Modeling of Strain Localization Characteristics in Boom Clay

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« Université de Liège, Belgium »

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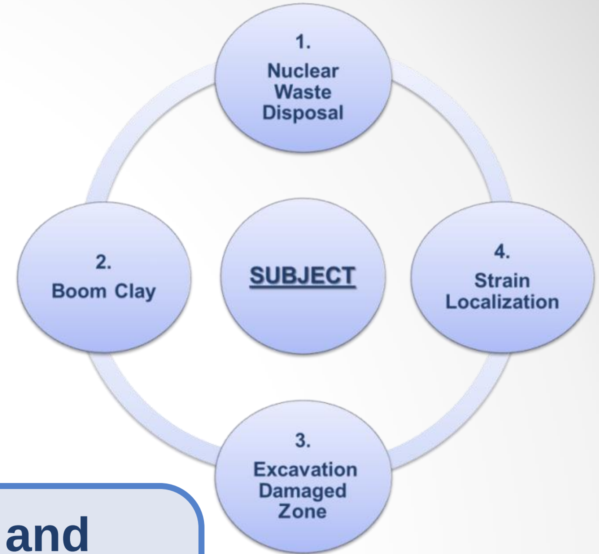
- Context
- Mechanical constitutive laws
- Numerical modeling of strain localization
  - Biaxial compression test
  - Gallery excavation
- Conclusions

- **Context**
- **Mechanical constitutive laws**
- **Numerical modeling of strain localization**
  - **Biaxial compression test**
  - **Gallery excavation**
- **Conclusions**

Excavation Damaged Zone



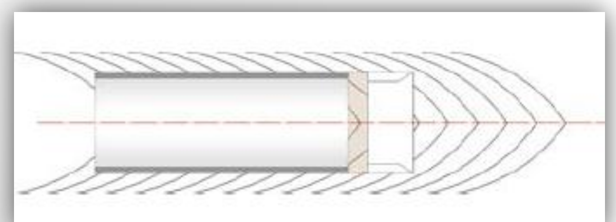
Gallery excavation

Perturbation & stress redistribution

Triggering of fracturing and localized micro-crack propagation & creating the so-called excavation damaged zone (EDZ)

Strain-Localization phenomenon

Altering of the origin host rock's hydro-mechanical properties in EDZ



Fractures observed during the construction of the connecting gallery at the URL in Mol; (EURIDICE report. 2003)

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Strain Localization

Main objective:

- Characterize the damaged zone in the underground structures scale
- Modeling the extension of EDZ and fracturing pattern

Development of Strain Localization bands.

Induced fracturing pattern during the excavation of Praclay gallery, Mol (EIG EURIDICE 2007)

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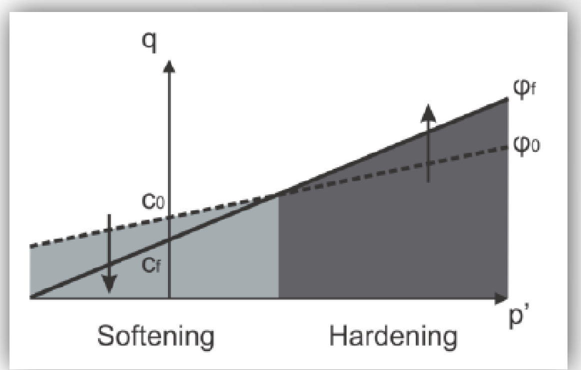
Mechanical model-1st gradient model

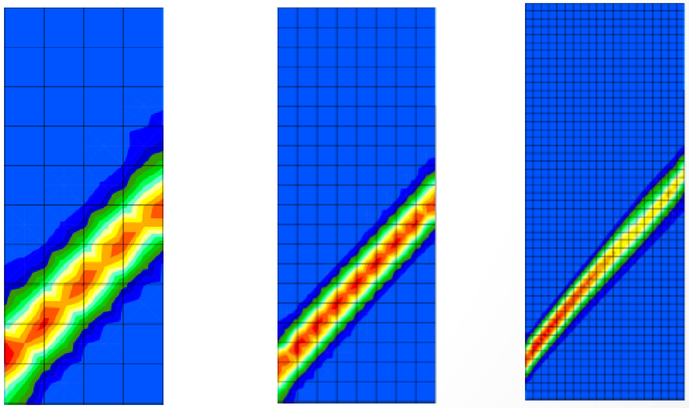
Using the Finite Element code, LAGAMINE:

✓ **Non-associated frictional elasto-plastic model with the Drucker-prager yield surface**



$$F = II_{\hat{\sigma}} + m\left(I_{\sigma} - \frac{3c}{\tan\phi_c}\right) = 0$$

✓ **Mesh size dependency in modeling of strain localization with the classical FE** **(Collin et al. 2009)**



Deviatoric strain:

Elements of 10×4 | **Elements of 20×8** | **Elements of 50×20**

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Mechanical model-2[d] gradient model

- ✓ **Among different regularization methods: Second gradient model (Chambon et al. 1998 & 2001)**

Virtual work equation:

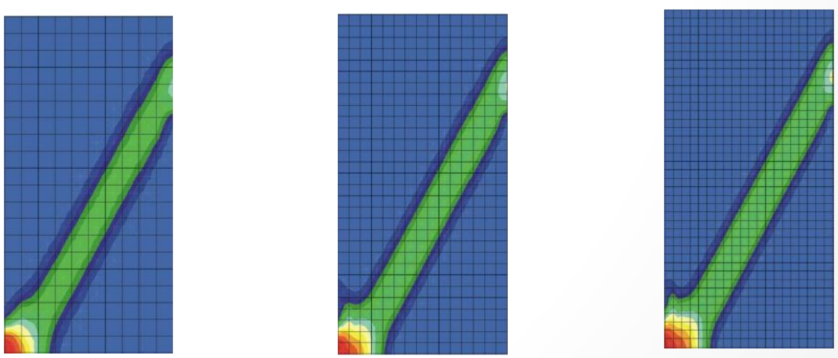
$$\int_\Omega \left(\sigma_{ij} \frac{\partial u_i^*}{\partial x_i} + \Sigma_{ijk} \frac{\partial^2 u_i^*}{\partial x_i \partial x_k} \right) d\Omega = \int_\Omega G_i u_i^* d\Omega + \int_{\Gamma_\sigma} \left(\bar{t}_i u_i^* + \bar{T}_i D u_i^* \right) d\Gamma$$

- ✓ **The shear band width is proportional to new elastic parameter D (Chambon et al. 1998 & Kotronis et al. 2007).**

$$\widetilde{\Sigma_{ijk}} = f\left(D, \frac{\partial^2 u_i^*}{\partial x_j \partial x_k} \right)$$

- ✓ **No mesh dependency!**

Deviatoric strain:



Elements of 20×10 | **Elements of 30×15** | **Elements of 40×20**

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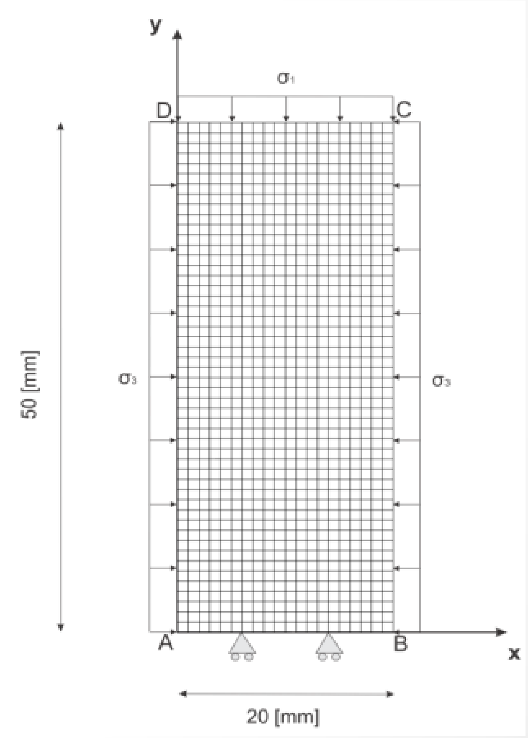
Strain localization in a biaxial compression test

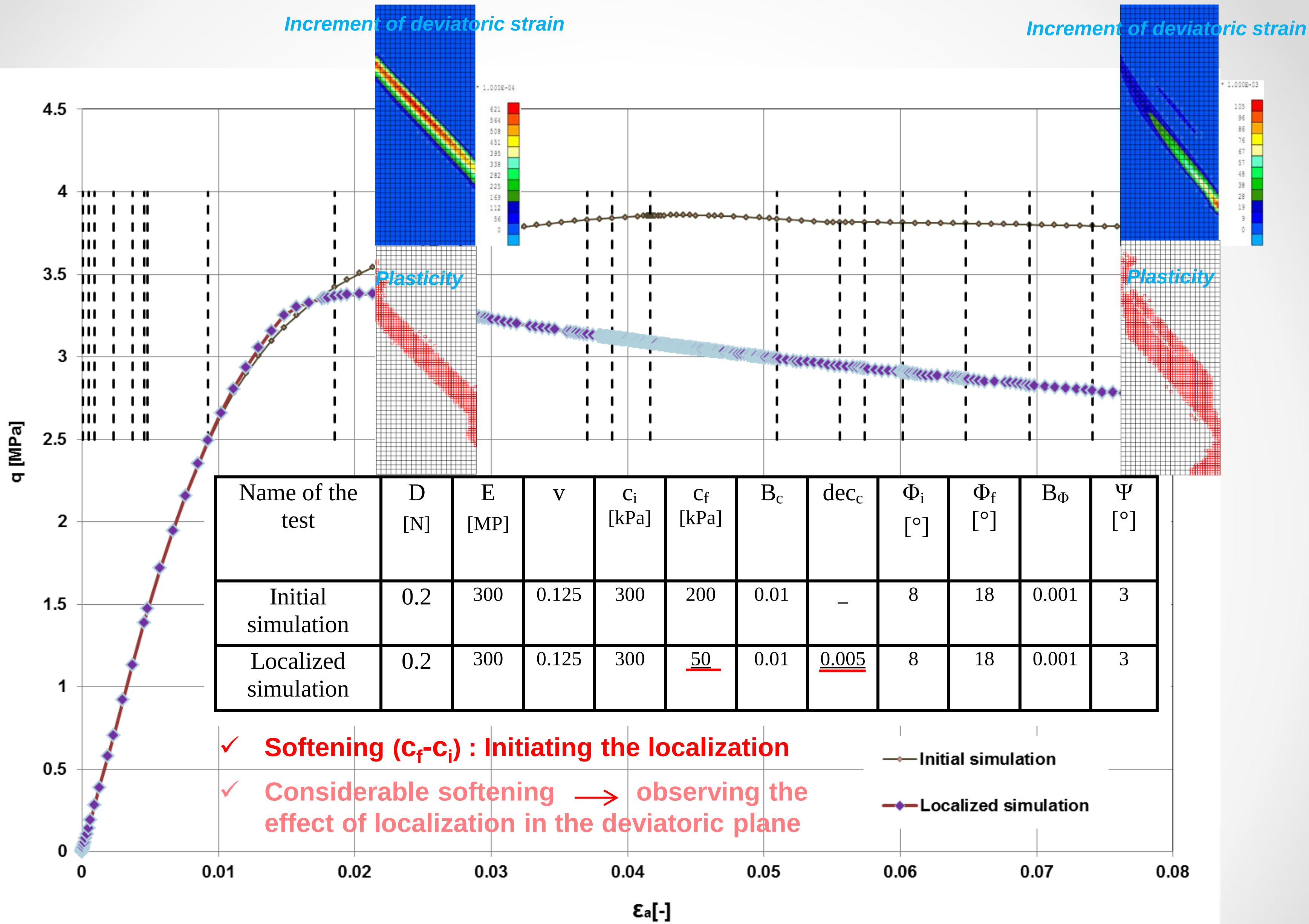
- ✓ **Modeling of the drained biaxial compression test**
- ✓ **2D plane strain simulation**
- ✓ **σ_3=2.3 MPa**

Ultimate displacement=4 mm



E' [MP]	v'	c_i' [kPa]	c_f' [kPa]	B_c	Φ_i' [°]	Φ_f' [°]	B_Φ	Ψ' [°]
300	0.125	300	200	0.01	8	18	0.001	3

(Bernier et al. 2007)



Name of the test	D [N]	E [MP]	v	c_i [kPa]	c_f [kPa]	B_c	dec_c	Φ_i [°]	Φ_f [°]	B_Φ	Ψ [°]
Initial simulation	0.2	300	0.125	300	200	0.01	–	8	18	0.001	3
Localized simulation	0.2	300	0.125	300	50	0.01	0.005	8	18	0.001	3

- ✓ **Softening (c_f-c_i) : Initiating the localization**
- ✓ **Considerable softening → observing the effect of localization in the deviatoric plane**

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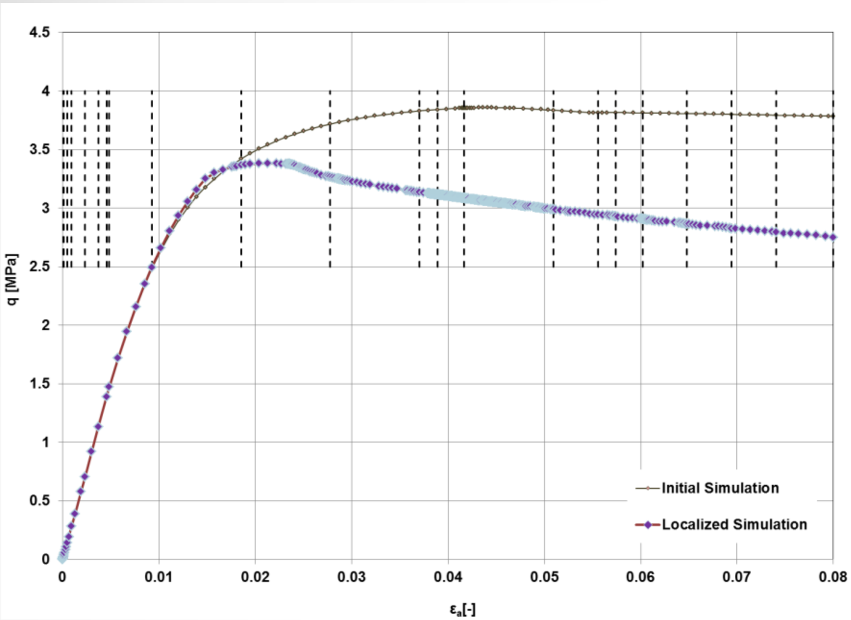
With BC parameters



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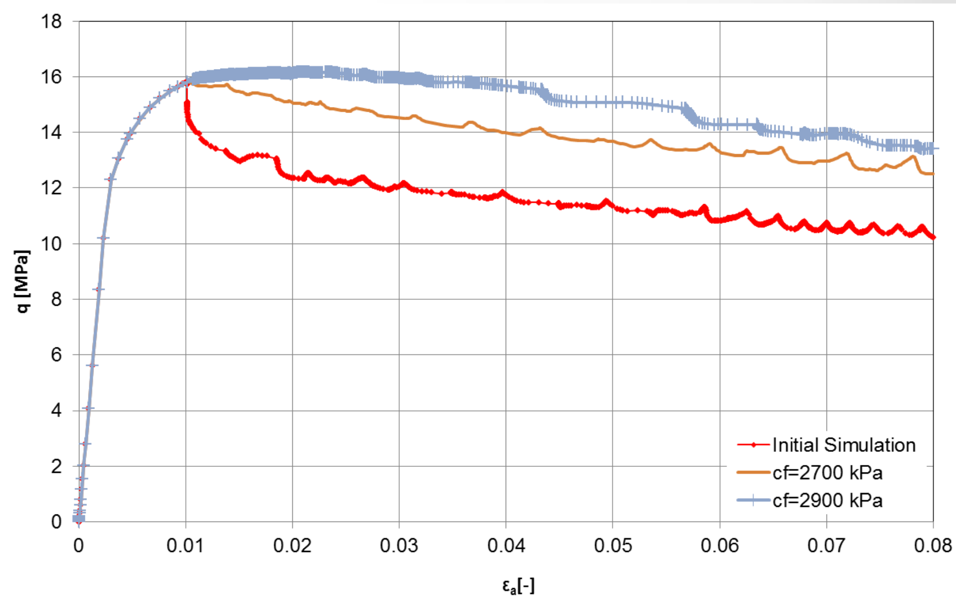
With Cox parameters



Name of the test	D [N]	E [MP]	v	c_i [kPa]	c_f [kPa]	B_c	dec_c	Φ_i [°]	Φ_f [°]	B_Φ	Ψ' [°]
Initial Simulation	**0.5**	**4000**	**0.3**	**3000**	**2000**	**0.01**	**0.0085**	**15**	**20**	**0.002**	**0.5**
C_f=2700 KPa	0.5	4000	0.3	3000	2700	0.01	0.0085	15	20	0.002	0.5
C_f=2900 KPa	0.5	4000	0.3	3000	2900	0.01	0.0085	15	20	0.002	0.5

1. Intermediate conclusion: → ***Origin properties of the host rock are responsible for its behavior in the deviatoric plane!***

- Context
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Strain localization in Praclay gallery

- ✓ By symmetry: quarter of the gallery
- ✓ 2D plane strain simulation
- ✓ Hydro-Mechanical modeling
- ✓ Initial anisotropic stress state:

σ_{yy}=4.5 MPa; — Excavation/on gallery wall → 0.1 MPa

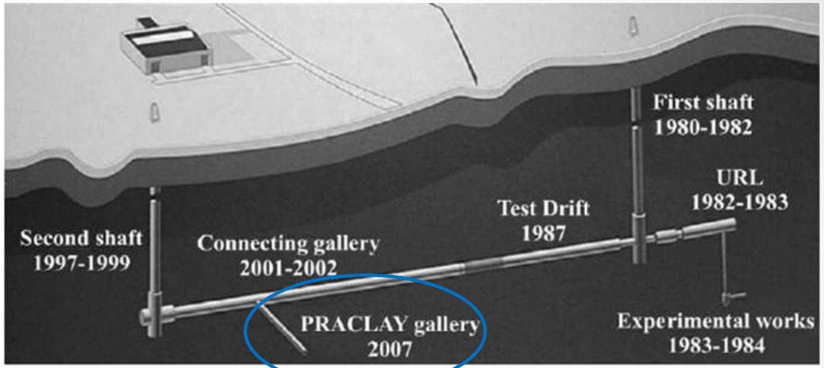
σ_{xx}= σ_{zz}=3.825 MPa

- ✓ Initial water pressure: 2.25 Mpa

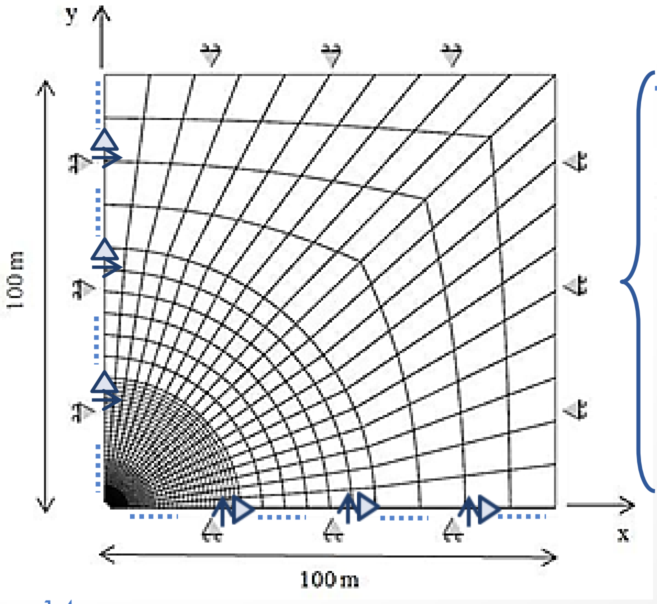
P_w= 2.25 MPa — Excavation/on gallery wall → 0.1 MPa

Excavation phase: 1 day

Waiting phase: 3.5 years



Sketch of different galleries for studying high-level nuclear waste disposal in the underground laboratory in Mol; (Bastiaens et al., 2007)



- Impervious boundary
- Constrained displacement perpendicular to the boundary
- Constrained normal derivative

(Zevros et al. 2001)

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Mechanical and Hydraulic parameters

- **Mechanical properties**

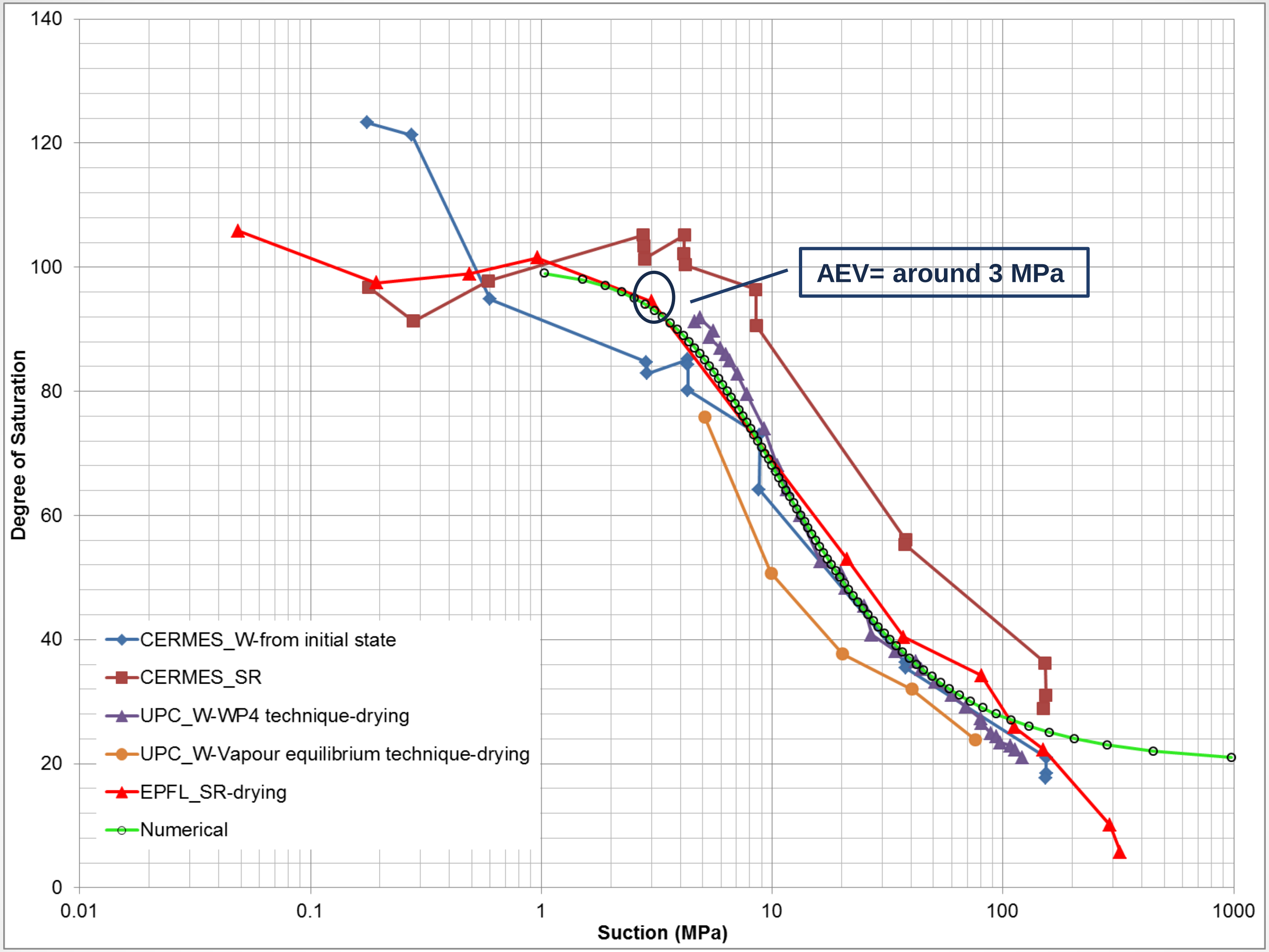
Parameter	Symbol	Value	Unit
Young modulus	E	300	MPa
Poisson ratio	υ	0.125	—
Specific mass	ρ	2700	Kg/m^3
Initial friction angle	Φ_0	8	°
Final friction angle	Φ_f	18	°
Hardening/softening coefficient	B_ϕ	0.001	—
Initial cohesion	c_0	300	kPa
Final cohesion	c_f	200	kPa
Hardening/softening coefficient	B_c	0.01	—
Dilatancy angle	Ψ	0	°
Second gradient elastic modulus	D	2000	N

(Bernier et al. 2007)

- **Hydraulic properties**

Parameter	Symbol	Value	Unit
Water permeability	k_w	$3\ 10^{-19}$	m^2
Specific mass of water	ρ_w	$1\ 10^3$	Kg/m^3
Porosity	ϕ	0.39	—
Water compressibility	$1/\chi_w$	$5\ 10^{-10}$	Pa^{-1}
Van Genuchten parameter*	m	0.47	—
Van Genuchten parameter*	n	1.887	—
Van Genuchten parameter*	P ($1/\alpha$)	7.0	MPa

* $$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^m} \qquad K_r(\Theta) = \Theta^{1/2}\left[1 - \left(1 - \Theta^{1/m}\right)^m\right]^2$$



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2	Initial cohesion	c_0	300	kPa
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3	Dilatancy angle	Ψ	0	°
1	Second gradient elastic modulus	D	2000	N

(Bernier et al. 2007)

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- **Mechanical properties**

Parametric study

- **Hydraulic properties**

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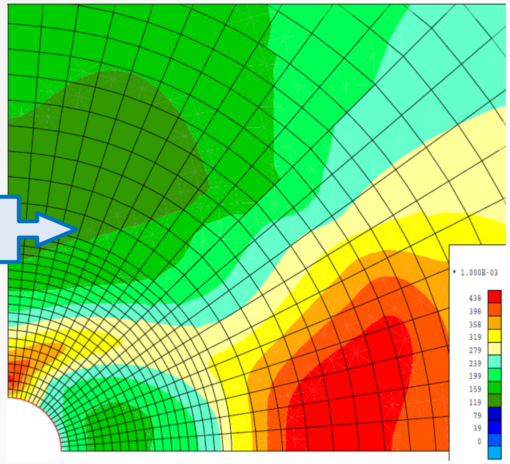
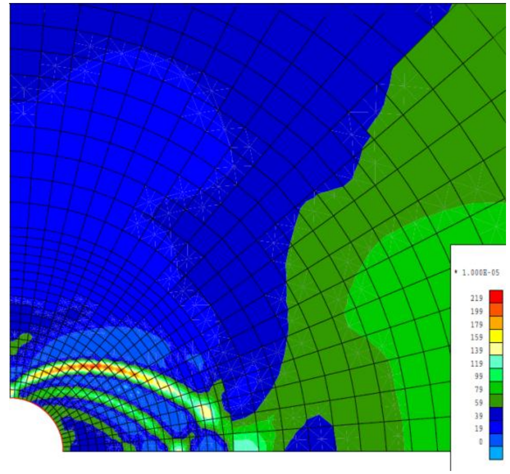
Increment of deviatoric strain

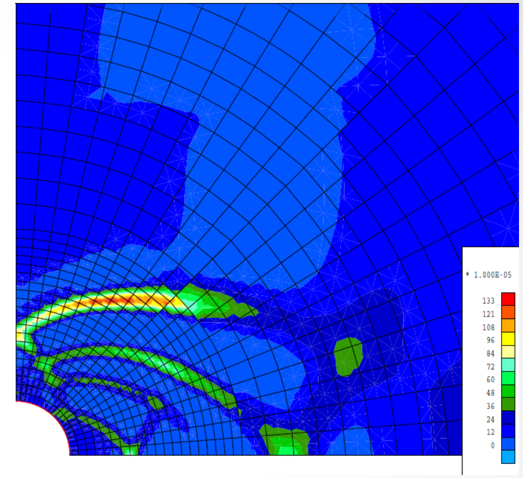
D=0.2 N



1 day-end of excavation

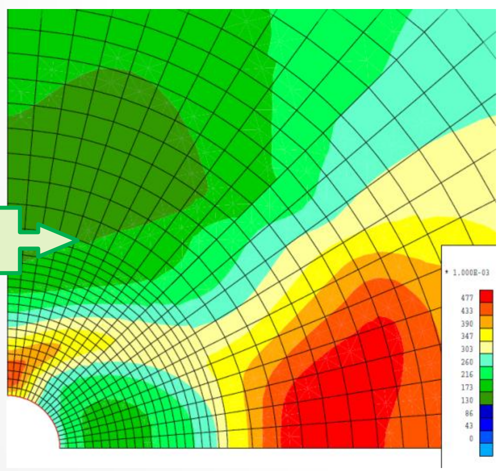


100 days

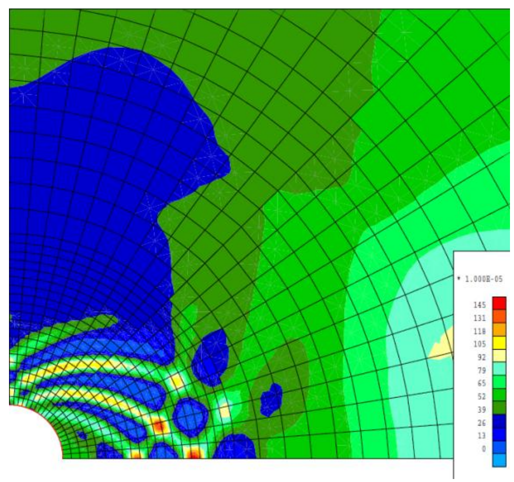


1277.5 days (3.5 years)

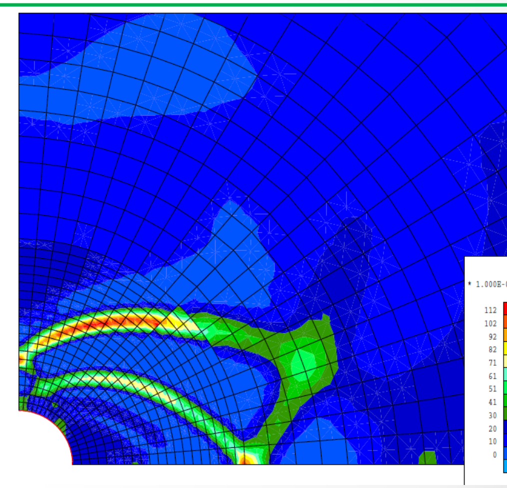
D=2000 N



1 day-end of excavation



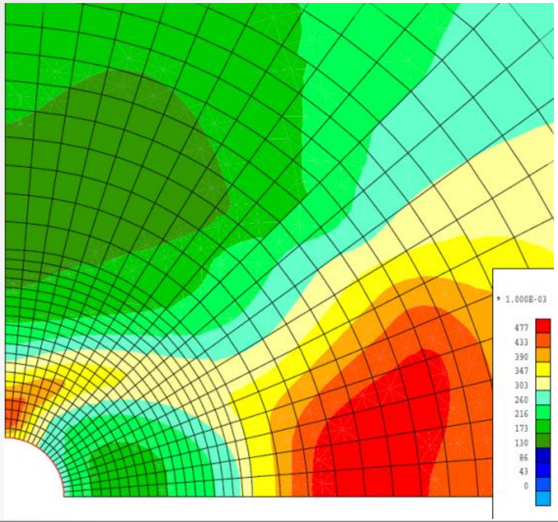
100 days



1277.5 days (3.5 years)

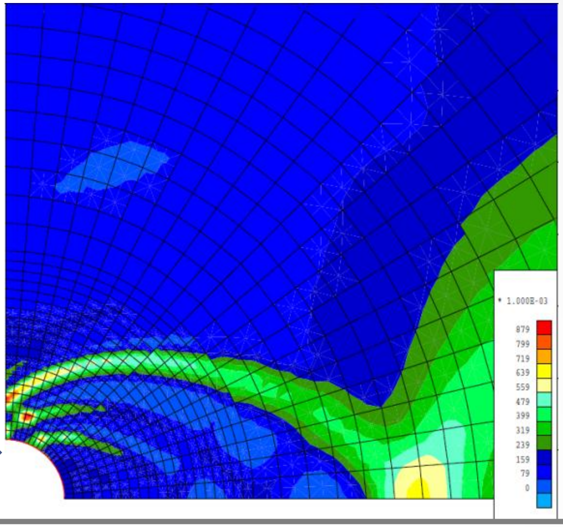
Increment of deviatoric strain

End of excavation

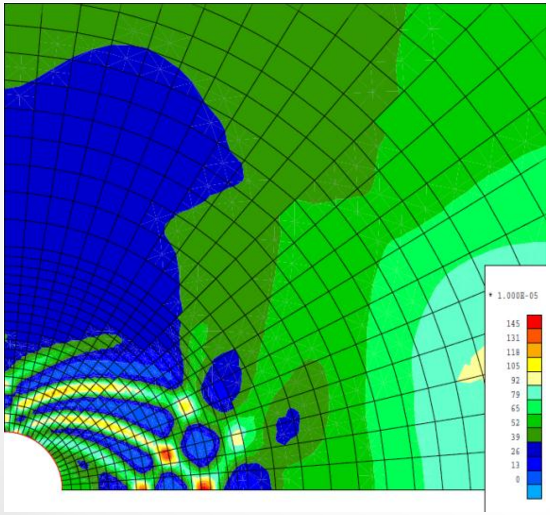


2. The effect of cf

cf=2 10^5 Pa → cf=3 10^4 Pa

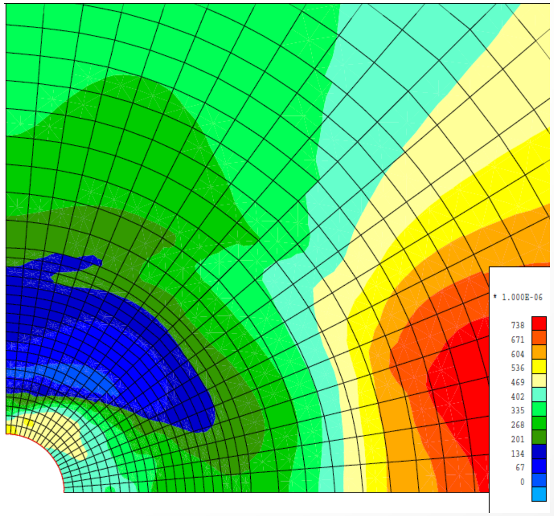


100 days



3. The effect of dilatancy

Dilatancy=0° → Dilatancy=5°



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Initial cohesion	c_0	300	kPa
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Hardening/softening coefficient	B_c	0.01	—
Dilatancy angle	Ψ	0	°
Second gradient elastic modulus	D	2000	N

(Bernier et al. 2007)

- **Mechanical properties**

Parametric study

→ **Friction angle hardening**

→ **Cohesion softening**

2. Intermediate conclusion: → ***Effect of the considered host rock's parameters!***

✓ **Softening is necessary for initiating the localization**

✓ **Dilatancy postpones the appearance of localization bands**

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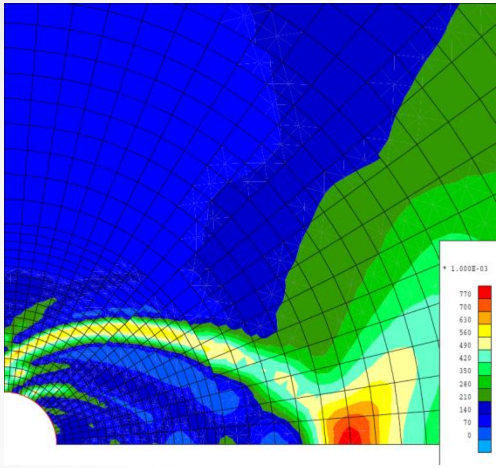
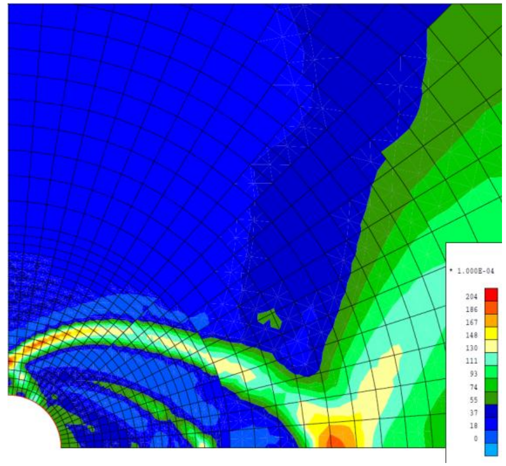
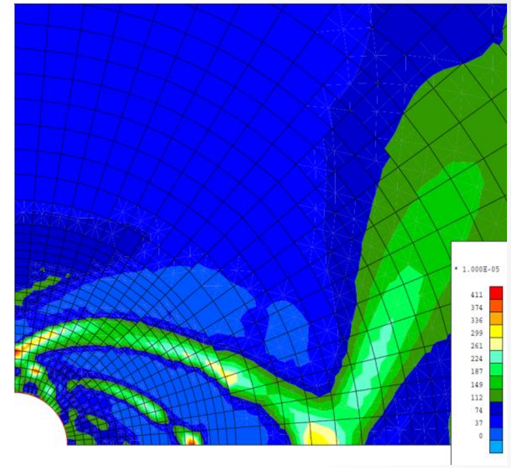
Increment of deviatoric strain



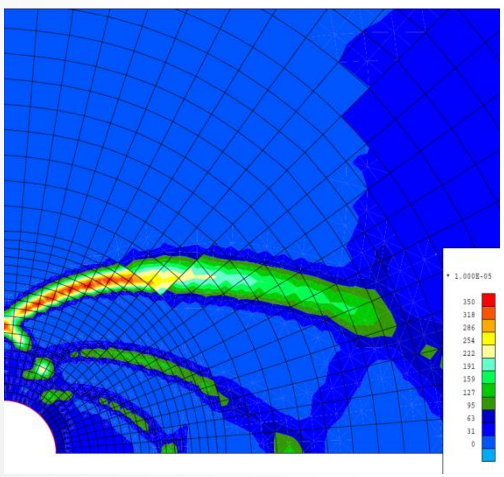
1 day-end of excavation



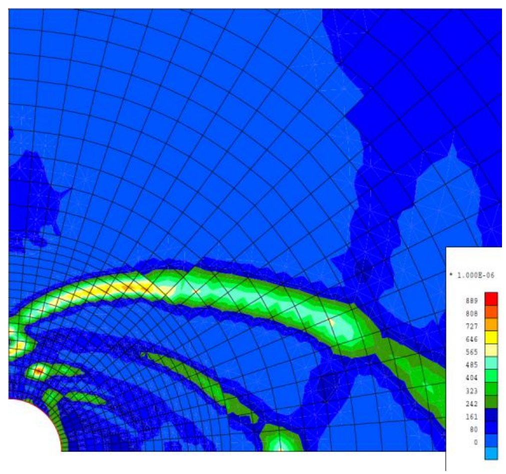
10 days



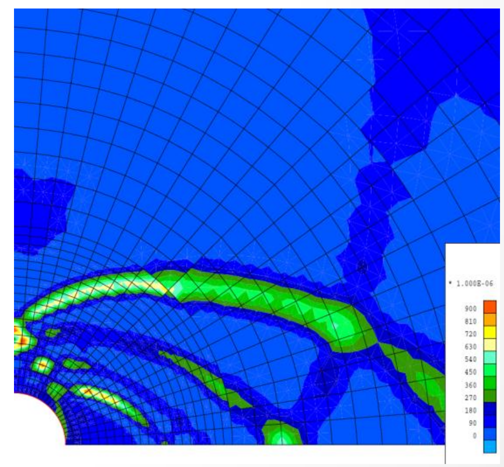
100 days



500 days

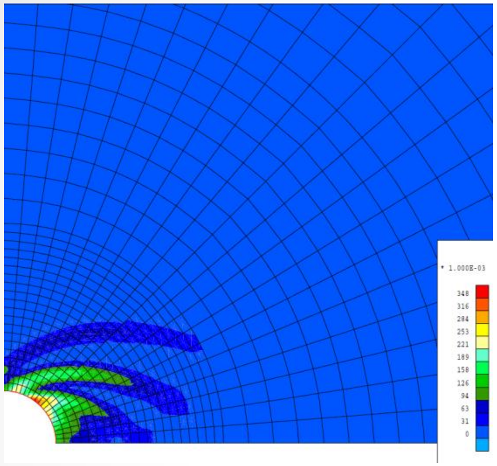


1100 days

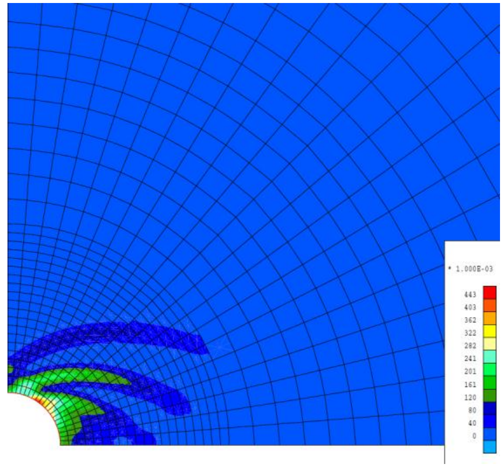


1277.5 days (3.5 years)

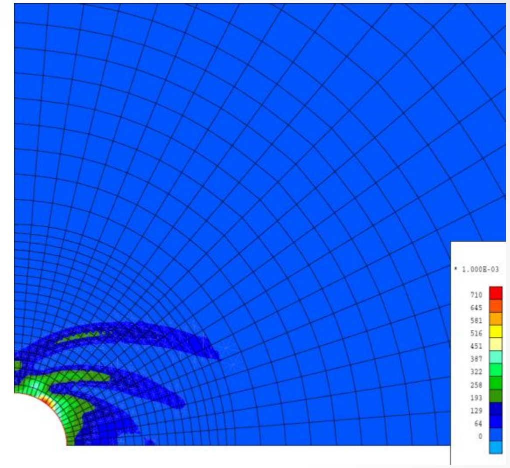
Total deviatoric strain



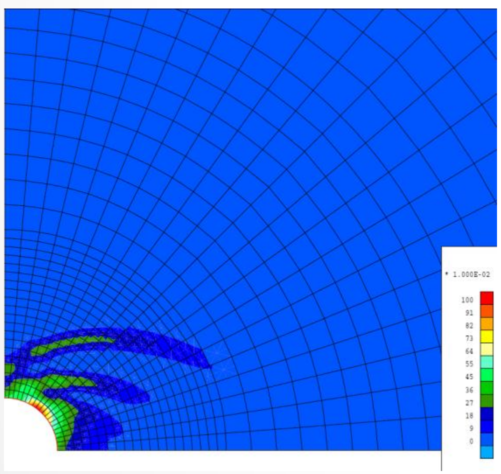
1 day-end of excavation



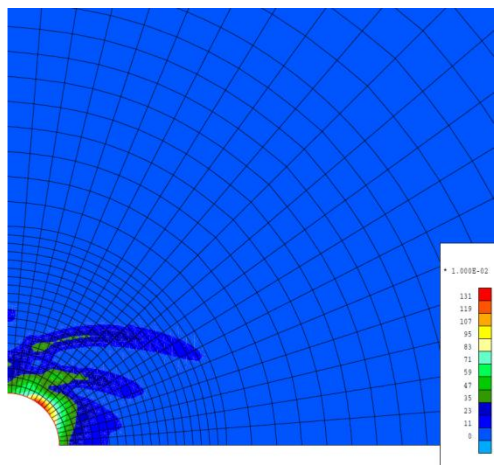
10 days



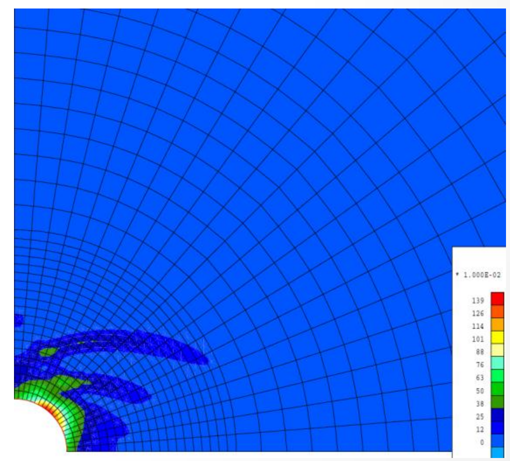
100 days



500 days



1100 days



1277.5 days (3.5 years)

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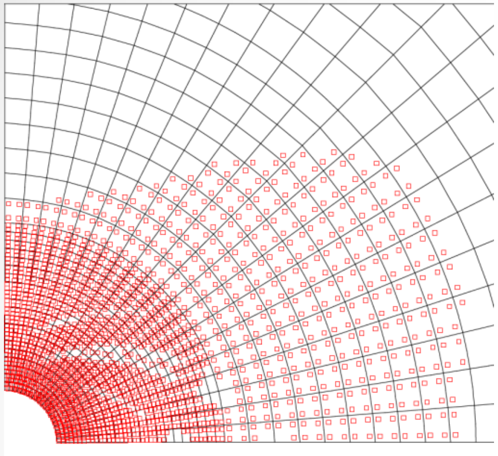
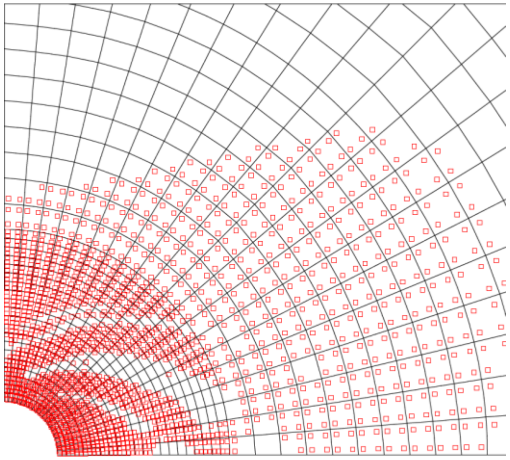
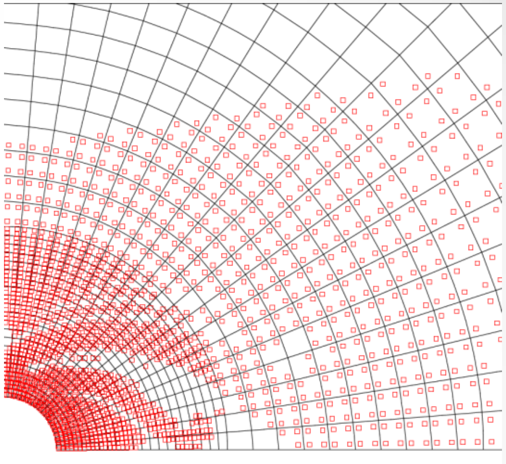
Plasticity



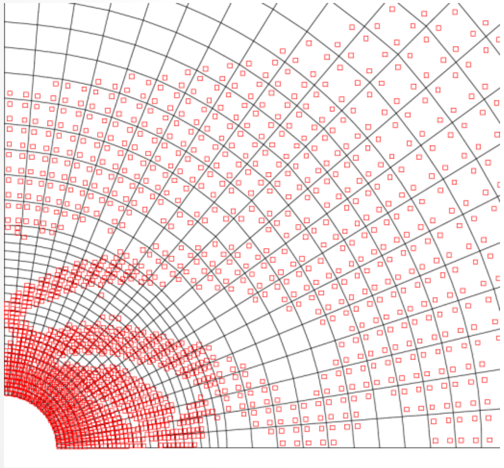
1 day-end of excavation



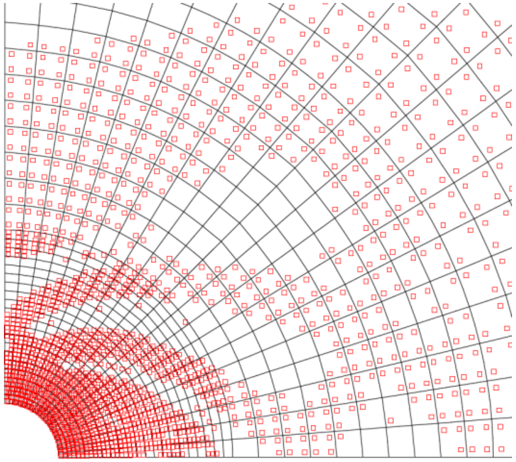
10 days



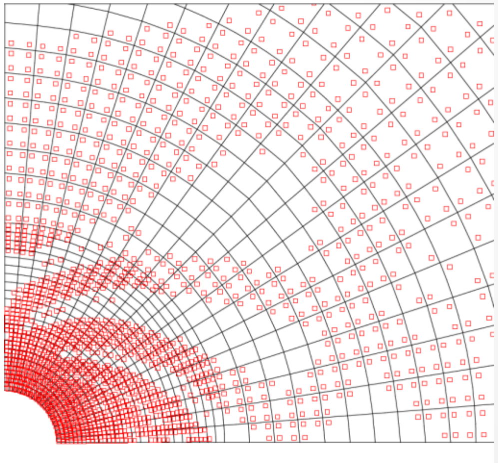
100 days



500 days



1100 days



1277.5 days (3.5 years)

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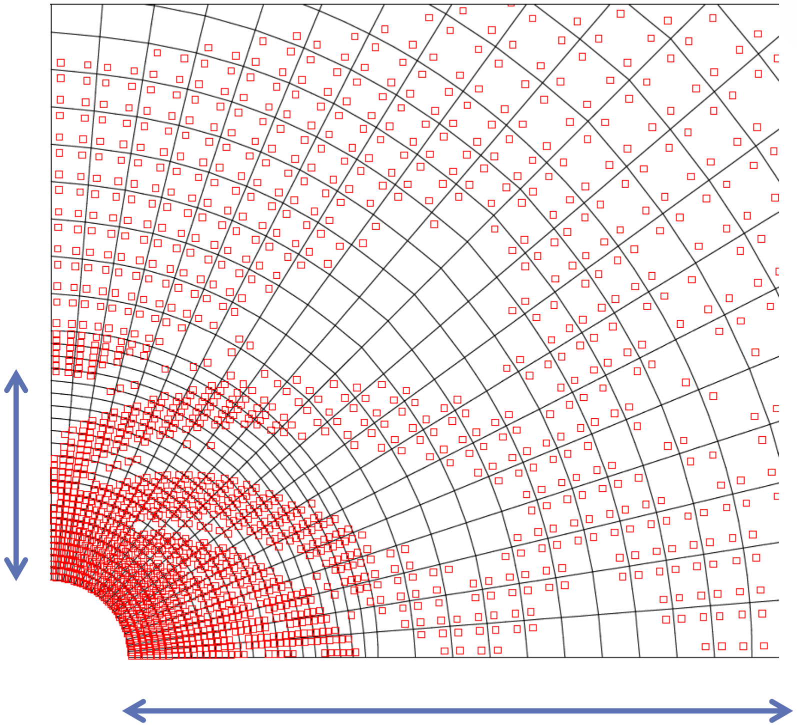
Localized Zone

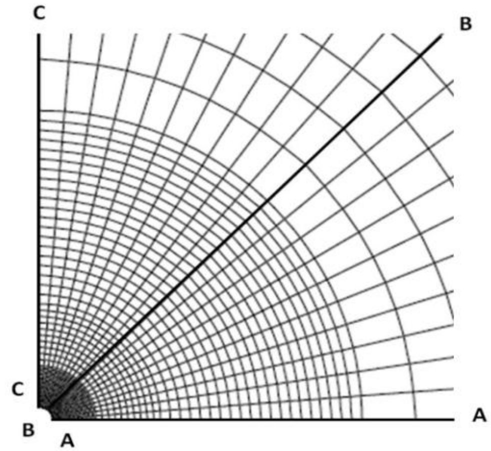


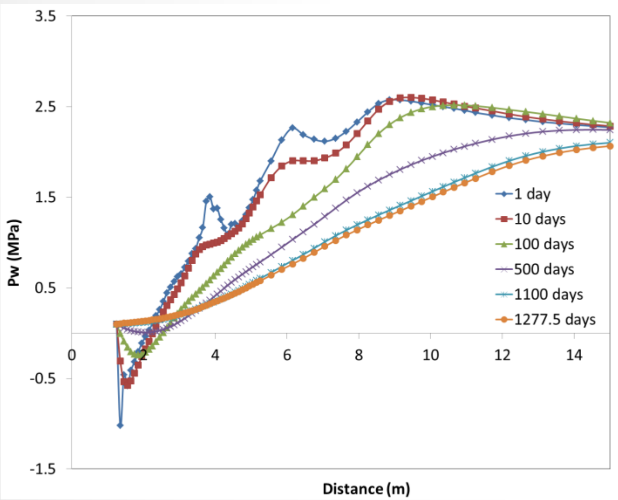
Vertically: 3.5 m

Horizontally: 10.25 m

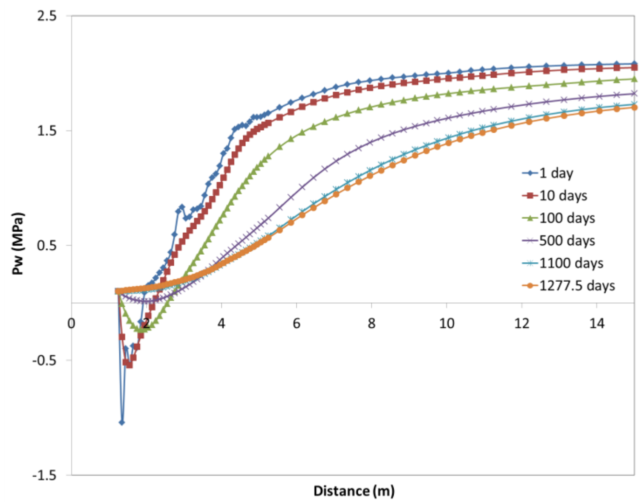
The fractures pattern show → anisotropic stress state

Evolution of pore water pressure

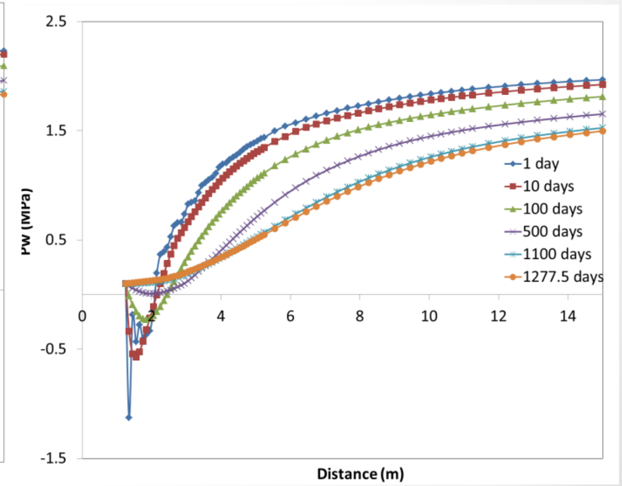




A_A



B_B



C_C

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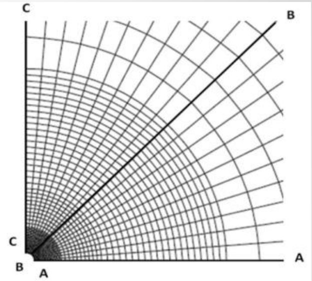
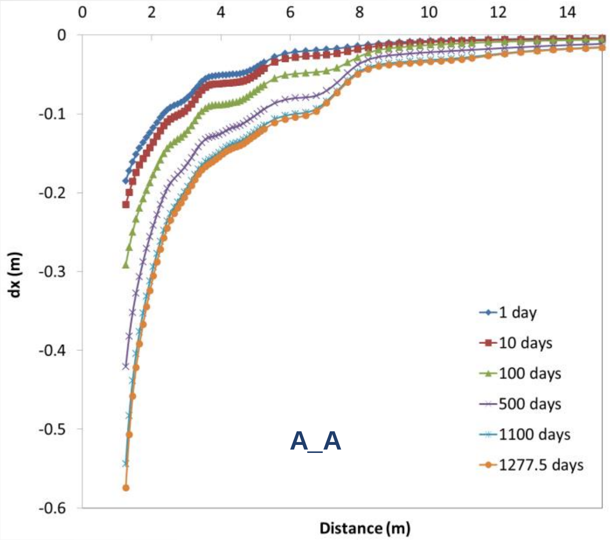
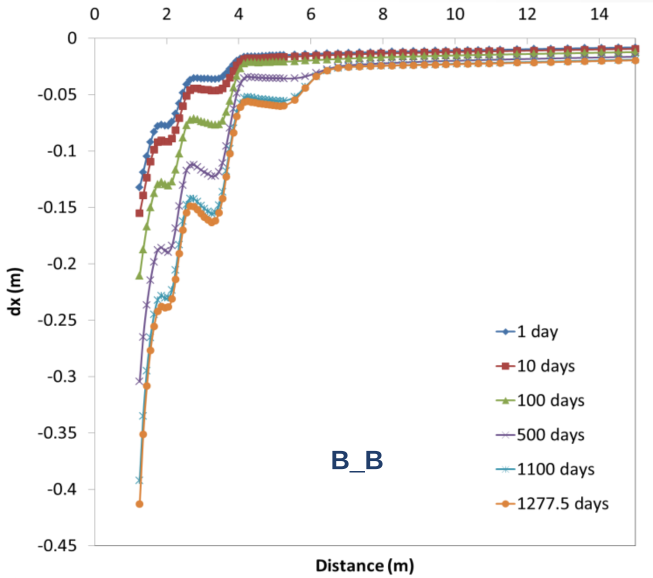
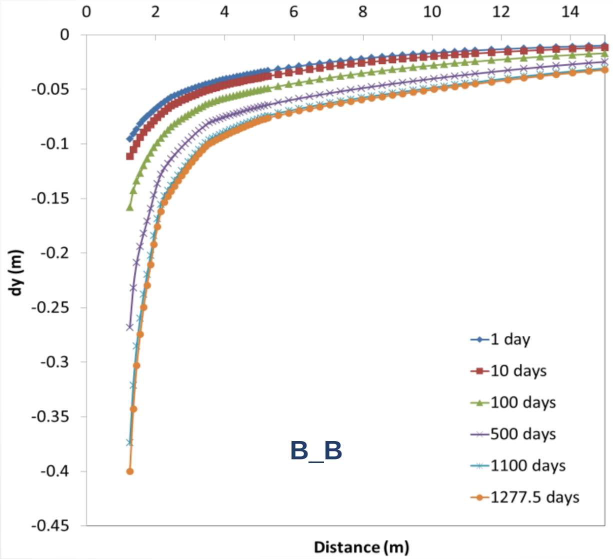
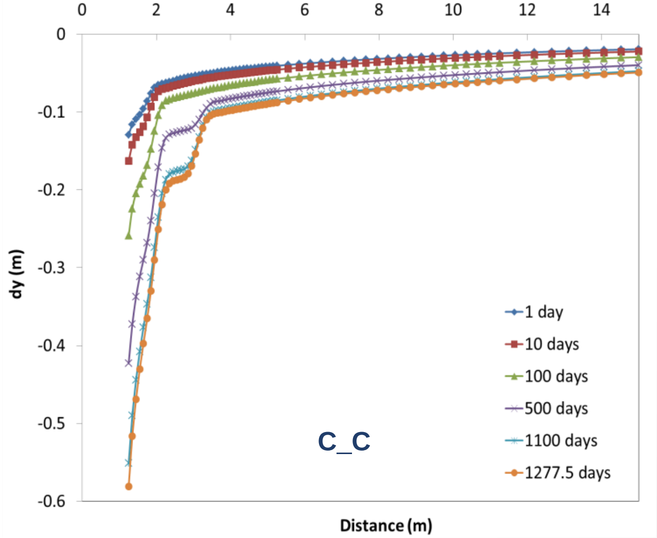
Evolution of displacement





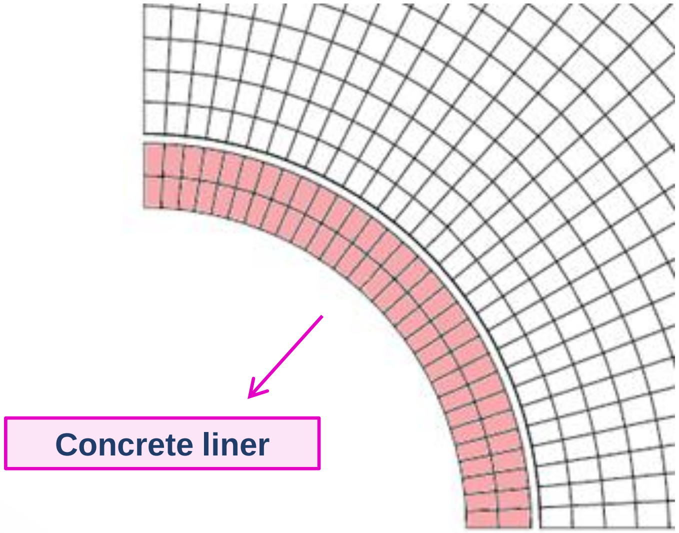






3. Intermediate conclusion:

The need for the lining is emphasized for decreasing the extension of EDZ and also the effects of localization in terms of evolution of pore water pressure and convergence!

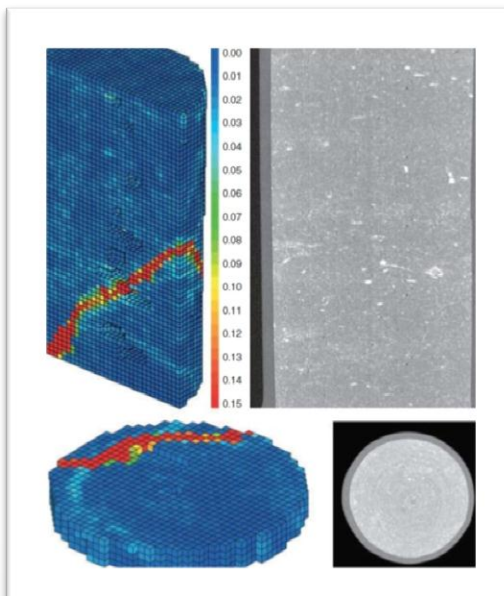


- Context
- Mechanical constitutive laws
- Numerical modeling of strain localization
  - Biaxial compression test
  - Gallery excavation
- **Conclusions**

Conclusions

- ✓ **Boom Clay has been selected as a potential host rock formation for the deep geological disposal of nuclear waste in Belgium.**
- ✓ **The stress redistribution due to excavation of gallery induces Excavation Damaged Zone.**
- ✓ **Extension of EDZ and fracture network in the framework of strain localization have been modeled realistically around the Praclay gallery in Boom Clay.**
- ✓ **The evolution of plastic zone and strain localization is time-dependant because of the coupled hydro-mechanical process.**
- ✓ **The effect of strain localization was obvious in terms of evolution of pore water presssure and displacements which could also emphasize the role of the liner.**

Thank you!



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