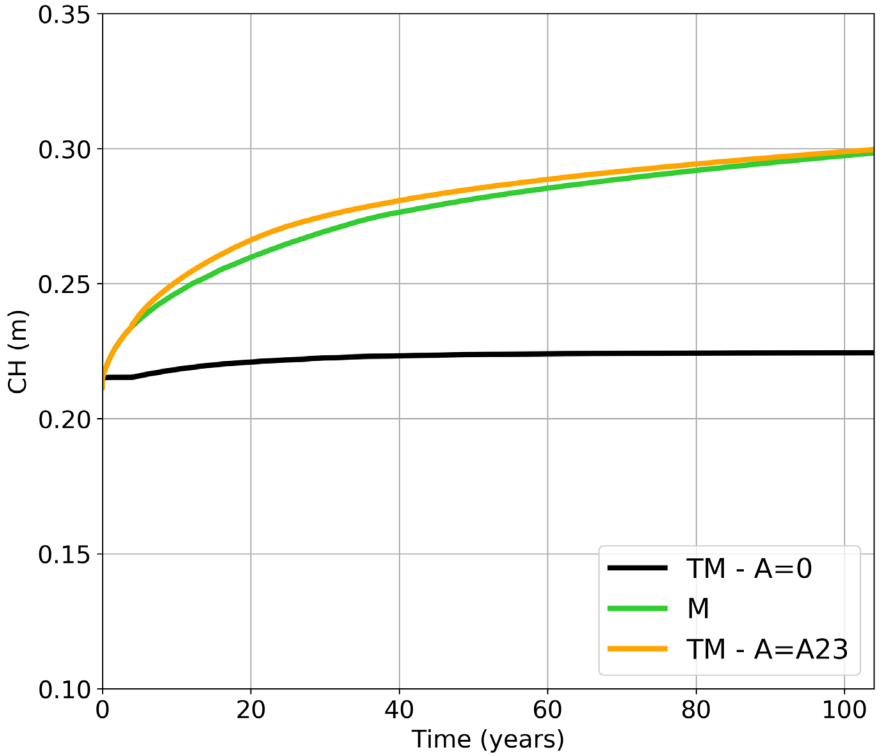


TM – A=0 (only thermal expansion)

M (no thermal expansion)

Thermal-mechanical modelling – Tunnel convergence



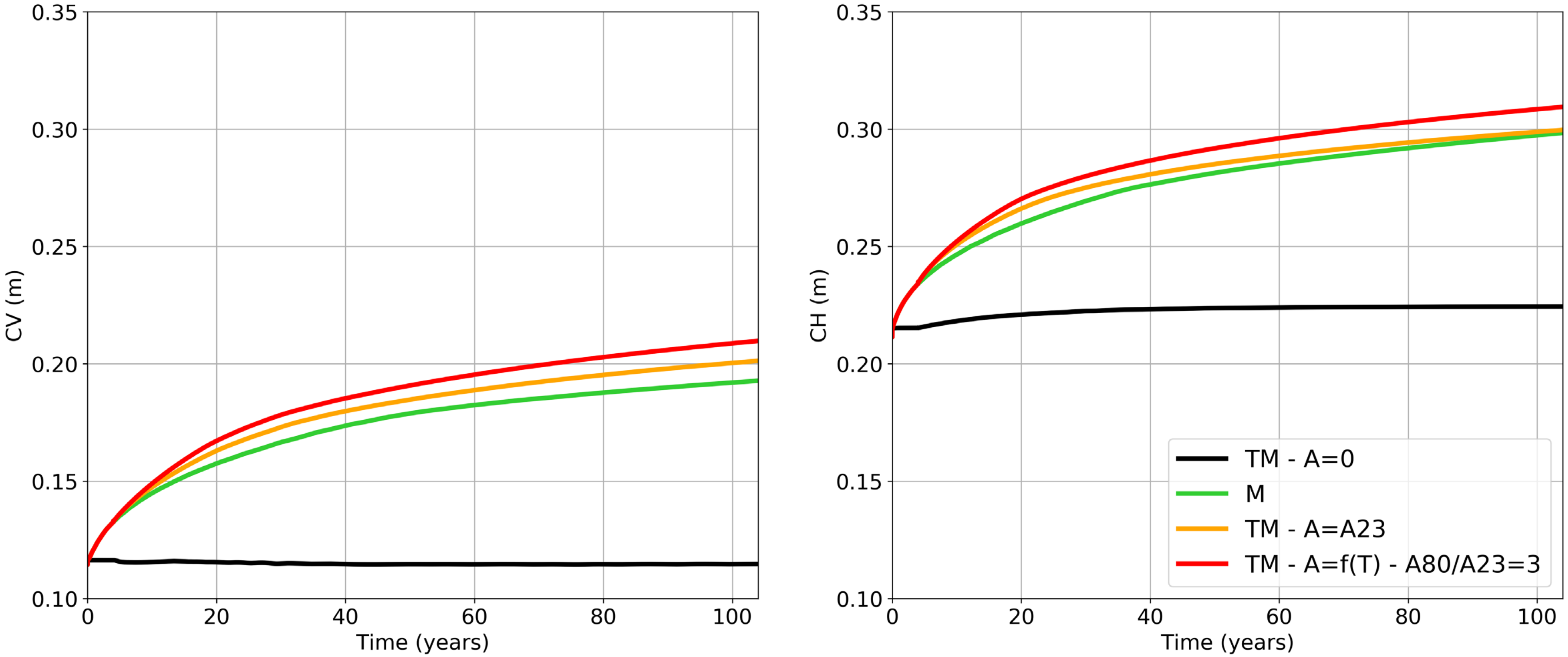


TM – A=0 (only thermal expansion)

M (no thermal expansion)

TM – A=A23
M + thermal expansion

Thermal-mechanical modelling – Tunnel convergence



TM – A=0 (only thermal expansion)

M (no thermal expansion)

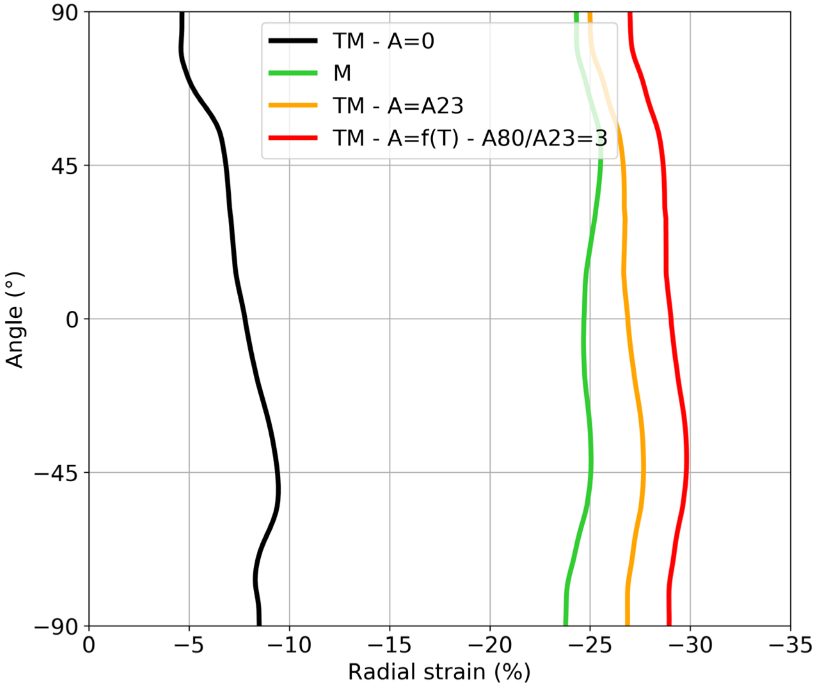
TM – A=A23
M + thermal expansion

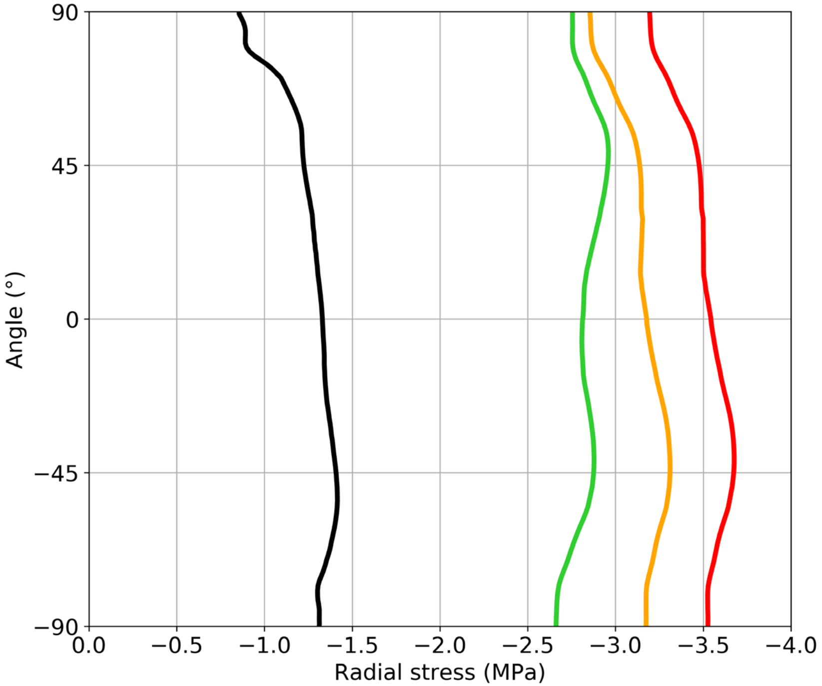
TM – A=f(T)

CH > CV

- Anisotropy in tunnel convergences is mainly due to the excavation process and the generation of the EDZ
- Increase of displacement over the long term is mainly isotropic (thermal and creep properties of the EDZ are equal to those of the intact rock

Thermal-mechanical modelling – Compressible material



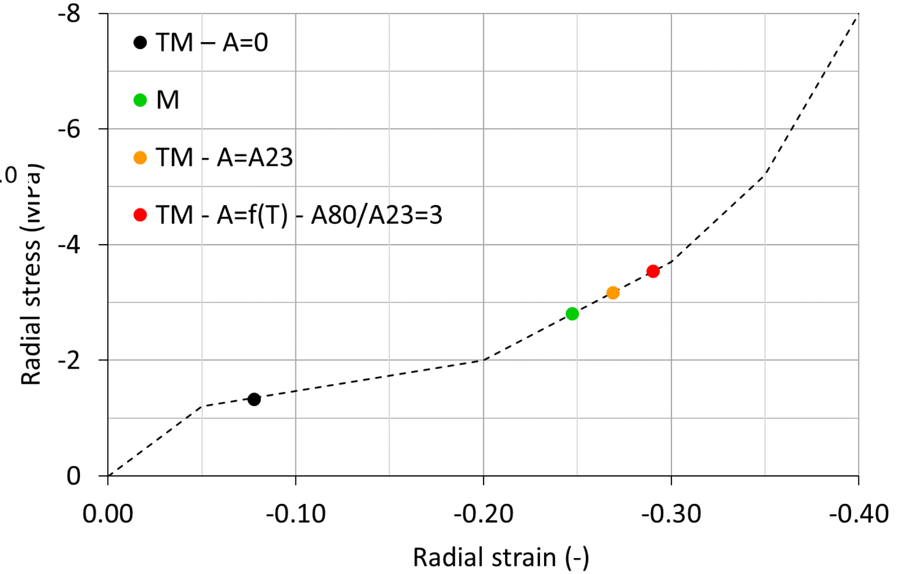


TM – A=0

M

TM – A=f(23°C)

TM – A=f(T)



Radial strains and stresses, 100 years after waste disposal

Isotropic distribution of stresses and strain along the tunnel boundary

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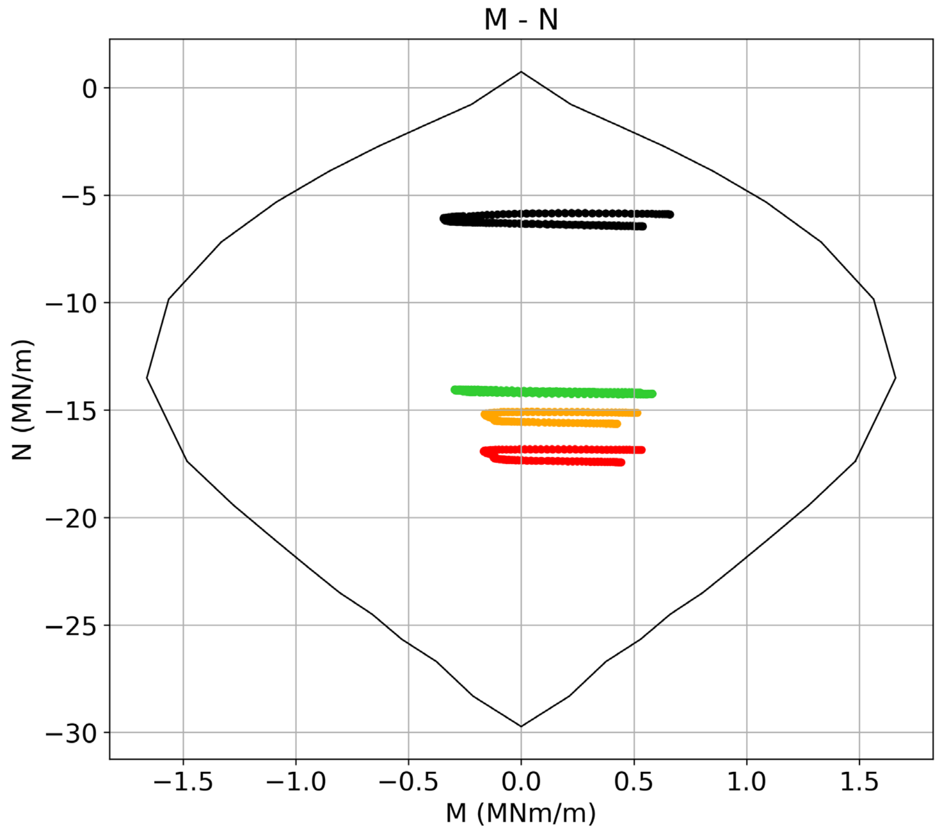
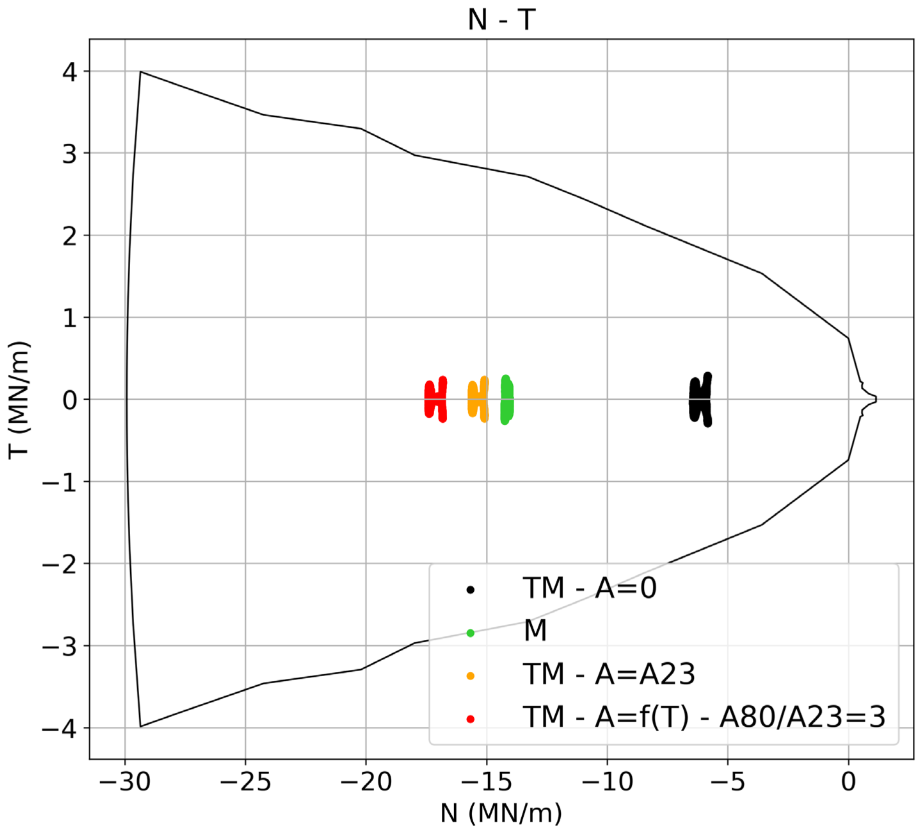
Thermal-mechanical modelling – Lining stress resultants





f_{ck} = 60MPa

Conclusions

Conclusions

- *FLAC3D* thermo-mechanical analyses have been performed for the design of CIGEO disposal tunnels with exothermic waste canisters

- Following previous work by Saitta et al, 2017 and based on extensive in situ observations, a simplified modelling of the rock mass around the drift has been accounted for, including:

  - A simple constitutive law (POWER-MOHR), based on a Mohr-Coulomb criterion

  - An indirect modelling of the EDZ through a zone of weaker properties, whose size and orientation reproduce in situ measurements of the fractured mass

- Analysis of the effect of creep and thermal processes on drift behavior has shown that creep is the major phenomenon.

- When both thermal and creep processes are active, convergences and resultants become the highest and their values mainly depend on the evolution of the viscosity parameter with the temperature.

Thank you for your attention