Geotechnical and Environmental Coupled Models Involving Unsaturated Soils and Rocks
CODE_BRIGHT-GiD

Part I Description

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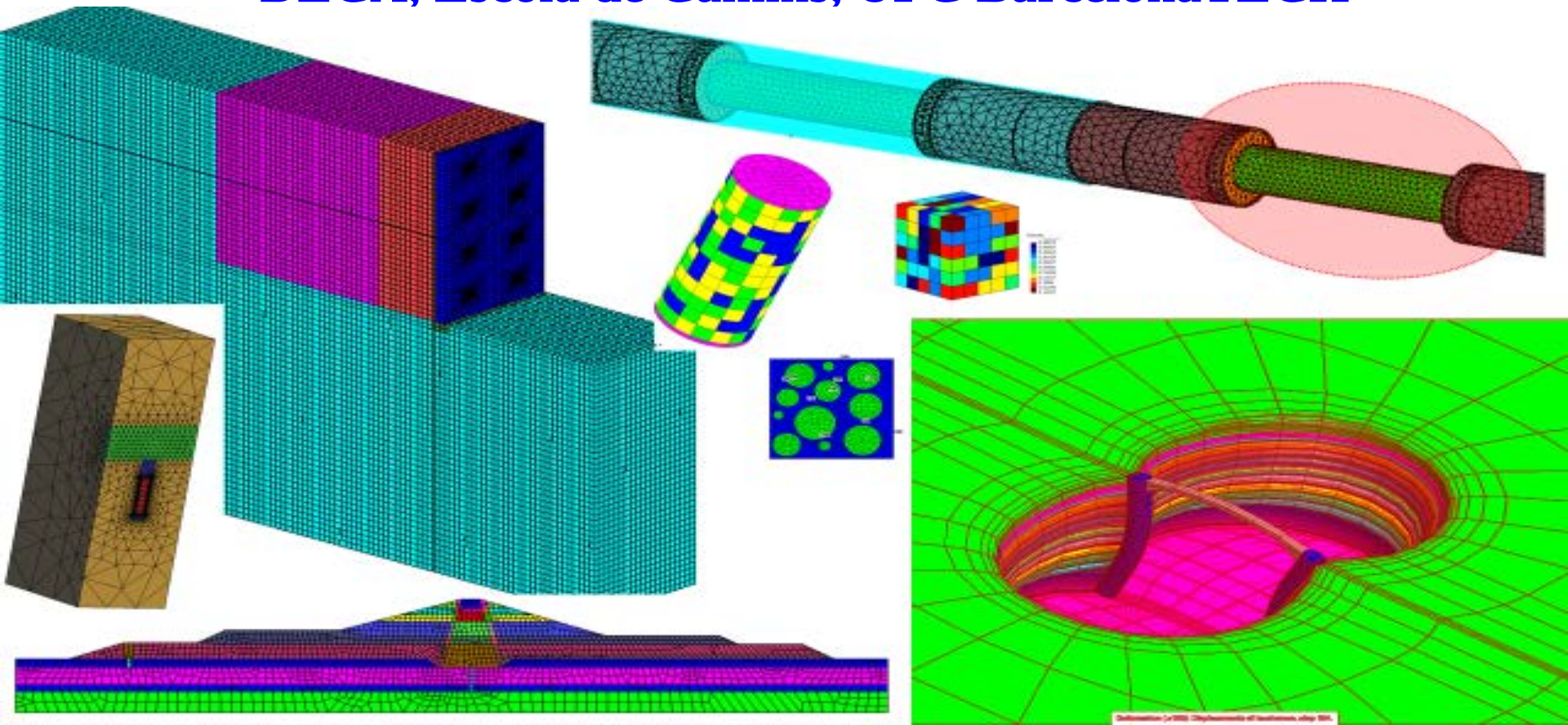
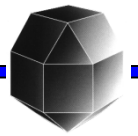


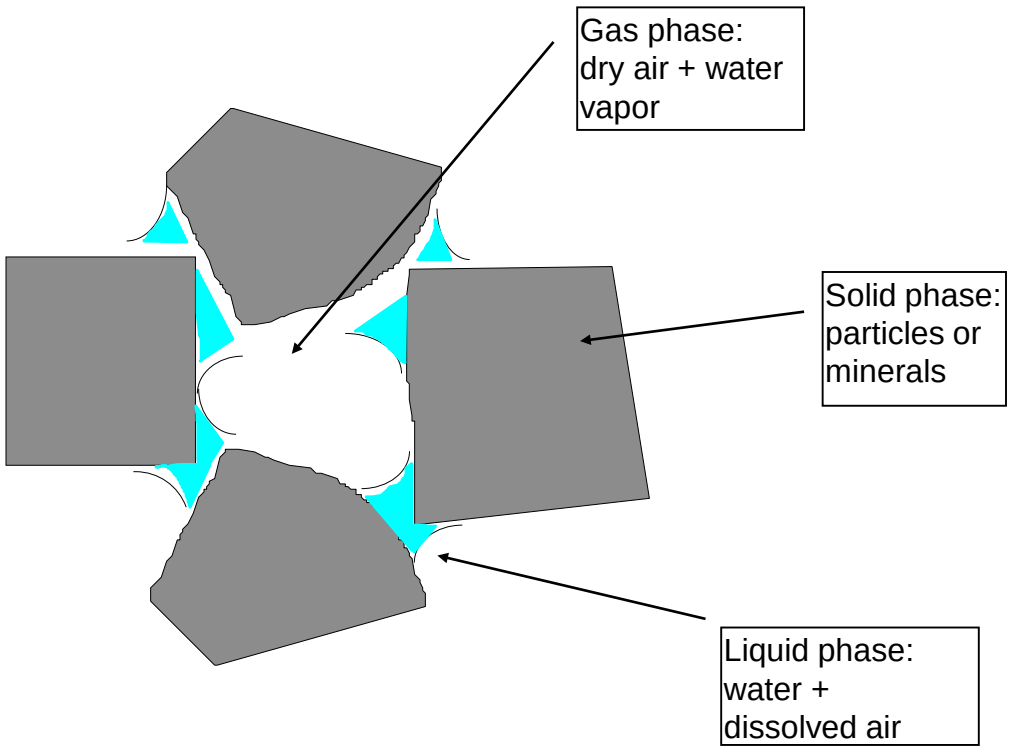
Topics



- Unsaturated soils
- Multiphase flow
- Coupled problems THMC
- Laboratory investigation
- Laboratory equipment development
- Finite elements
- Material point method
- ...

- Earth dams
- Slope stability
- Tunnels
- Foundations
- Underground waste storage
- Geothermal energy
- Off shore
- CO2 sequestration
- ...

BASIC FORMULATION



The three phases are:

- solid phase (***s***) :mineral
- liquid phase (***l***) :water + air dissolved
- gas phase (***g***) :mixture of dry air and water vapour

The three species are:

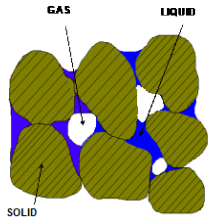
- Solid (-): the mineral is coincident with solid phase
- Water (*w*):as liquid or evaporated in the gas phase
- Air (*a*) :dry air, as gas or dissolved in the liquid phase

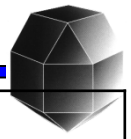
The basic formulation is presented here. Variants are related to CO_2, solute transport, geochemistry, solubility, …

Notation example:

$$\omega_g^w \rho_g S_g$$

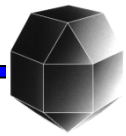
BALANCE EQUATIONS





MASS BALANCE OF WATER	
$\frac{\partial\left(\left(\omega_g^w \rho_g S_g + \omega_l^w \rho_l S_l\right)\phi\right)}{\partial t} + \nabla \cdot \left(\mathbf{j}_g^w + \mathbf{j}_l^w\right) = f^w$	**Unknown: P_l**
MASS BALANCE OF AIR	
$\frac{\partial\left(\left(\omega_g^a \rho_g S_g + \omega_l^a \rho_l S_l\right)\phi\right)}{\partial t} + \nabla \cdot \left(\mathbf{j}_g^a + \mathbf{j}_l^a\right) = f^a$	**Unknown: P_g**
INTERNAL ENERGY BALANCE FOR THE MEDIUM	
$\frac{\partial\left(e_s\rho_s(1-\phi) + e_g\rho_g S_g\phi + e_l\rho_l S_l\phi\right)}{\partial t} - \frac{\phi S_g p_g}{\rho_g}\frac{\partial \rho_g}{\partial t} + \nabla \cdot \left(\mathbf{i}_c + \mathbf{j}_{es} + \mathbf{j}_{eg} + \mathbf{j}_{el}\right) = f^E$	**Unknown: T**
MASS BALANCE OF SPECIES (SOLUTE TRANSPORT)	
$\frac{\partial\left(\left(\omega_g^c \rho_g S_g + \omega_l^c \rho_l S_l\right)\phi\right)}{\partial t} + \nabla \cdot \left(\mathbf{j}_g^c + \mathbf{j}_l^c\right) = f^c$	**Unknown: c**
MOMENTUM BALANCE FOR THE MEDIUM	
$\nabla \cdot \boldsymbol{\sigma} + \mathbf{b} = \mathbf{0}$	**Unknown: u**

Constitutive equations and equilibrium restrictions



Ideal gas

$$\rho_l = \rho_{l0}\exp(\beta(P_l - P_{lo}) + \alpha(T - T_o))$$

$$\rho_g = \rho_v + \rho_a = \frac{P_v M_v}{R(T+273.15)} + \frac{P_a M_a}{R(T+273.15)}$$

$$P_v(T,P_c) = P_v(T)\times F(P_c,T)$$

$$P_v(T) = 136075\exp\left(\frac{-5239.7}{273+T}\right)$$

$$F(P_c,T) = \exp\left(\frac{-P_c M_w}{R(273+T)\rho_l}\right)$$

Fourier

$$\mathbf{i}_c = -\lambda\nabla T$$

$$\lambda = \lambda_{sat}^{S_l}\lambda_{dry}^{(1-S_l)}$$

$$\lambda_{sat} = \lambda_{solid}^{(1-\phi)}\lambda_{liq}^{\phi}$$

$$\lambda_{dry} = \lambda_{solid}^{(1-\phi)}\lambda_{gas}^{\phi}$$

Fick

$$\mathbf{i}_\alpha^i = -\left(\phi\rho_\alpha S_\alpha \tau D_m^i \mathbf{I}\right)\nabla\omega_\alpha^i$$

$$\mathbf{i}_\alpha^i = -\left(\rho_\alpha \mathbf{D'}_\alpha\right)\nabla\omega_\alpha^i$$

$$\mathbf{D'}_\alpha = d_t|\mathbf{q}_\alpha|\mathbf{I} + (d_l - d_t)\frac{\mathbf{q}_\alpha\mathbf{q}_\alpha^t}{|\mathbf{q}_\alpha|}$$

Mechanical

van Genuchten

$$S_e = \frac{S_l - S_{\min}}{S_{\max} - S_{\min}} = \left(1+\left(\frac{P_g - P_l}{P}\right)^{1/(1-\lambda)}\right)^{-\lambda}$$

Darcy

$$\mathbf{q}_\alpha = -\frac{\mathbf{k}k_{r\alpha}}{\mu_\alpha}\left(\nabla P_\alpha - \rho_\alpha \mathbf{g}\right)$$

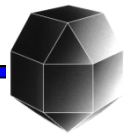
$$\mathbf{k} = \mathbf{k}_o\frac{\phi^3}{(1-\phi)^2}\frac{(1-\phi_o)^2}{\phi_o^3}$$

$$k_{rl} = \sqrt{S_e}\left(1-\left(1-S_e^{1/\lambda}\right)^{\lambda}\right)^2$$

$$\mu_l = A\exp\left(\frac{B}{273.15+T}\right)$$

$$\mu_g = \frac{A\sqrt{273+T}}{\left(1+\frac{B}{273+T}\right)}\frac{1}{1+\frac{b_k}{P_g}}$$

Set of equations for mechanical models



VP-General

$$\frac{d\varepsilon}{dt} = \Gamma\left\langle \phi(F)\right\rangle \frac{\partial G}{\partial \sigma'} \qquad \phi(F) = \left(\frac{F}{F_o}\right)^N$$

$$F\left(J_1, J_{2D}, J_{3D}, s\right) = aJ_{2D} - \mu^2 F_b F_s$$

$$F_b = \gamma\left[-\left(J_1^0(s) + k_2 s + k_4\right)^{2-n}\left(J_1 + k_1 s + k_4\right)^n + \left(J_1 + k_1 s + k_4\right)^2 - k_3 s J_1^0(s)\right]$$

$$J_1^0(s) = 3p^c\left(\frac{J_1^{0*}}{3p^c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \qquad p_o(s) = J_1^0(s)/3$$

$$dJ_1^{0*} = \frac{1+e}{\left(\lambda(0)-\kappa\right)} J_1^{o*} d\varepsilon_v^{vp} \Leftrightarrow dp_o^* = \frac{1+e}{\left(\lambda(0)-\kappa\right)} p_o^* d\varepsilon_v^{vp} \Leftrightarrow \frac{dp_o^*}{p_o^*} = \frac{1+e}{\chi(0)} d\varepsilon_v^{vp}$$

creep

$$\frac{d\,\varepsilon^{FADT}}{dt} = \frac{1}{2\,\eta^d_{FADT}}(\sigma' - p'\mathrm{I}) + \frac{1}{3\,\eta^v_{FADT}} p'\,\mathrm{I} \qquad \frac{d\,\varepsilon^{DC}}{dt} = \frac{1}{\eta^d_{DC}}\Phi(F)\frac{\partial G}{\partial \sigma'}$$

BBM

$$d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}^e + d\boldsymbol{\varepsilon}^p = (\mathbf{D}^e)^{-1} d\boldsymbol{\sigma}' + \alpha \mathbf{I} ds + \Lambda \frac{\partial G}{\partial \boldsymbol{\sigma}'}$$

$$d\varepsilon_v^e = \frac{\kappa_i(s)}{1+e}\frac{dp'}{p'} + \frac{\kappa_s(p',s)}{1+e}\left(\frac{ds}{s+0.1}\right)$$

$$F = \frac{3J^2}{g_y^{\,2}} - L_y^{\,2}\left(p' + p_s\right)\left(p_o - p'\right) = 0$$

$$p_o = p^c\left(\frac{p_o^*(T)}{p^c}\right)^{\frac{\lambda(o)-kio}{\lambda(s)-kio}}$$

$$p_o^*(T) = p_o^* + 2(\alpha_1 \Delta T + \alpha_3 \Delta T\left|\Delta T\right|)$$

$$dp_o^* = \frac{1+e}{\lambda(0) - k_{io}} p_o^* d\varepsilon_v^p$$

argillite (damage and bonding)

$$d\sigma_{ij}^M = D_{ijkl}^{eM}\left(d\varepsilon_{kl}^M - \delta_{kl}\frac{ds}{K_s^M} - d\varepsilon_{kl}^p\right)$$

$$F^p = J^{M\,2} - \frac{M^{M\,2}}{3}\left(p^M + p_t^M\right)\left(p^M - p_0^M\right) \geq 0$$

$$F^p = \left(\cos\theta^M + \frac{1}{\sqrt{3}}\sin\theta^M \sin\phi'^M\right) J^M - \sin\phi'\left(p^M + p_t^M\right) \geq 0$$

$$d\sigma_{ij}^b = D_{ijkl}^{eb}\left(d\varepsilon_{kl}^b - d\varepsilon_{kl}^d\right) \qquad p_t^M = \frac{R_{c0}^M}{m^M}\left[1\text{-}(1-\alpha^M)\frac{\max(\varepsilon_1^{pM}, \xi_r^M)}{\xi_r^M}\right]^2$$

BExM

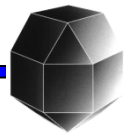
$$d\sigma_{ij} = D_{ijkl}^{Macro}\left(d\varepsilon_{kl}^{Macro} - \delta_{kl}\frac{ds^{Macro}}{3K_s^{Macro}} - d\varepsilon_{kl}^{LC} - d\varepsilon_{kl}^{SD} - d\varepsilon_{kl}^{SI}\right)$$

$$d\sigma_{ij} = D_{ijkl}^{micro}\left(d\varepsilon_{kl}^{micro} - \delta_{kl}\frac{ds^{micro}}{3K_s^{micro}}\right)$$

$$p_0 = p_c\left(\frac{p_0^*}{p_c}\right)^{\frac{\lambda(0)-\kappa^{Macro}}{\lambda(s)-\kappa^{Macro}}} \quad \text{with} \quad \lambda(s) = \lambda(0)\left[(1-r)e^{-\beta s} + r\right]$$

$$F^{SI} = p + s - \gamma^{SI} \qquad F^{LC} = J^2 - \frac{M^2}{3}\left(p + p_t\right)\left(p_0 - p\right) \leq 0 \qquad F^{SD} = \gamma^{SD} - p - s$$

NUMERICAL APPROACH, GENERAL COMMENTS



The system of PDE's (Partial Differential Equations) is solved numerically. The numerical approach can be viewed as divided into two parts: spatial and temporal discretizations.

Finite elements in space:

–Different types of elements available
–Element-wise, modified cell-wise and node-wise variables
–Secant method for non-advective terms (a)

Finite differences in time:

–Storage terms: mass conservative approach (secant) (b)
–Implicit scheme (intermediate times)
–Full Newton-Raphson method to solve nonlinearities
–Only first derivatives of nonlinear functions (due to a,b)

Solution of the linear system of equations:

–Iterative solver, sparse storage.

FINAL EQUATIONS FOR THM PROBLEMS

After the spatial discretization of the partial differential equations, the residuals that are obtained can be written (for one finite element) as:

$$\begin{pmatrix} \mathbf{r}_u \\ \mathbf{r}_{P_l} \\ \mathbf{r}_{P_g} \\ \mathbf{r}_T \end{pmatrix} = \frac{d}{dt}\begin{pmatrix} \mathbf{d}_u \\ \mathbf{d}_{P_l} \\ \mathbf{d}_{P_g} \\ \mathbf{d}_T \end{pmatrix} + \begin{pmatrix} \mathbf{a}_u \\ \mathbf{a}_{P_l} \\ \mathbf{a}_{P_g} \\ \mathbf{a}_T \end{pmatrix} + \begin{pmatrix} \mathbf{b}_u \\ \mathbf{b}_{P_l} \\ \mathbf{b}_{P_g} \\ \mathbf{b}_T \end{pmatrix} = \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \end{pmatrix}$$

where **r** are the residuals, *d***d**/*dt* are the storage or accumulation terms, a are the conductance terms, and b are the sink/source terms and boundary conditions.

After time discretization a more compact form can read as:

$$\mathbf{r}(\mathbf{X}^{k+1}) = \frac{\mathbf{d}^{k+1} - \mathbf{d}^{k}}{\Delta t^{k}} + \mathbf{A}(\mathbf{X}^{k+\varepsilon})\mathbf{X}^{k+\theta} + \mathbf{b}(\mathbf{X}^{k+\theta}) = \mathbf{0}$$

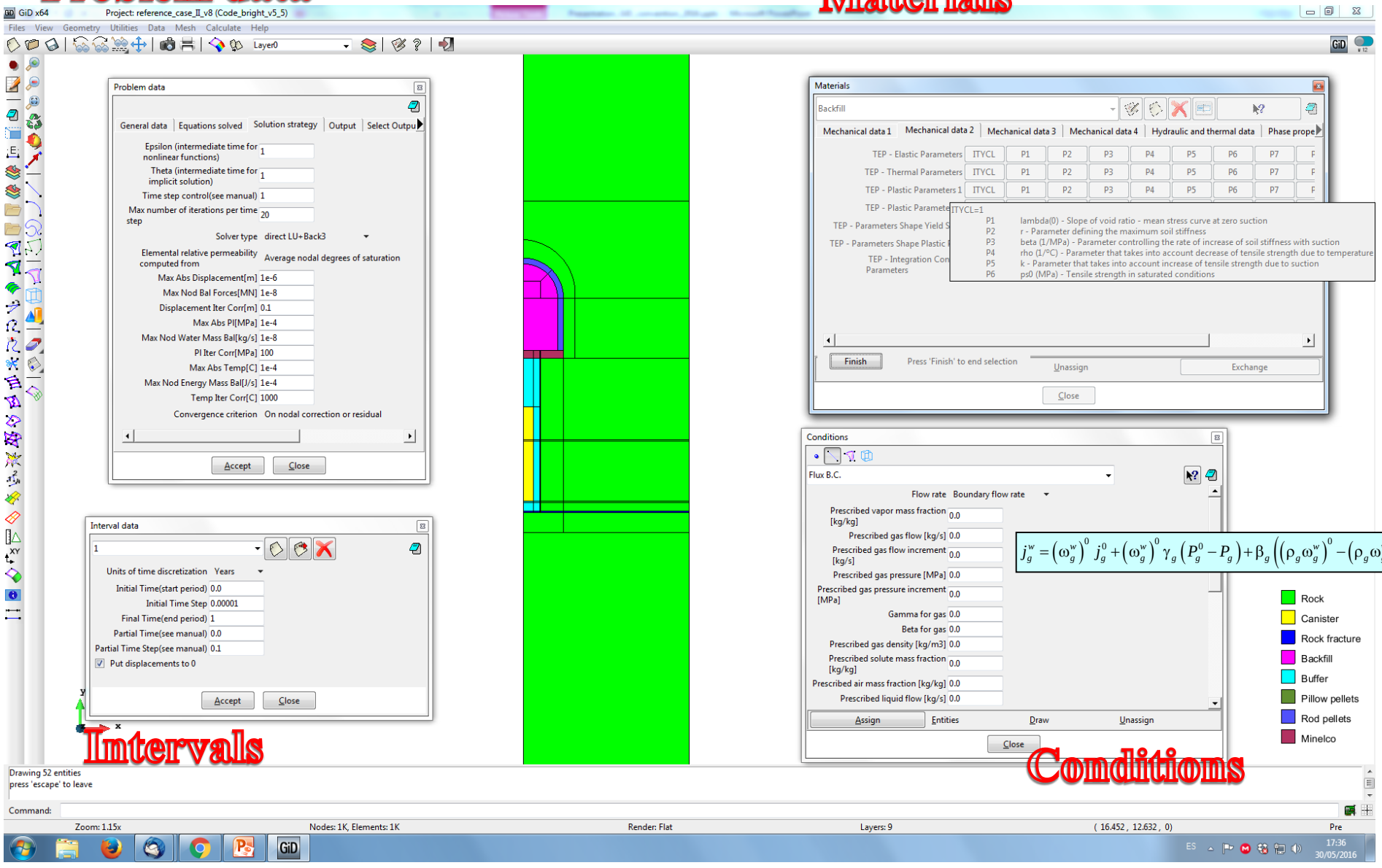
Newton-Raphson scheme:

$$\frac{\partial \mathbf{r}(\mathbf{X}^{k+1})}{\partial \mathbf{X}^{k+1}}(\mathbf{X}^{k+1,l+1} - \mathbf{X}^{k+1,l}) = -\mathbf{R}(\mathbf{X}^{k+1,l})$$

CODE_BRIGHT: Problem Type in GiD

Problem data

Materials

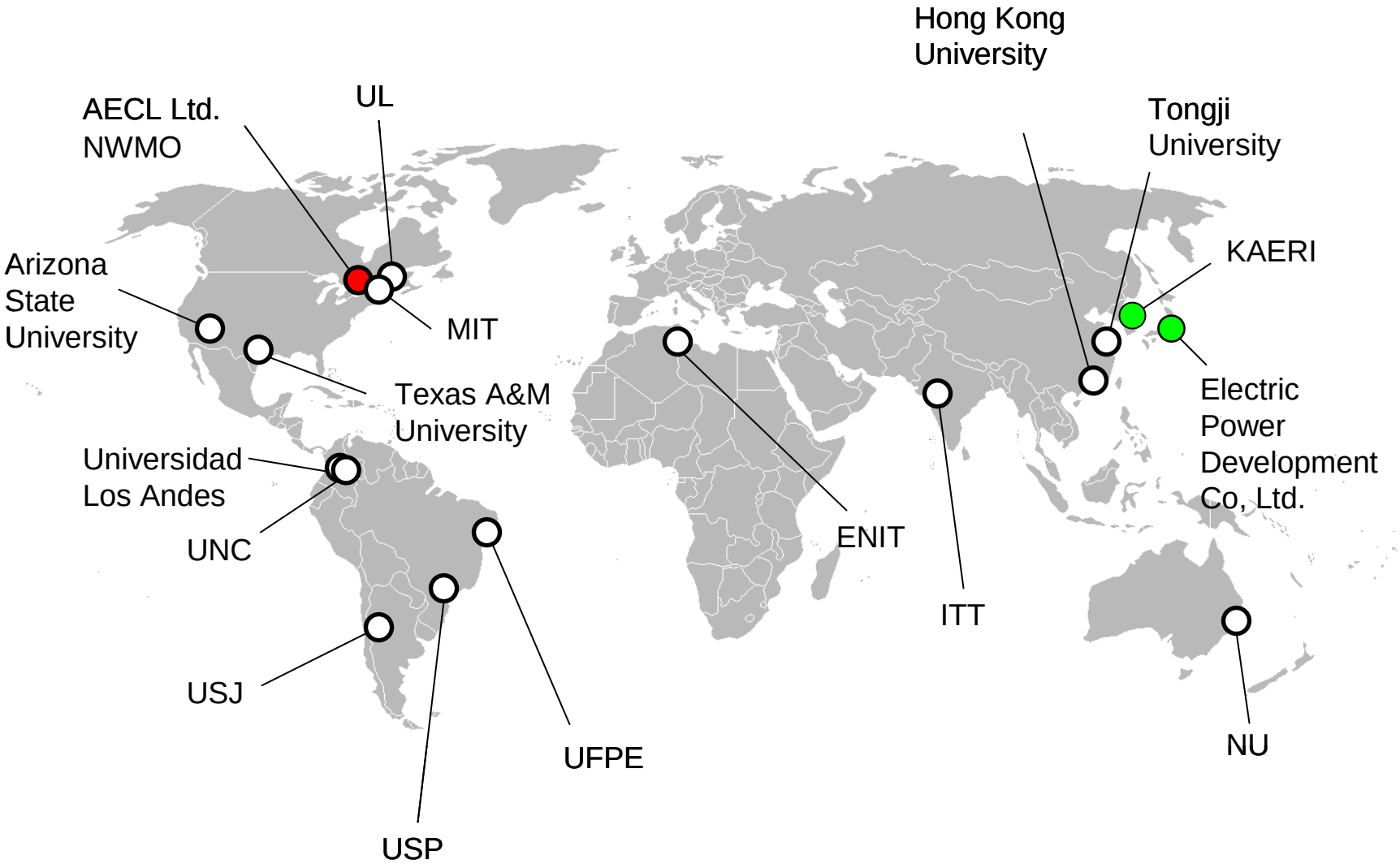


Intervals

Conditions

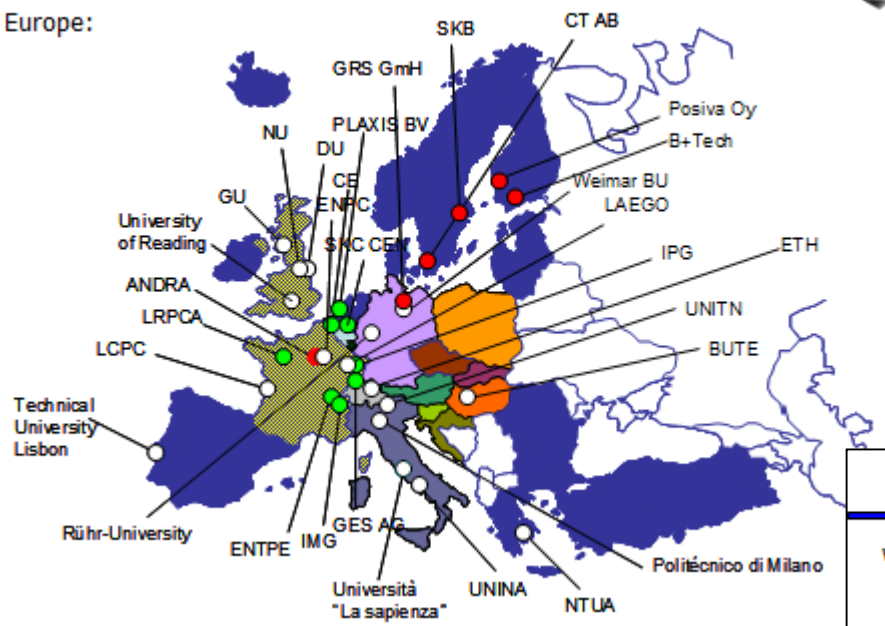
CODE_BRIGHT research collaborations

Worldwide:



CODE_BRIGHT research collaborations

Europe:

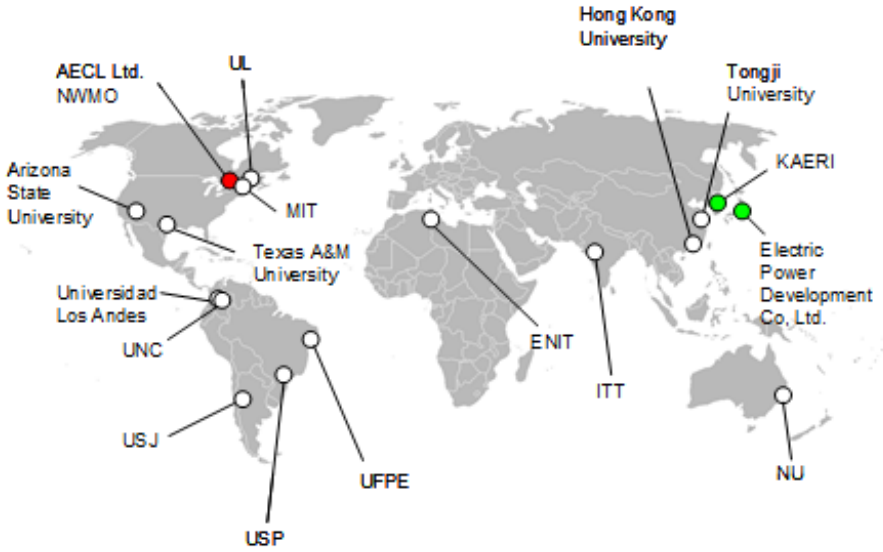


CONSORTIUM CODE_BRIGHT

SKB (SWEDEN) Coordination
POSIVA (FINLAND)
ANDRA (FRANCE)
GRS (GERMANY)

CODE_BRIGHT research collaborations

Worldwide:



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Code_Bright in social networks

Tutorials

- Tutorials in CB

Beginners

Detailed description of:
- Geometry; Boundary conditions
- Materials, Mesh, Post-process

Type of analysis: **Linear, uncoupled**

Examples:
- Foundation (**M** problem)
- Heat flow problem (**T** problem)
- Drainage around a trench (**H** problem)
- Conservative contaminant migration (**H-W** problem)
- Gas Injection Problem (**H** problem)
- CO2 injection in a sample and in an aquifer (**H** problem)

WE USE THEM AT BACHELOR AND MASTER SELECTED CLASSES

Advanced users

Basic description of:
- Geometry; Boundary conditions
- Materials, Mesh; Post-process

Type of analysis: **Non-linear, coupled**

Examples:
- Dam (**H-M** problem)
- Mock-up test (**T-H-M** problem)
- CO2 injection in an aquifer-caprock system (**H-M** problem)
- Sequential Excavation method (**H-M** problem)
- Consolidation of a porous medium with a vertical joint (**H-M** problem)
- Hydraulic shear test with a horizontal joint (**H-M** problem)
- BExM tutorial (**H-M** problem)
- Atmospheric tutorial (**T-H-M** problem)

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Part II APLICATIONS

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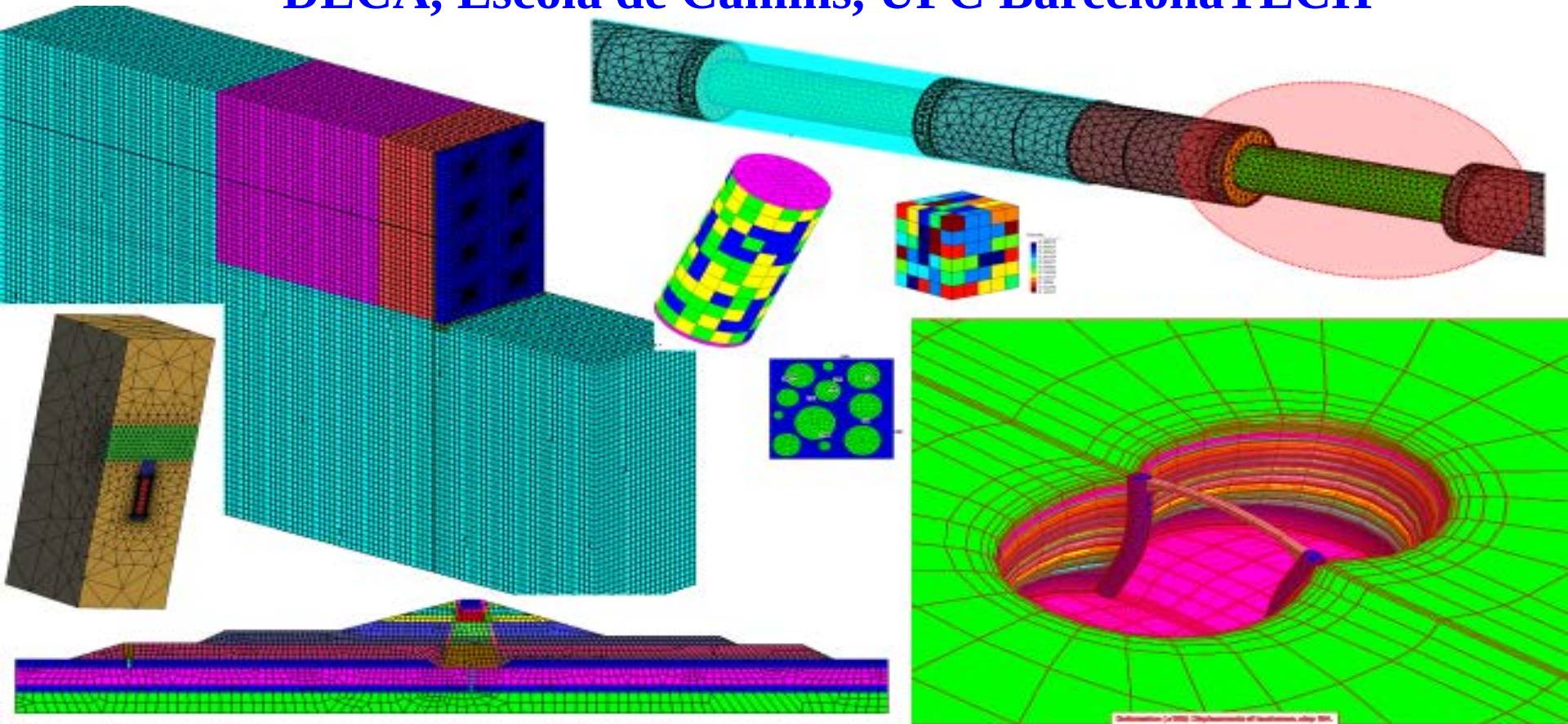
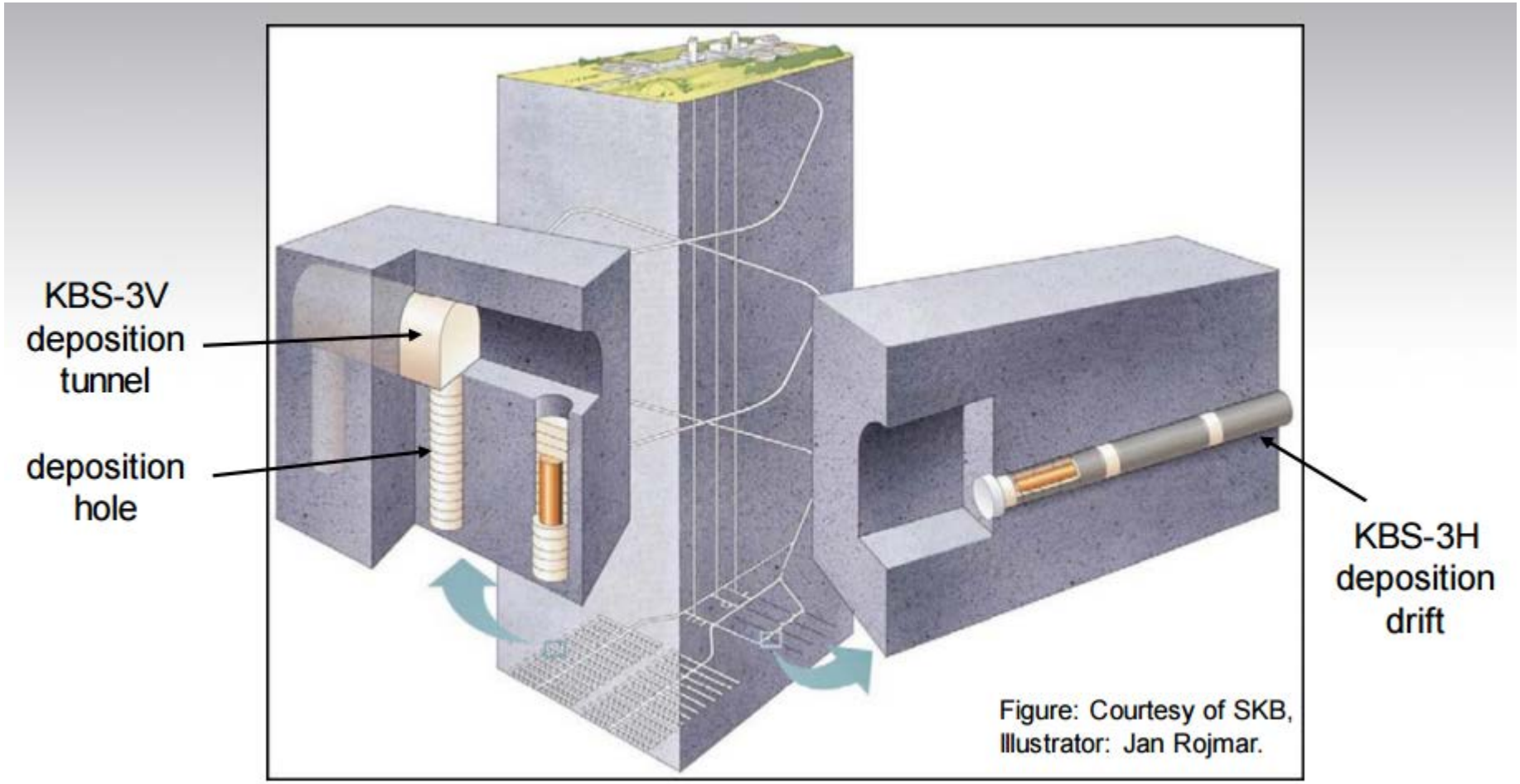
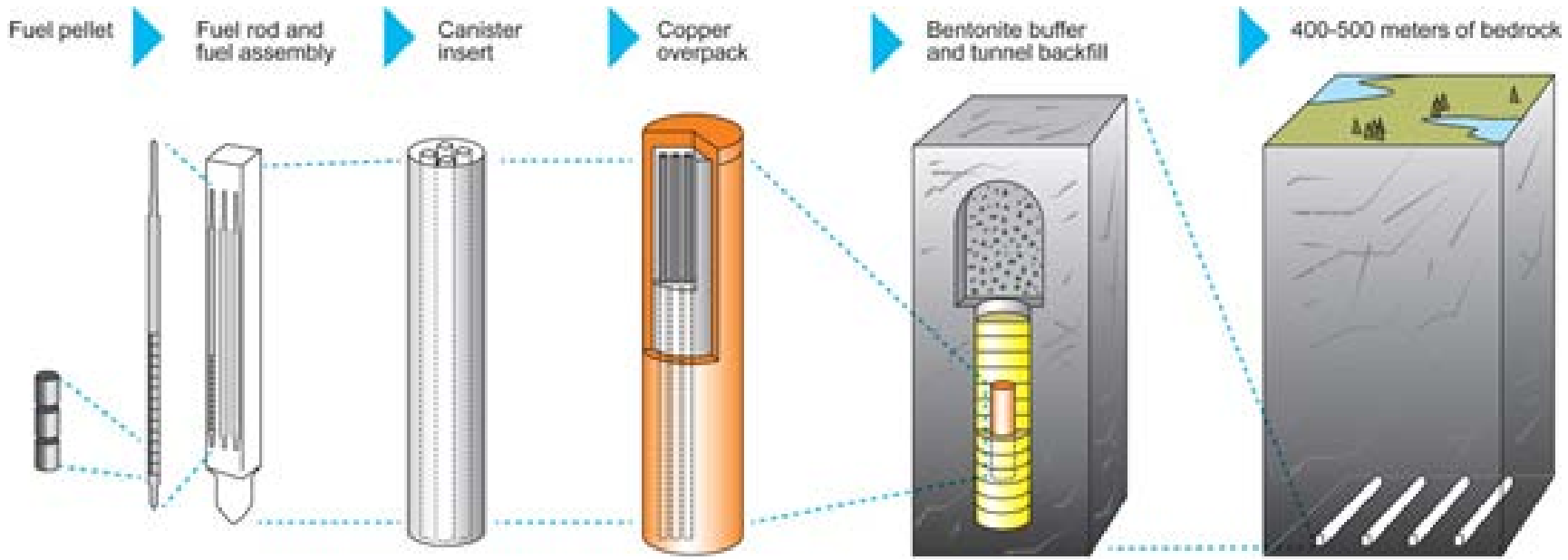


SPENT FUEL DISPOSAL

Project by POSIVA
Contract by Saanio and Riekkola Oy



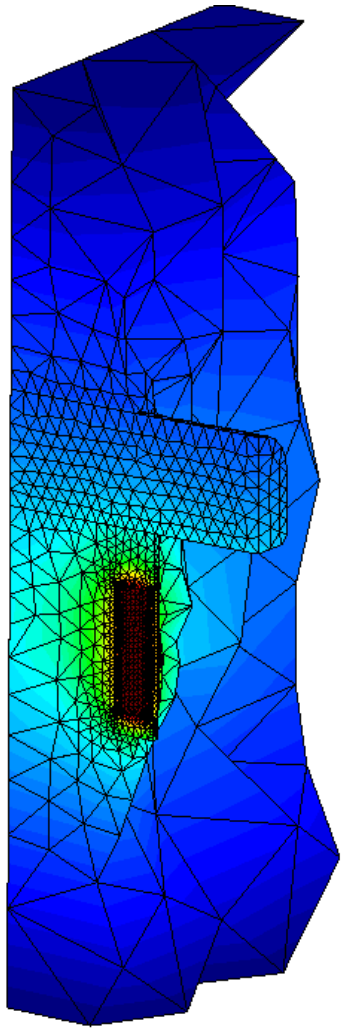
Vertical emplacement of spent fuel

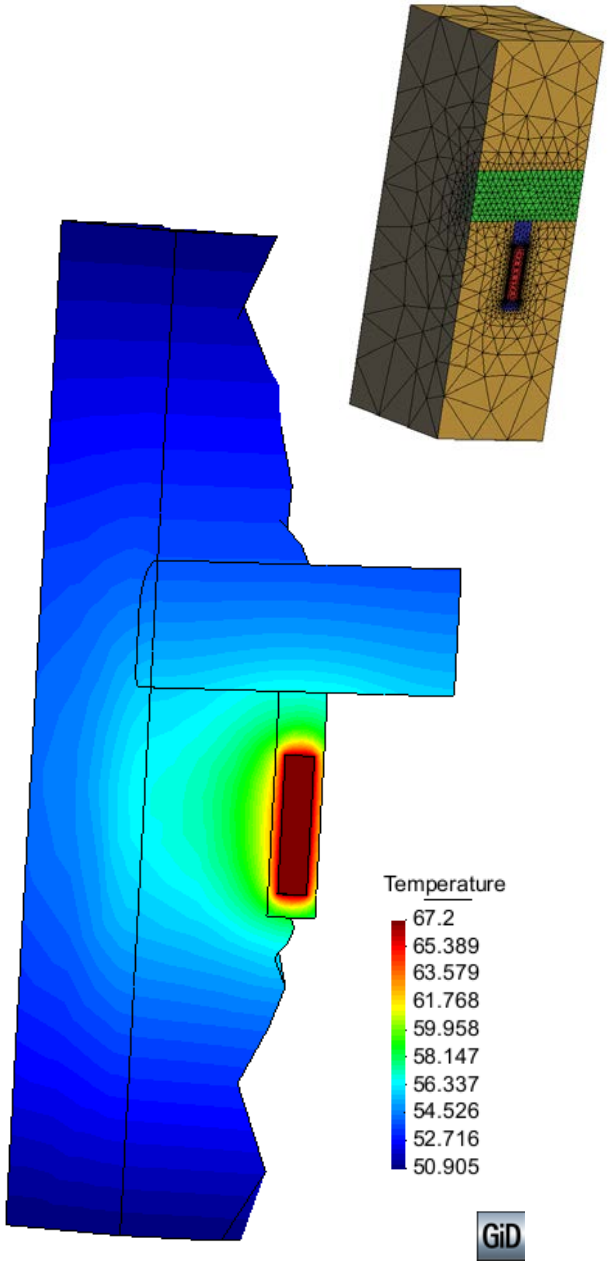


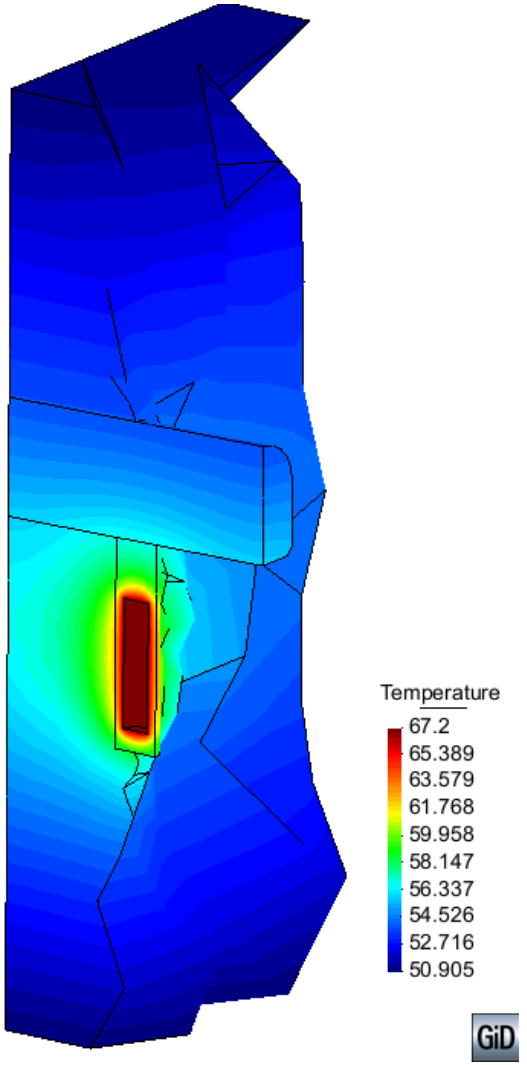
The spent nuclear fuel elements are disposed of in a repository located deep in the Olkiluoto bedrock. The release of radionuclides is prevented with a multi-barrier disposal system consisting of a system of engineered barriers (EBS) and host rock such that the system effectively isolates the radionuclides from the living environment.

THM applications

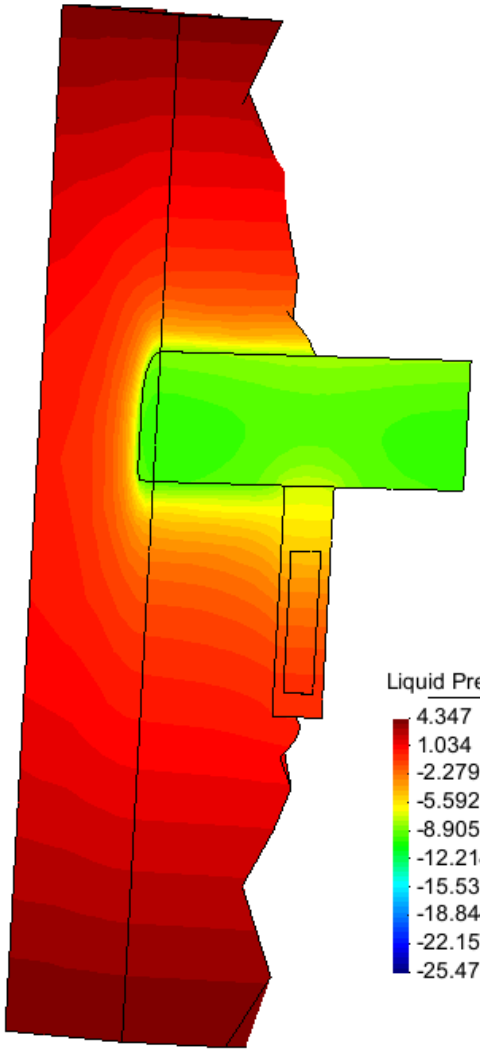
Erdem Toprak PhD
and related papers

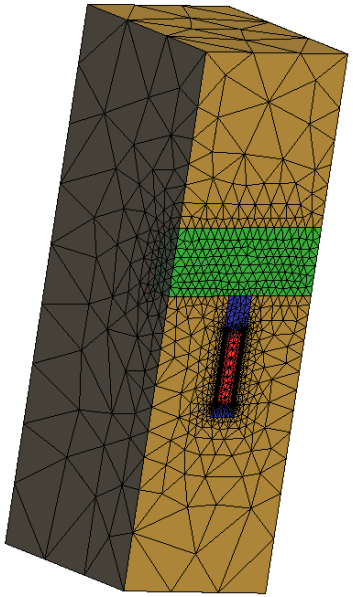


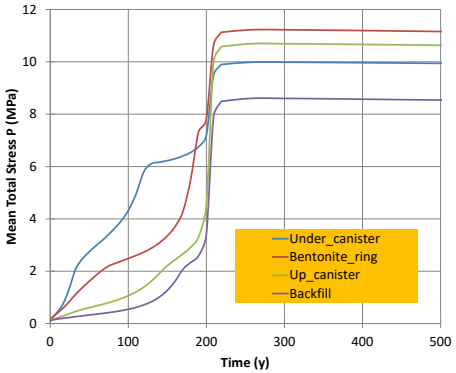


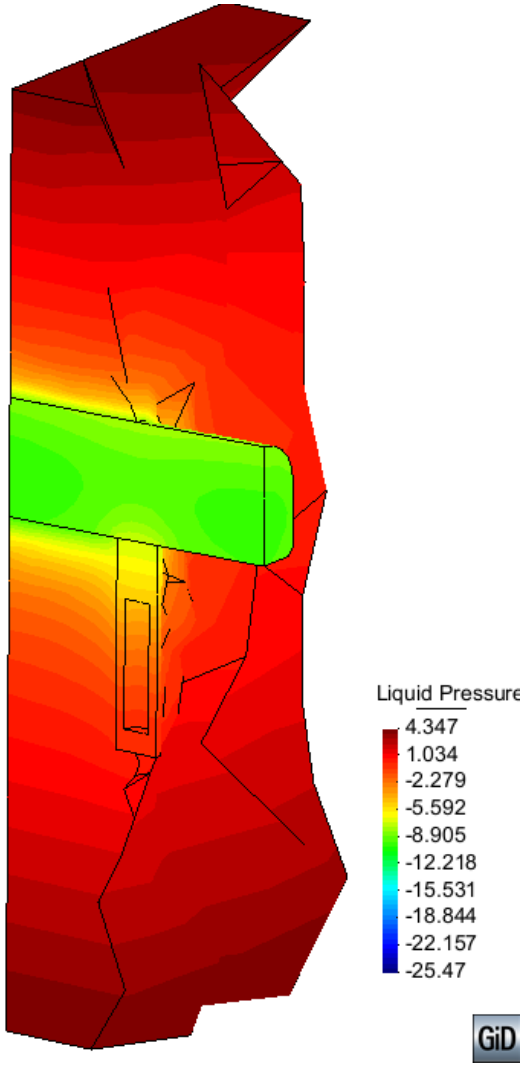


THM applications





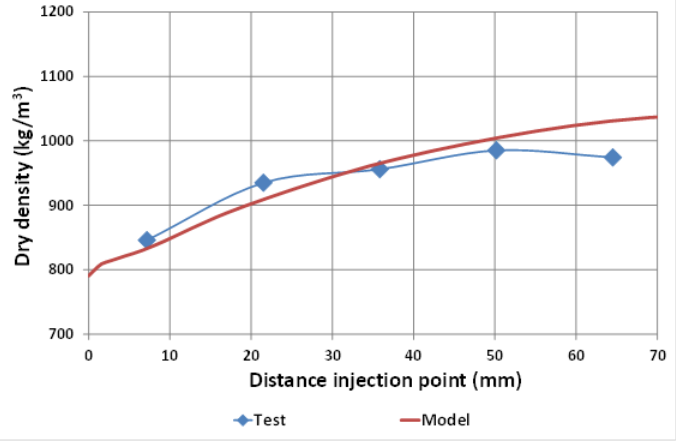


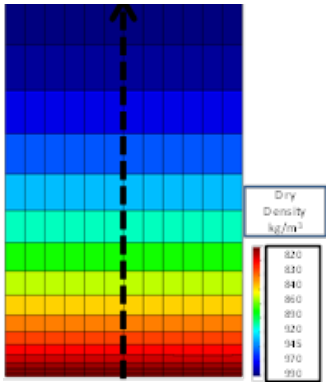


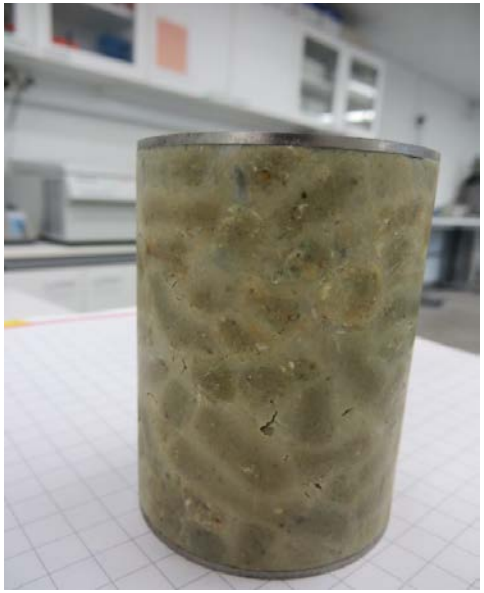
Buffer and backfill materials

Rod Pellets

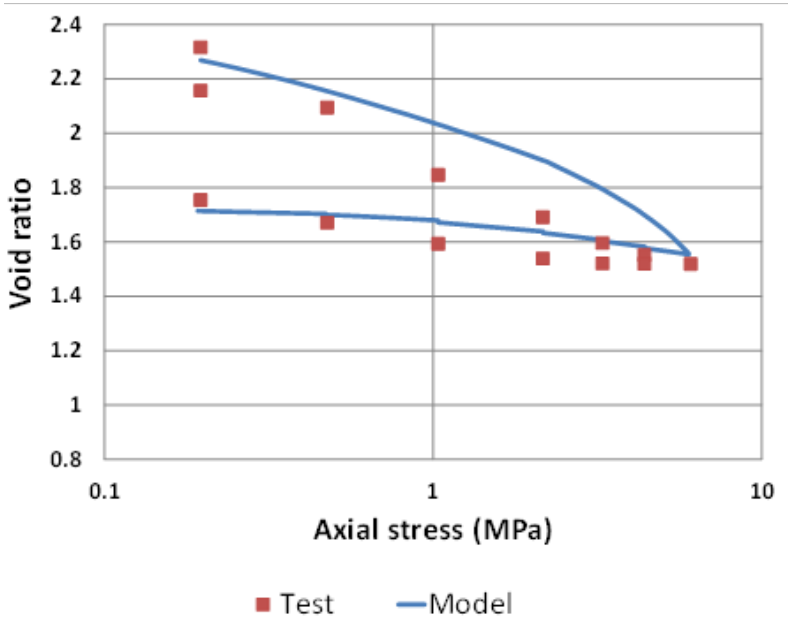
Infiltration

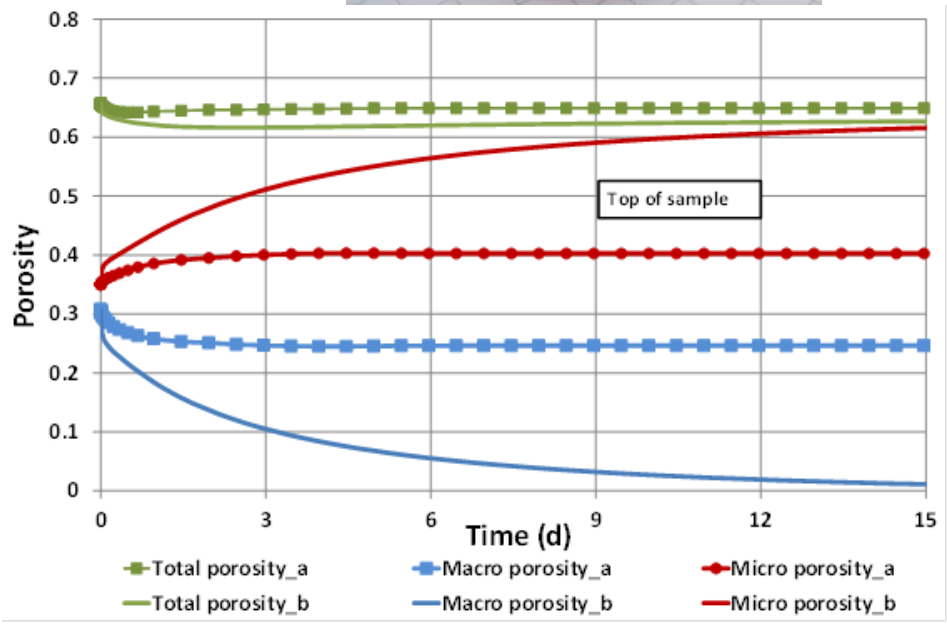




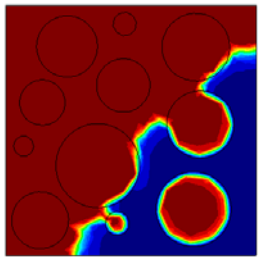


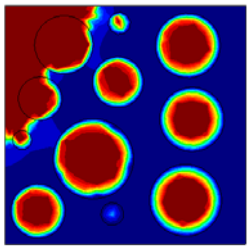
Oedometer Test

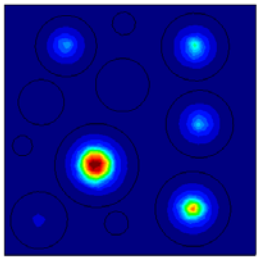


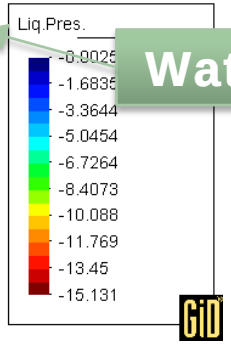


Interpretation of double structure by means of simple models

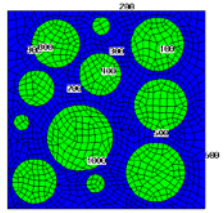


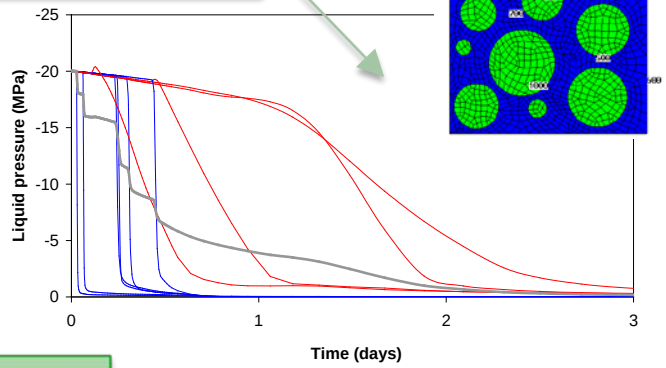


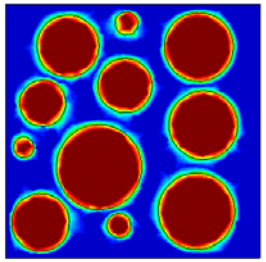


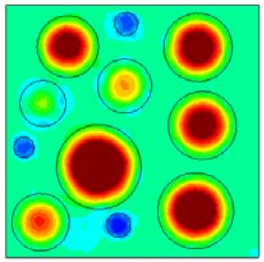


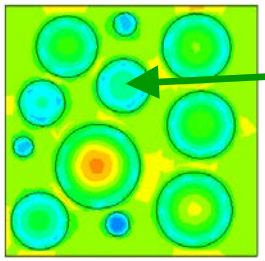
Water pressure

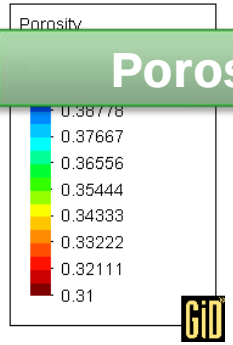




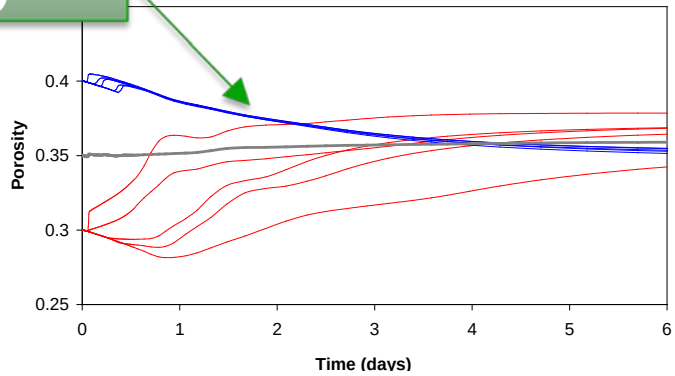


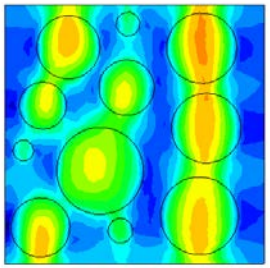


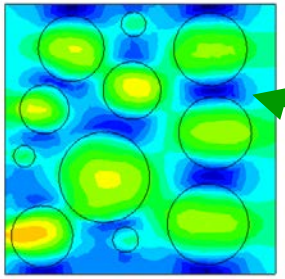


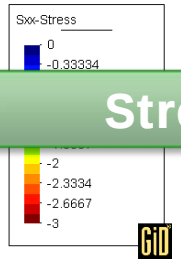


Porosity

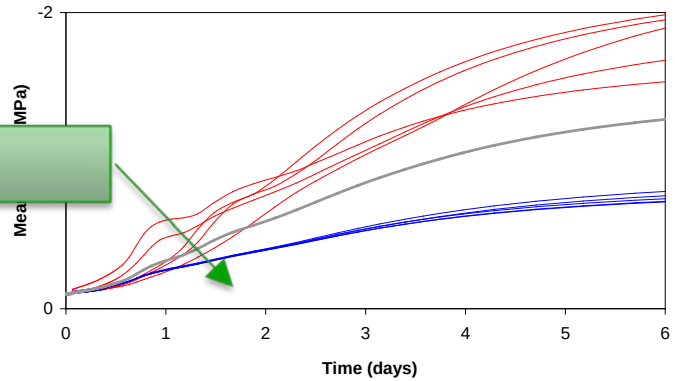




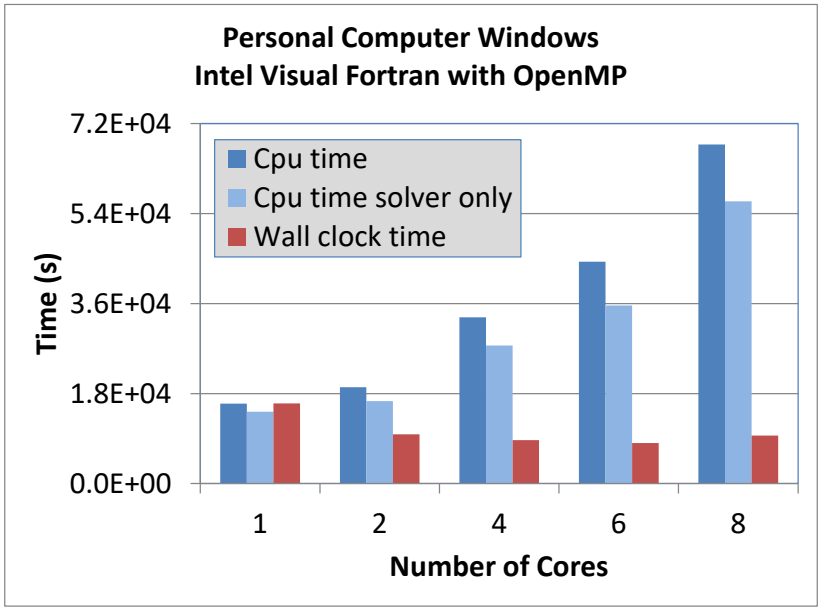


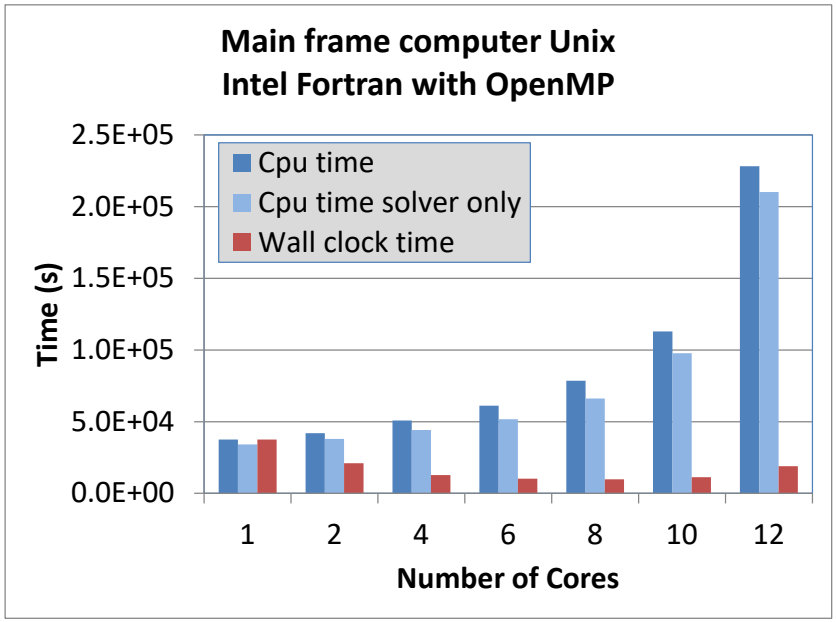


Stress

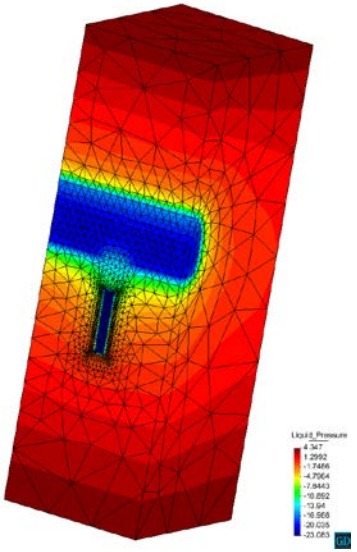


Windows environment – CPU time

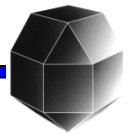




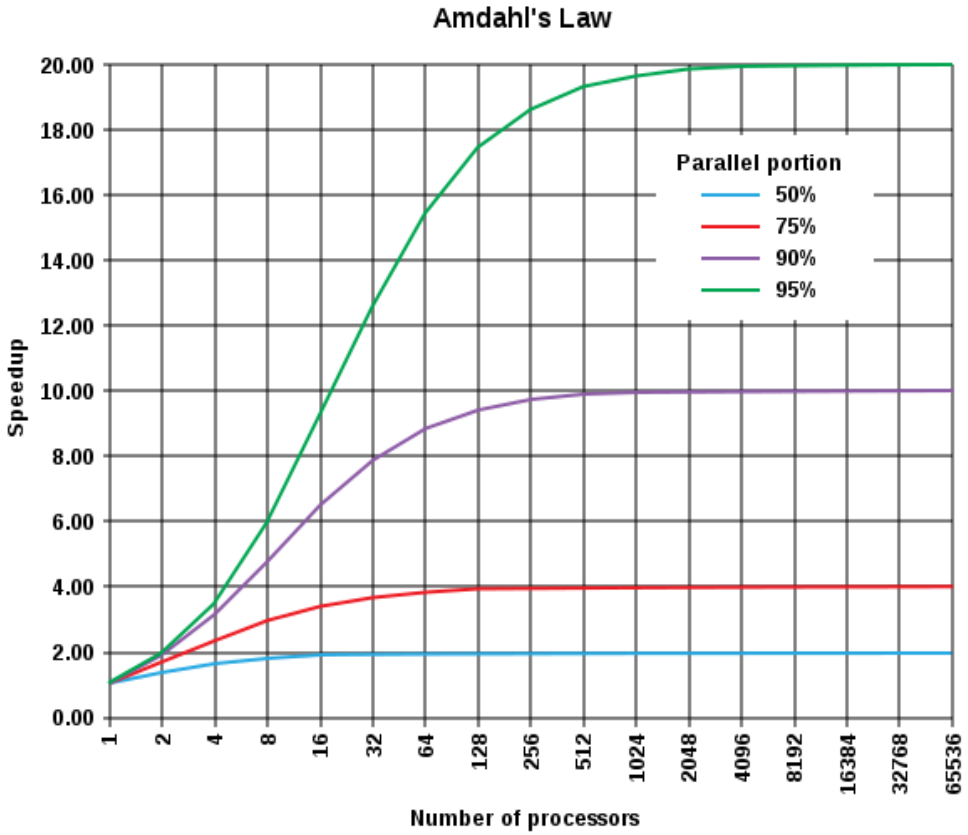
3D model
THM
(3982 x 5dof
= 19910 dof)



Concluding remarks

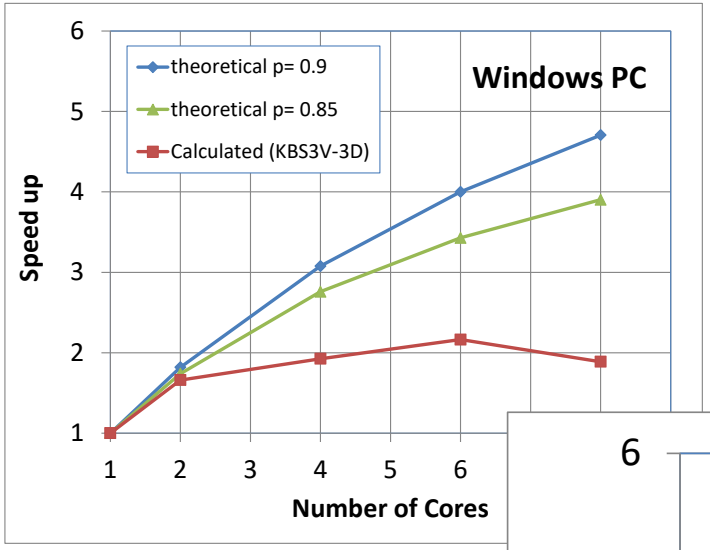


- This case uses ≅90% of CPU time for the solver. If the solver was fully parallelizable (90%), Speed up would be limited by 10
- Only matrix times vector operations have been parallelized.

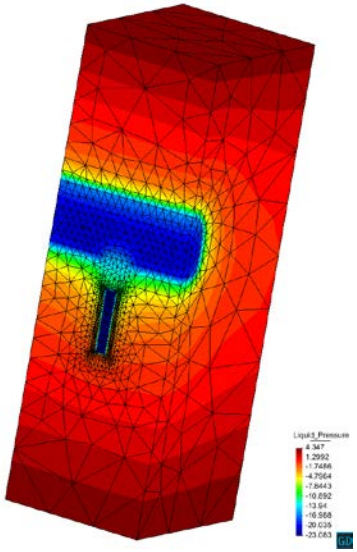


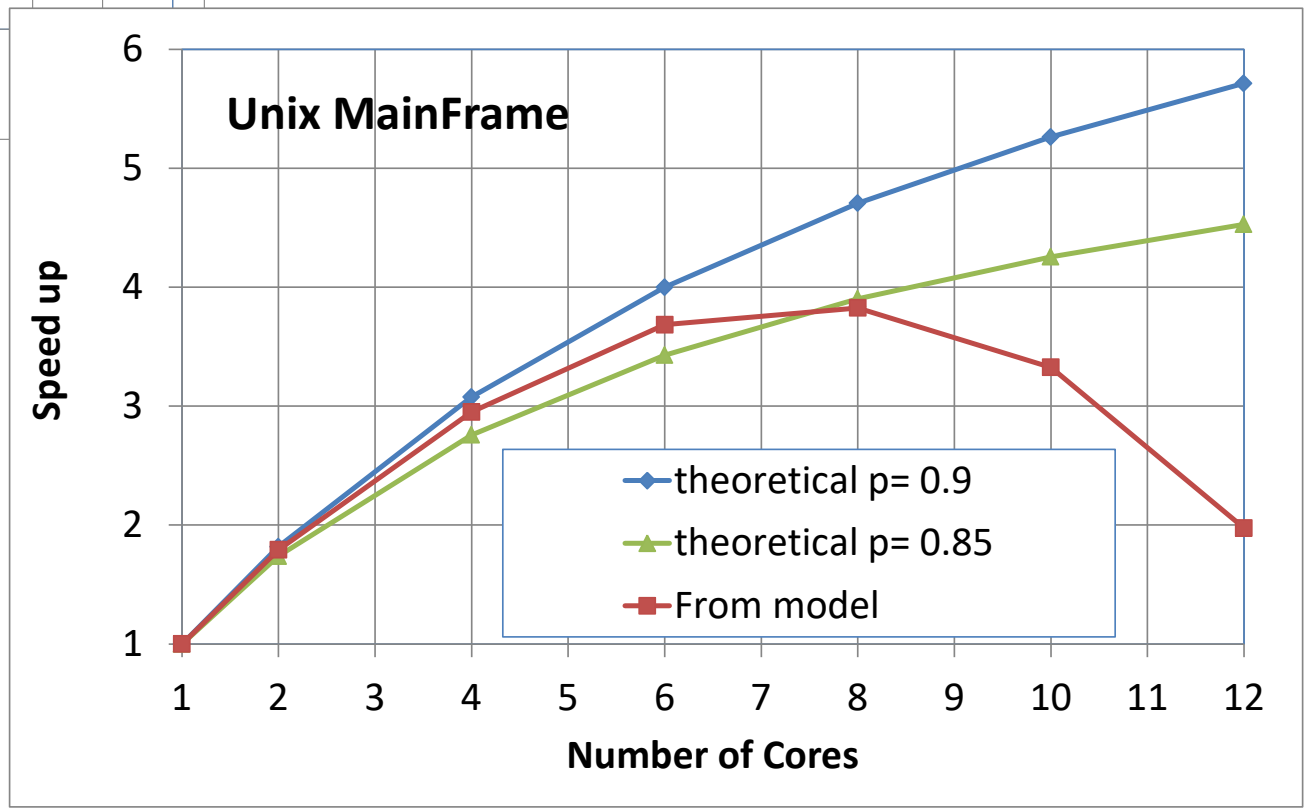
However:
Parallelized portion “p” is problem dependent
But:
It increases with problem size

Theoretical vs calculated speed up

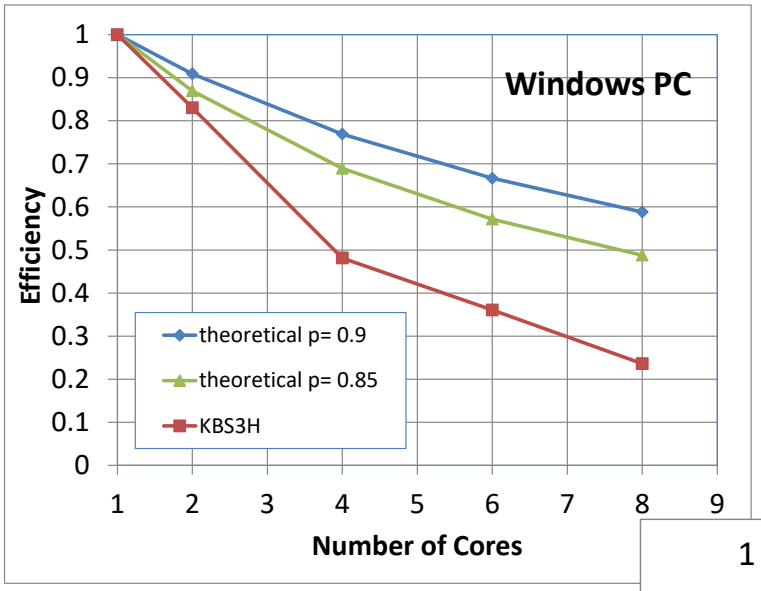


3D model THM (3982 x 5dof = 19910 dof)

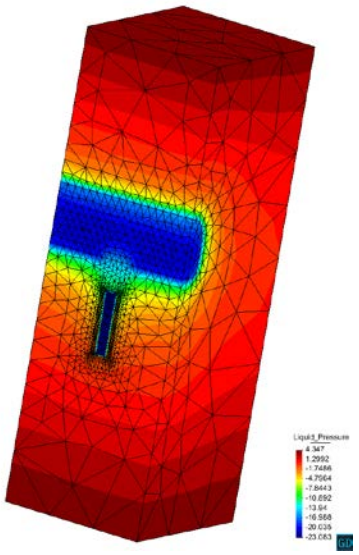


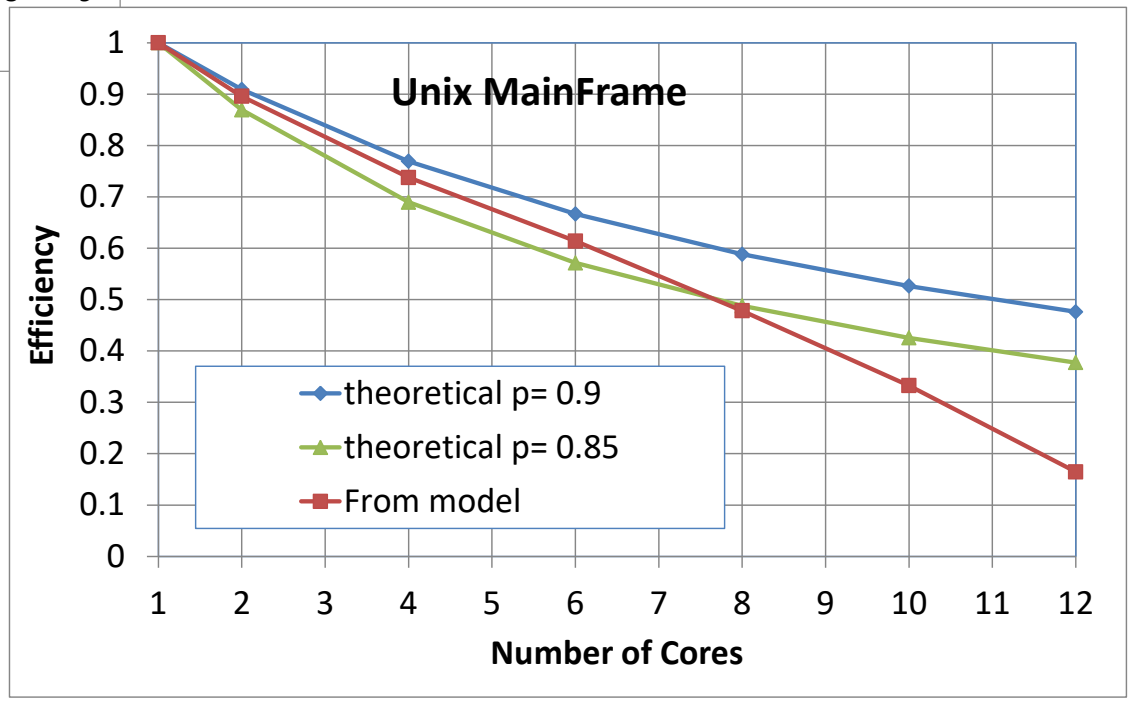


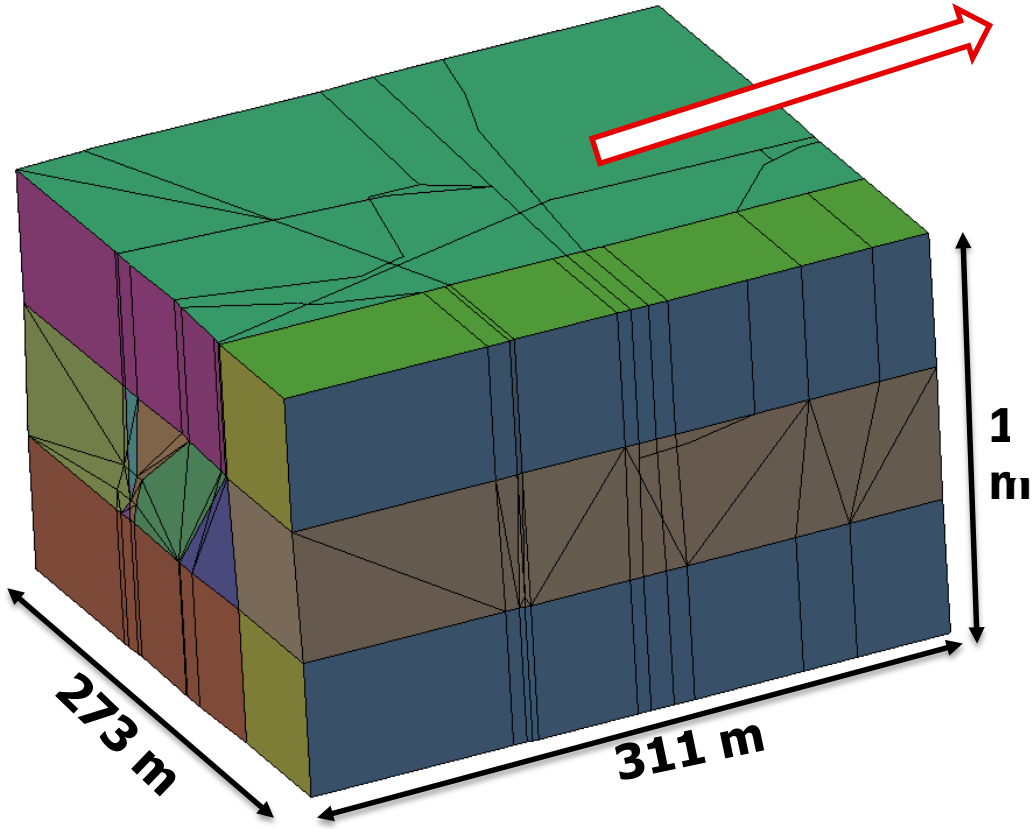
Theoretical vs calculated efficiency

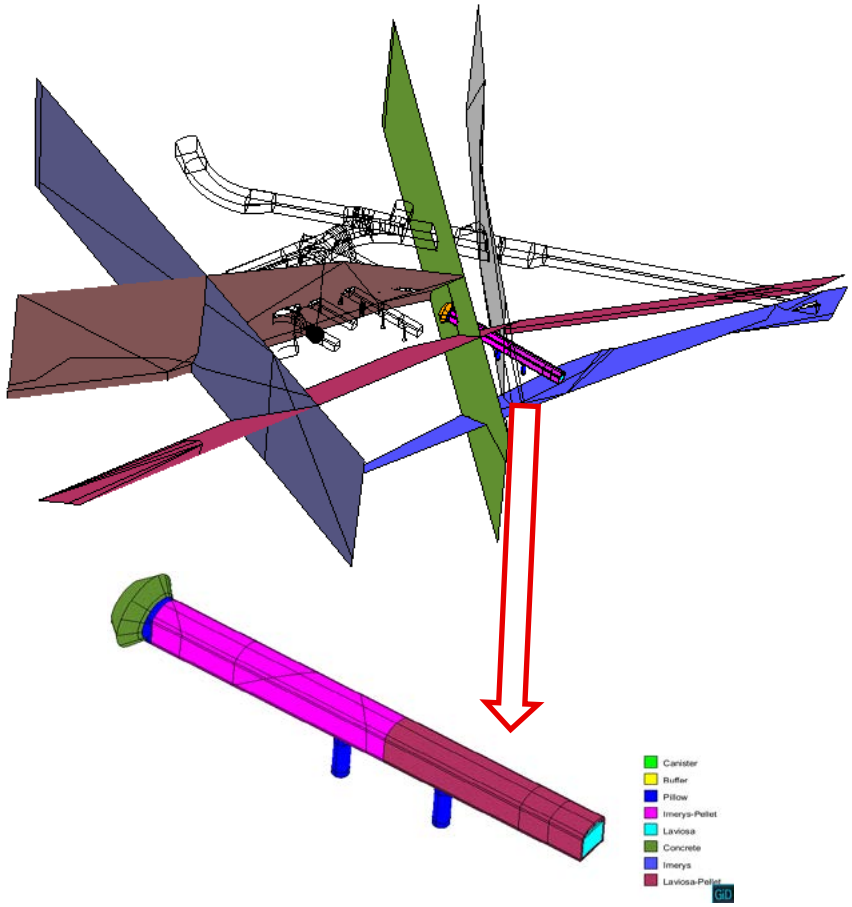


3D model THM (3982 x 5dof = 19910 dof)





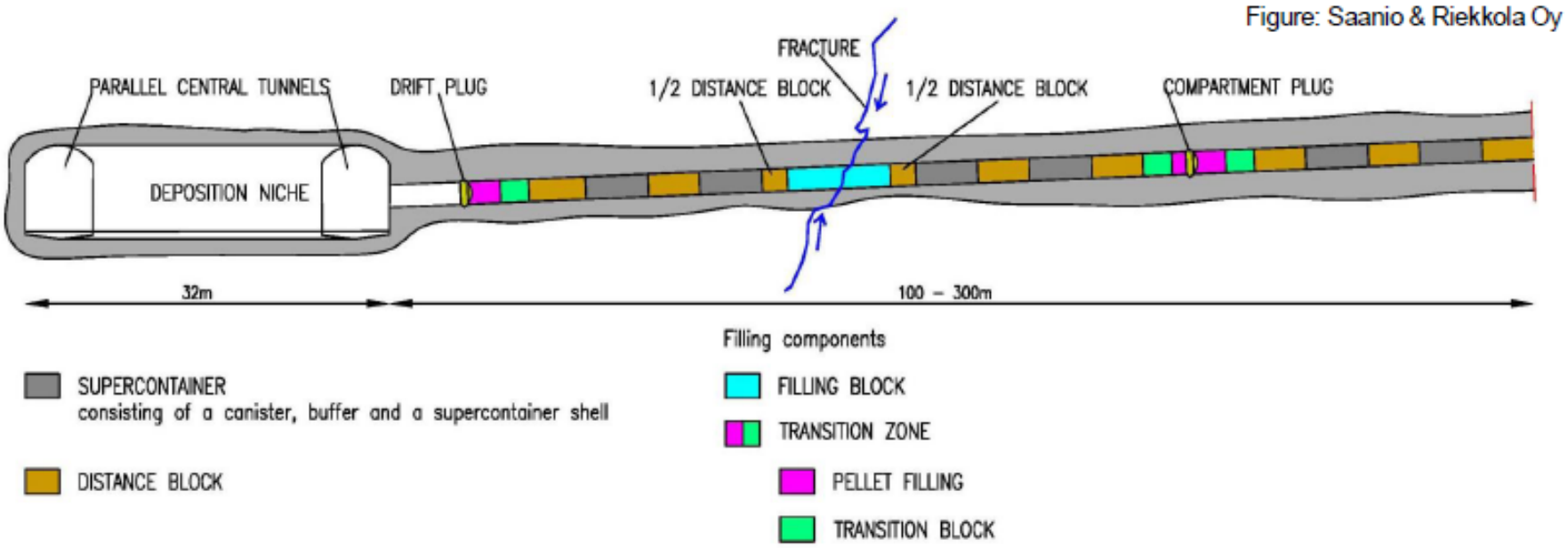




Fracture OL-BFZ084 V2
Fracture OL-BFZ346 (005) V2
Fracture OL-BFZ297
Fracture OL-BFZ300
Concrete
Concrete POPLU
Imerys
Laviosa-Pellet
Canister
Buffer
Pillow
Imerys-Pellet
Laviosa
Fracture OL-BFZ045
Fracture DSM-BFZ002

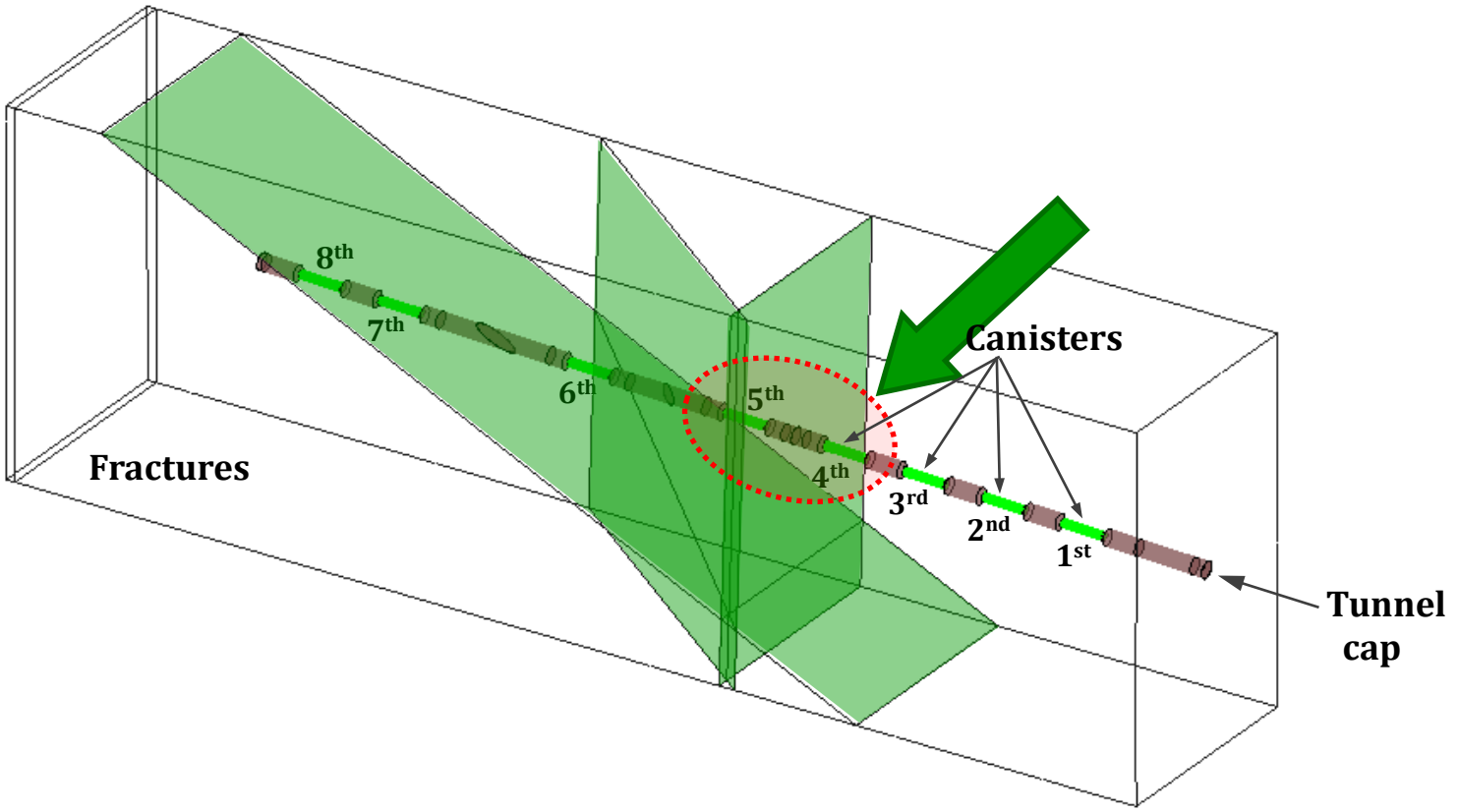
HORIZONTAL SPENT FUEL DISPOSAL

Project by POSIVA
Contract by Saanio and Riekkola Oy



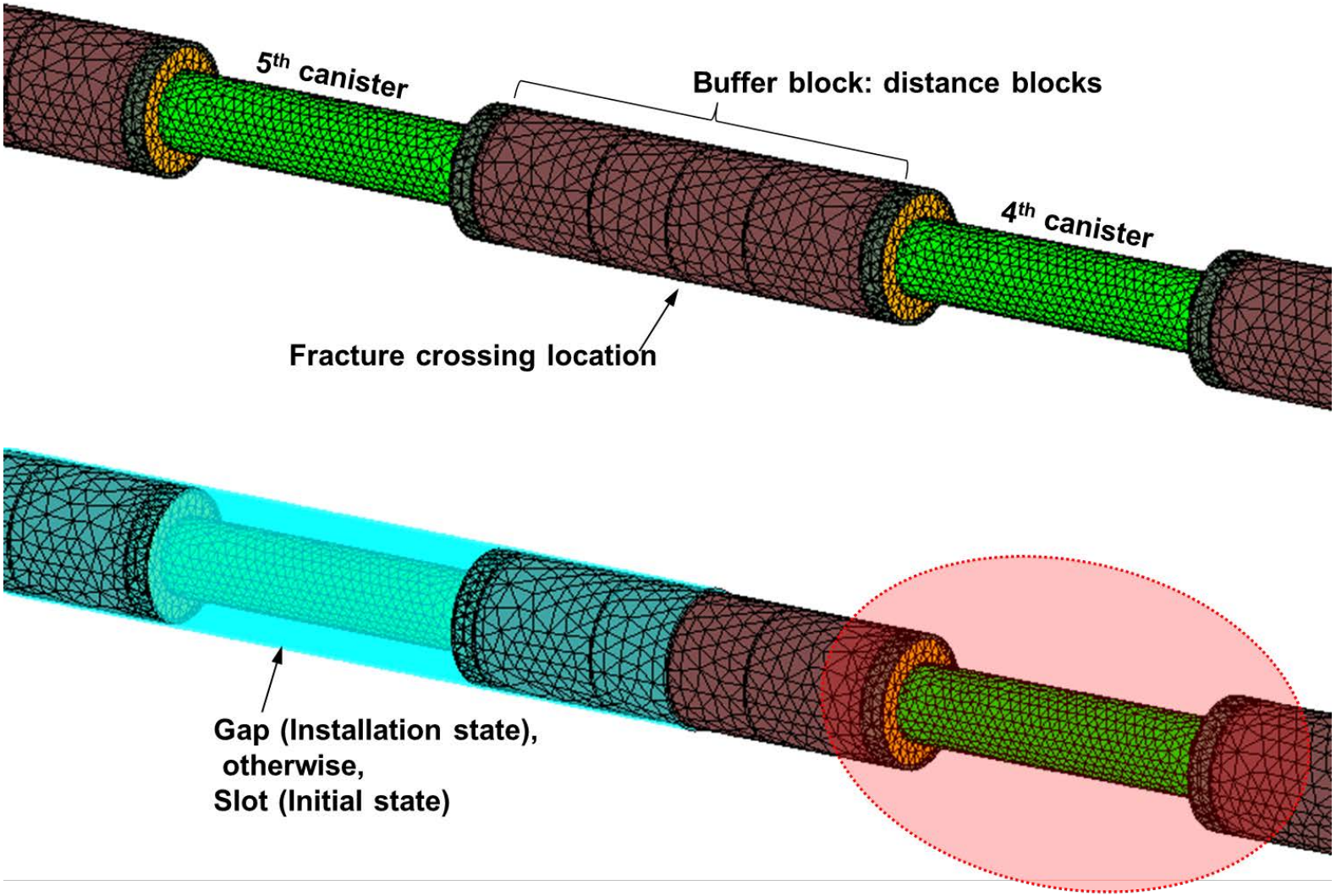
- ✓ **CANISTER**
- ✓ **BUFFER (in *Supercontainers* and in *Distance blocks*)**
- ✓ **HOST ROCK**

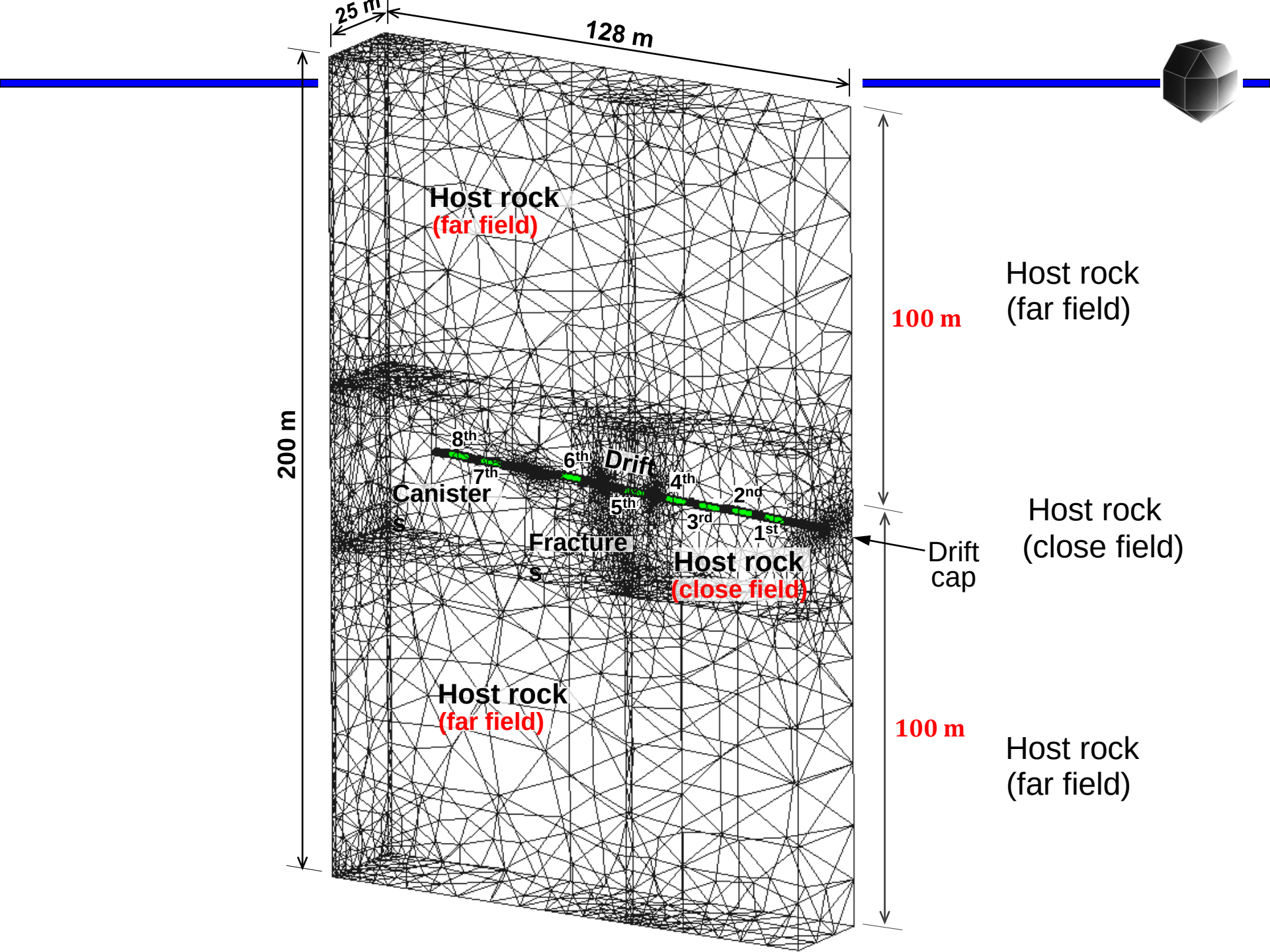
MODEL GEOMETRY AND COMPONENTS



Ivan Puig post doctoral work

MODEL GEOMETRY AND COMPONENTS




25 m
128 m
200 m
Host rock
(far field)
8th
7th
6th
Drift
5th
4th
3rd
2nd
1st
Canister
s
Fracture
s
Host rock
(close field)
Host rock
(far field)
100 m
Host rock
(far field)
Drift
cap
Host rock
(close field)
100 m
Host rock
(far field)

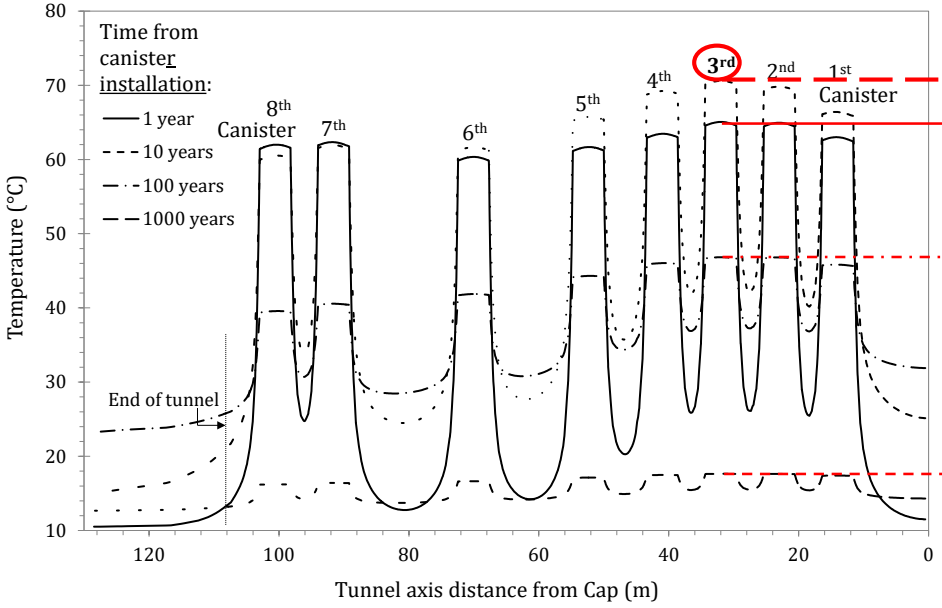
RESULTS: HOST ROCK THICKNESS

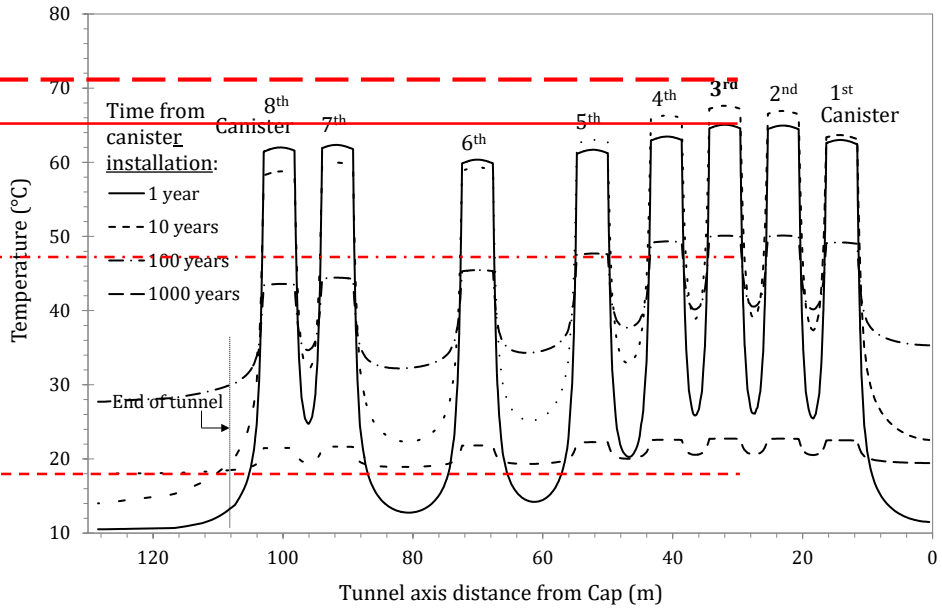
Temperature: tunnel axis distribution

(Initial state)

±20 m host rock
(close-field only)

±100 m host rock
(close-field and far-field)





RESULTS

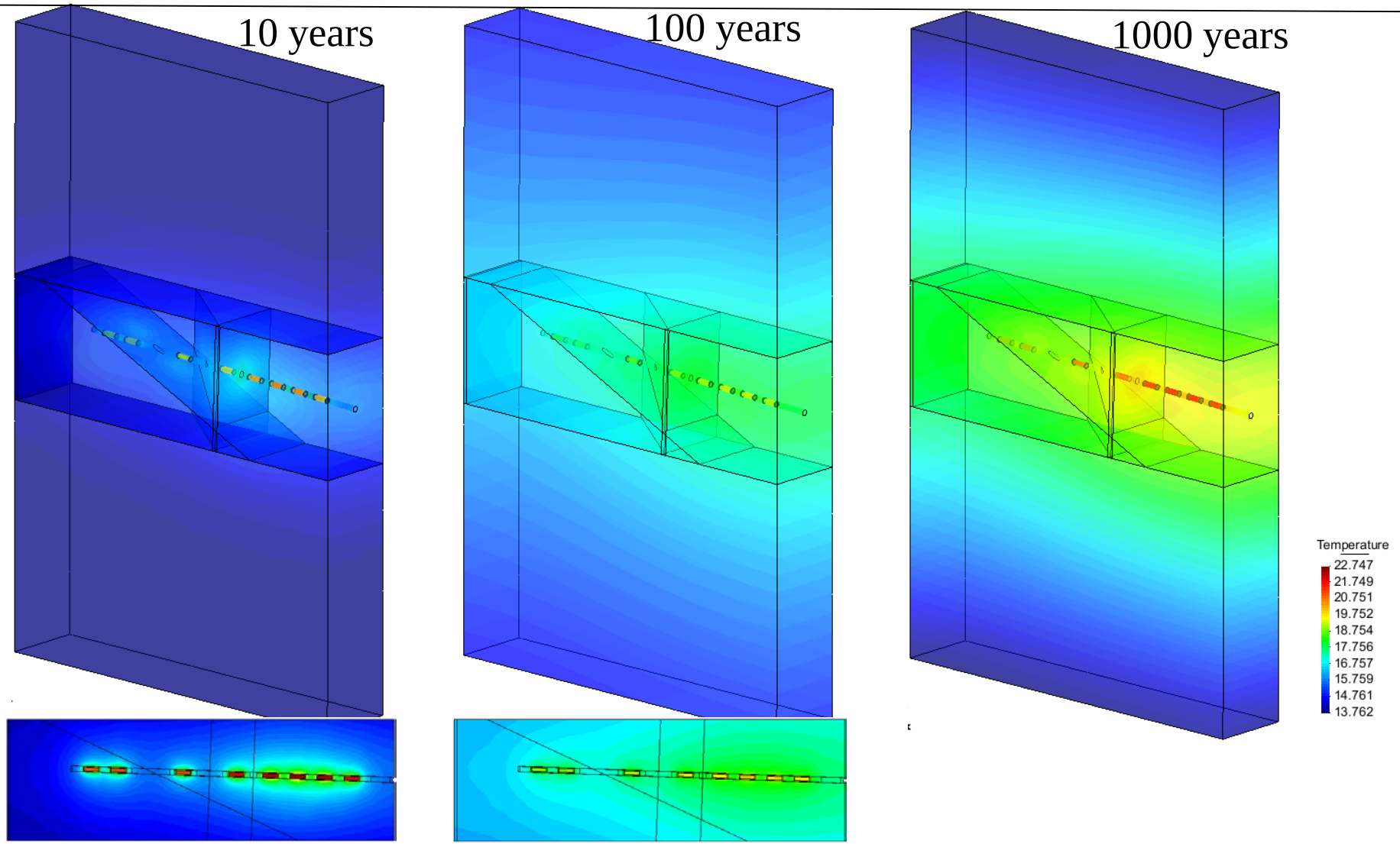
(Initial state)

Temperature: whole domain distribution

10 years

100 years

1000 years

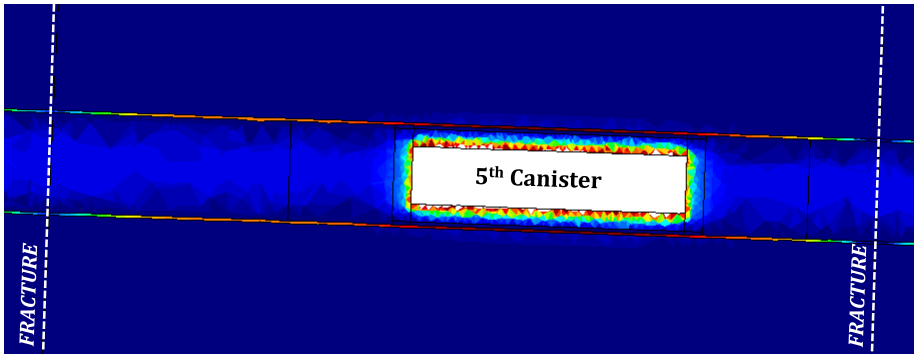


RESULTS: OPEN-GAP EFFECT

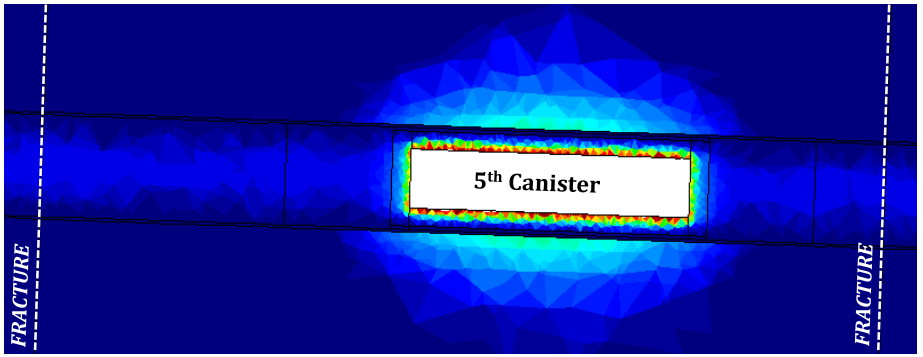
Degree of Saturation

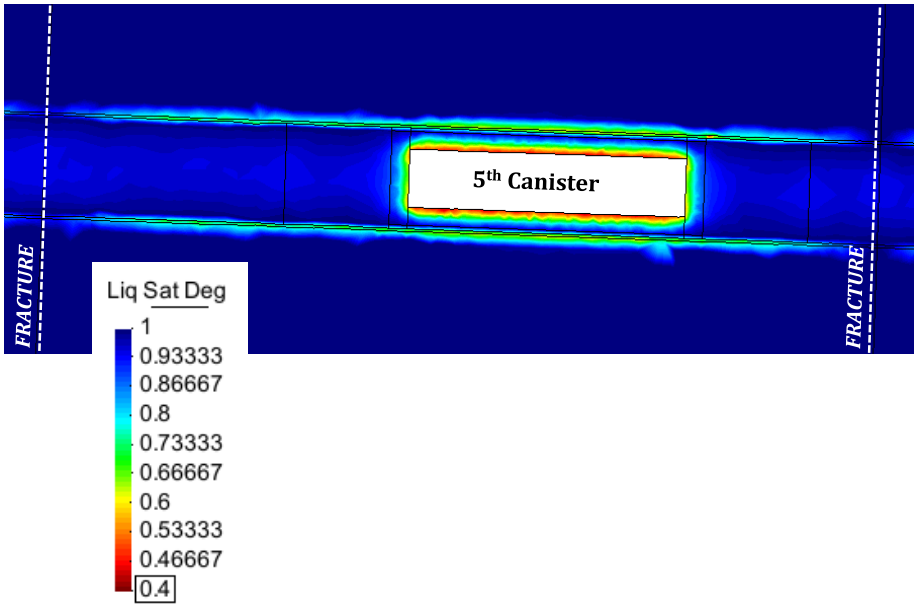
1 year (after canisters placement)

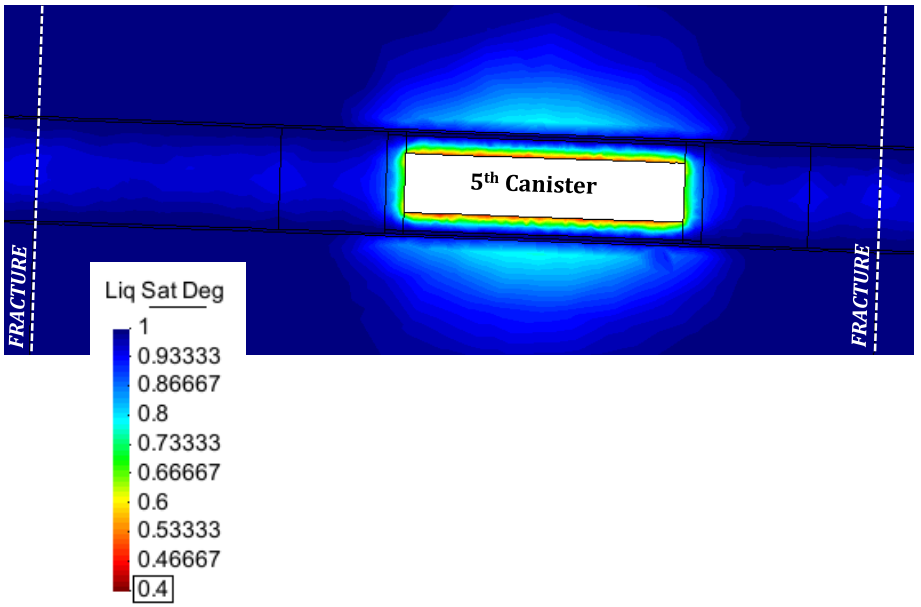
Installation state:



Initial state:

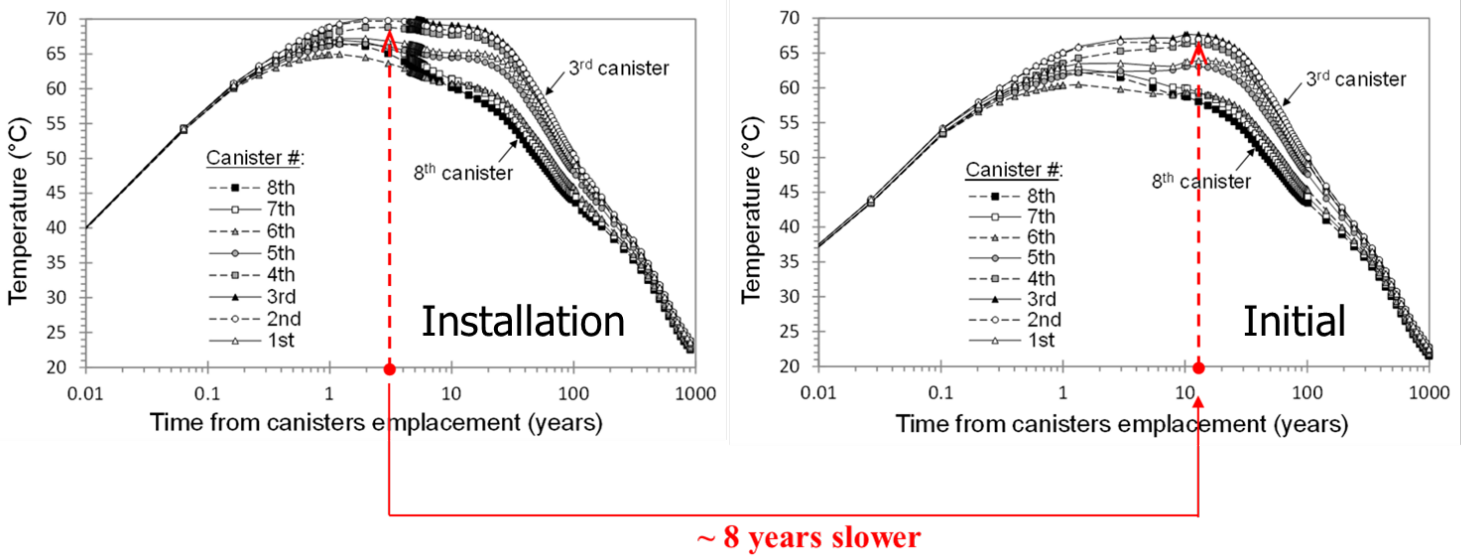




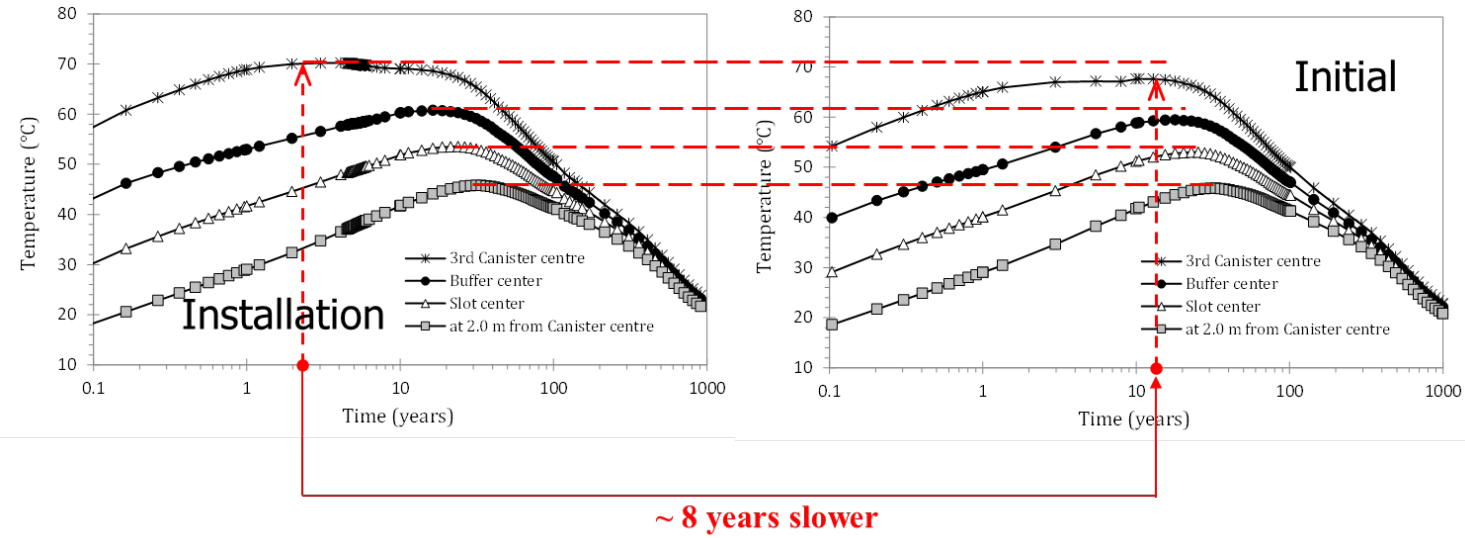


RESULTS: OPEN-GAP EFFECT

Temperature at canisters center:



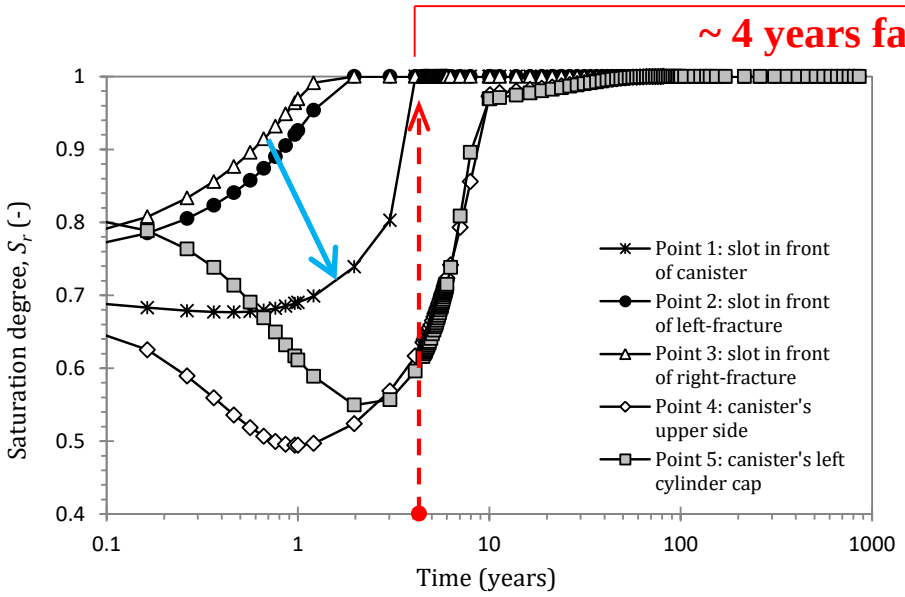
Temperature at 3rd canister



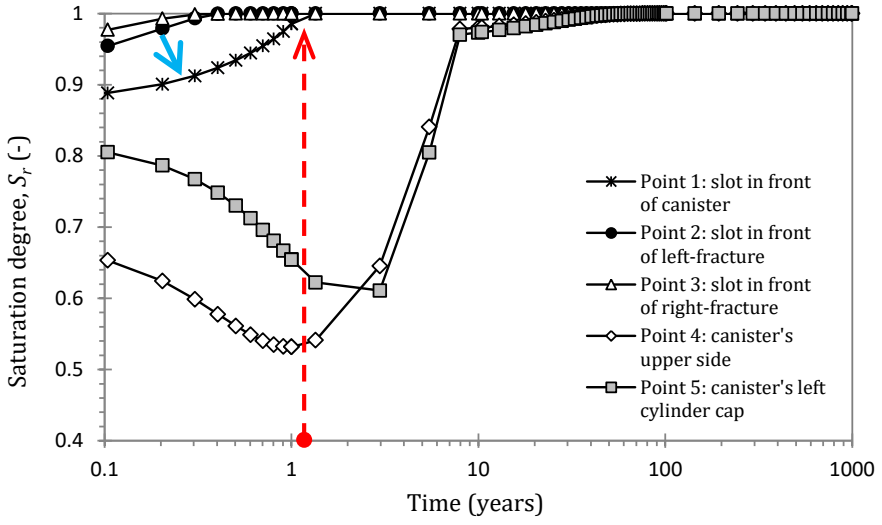
RESULTS: OPEN-GAP EFFECT

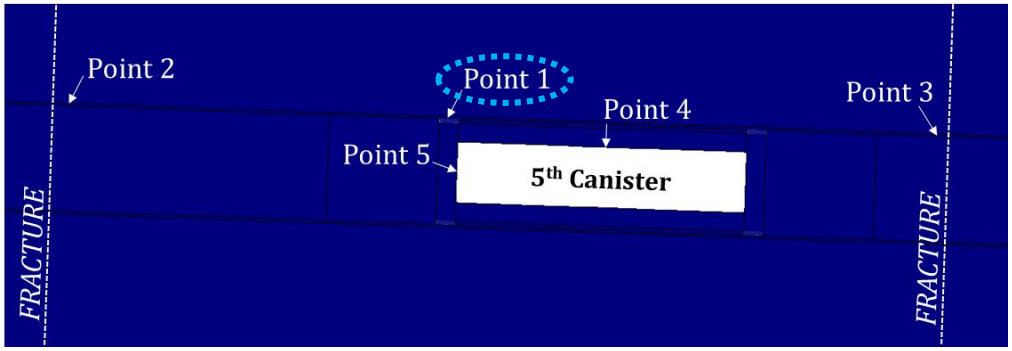
Degree of Saturation

Installation:



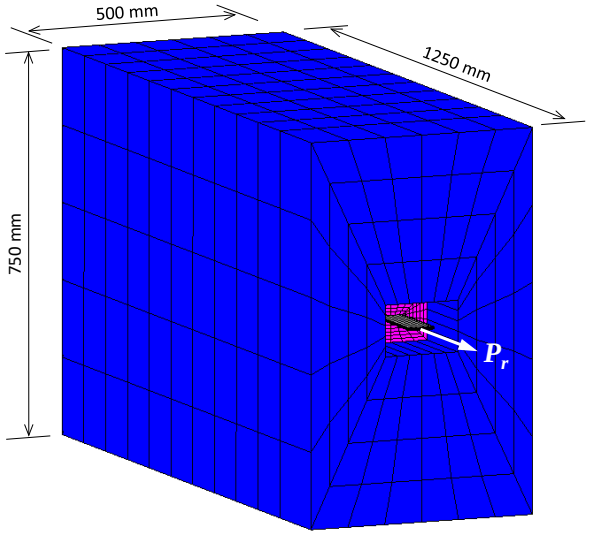
Initial:





REINFORCED WALLS

✓ Pullout in lab: Calibrate the numerical model!



Finite element mesh:
Hexahedral elements &
structured mesh
(1350 elements & **1652** nodes)

CODE_BRIGHT

Ivan Puig Damians contributions as part of PhD at UPC

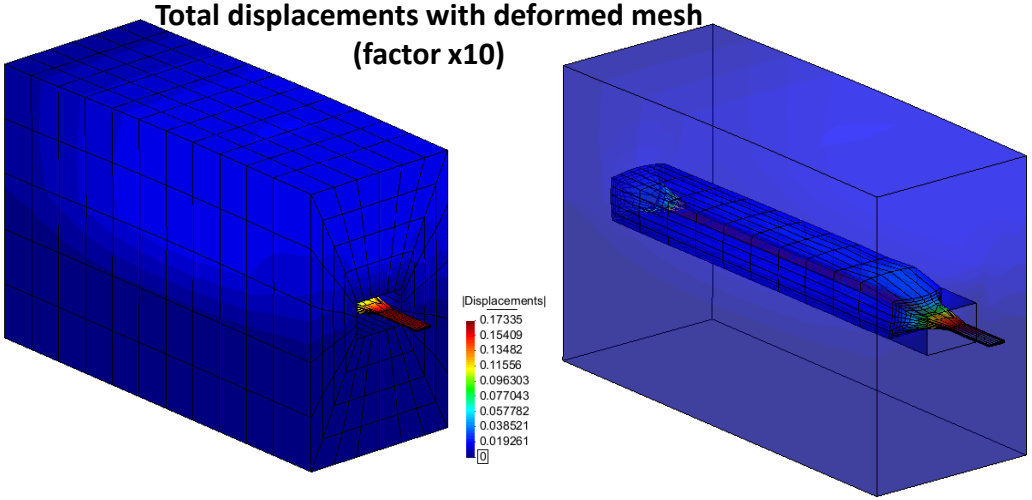
✓ Pullout in lab: Series of tests! STEEL LADDERS

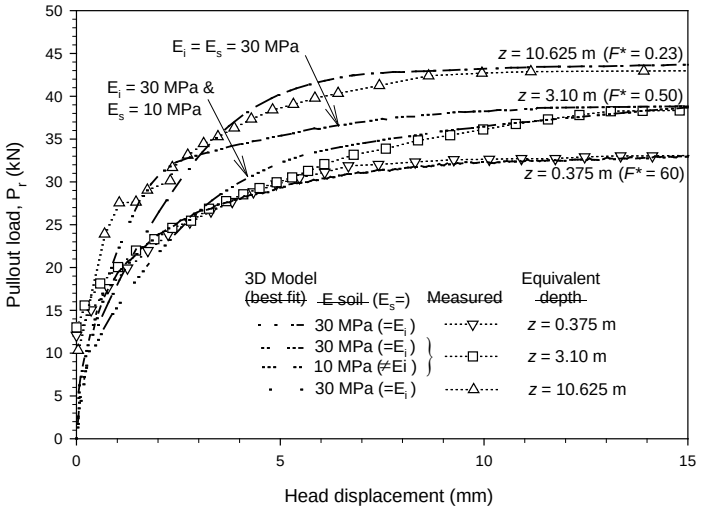
✓ Pullout in lab:

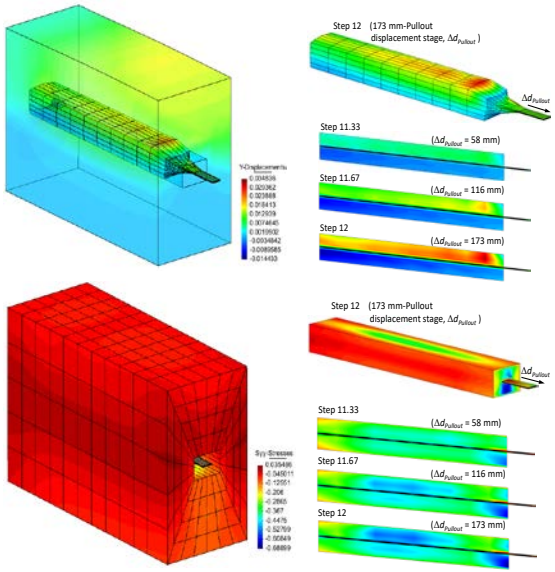
$2 \cdot 10^{-6}$ **m/s displacement** applied **at t**o the head-edge of the reinforcement…

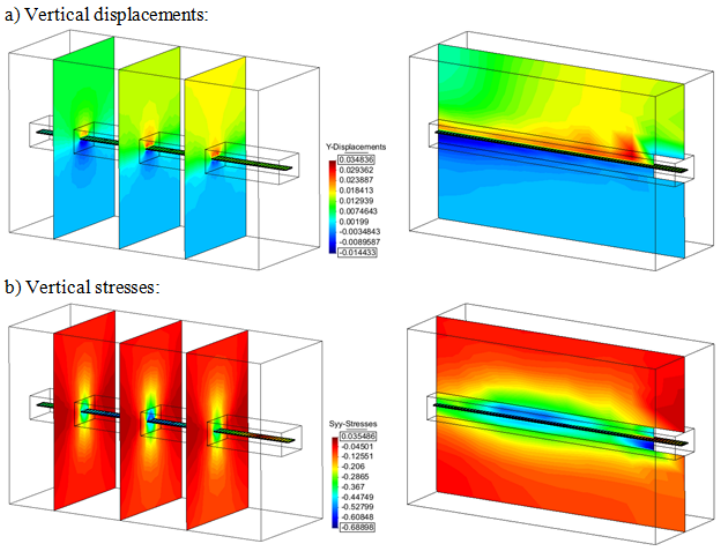
…which generates about **20**-cm axial displacement at **11 step**

Total displacements with deformed mesh (factor x10)

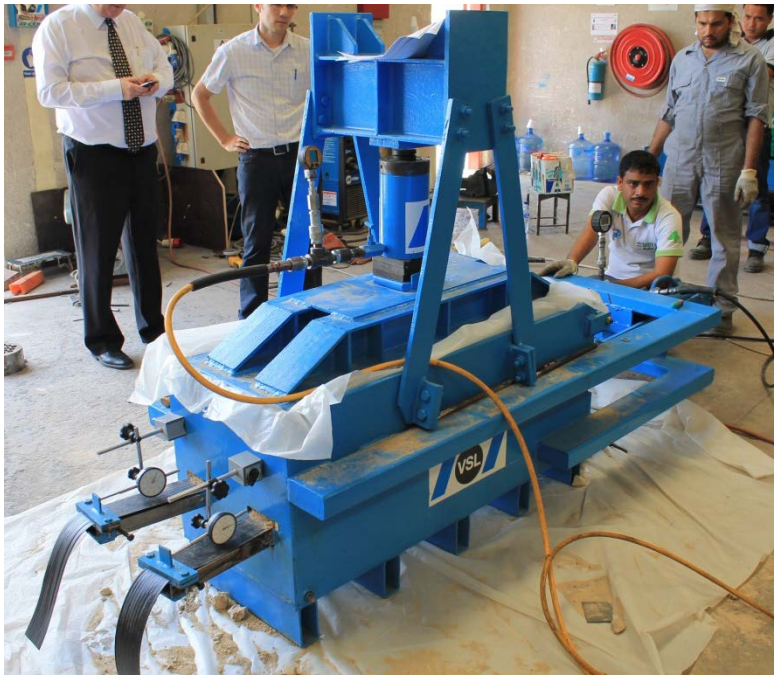


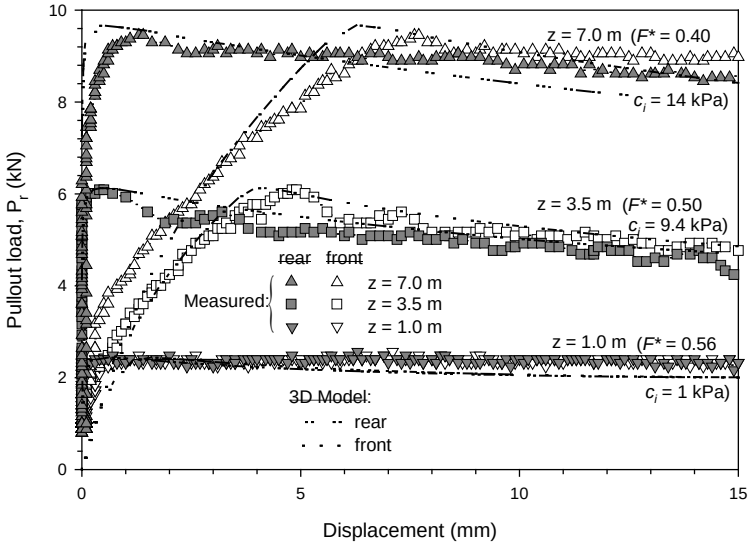




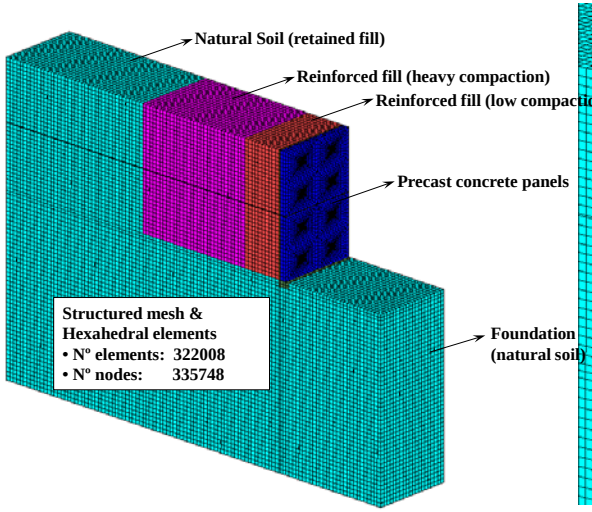


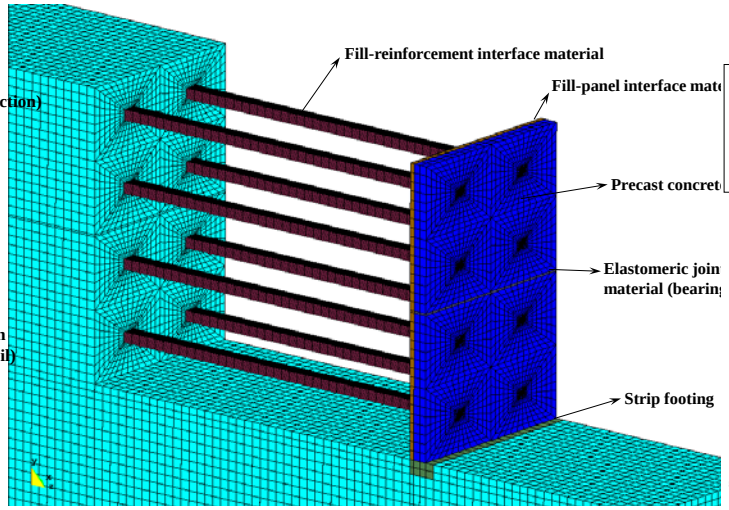
✓ Pullout in lab: Series of tests! POLYMERIC STRIP

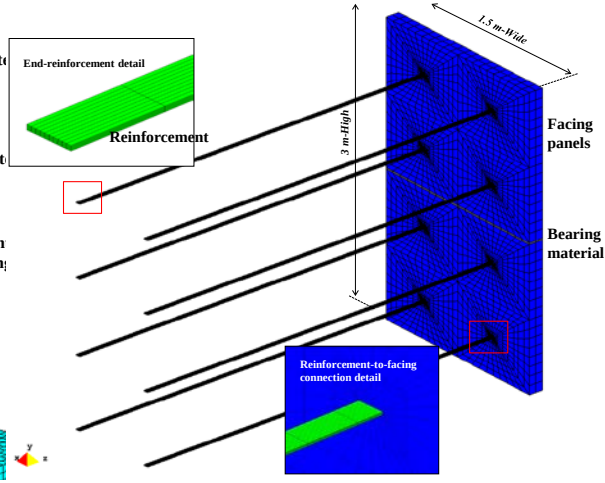


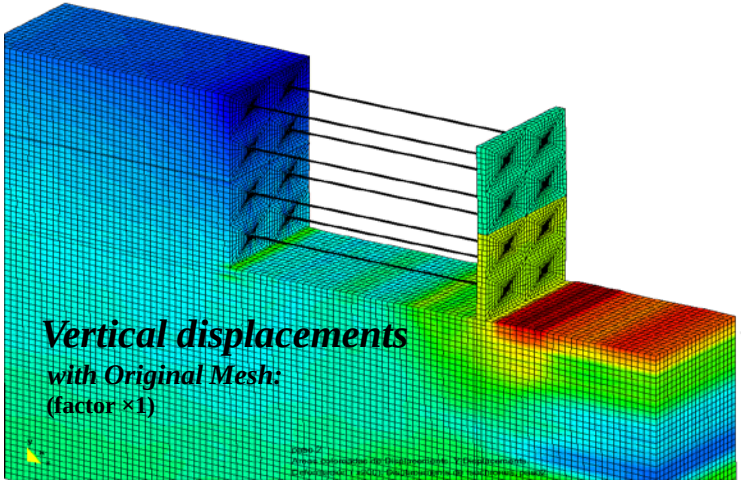


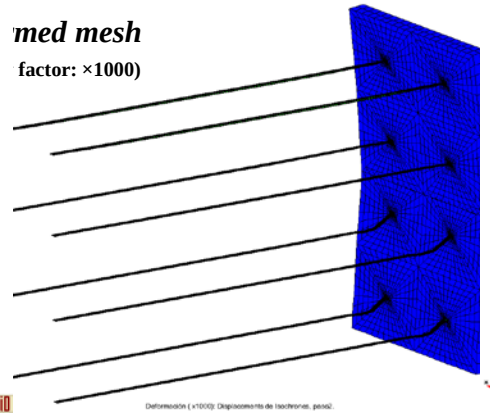
3D Models

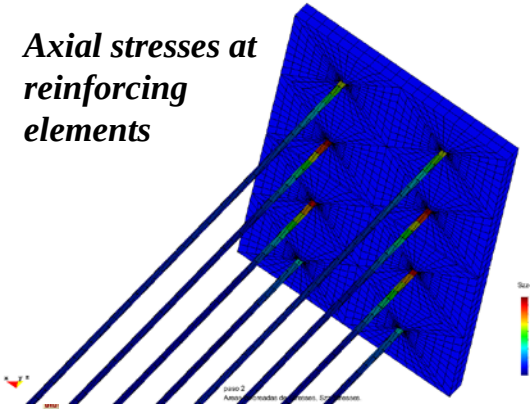

Natural Soil (retained fill)
Reinforced fill (heavy compaction)
Reinforced fill (low compaction)
Precast concrete panels
Foundation (natural soil)
Structured mesh & Hexahedral elements
• Nº elements: 322008
• Nº nodes: 335748


Fill-reinforcement interface material
Fill-panel interface mat
Precast concret
Elastomeric join material (bearin
Strip footing


End-reinforcement detail
Reinforcement
1.5 m-Wide
3 m-High
Facing panels
Bearing material
Reinforcement-to-facing connection detail


Vertical displacements
with Original Mesh:
(factor ×1)
Y-Displacements
0.0003151
0.00025434
0.00019359
0.00013283
7.2073e-05
1.1317e-05
-4.944e-05
-0.0001102
-0.00017095
-0.00023171

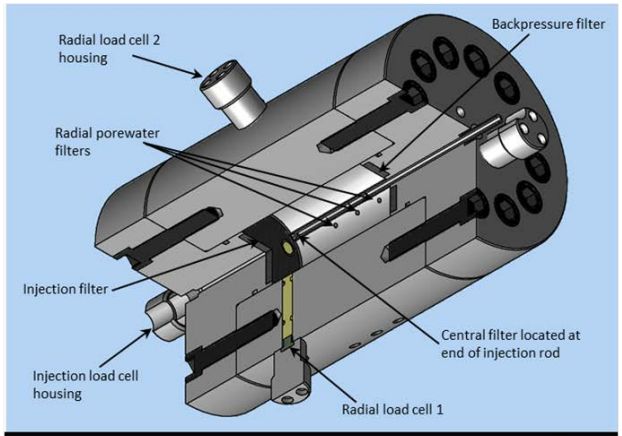

med mesh
factor: ×1000)

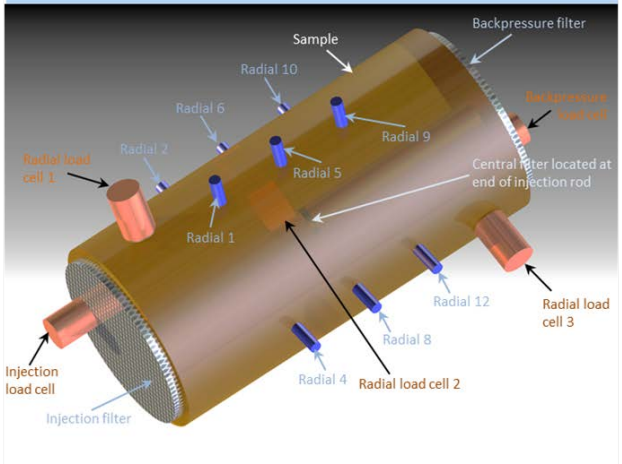

Axial stresses at reinforcing elements

Stage 1A: 1D flow through saturated bentonite under constant volume boundary conditions

Bentonite test – Mx80-D

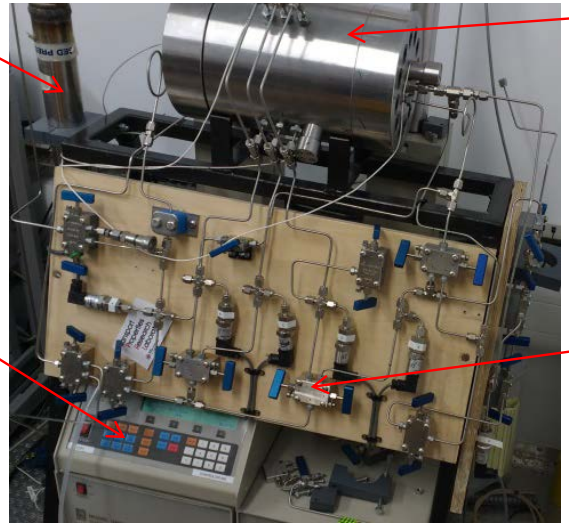
- A 1D gas injection test, performed on compact bentonite, is currently underway at the British Geological Survey.
- The test is comprised of a two stages:
  - hydration (using distilled water)
  - gas testing (using helium)
- After gas breakthrough and a period of gas flow through the sample, the injection pump was stopped whilst the stresses and porewater pressures have been continuously monitored.





Interface vessel

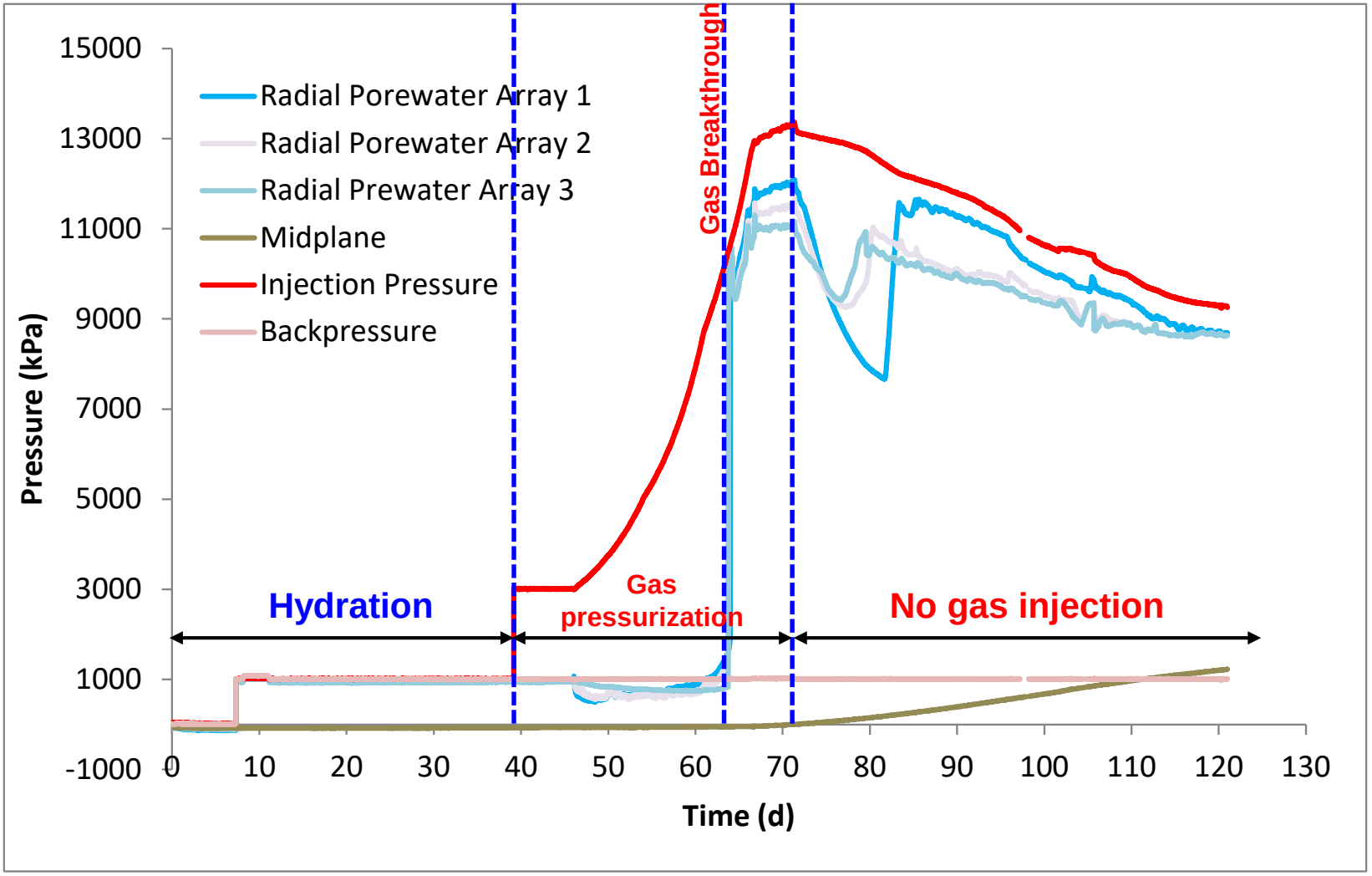
Pump controller



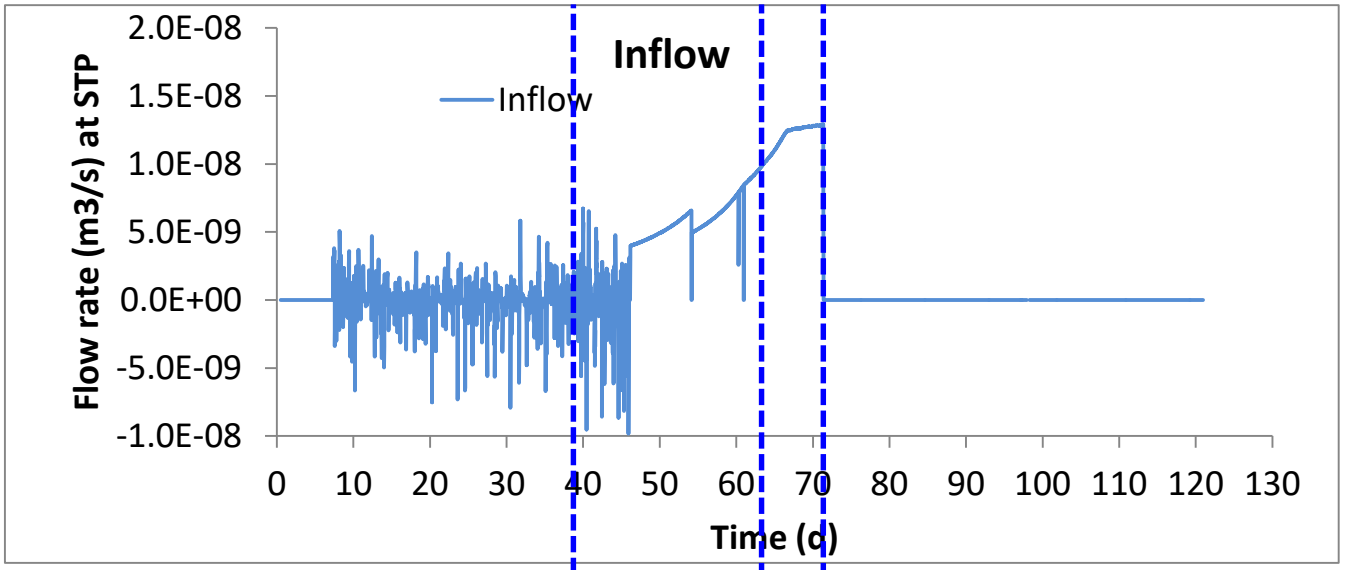
Pressure vessel containing sample

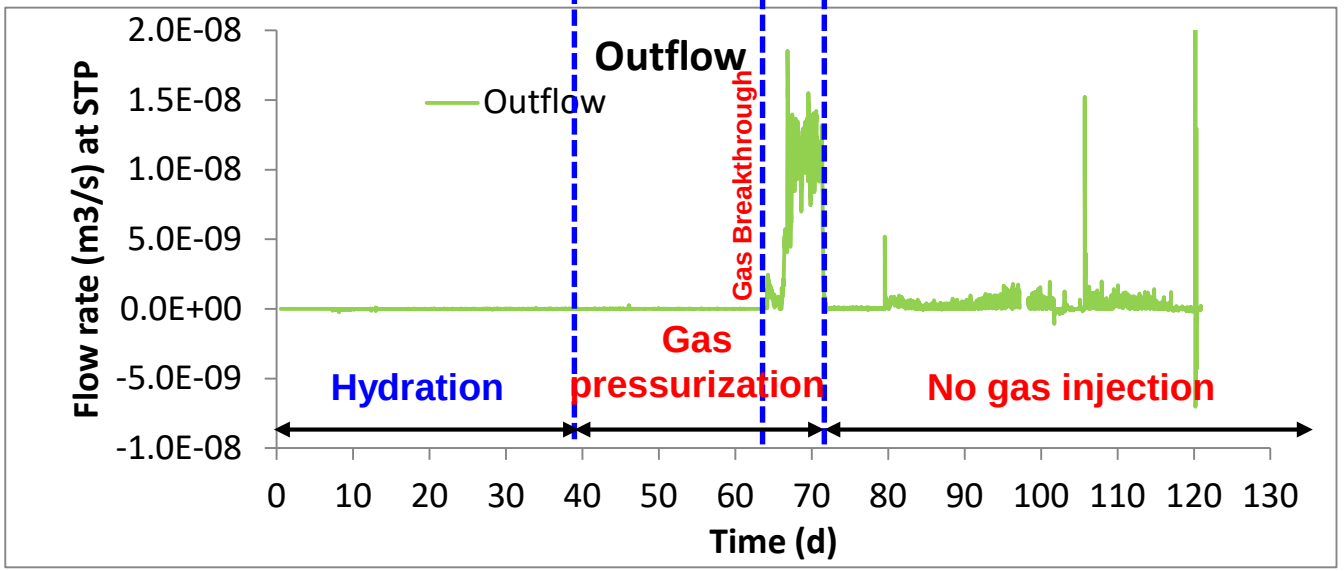
Valves controlling flow into and out of the sample

Pressure from test data

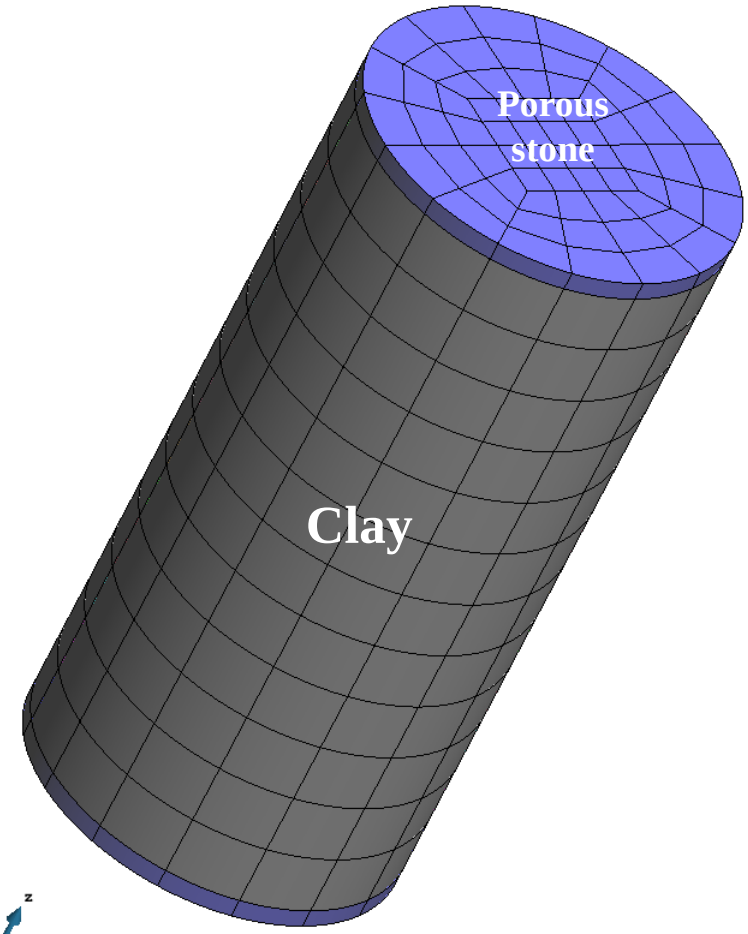


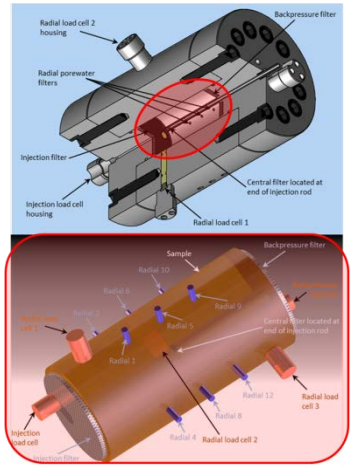
Inflow and outflow from test data

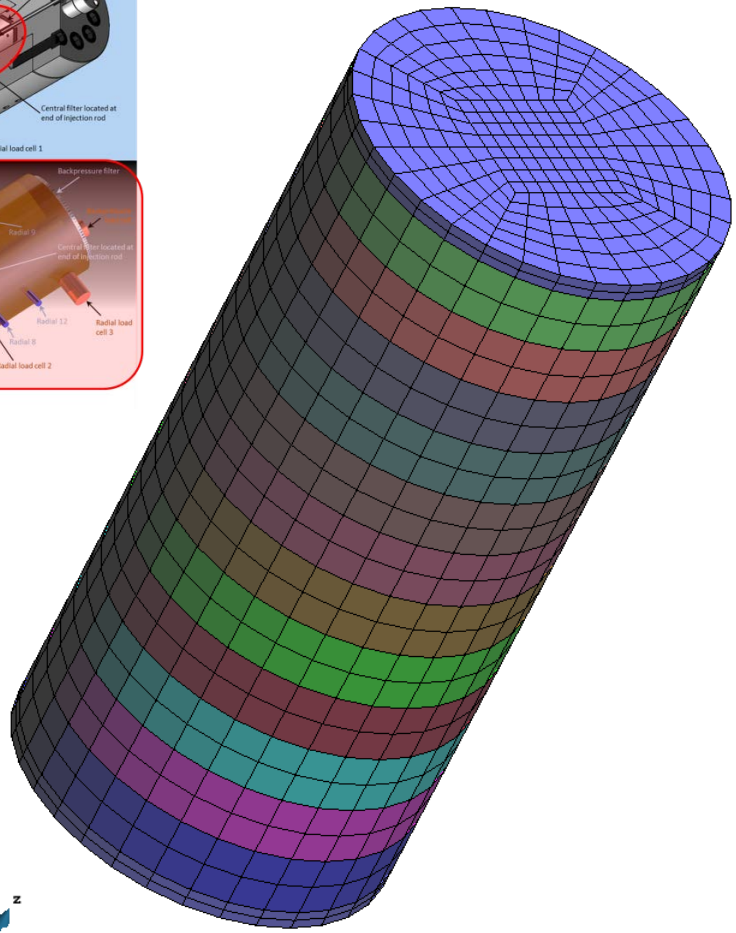




Model generation: volumes and mesh



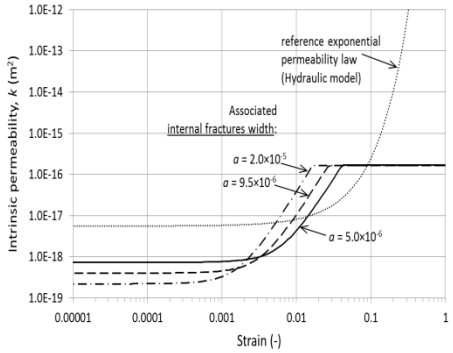




Volumes-material definition

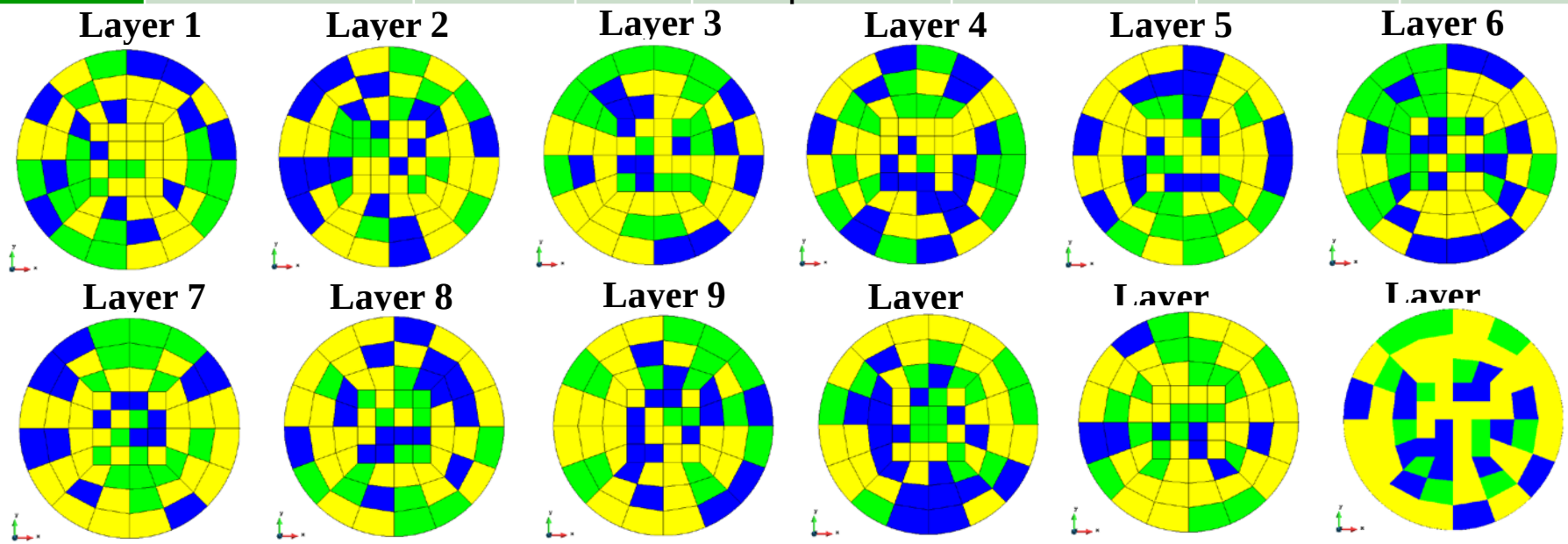
F.E. mesh definition

EMBEDDED FRACTURE: CUBIC LAW + RELATIVE PERMEABILITY

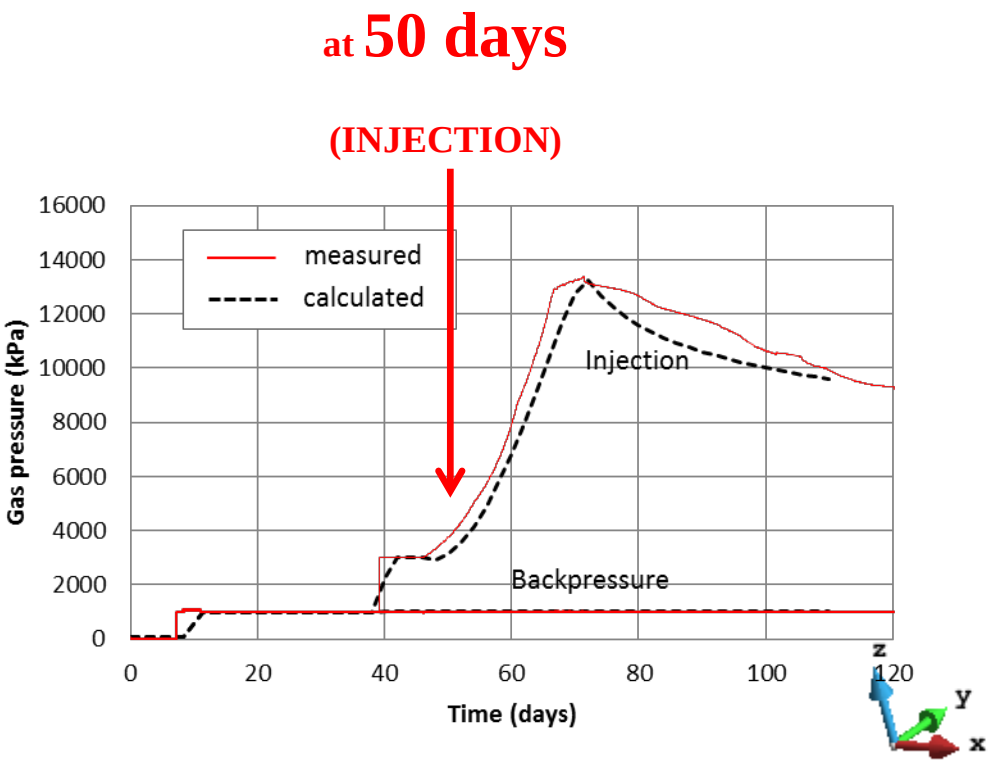


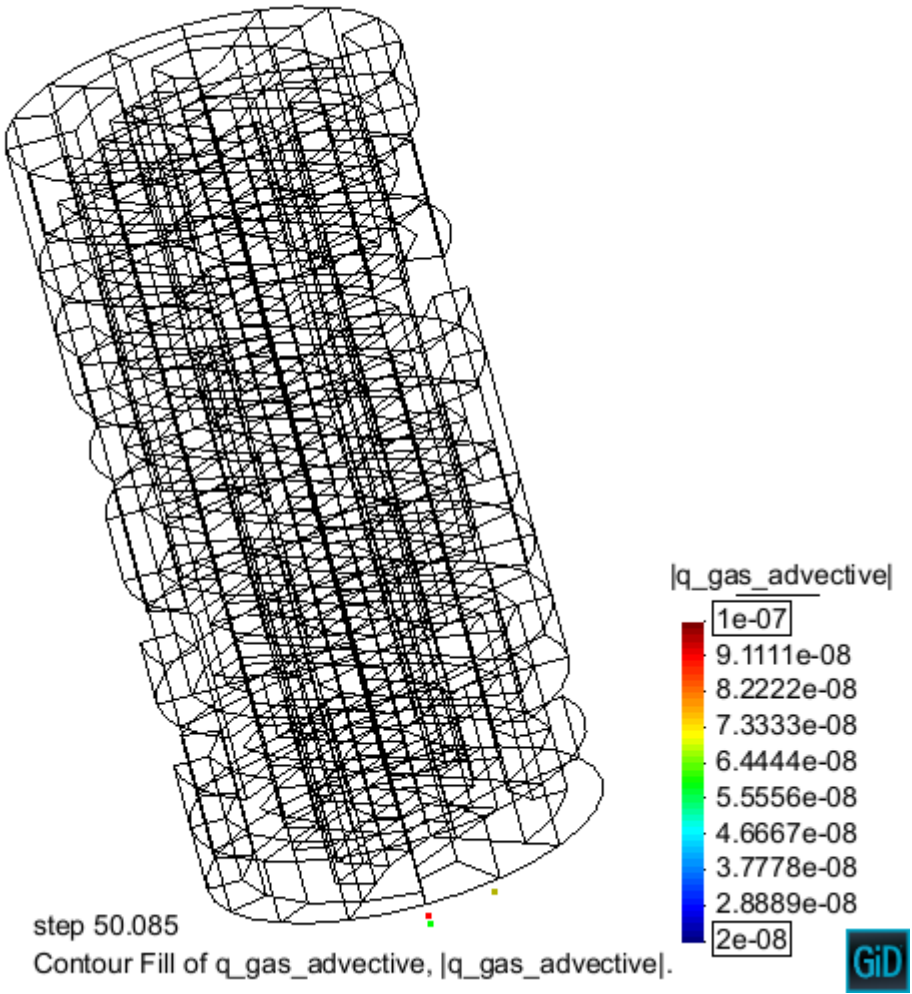
- **Intrinsic permeability heterogeneous in 3 zones (weighting 1/6, 1/6, 2/3).**
- **Porosity set to 0.40, 0.41 and 0.42 respectively for:**
- **k0 = 2.15, 3.90, 7.10 x 10^{-19} m2 and p0 = 37.8, 27.0, 19.4 MPa**
- **Elastic modulus = 307 MPa and Poisson ratio = 0.44**

Porosity (a)	Intrinsic permeability	Water retention curve (b)		Relative permeability (c)	a (d)	b_0 (e)	b_{max} (e)
		P_0	λ				
0.40	2.15×10^{-19}	37.80	0.45	2	2.0×10^{-5}	1.0×10^{-8}	3.40×10^{-6}
0.41	3.90×10^{-19}	27.00			9.5×10^{-6}		2.66×10^{-6}
0.42	7.10×10^{-19}	19.44			5.0×10^{-6}		2.16×10^{-6}
-	m^2	MPa	-	n-power	m	m	m

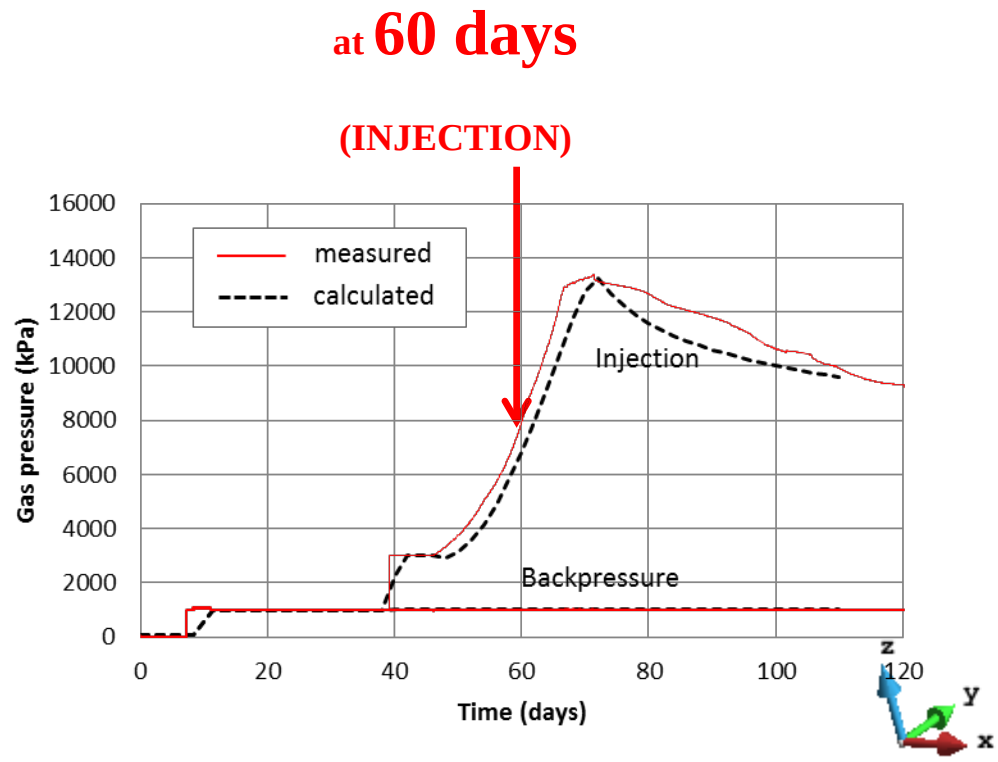


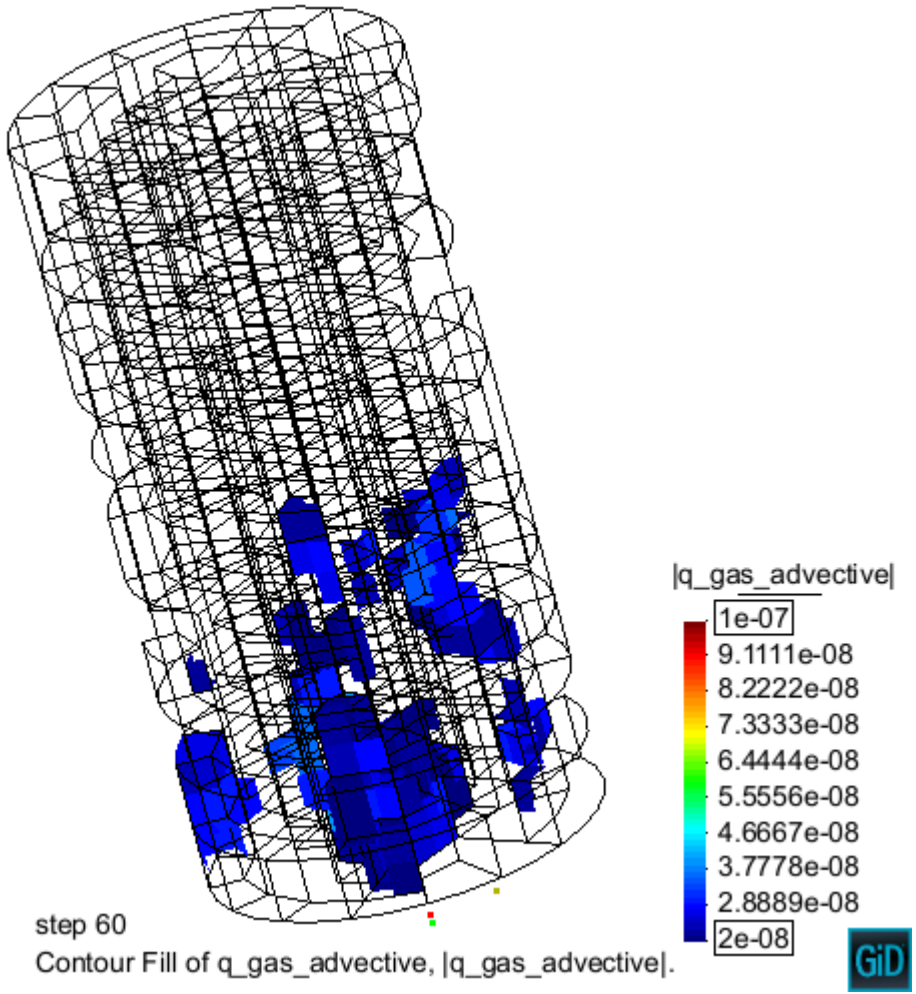
Gas advection at 50 days



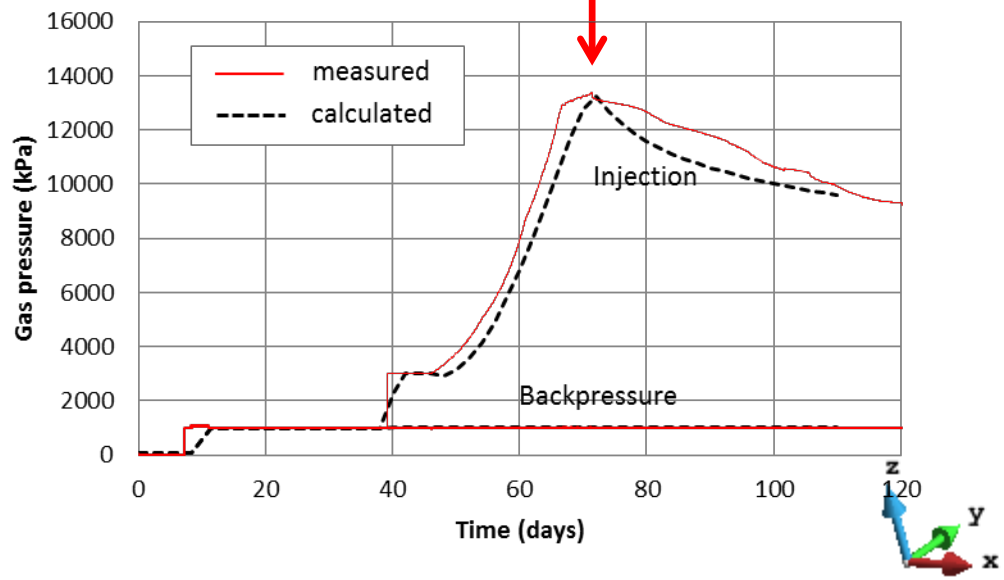


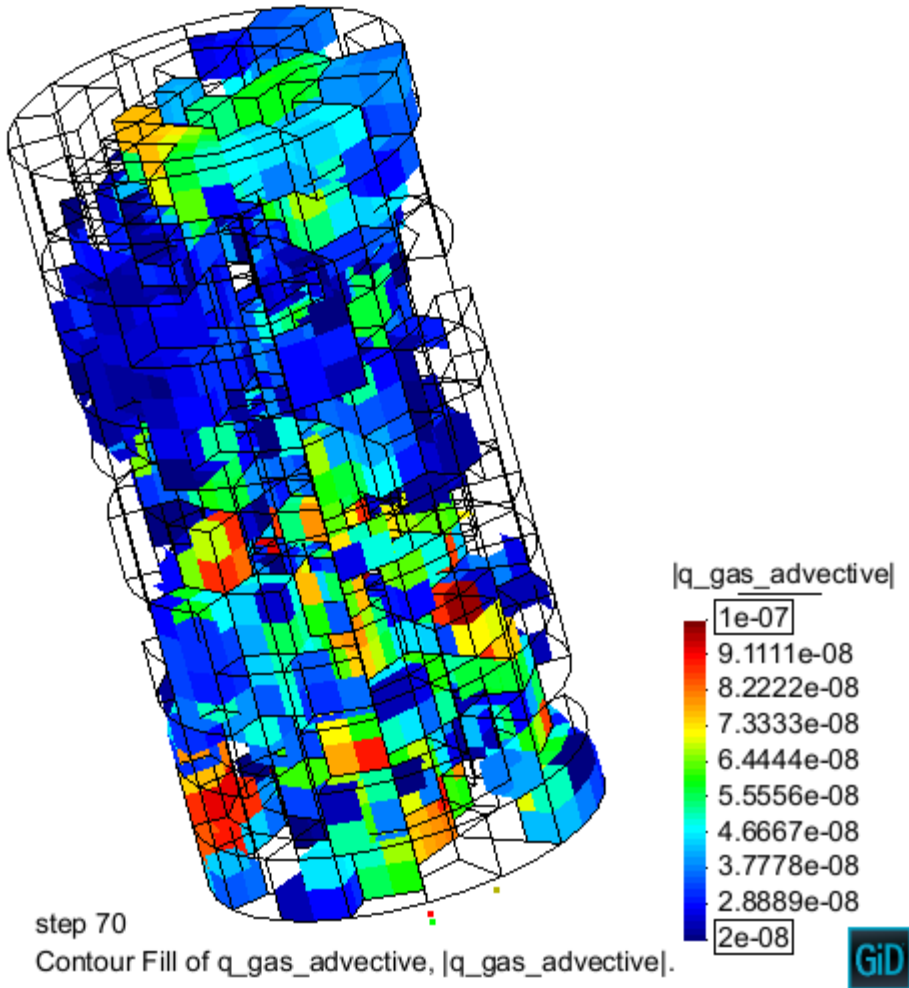
Gas advection at 60 days



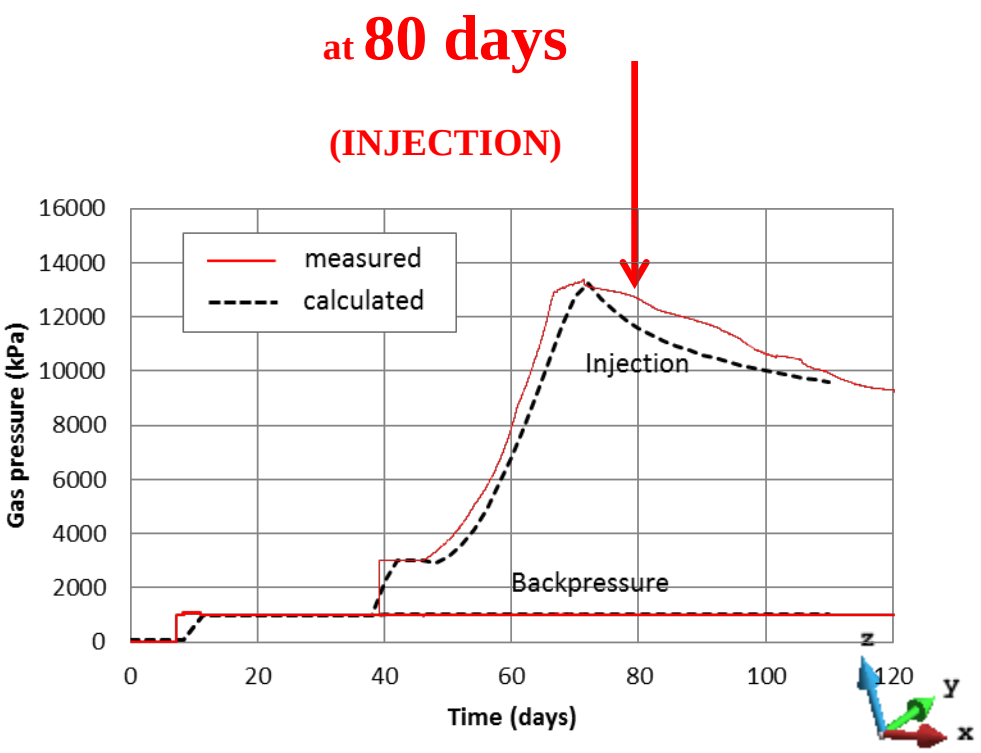


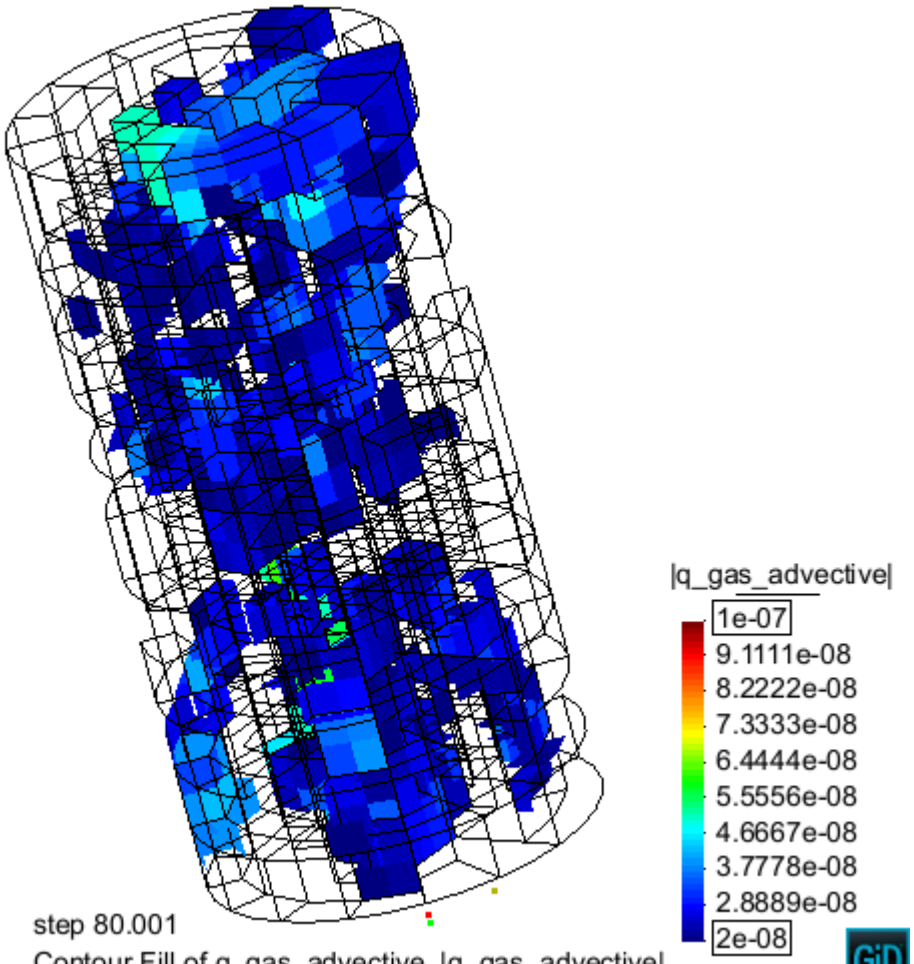
Gas advection at 70 days



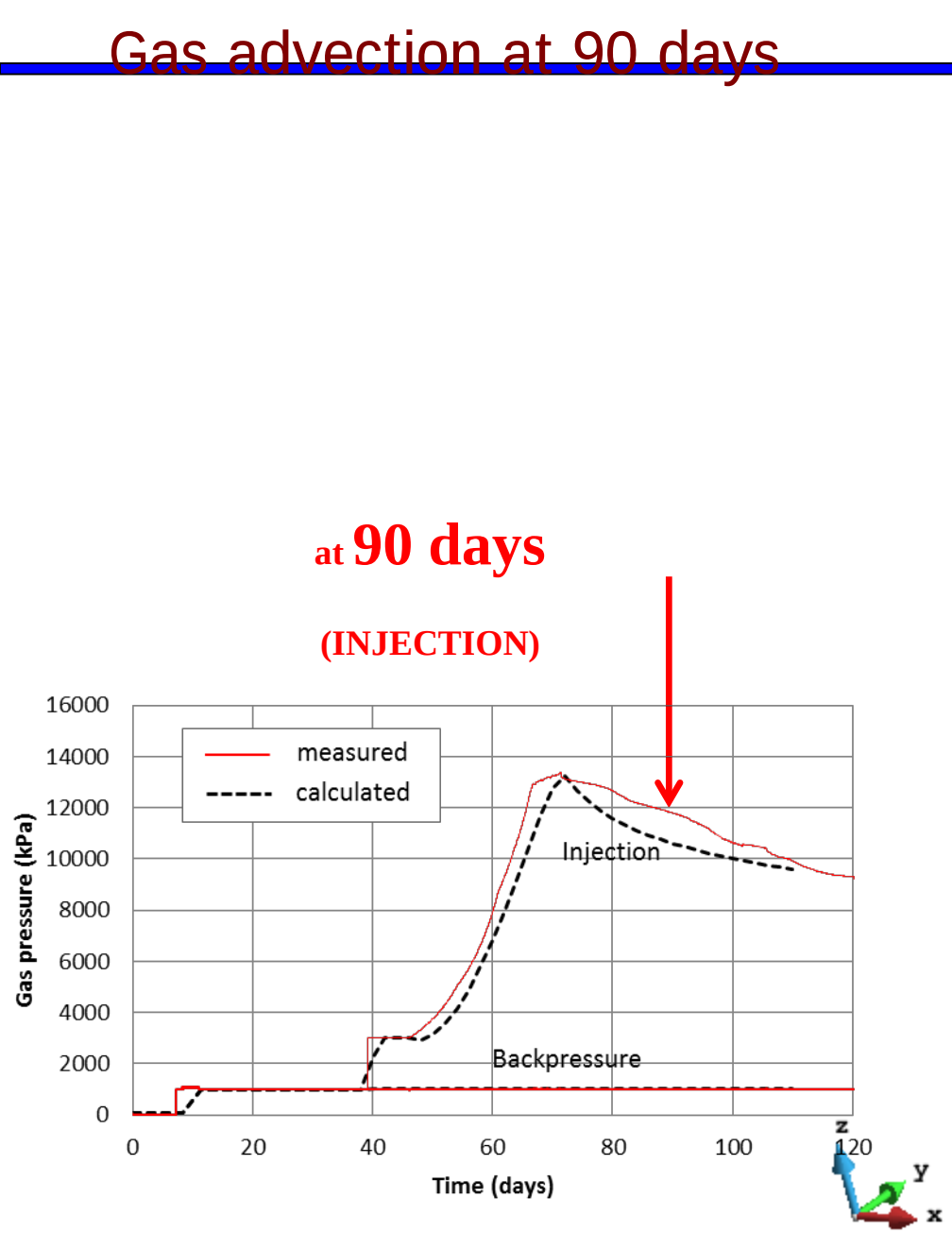


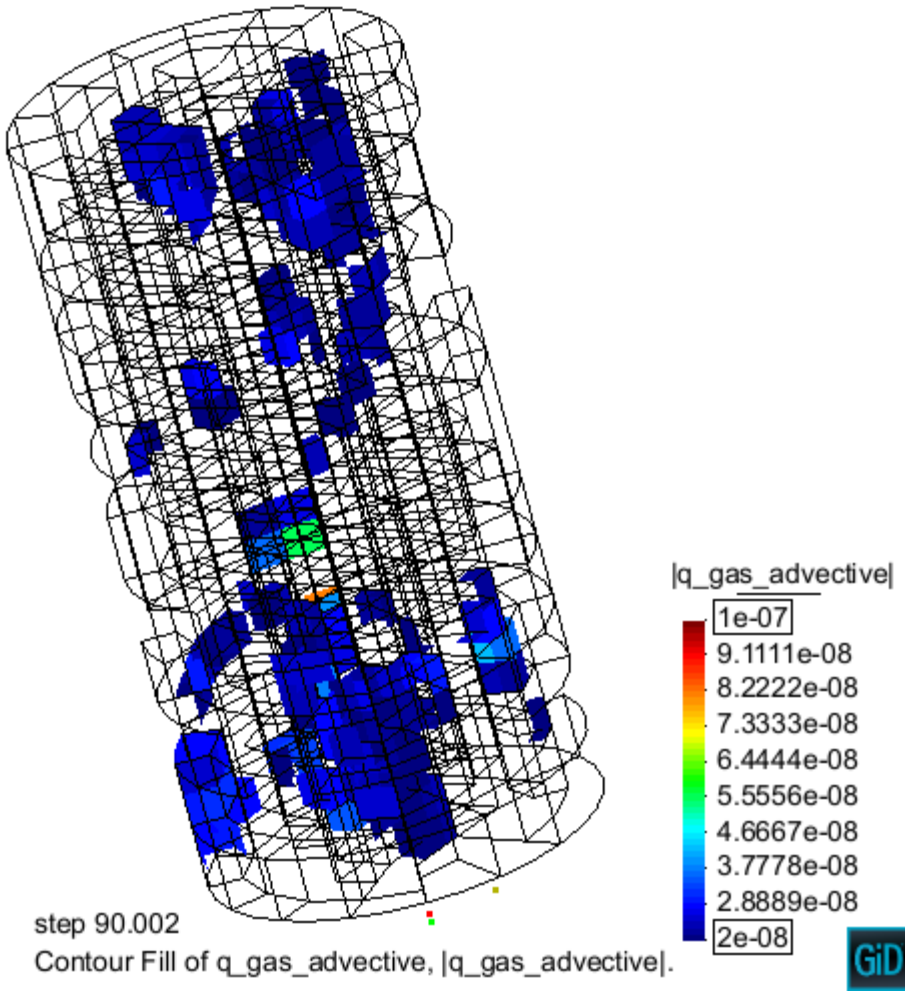
Gas advection at 80 days



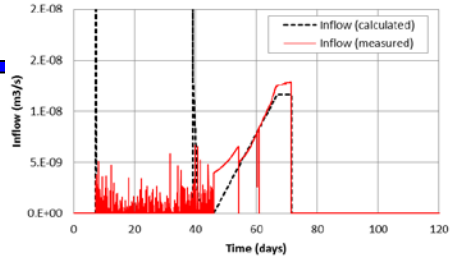


Gas advection at 90 days

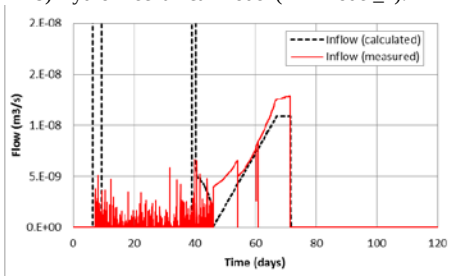




a) Hydraulic model:



b) Hydro-mechanical model (HM model_1):



c) Hydro-mechanical model (HM model_2):

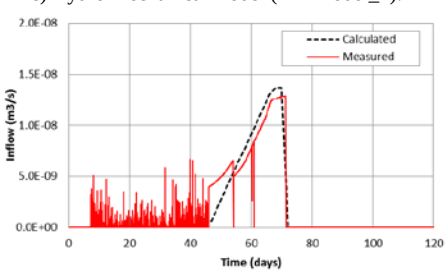
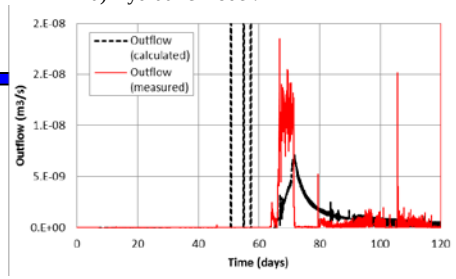
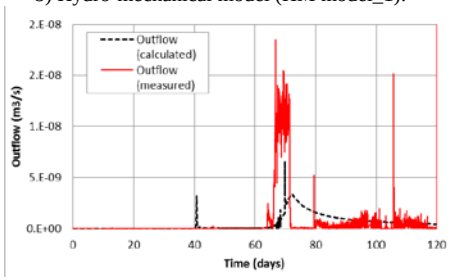


Figure 6. Inflow evolution results: (a) Hydraulic model, (b) HM model_1, and (c) HM model_2.

a) Hydraulic model:



b) Hydro-mechanical model (HM model_1):



c) Hydro-mechanical model (HM model_2):

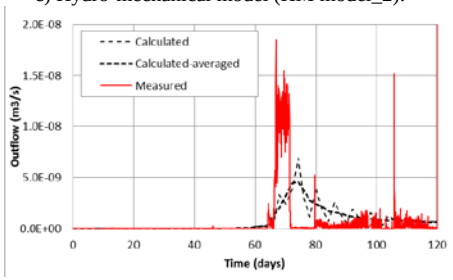
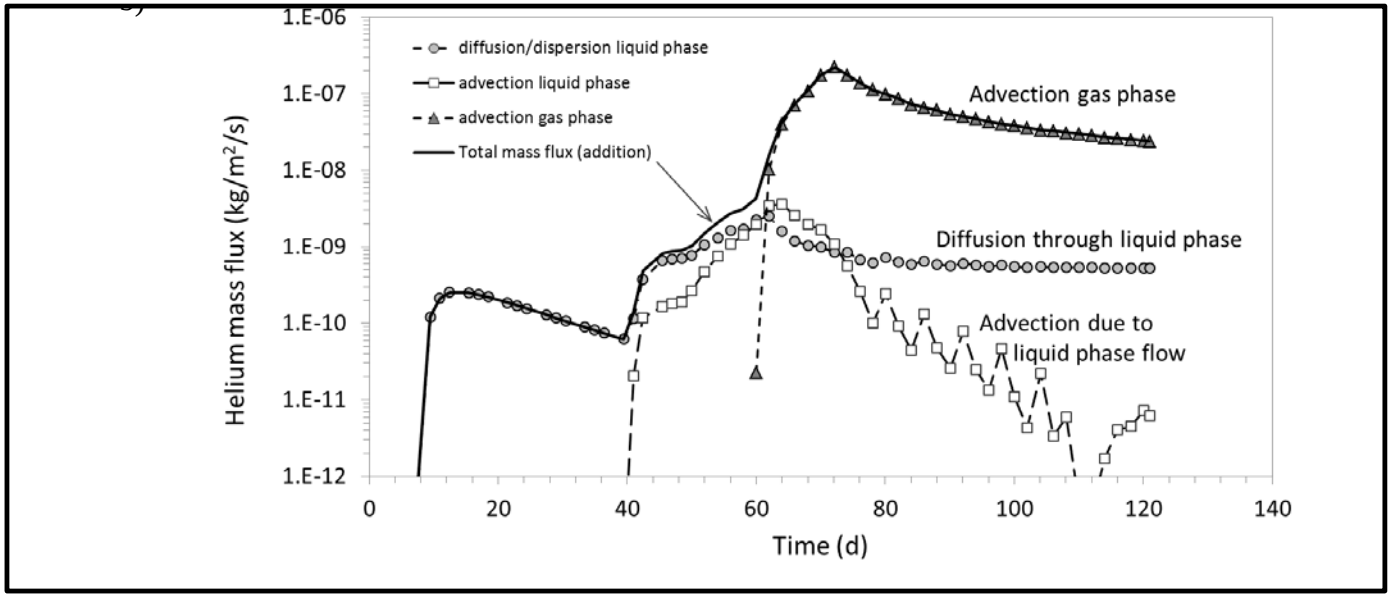
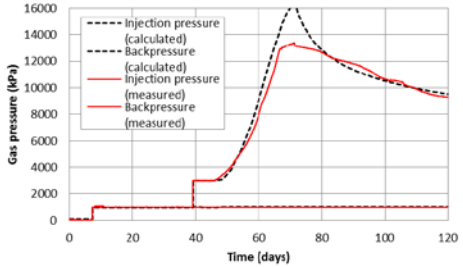


Figure 7. Outflow evolution results: (a) Hydraulic model, (b) HM model_1, and (c) HM model_2.

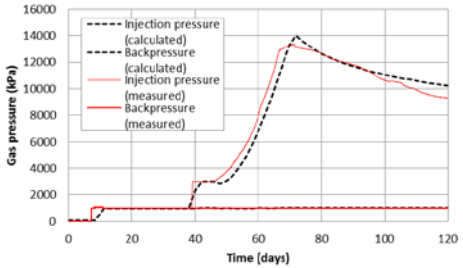
Flow rates and fluxes



a) Hydraulic model:



b) Hydro-mechanical model (HM model_1):



c) Hydro-mechanical model (HM model_2):

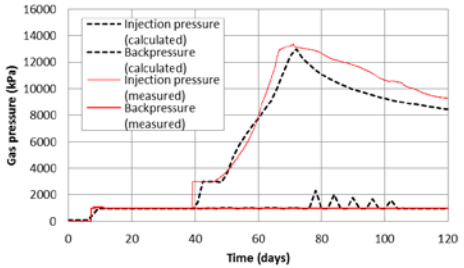
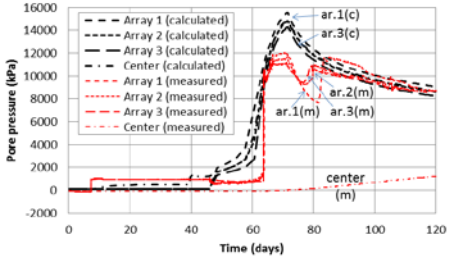
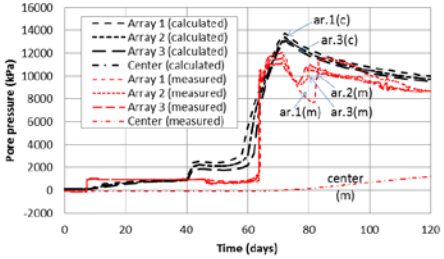


Figure 9. Injection and backpressure evolution results: (a) Hydraulic model, (b) HM model_1, and (c) HM model_2.

a) Hydraulic model



b) Hydro-mechanical model (HM model_1):



c) Hydro-mechanical model (HM model_2):

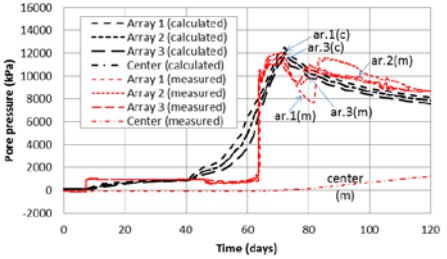


Figure 8. Pore pressure evolution results: (a) Hydraulic model, (b) HM model_1, and (c) HM model_2.

Pressures and stresses

a) Hydro-mechanical model (HM model_1):

b) Hydro-mechanical model (HM model_2):

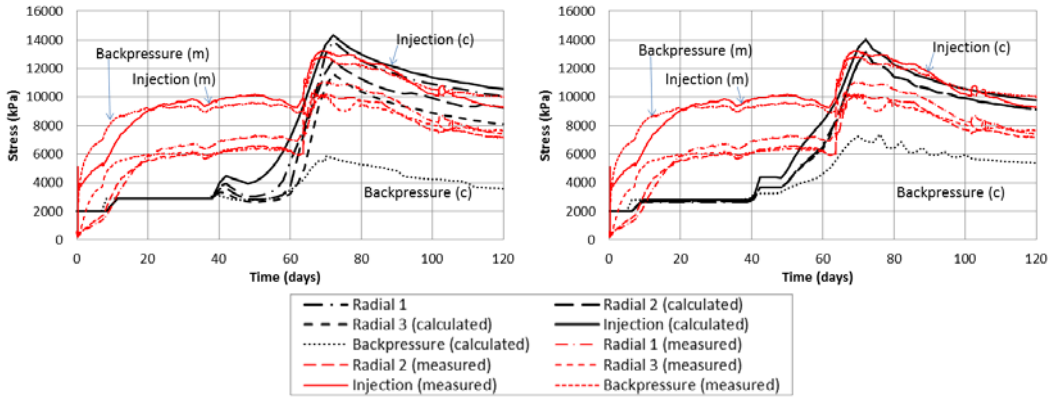
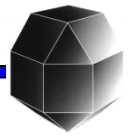


Figure 10. Stress results evolution results (hydro-mechanical models): (a) HM model_1 and (b) HM model_2.

Geomechanics group



- CIMNE and in particular GID play a key role in our research and technological development
- Thanks for your attention
- Questions?
- Other applications: CO2, Yucca M, Earth Dams, Metro Station, ...

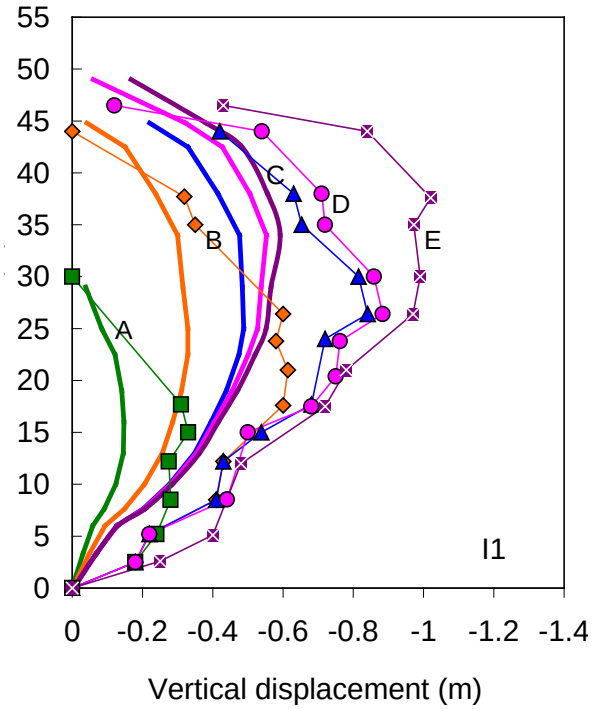
Modelling of Lechago Dam

Núria Pinyol doctoral and post doctoral contributions

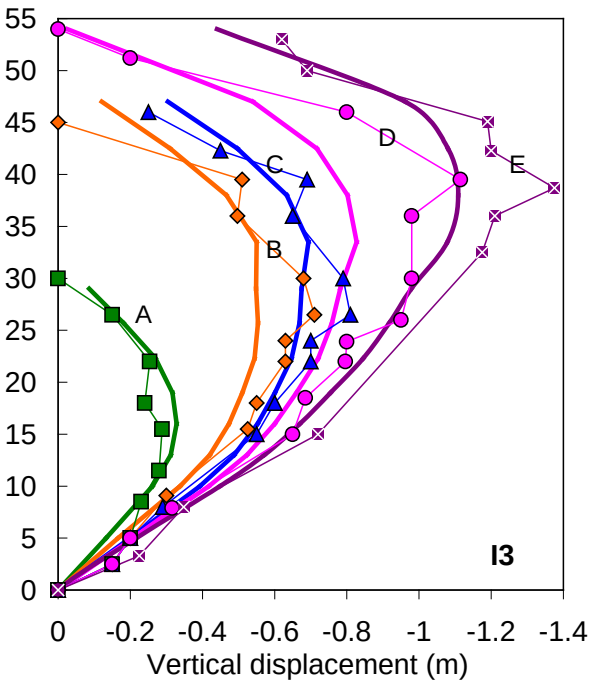
A paper modelling Beliche Dam published in **Geotechnique** was awarded by Institution of Civil Engineers (Crampton Price)

5. Comparison with field measurements

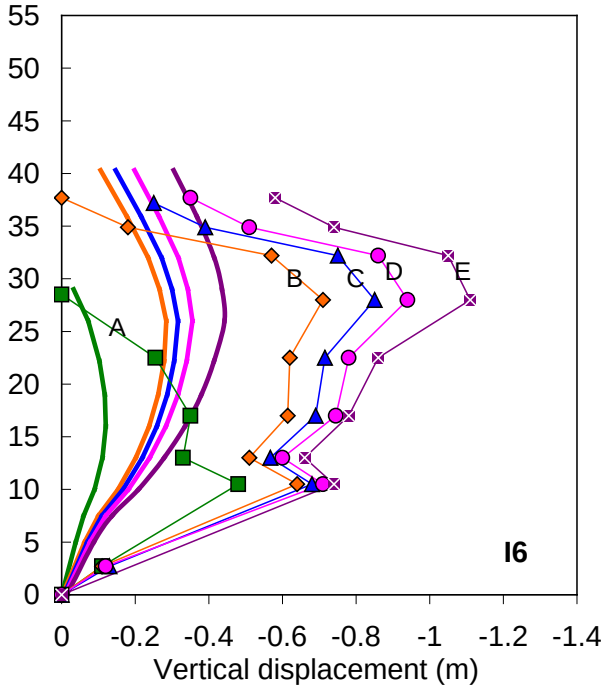
Settlements. Base case



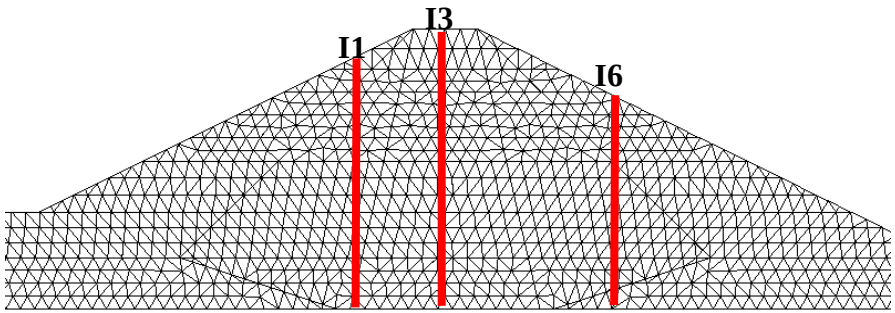
Inclinometer I1

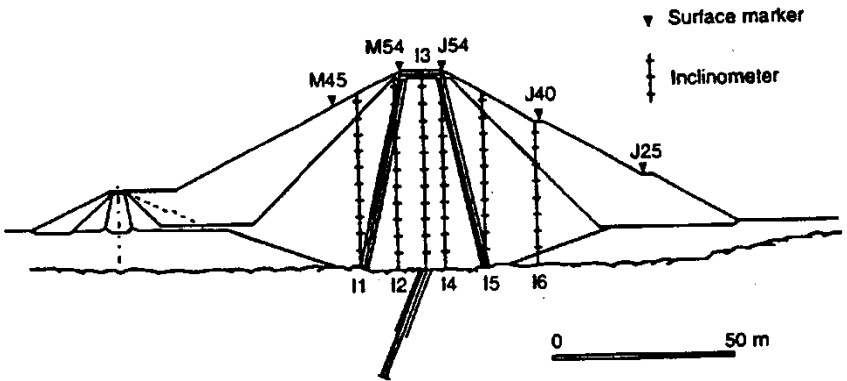


Inclinometer I3



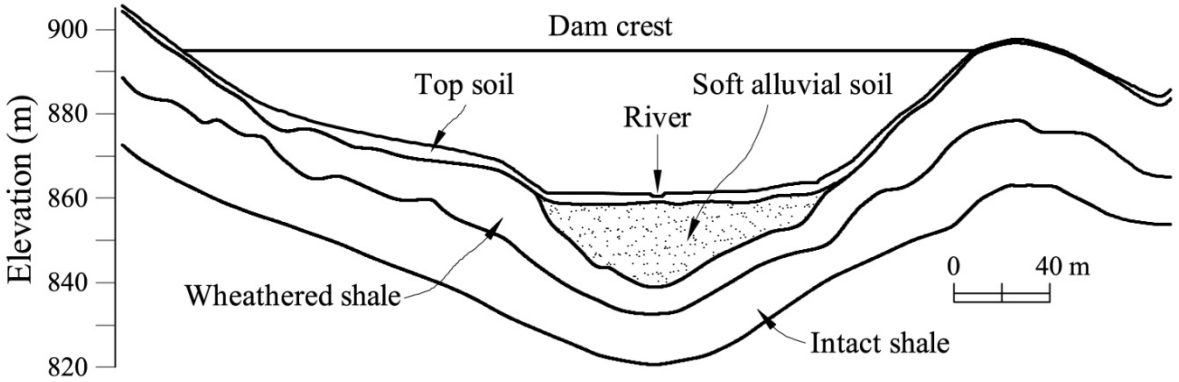
Inclinometer I6



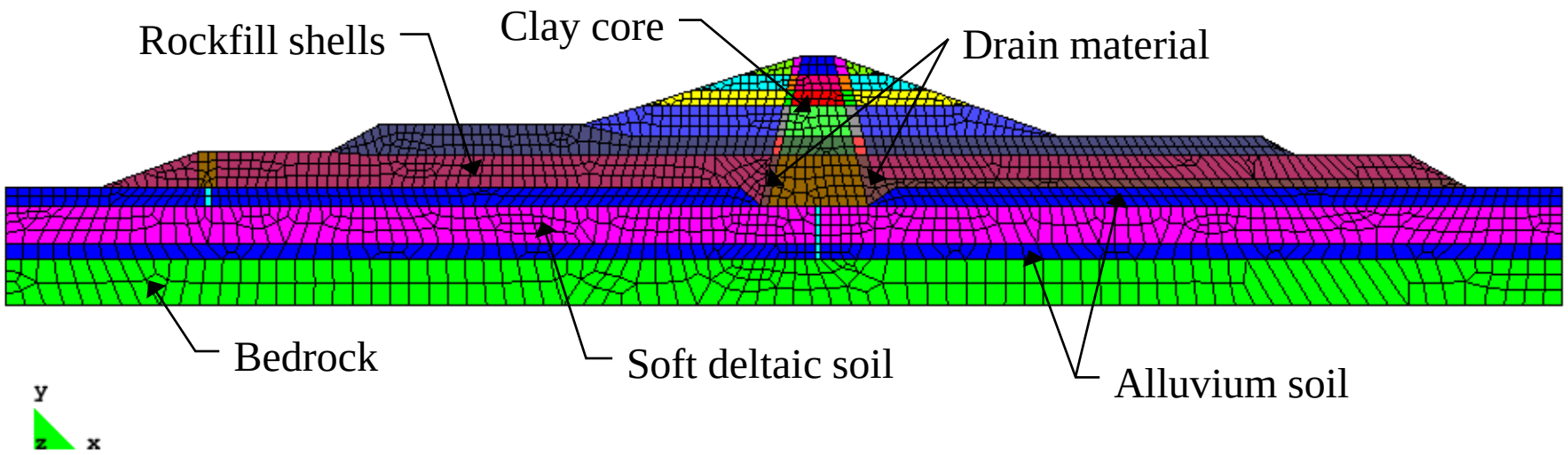


Modelling of Lechago Dam

Central cross-section:



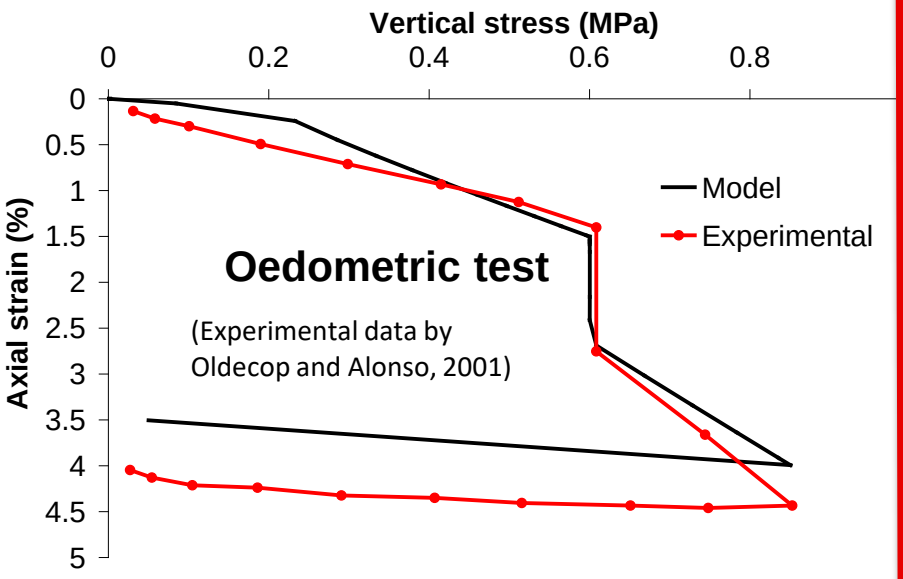
Geometry, materials and mesh:

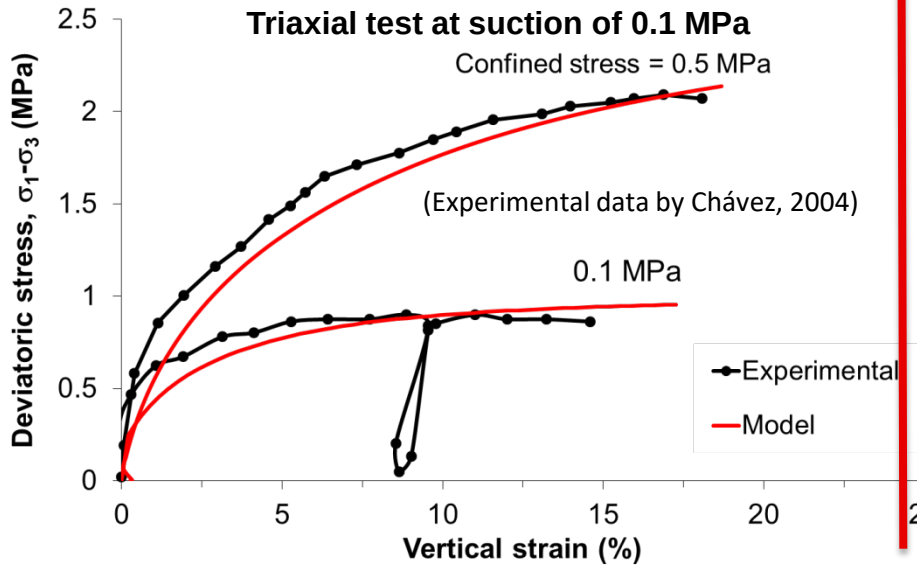


Modelling of Lechago Dam

Rockfill material:

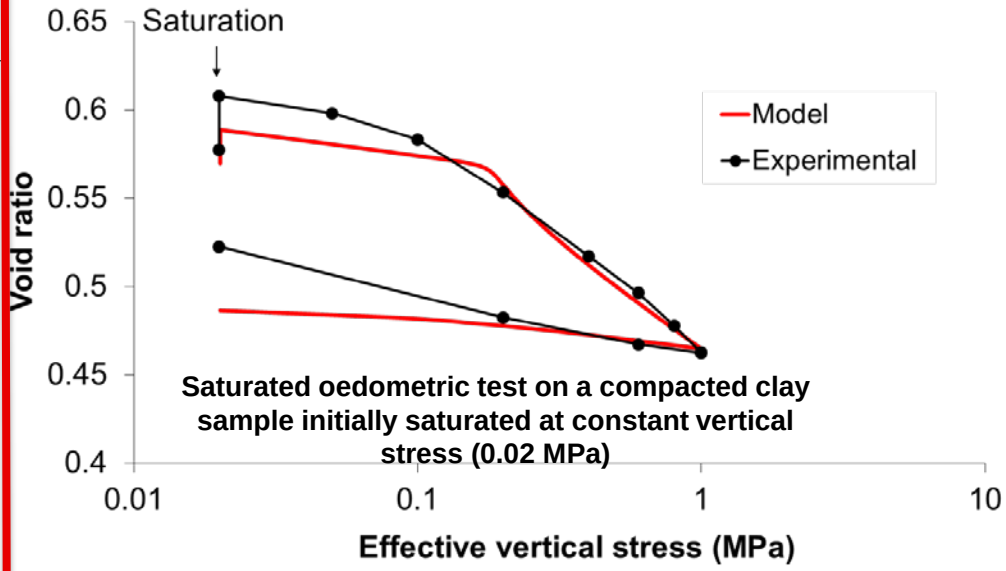
A constitutive model for Rockfill (Oldecop and Alonso, 2000)

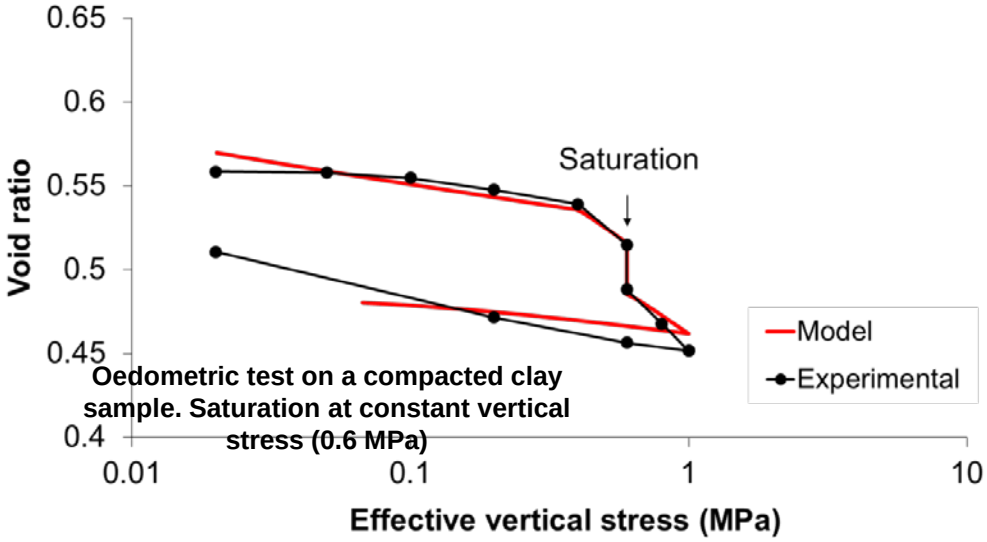




Clay core:

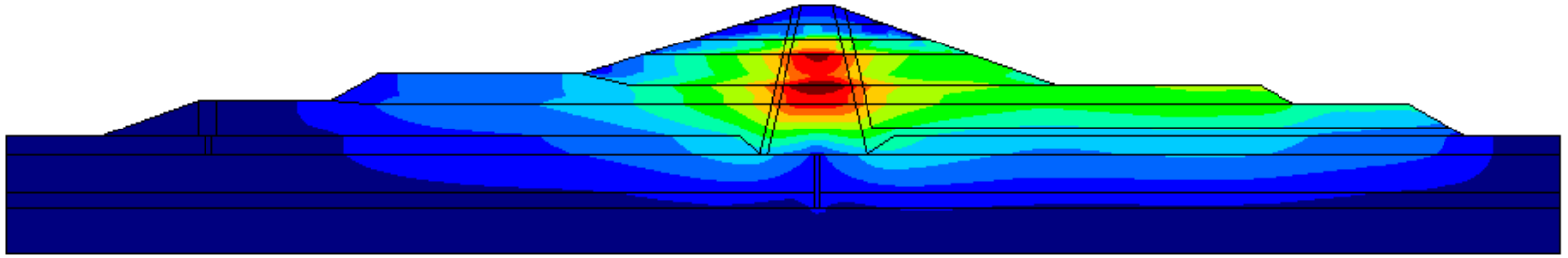
Barcelona Basic Model (Alonso et al.,1990)

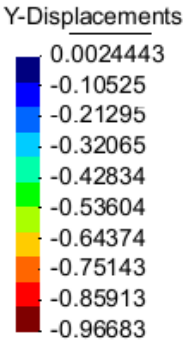


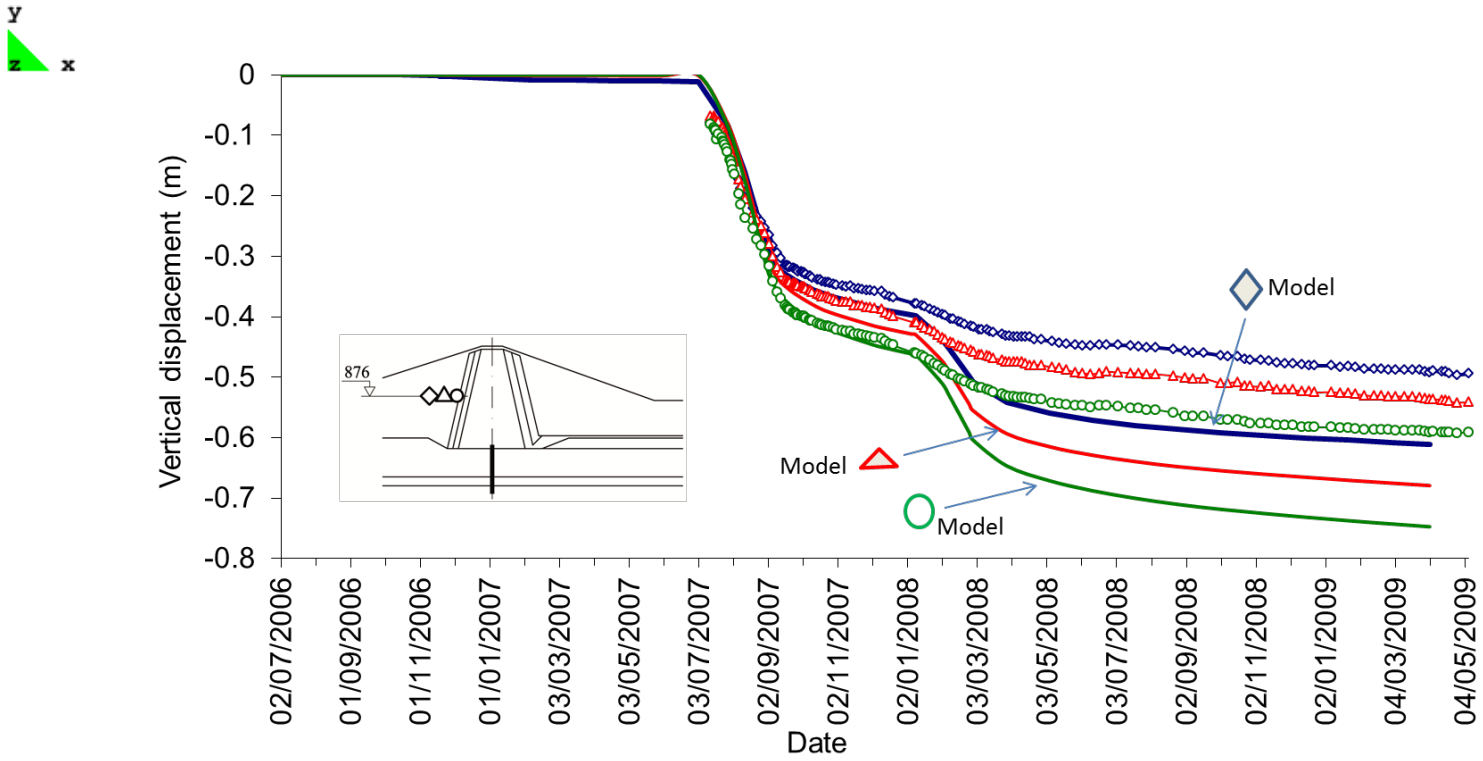


Modelling of Lechago Dam

Hydro-Mechanical response: Vertical displacements

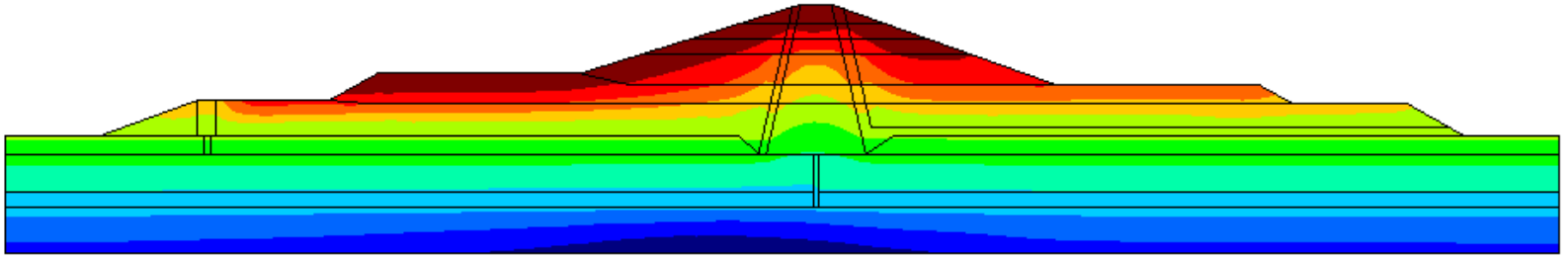


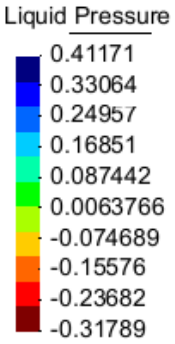


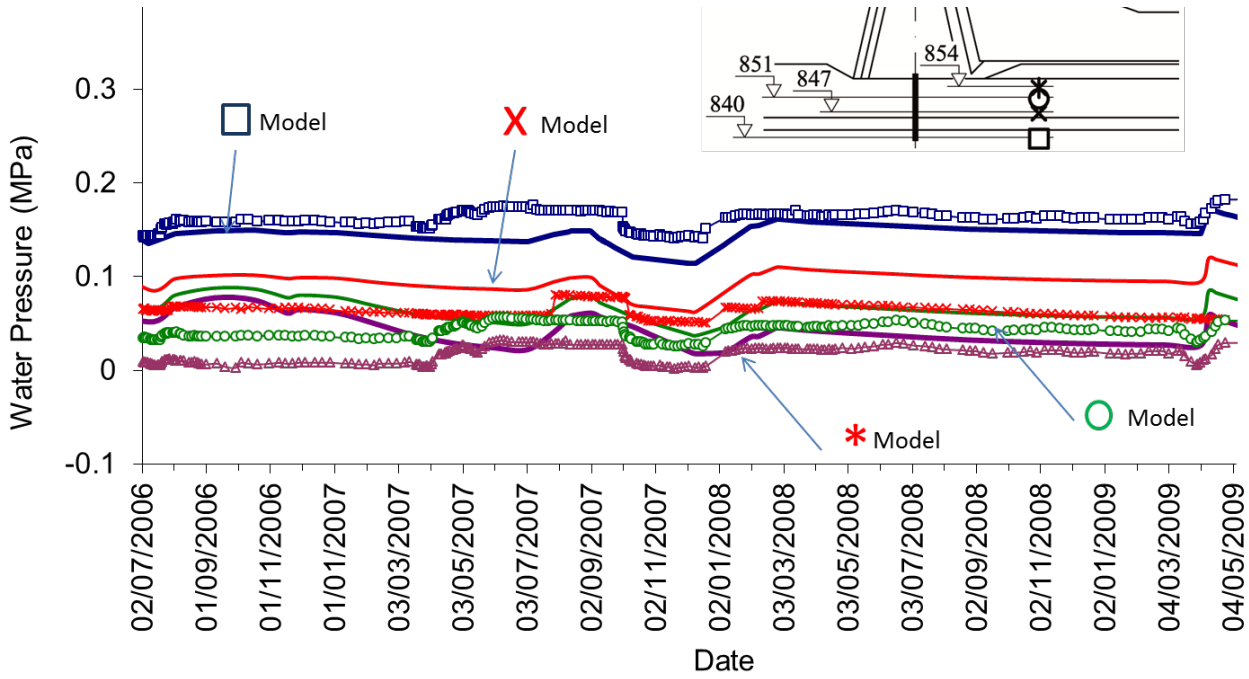


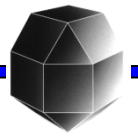
Modelling of Lechago Dam

Hydro-Mechanical response: Pore water pressure









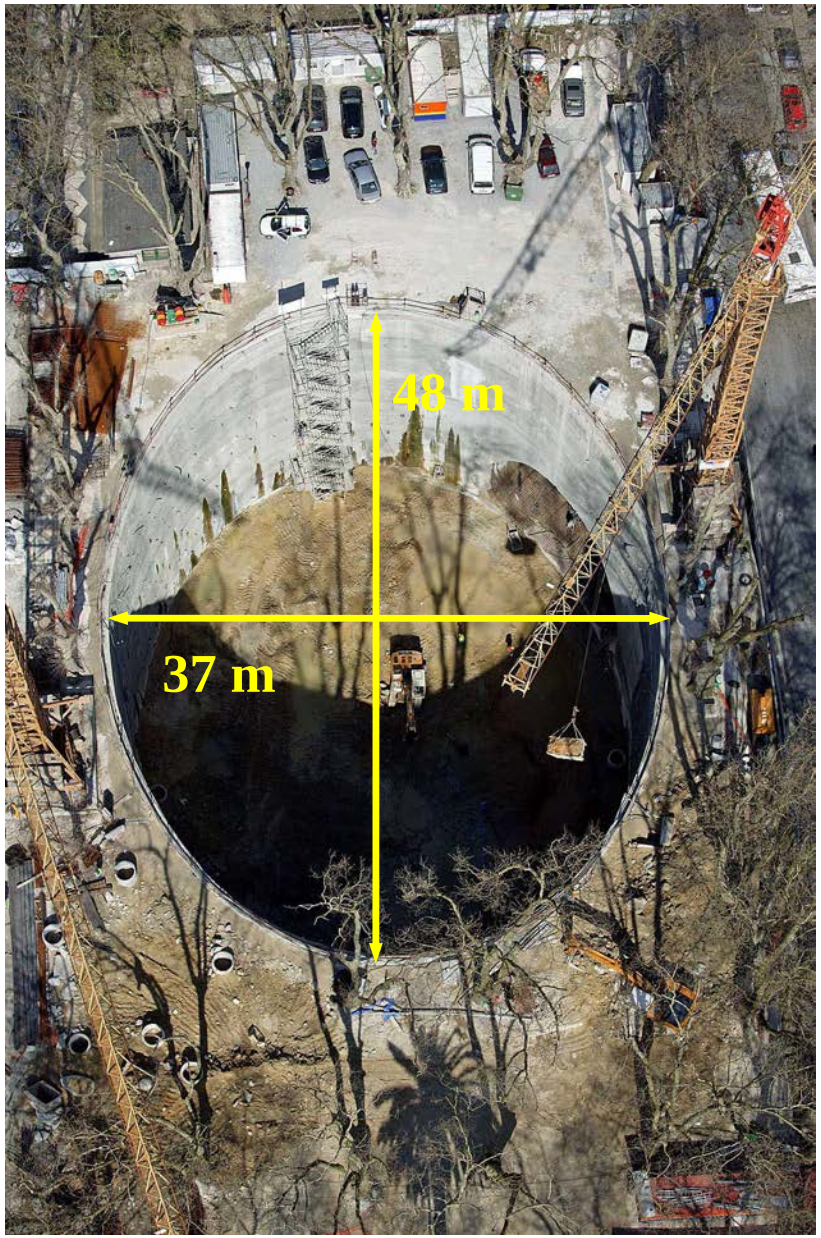
- Thanks for your attention

Sequential excavation

Cut and cover stations

Thickness: from 0.30 m to 0.60 m

Shotcrete + Wiremesh



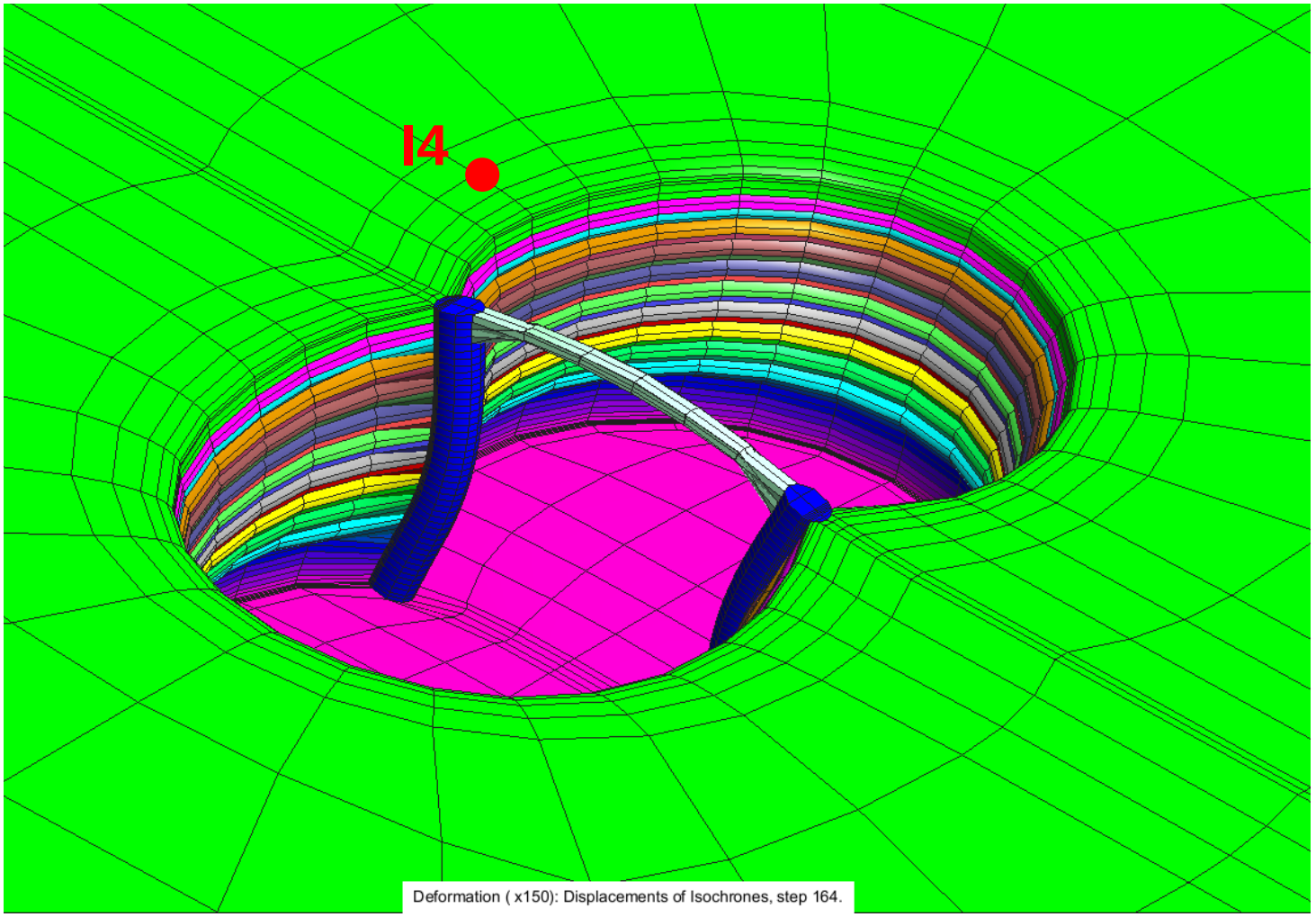
Marquês

Sequential excavation

Sequential excavation of elliptical shaft in unsaturated soil

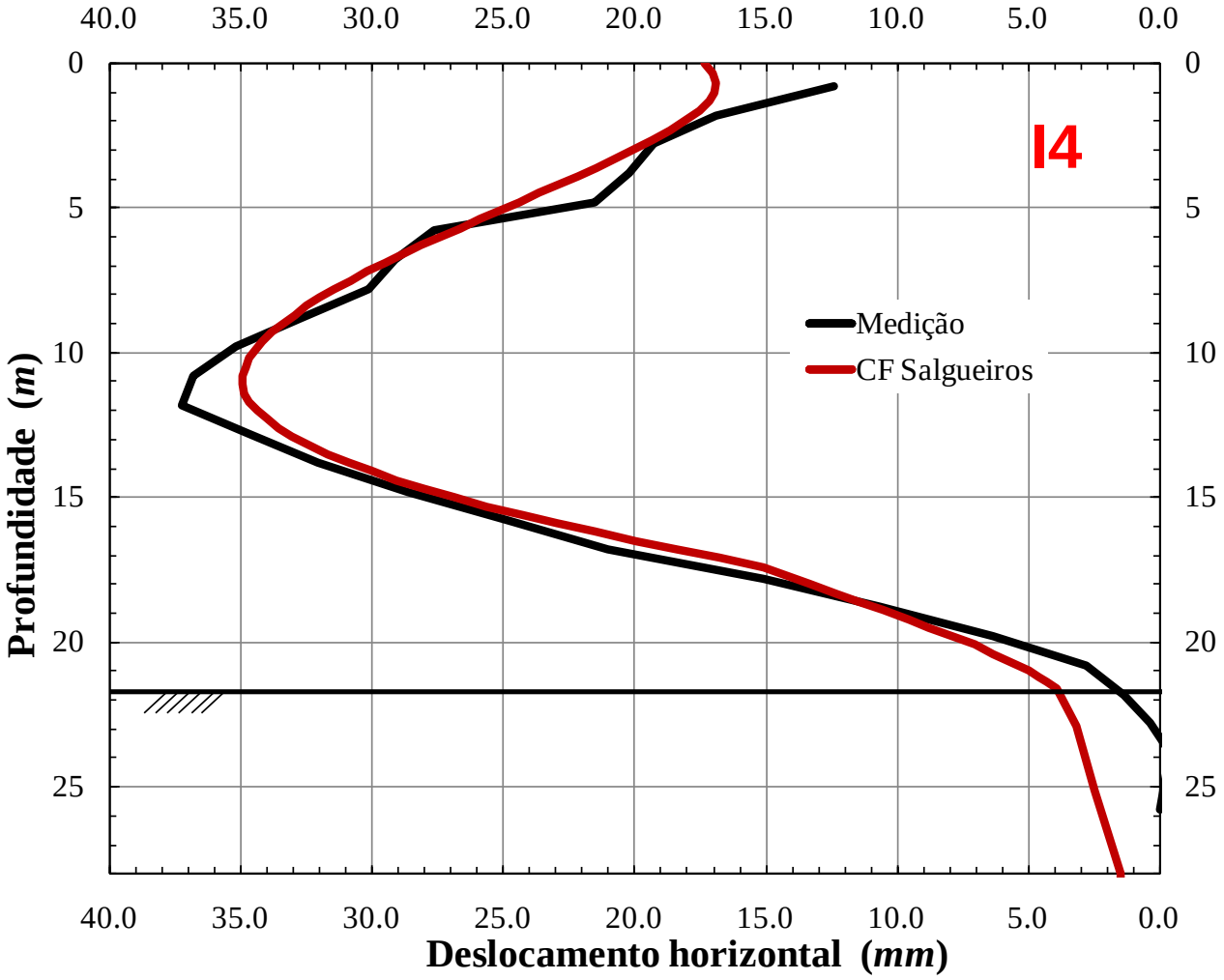
Sequential excavation

- Coupled behaviour of Hydro and Mechanical Phenomena
- Unsaturated conditions: Mohr-Coulomb model
- Stiffness and strength variation with depth



Sequential excavation

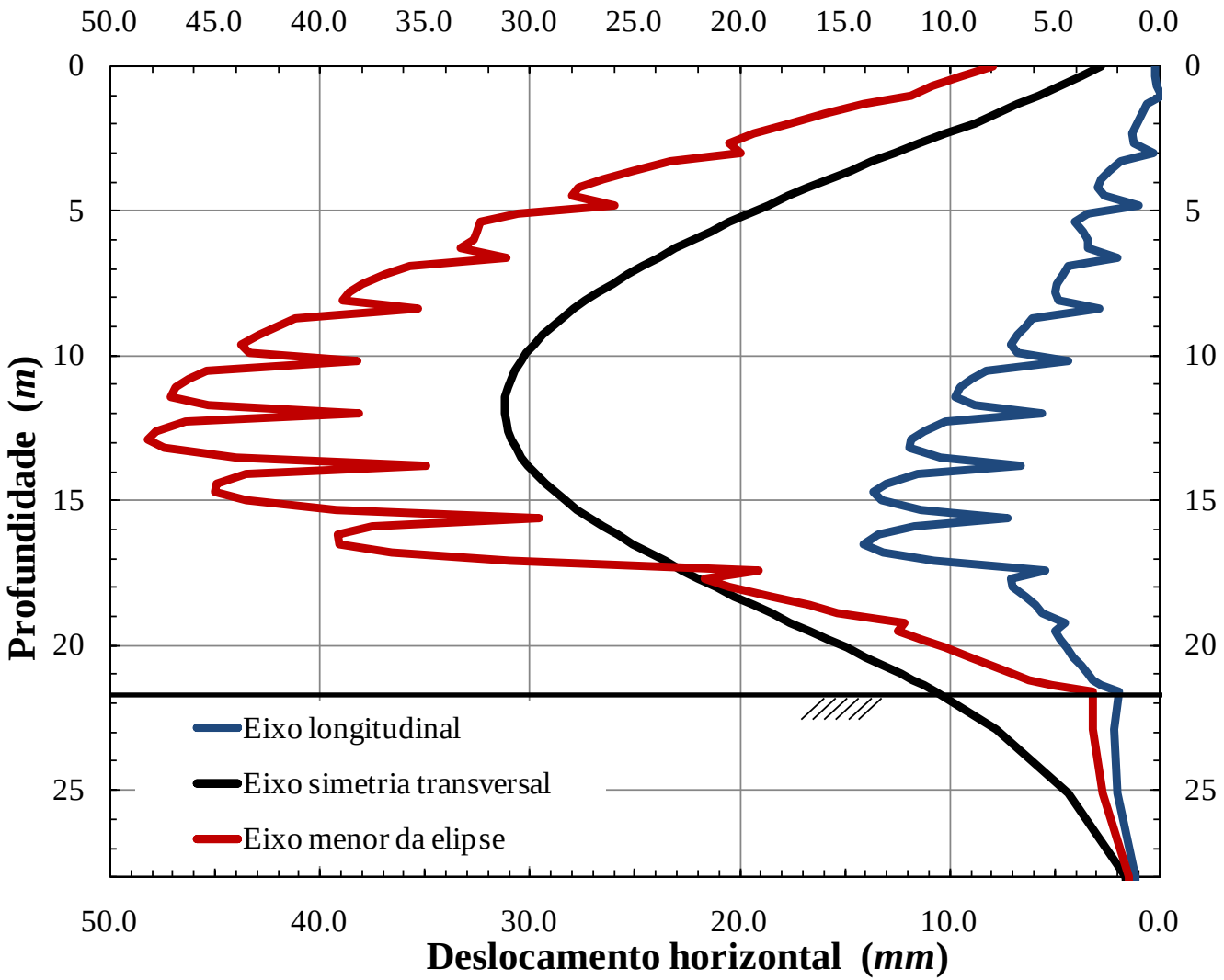
Results: Ground Displacements



- Stiffness variation due to the suction and strain levels
- Higher values of K_0 - 0.7 or even greather
- Stiffness for the vastructural elements

Sequential excavation

Results: Ground Displacements

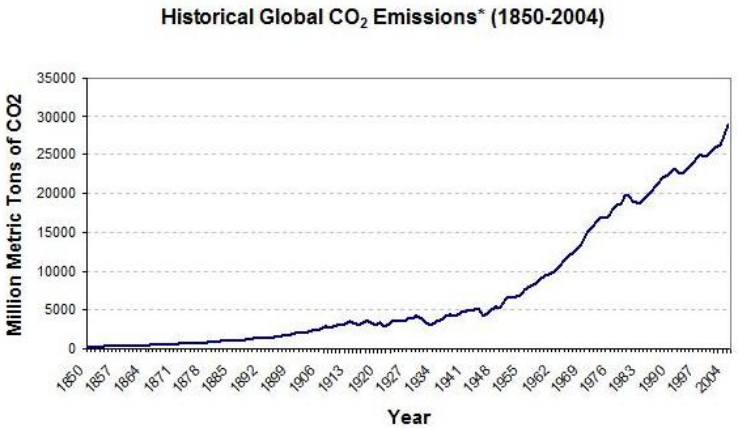


- Complete different behaviour for the different point of the ellipse
- Small shafts, although having 3,30m diameter were very flexible
- Important horizontal movements

CO2 Sequestration

CO_2 emissions have risen dramatically over the last decades

Affection to climate



*from Fuel Burning, Cement Manufacture, and Gas Flaring
Source: Marland et. al (2007) Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. CDIAC U.S.A.

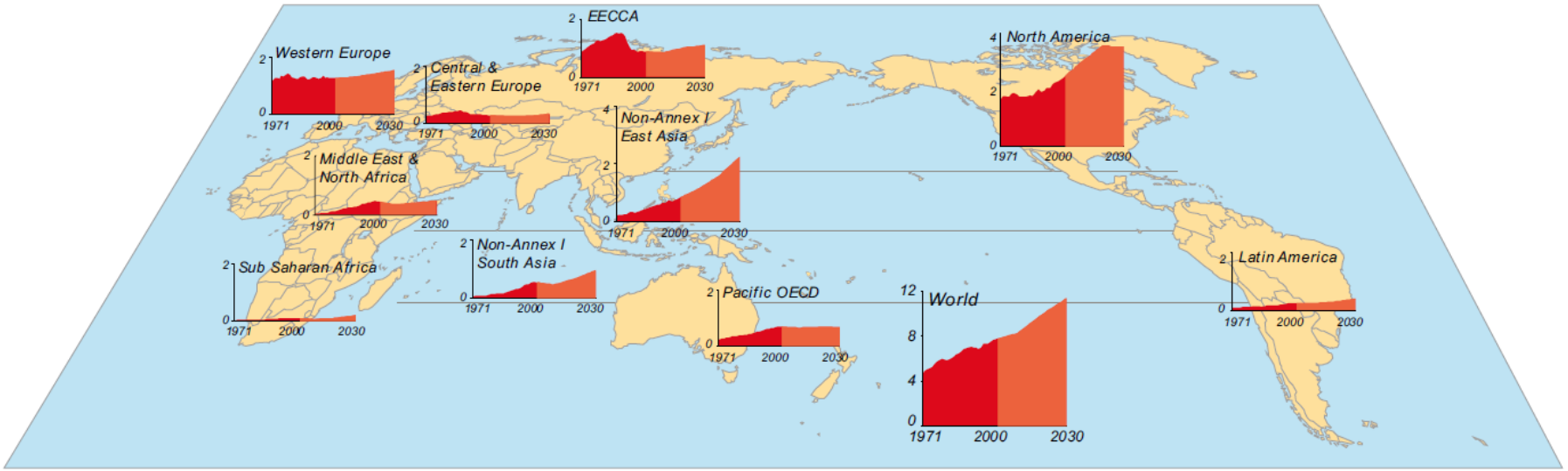


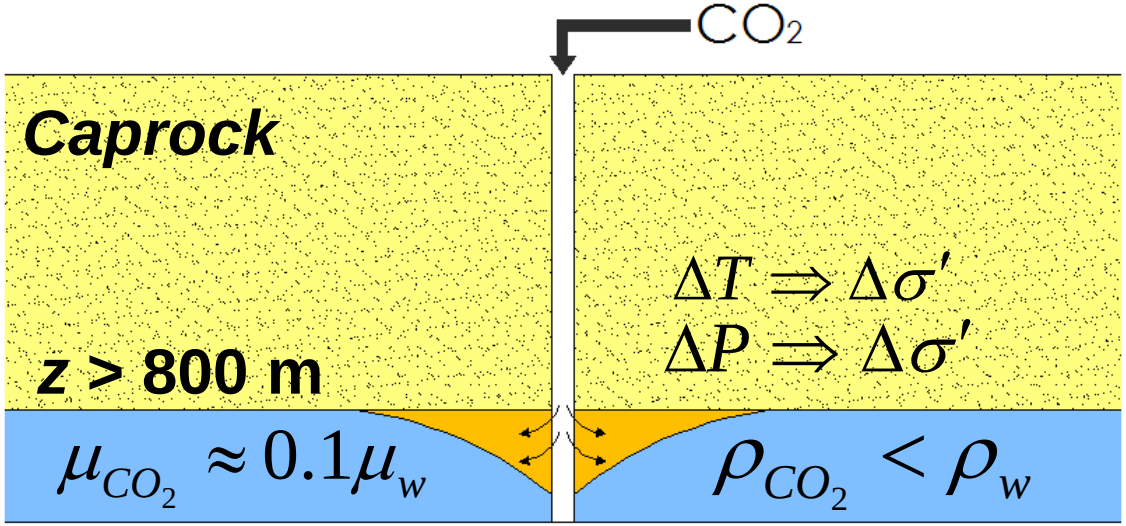
Figure TS.17: *CO_2 emissions ($GtCO_2$) from buildings including emissions from the use of electricity, 1971–2030 [Figure 6.2].*

Note: Dark red – historic emissions; light red – projection according to SRES B2 scenario. EECCA=Countries of Eastern Europe, the Caucasus and Central Asia.

IPCC

INTRODUCTION

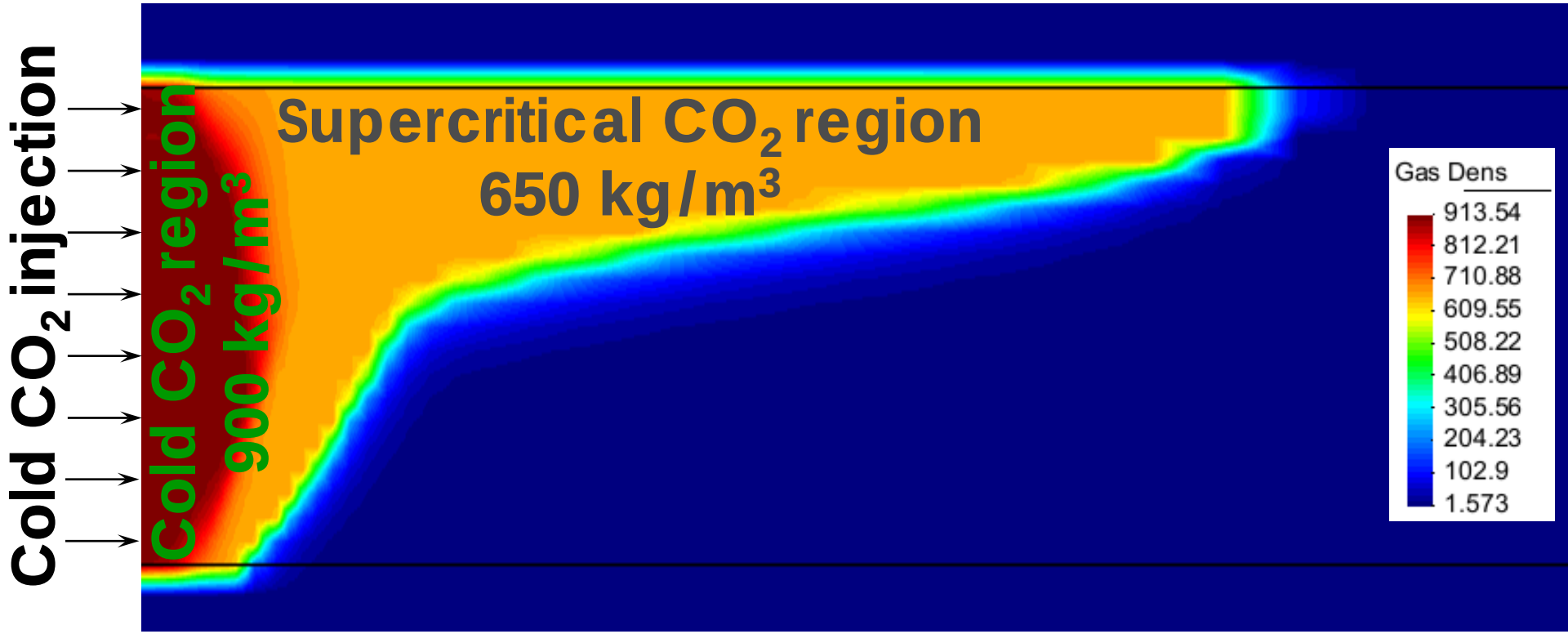
CO_2 Capture & Sequestration (CCS)



Density distribution in an aquifer

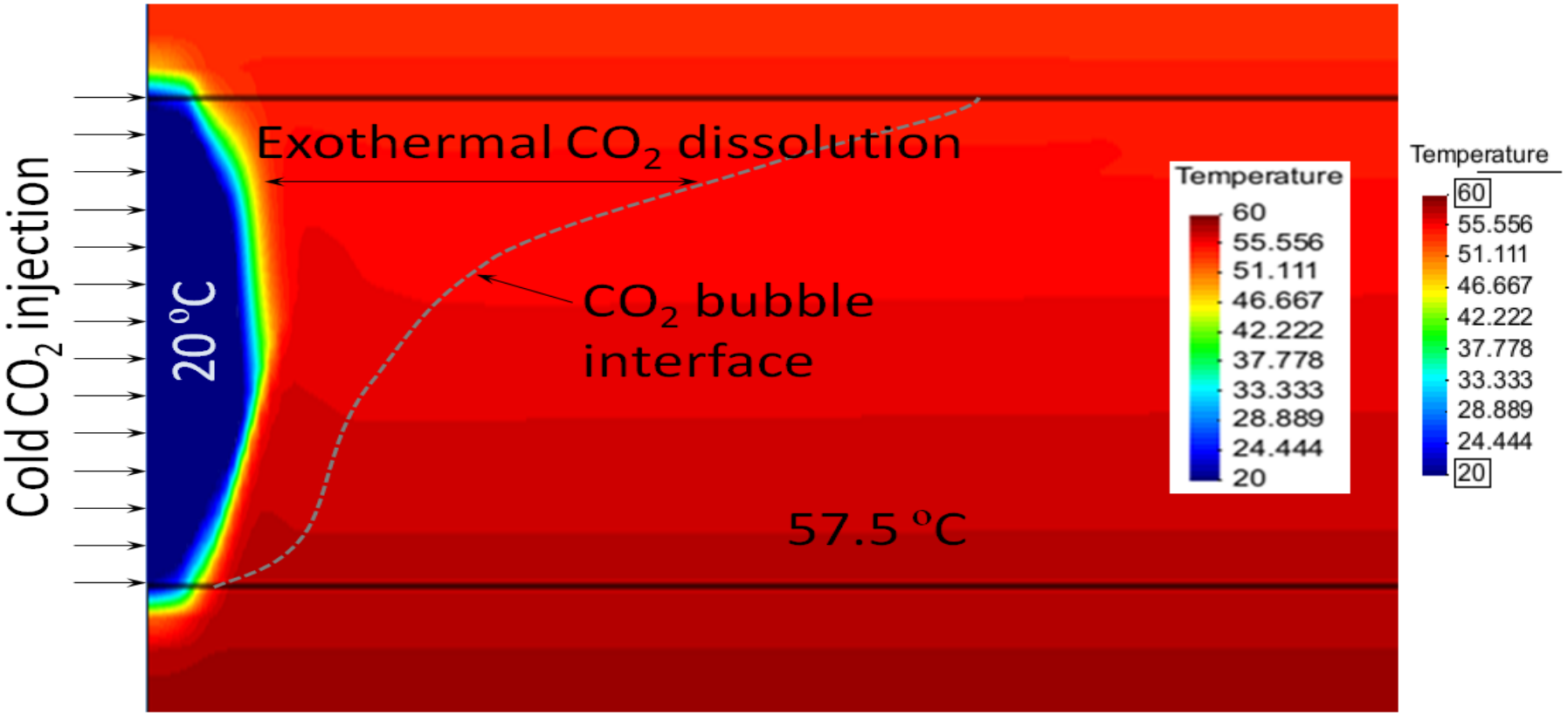
Victor Vilarrasa PhD and related papers on this topic

CO_2 density varies significantly within the CO_2 bubble because of pressure and temperature differences



Temperature distribution

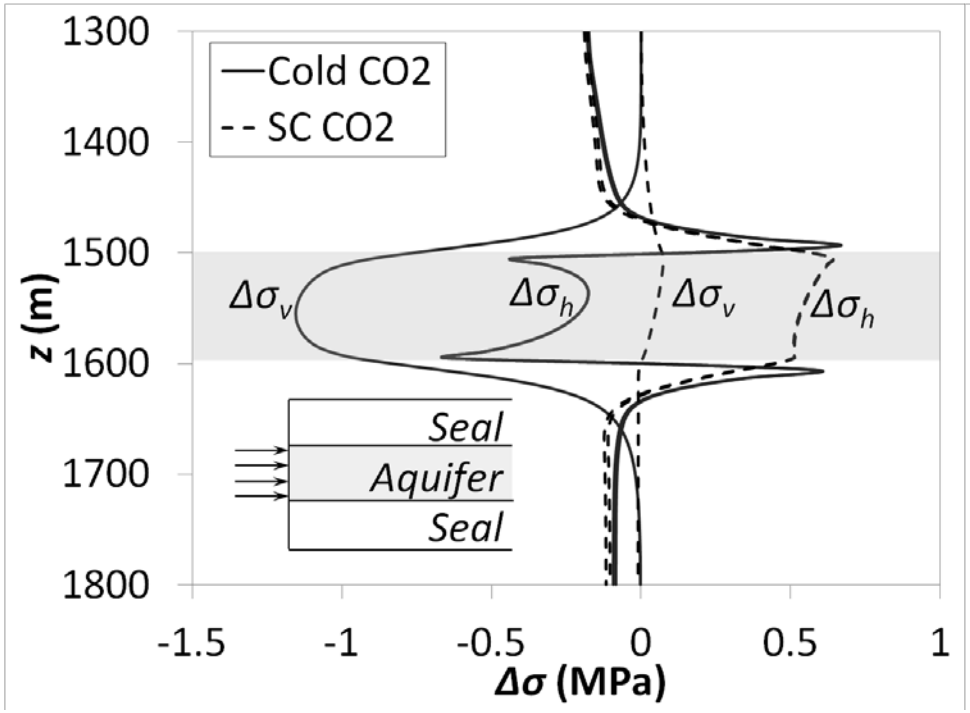
CO2 thermally equilibrates with the formation abruply. CO2 dissolution into the brine increases temperature

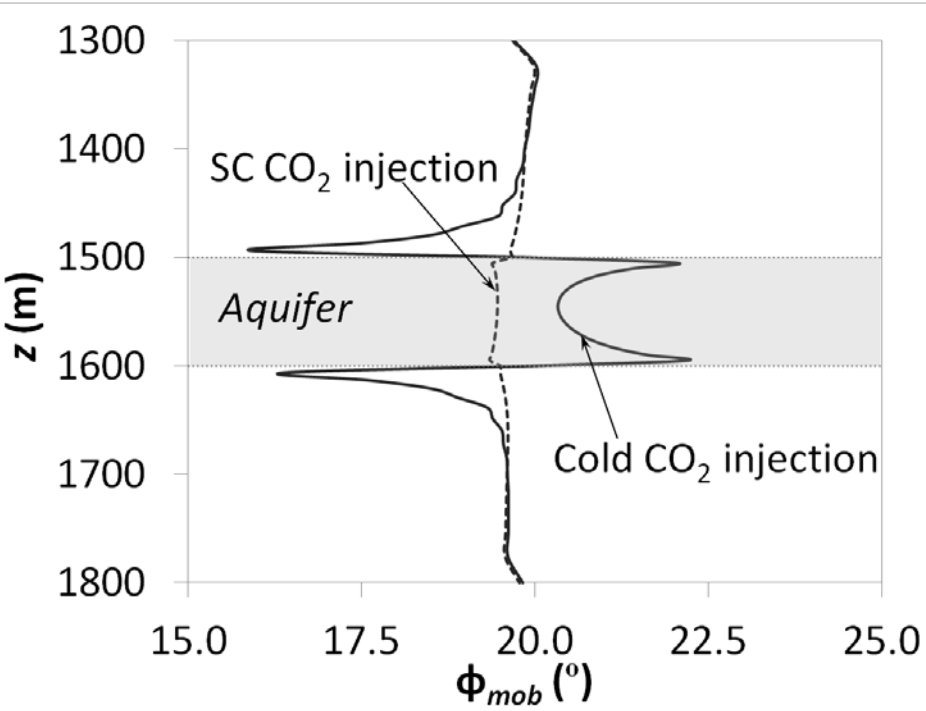


Stress variations caused by injection

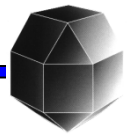
Mechanical stability

Isothermal injection increases horizontal stresses due to lateral confinement. Thermal contraction of the rock decreases both vertical and horizontal stresses. This increases the mobilized friction angle in the aquifer, but decreases it in the caprock.



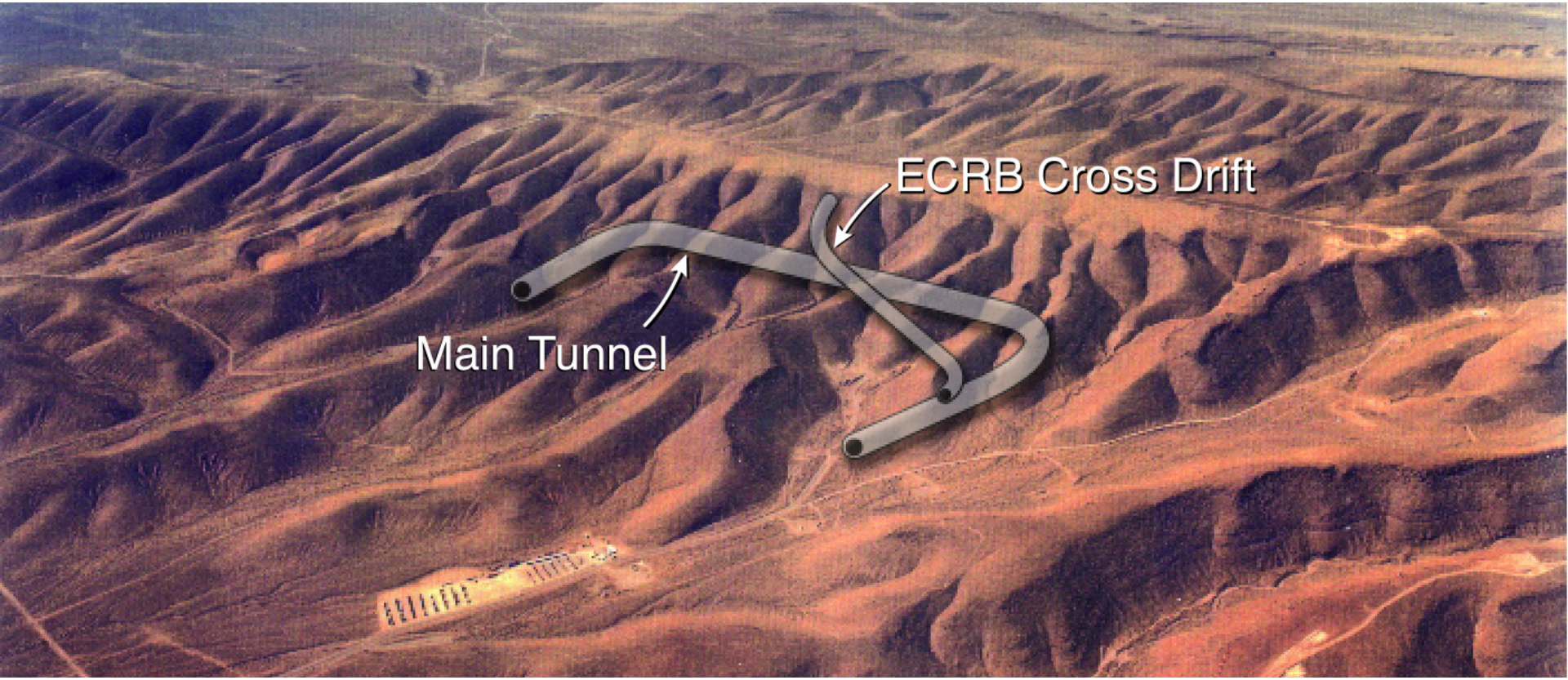


Victor Vilarrasa (PhD at UPC supervised by Carrera and Olivella) received EGU award for contributions on CO2 sequestration



Deep geological repository for high-level nuclear waste

- **THM coupling in the host rock**

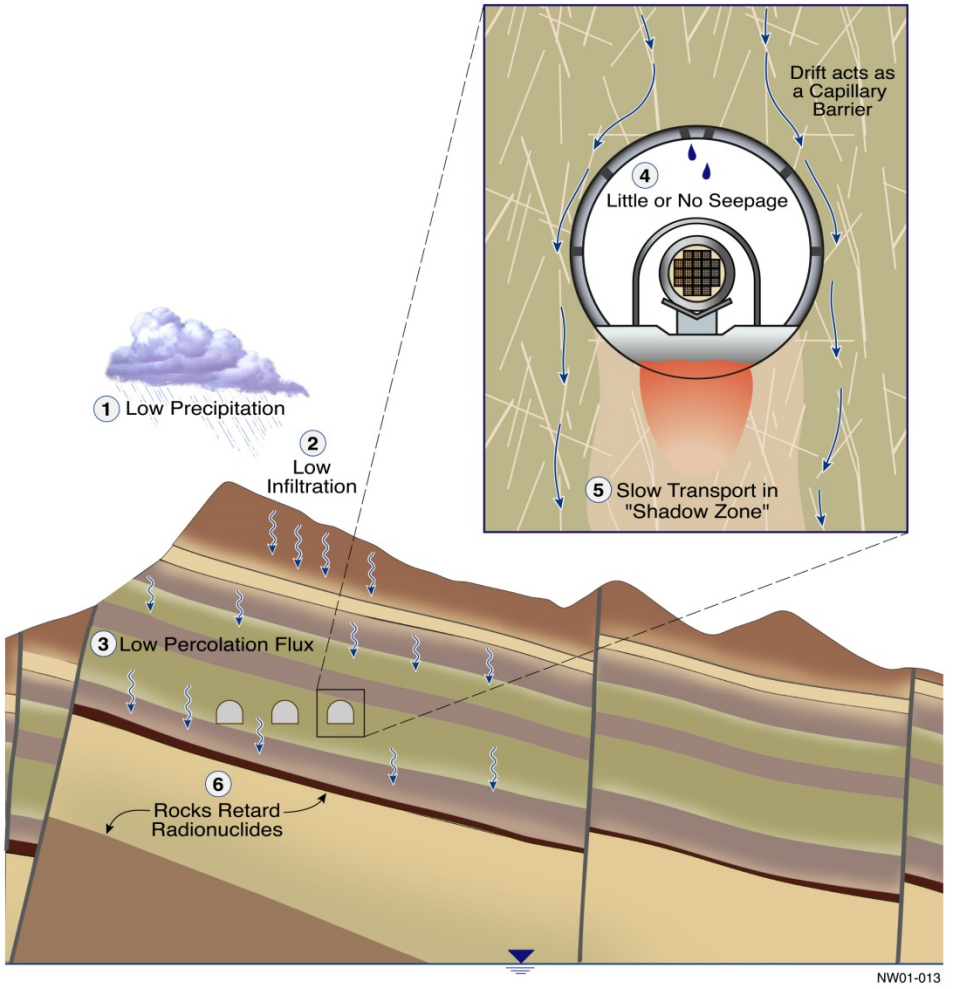


Yucca Mountain, Nevada, US

INTERNATIONAL BENCHMARK – DECOVALEX III

Deep geological repository for high-level nuclear waste

- **Yucca Mountain, Nevada, US**
  - **Unsaturated fractured tuff**
  - **No engineered barrier**



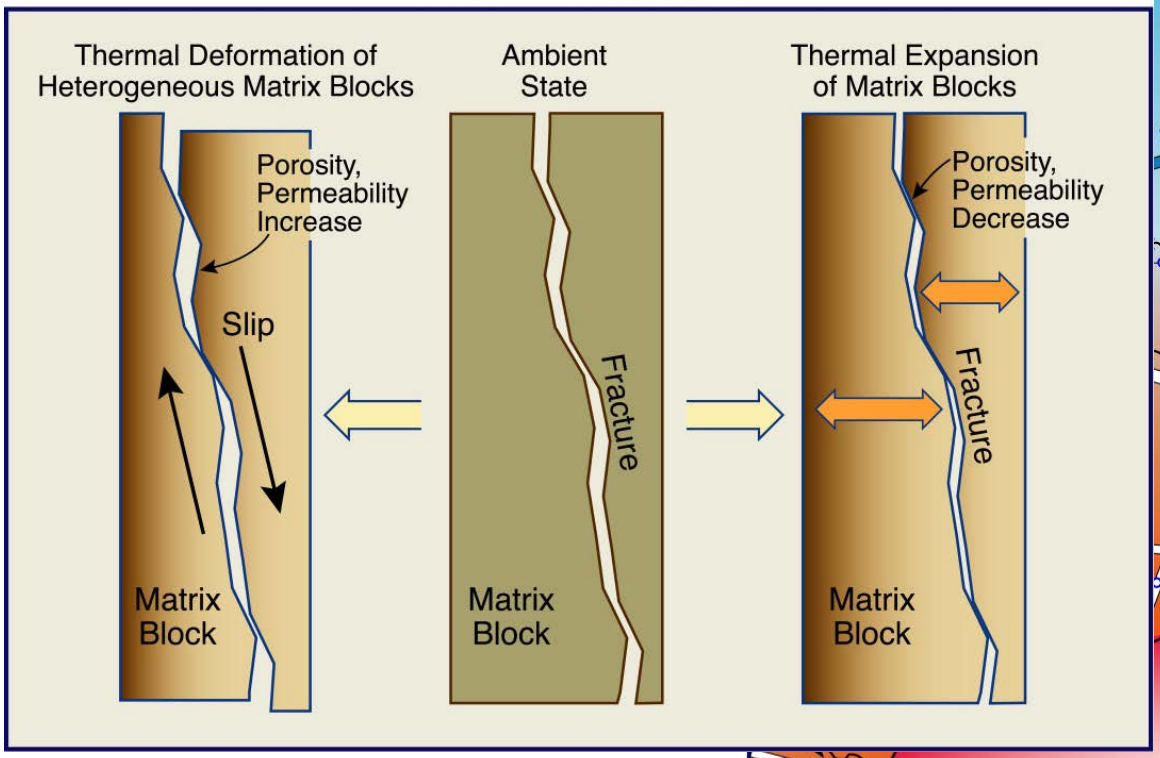
THM coupling in the host rock

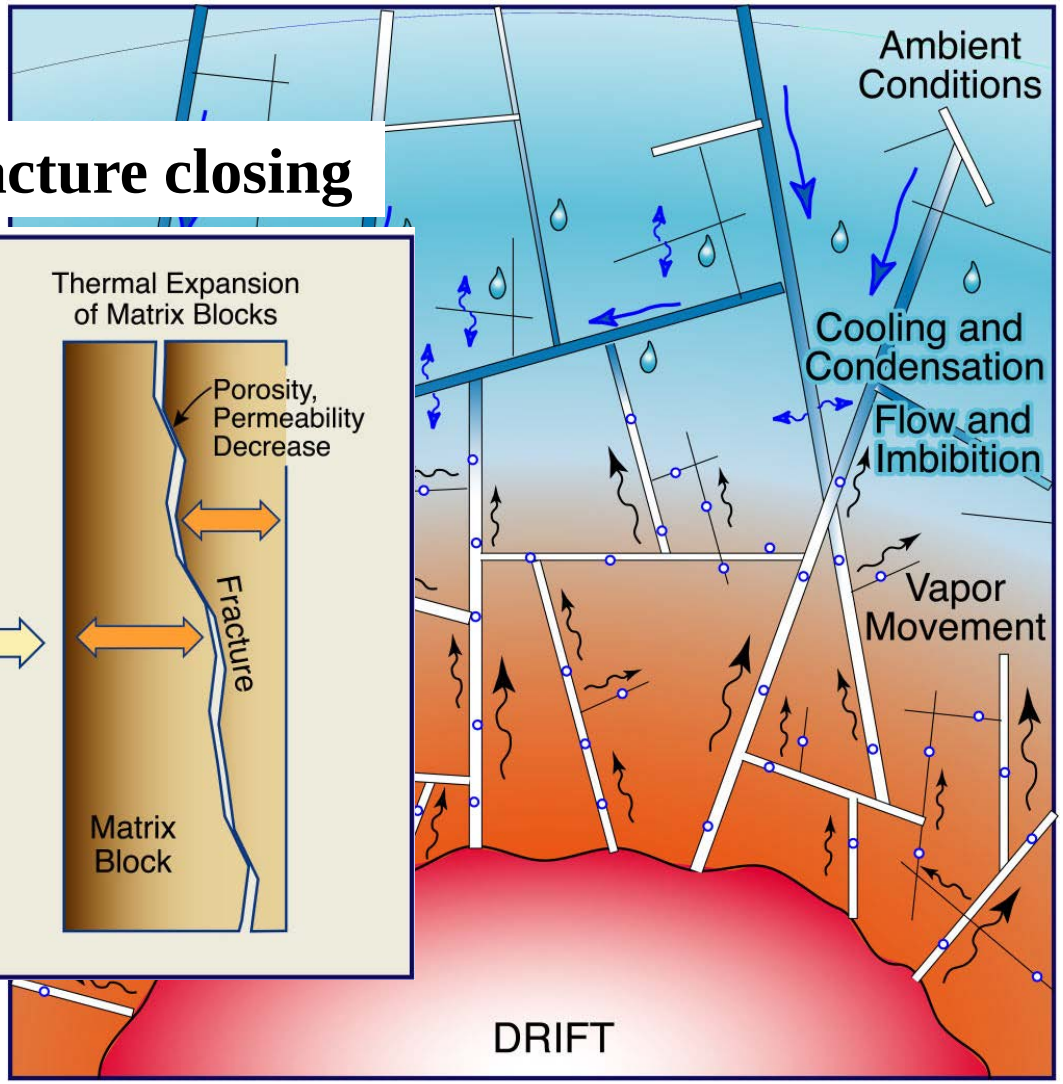
- Evaporation and condensation of water (fractured rock)

- Fracture response to an increase of temperature

Shear slip

Fracture closing





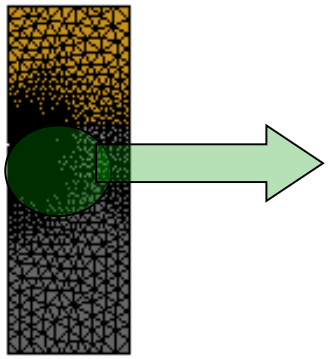
J. Rutqvist & C.-F. Tsang (2003)

FE mesh for double structure THM calculations

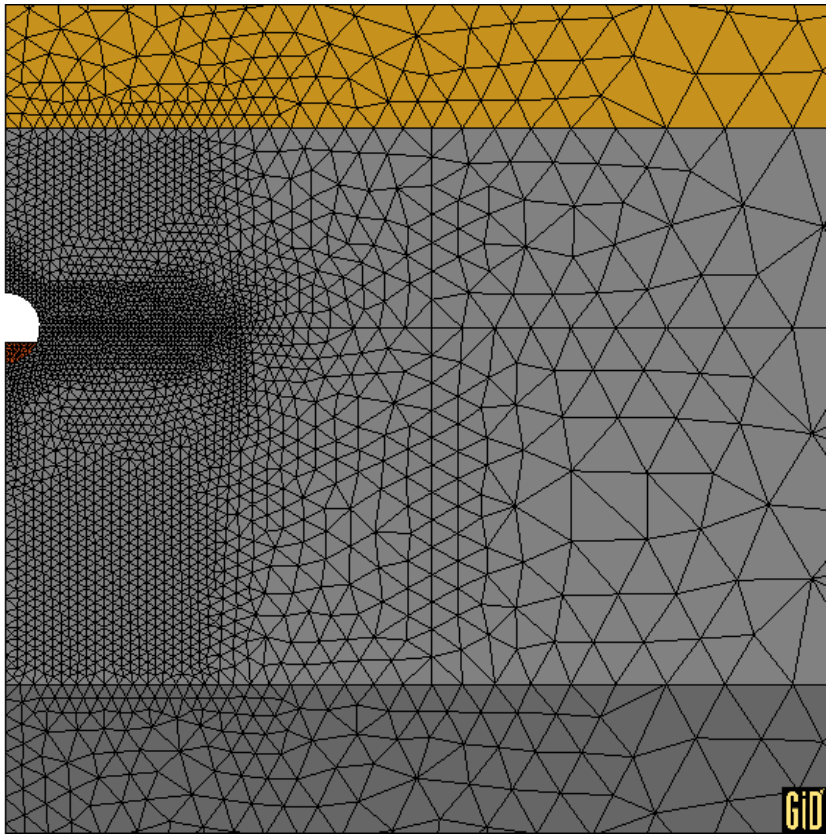
6508 nodes

15973 elements

5 d.o.f.

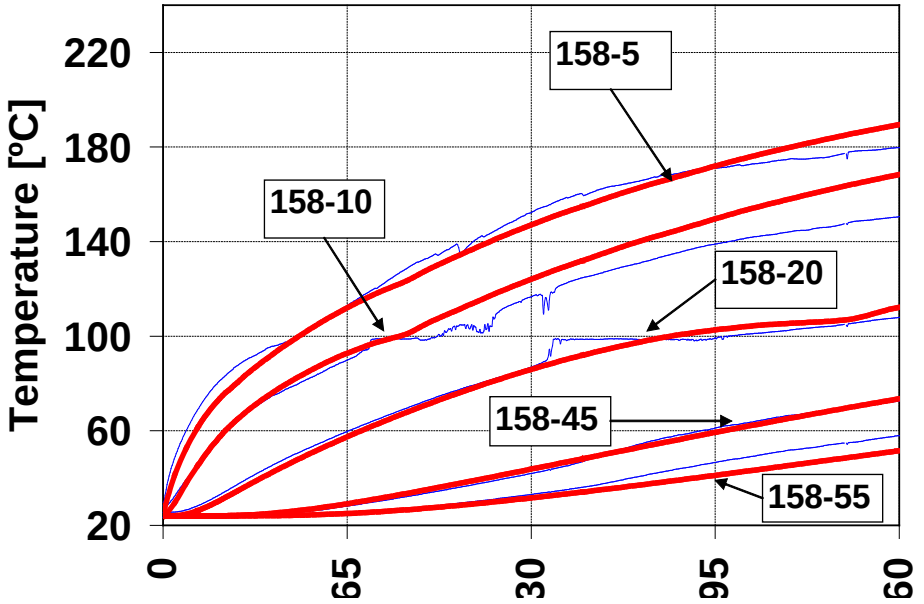


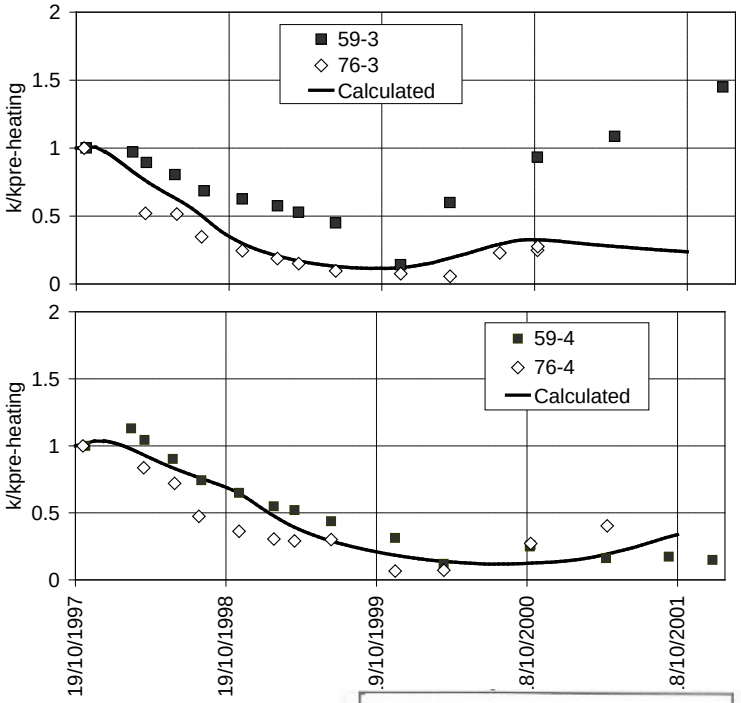
matrix

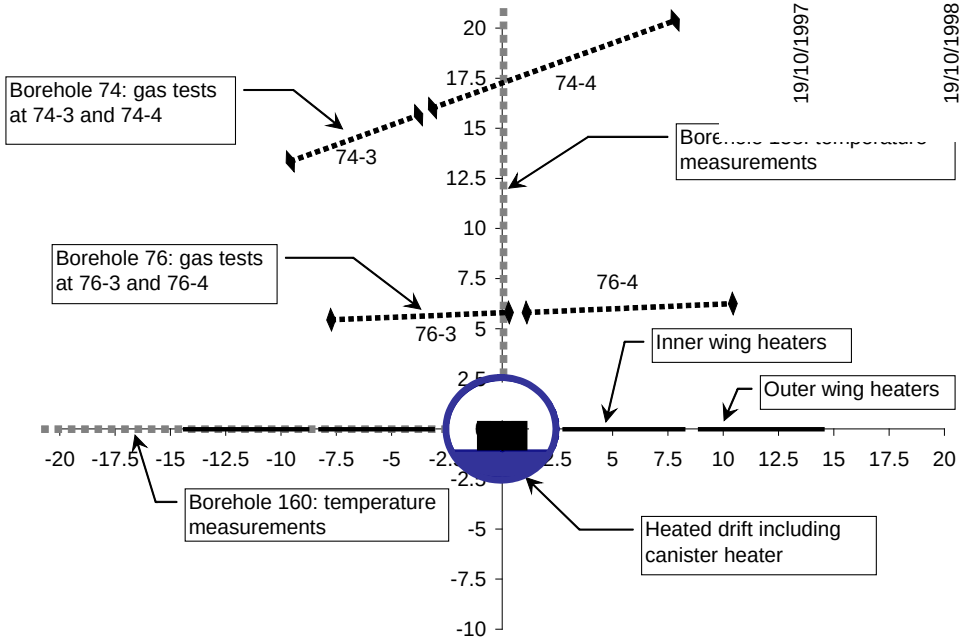


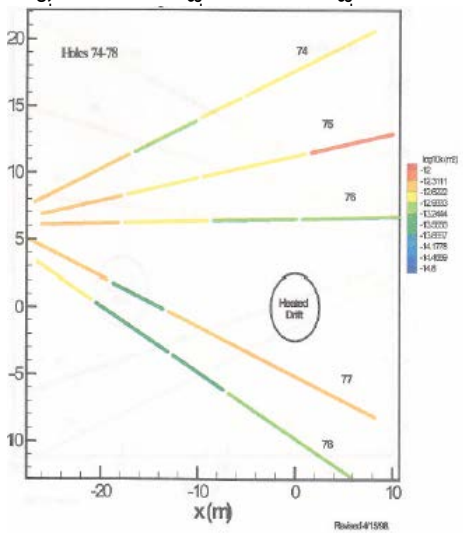
fracture

Temperature variation at Borehole 158
Gas permeability variation at Borehole 59 and 76

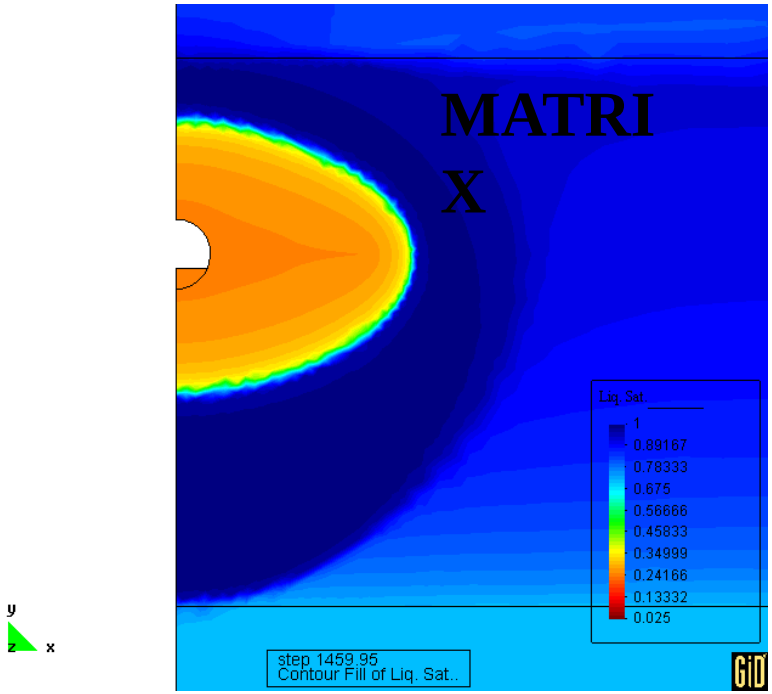


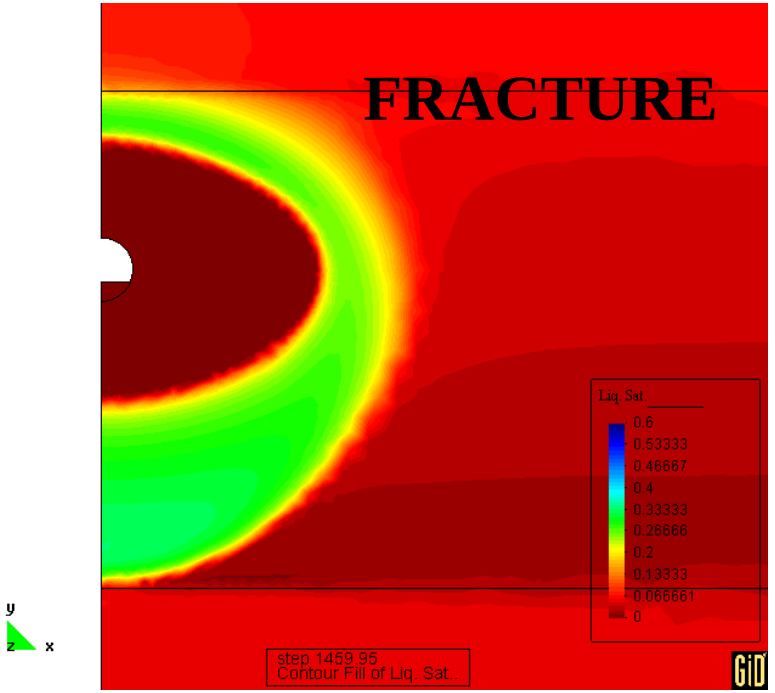






Degree of saturation at 4 year: Matrix and fracture





Different water content per unit volume of pores due to different retention properties

A paper published in IJRMMS was awarded by American Rock Mechanics Association