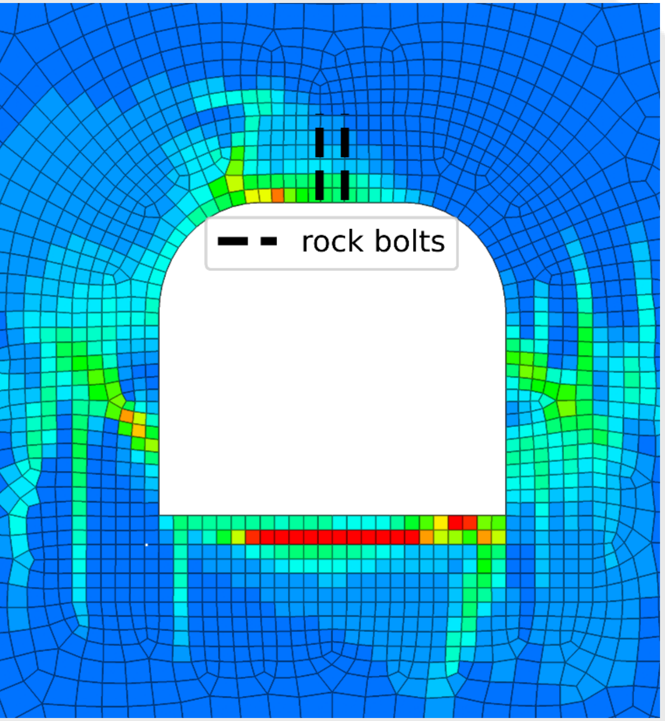
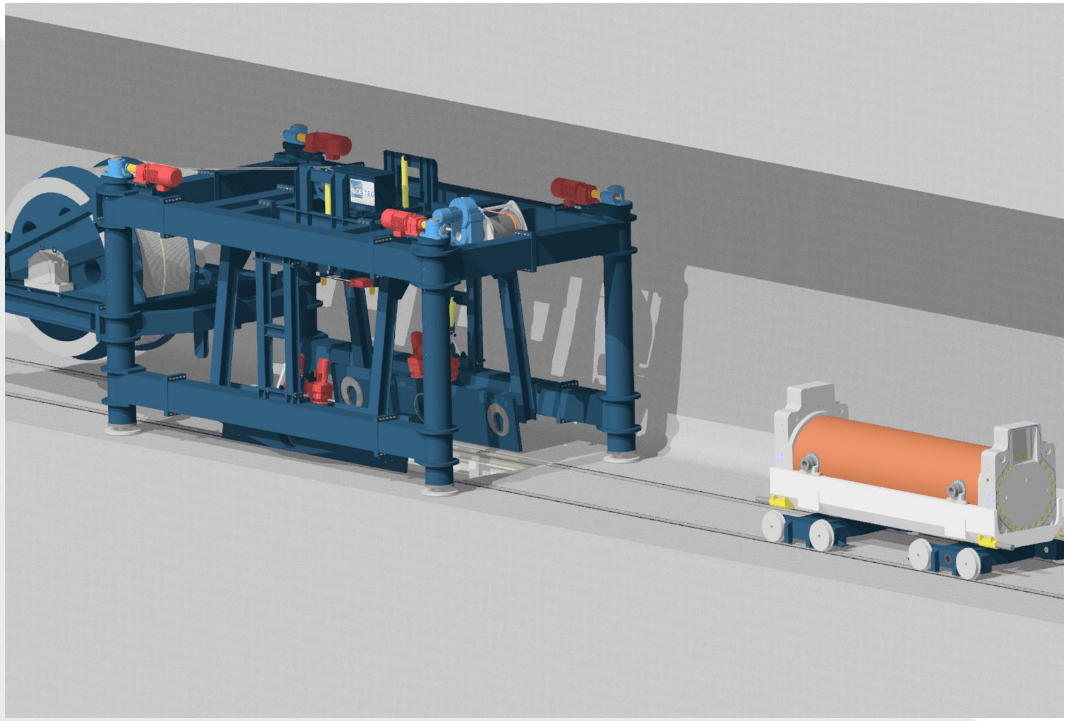


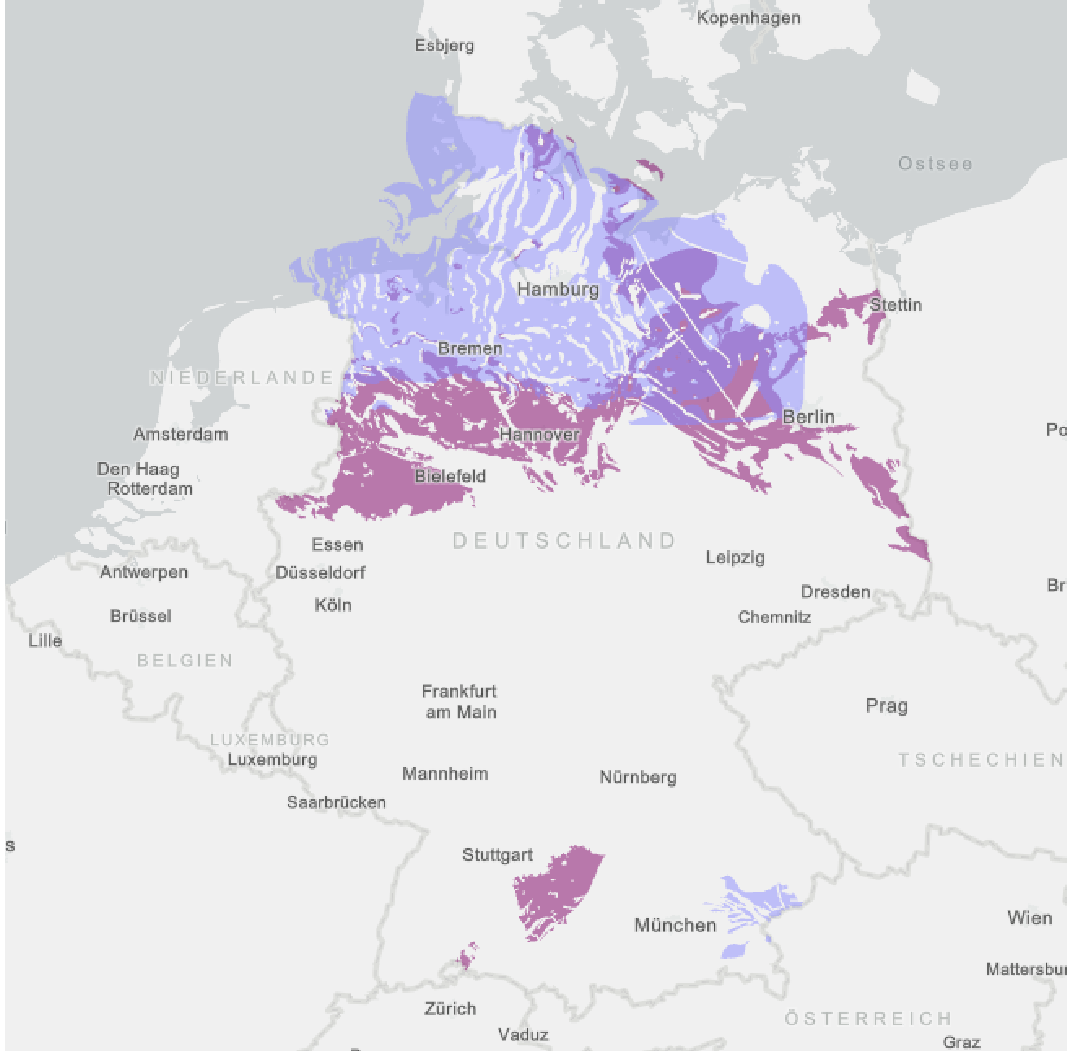


Implementation of clay rock and bentonite models using Mfront

Eric Simo, T. Helfer, P. Herold, M. Mánica, D. Masin, T. Nagel

Clay rock as potential host rock for high-level waste repositories

- **Clay rock formations** are considered to be a **suitable host rock** for the disposal of high-level waste (HLW)
- In Germany **nine formations** have been **selected** for further investigations
- The **safety** of a repository in a clay has to be proven for a period of **1 Million years**
- **The understanding of the complex THM-behaviour** of clay materials is therefore **necessary for the safety assessment** of repository



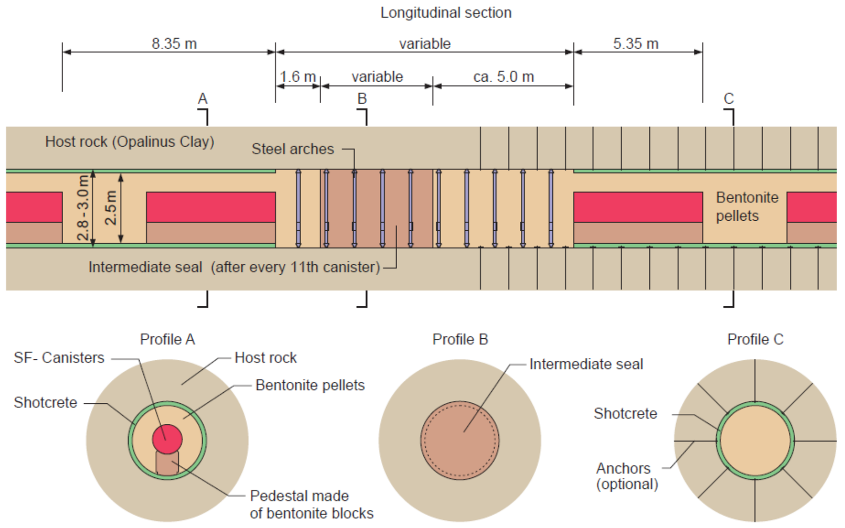
BGE (2020)

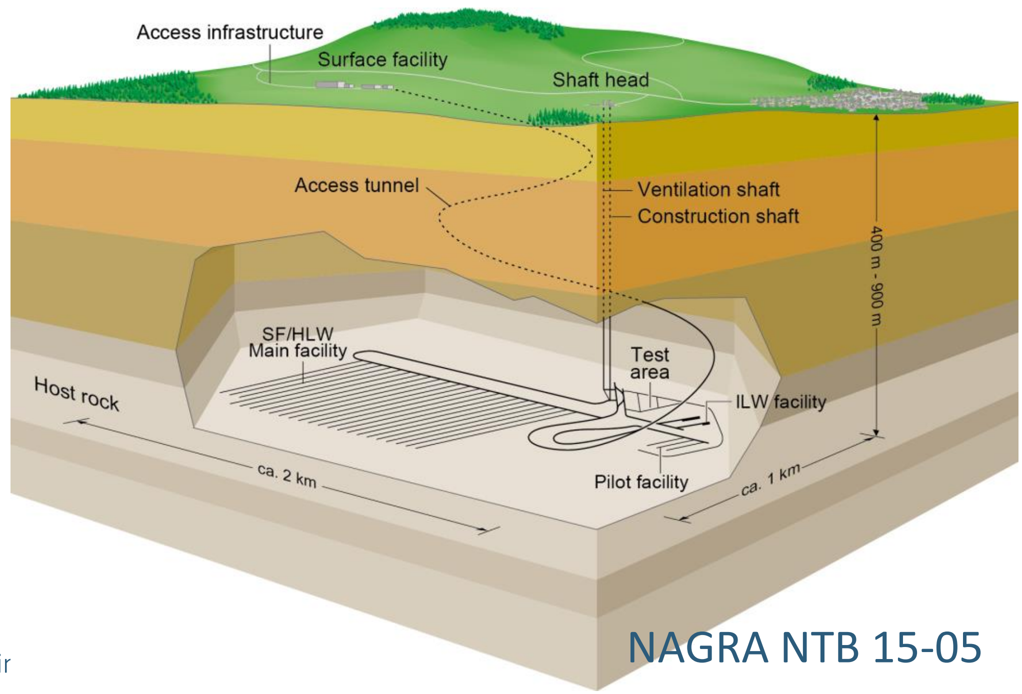
Bentonite as sealing material in radioactive waste repository

- **Bentonite materials** are considered as the **main sealing element** of the engineered barrier system for a HLW-repository in clay formations

- **Advantages of Bentonite:**
  - Very low Permeability: 10^{-17} -10^{-18} m^2
  - Swelling capacity
  - Sorption capacity

- A suitable **model for bentonite** taking into account all relevant **phenomena expected in the nearfield** of the disposed cask is **necessary for numerical based safety assessment**





NAGRA NTB 15-05

Hypoplastic THM-model for bentonite

Eric Simo

Material Behaviour of Bentonite

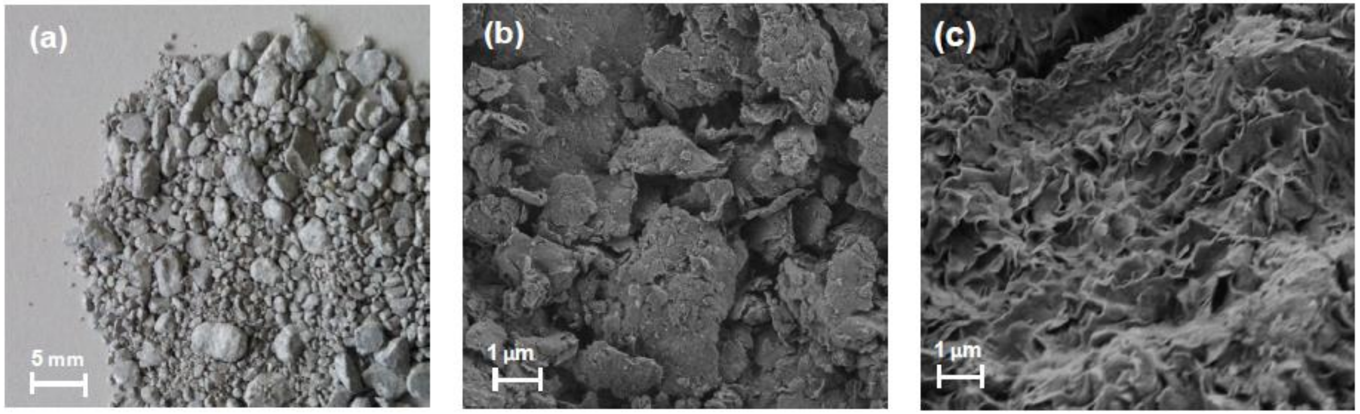
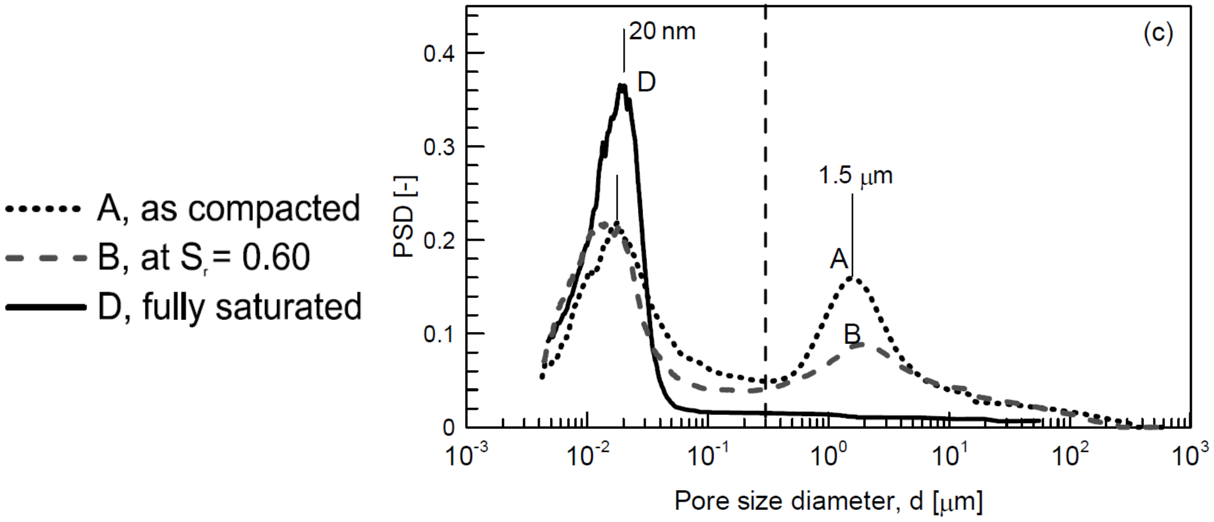
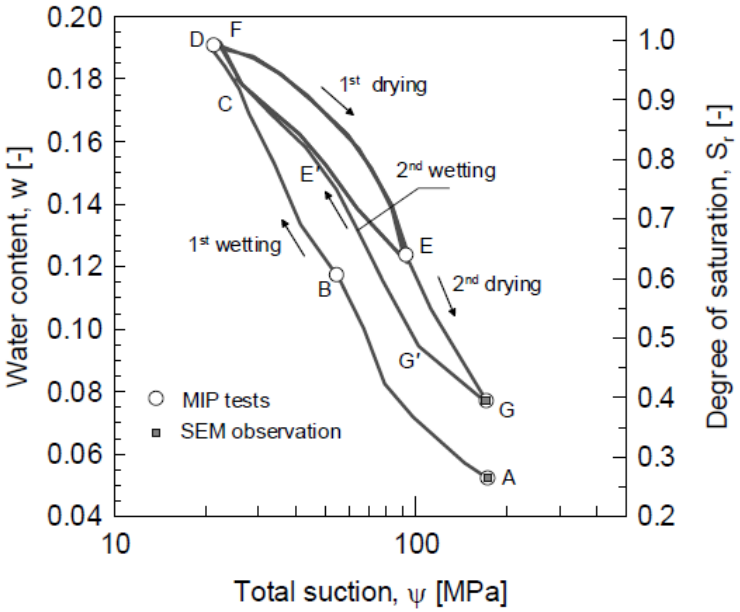


Fig. 1-4: Fabric of Wyoming granular bentonite: (a) appearance of granular bentonite at macroscopic scale; photomicrographs of the material at (b) the as compacted state, and (c) after wetting/drying cycles with significant modification of the fabric.

Seiphoori (2015)



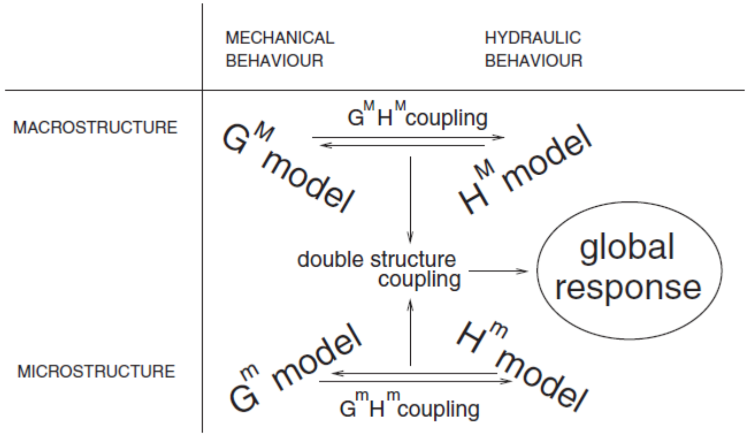


Description of the Bentonite Model

- Expression of the model proposed by (Mašín, 2013 & 2017)

$$\mathring{\boldsymbol{\sigma}}^{M} = f_s[\boldsymbol{\mathcal{L}} : (\dot{\boldsymbol{\epsilon}} - f_m \dot{\boldsymbol{\epsilon}}^m) + f_d \mathbf{N} \| \dot{\boldsymbol{\epsilon}} - f_m \dot{\boldsymbol{\epsilon}}^m \|] + f_u(\boldsymbol{H}_s + \boldsymbol{H}_T)$$

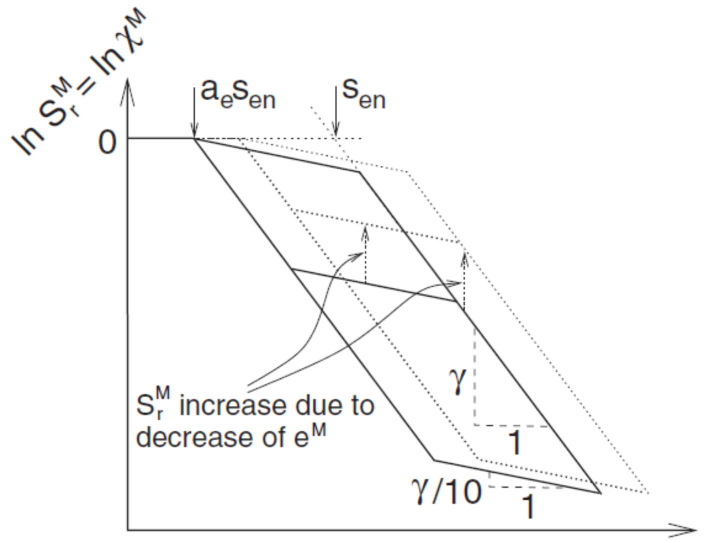
- Behaviour of the macrostructure based on hypoplasticity and Bishop equation: $\boldsymbol{\sigma}^M = \boldsymbol{\sigma}^{net} - \mathbf{1} S_r^M s$



- Behaviour of microstructure using elastic volumetric model and Terzaghi stress hypothesis:

$$\dot{\boldsymbol{\epsilon}}^m = \frac{1}{3}\left(\alpha_s \dot{T} - \frac{\kappa_m}{p^m} \dot{p}^m\right) \qquad \boldsymbol{\sigma}^m = \boldsymbol{\sigma}^{net} - \mathbf{1}s$$

- Double structure coupling through the factor f_m
- Hydraulic and thermal effect considered through $(\boldsymbol{H}_s + \boldsymbol{H}_T)$
- f_u controls the overconsolidation ratio, f_s and f_d control the effect of stress and void ratio on macrostructural soil stiffness

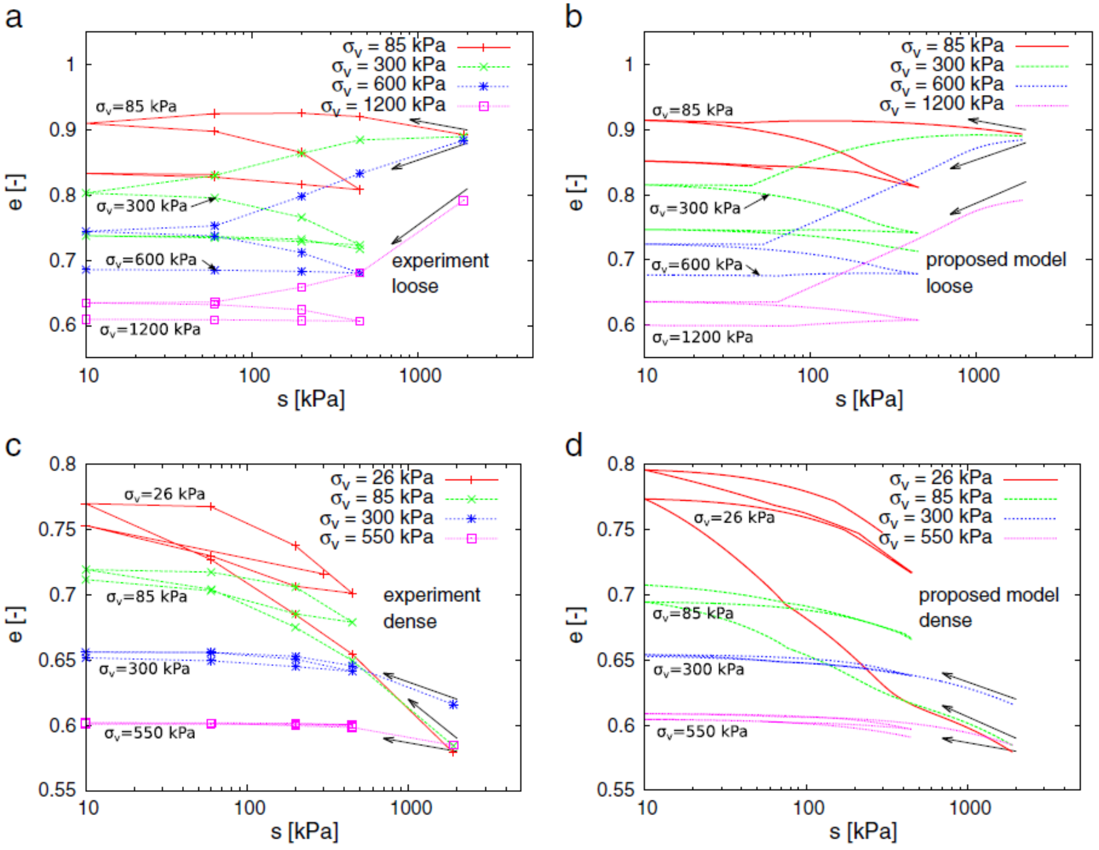


(Mašín, 2013 & 2017)

Description of the Bentonite Model

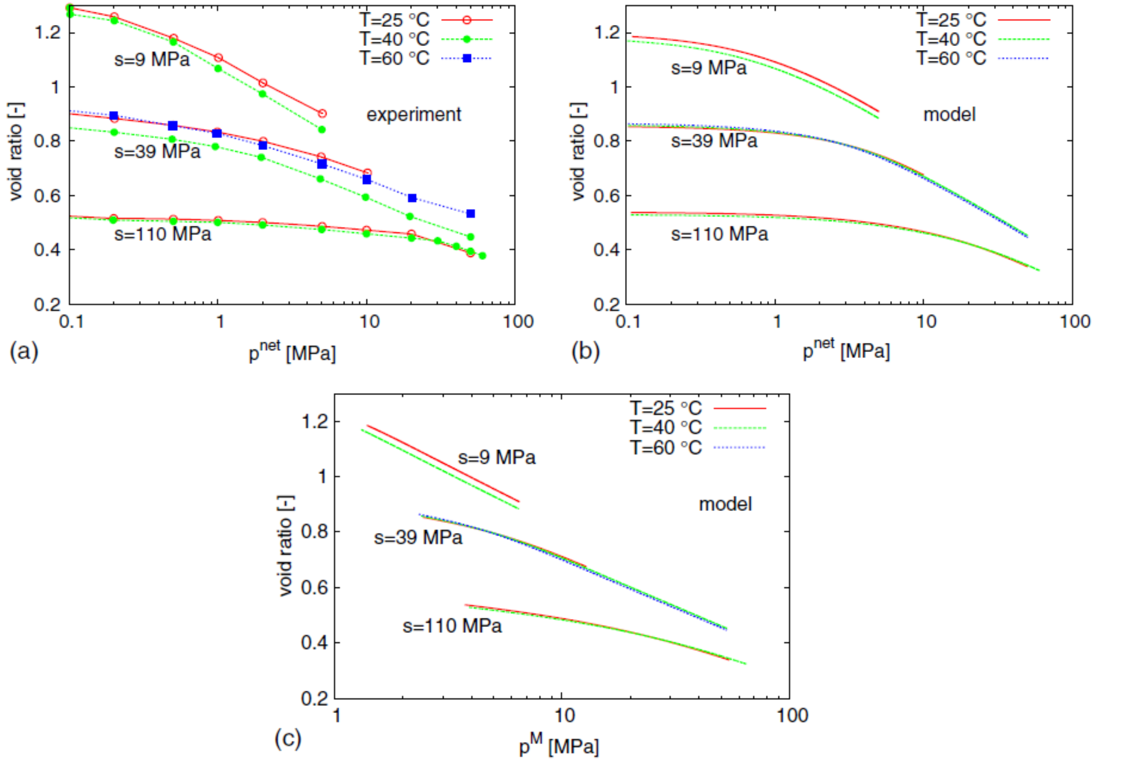
- Some applications of the model

wetting–drying oedometric experiments on Boom clay



Mašín(2013)

Isotropic compression tests at various suctions and temperatures



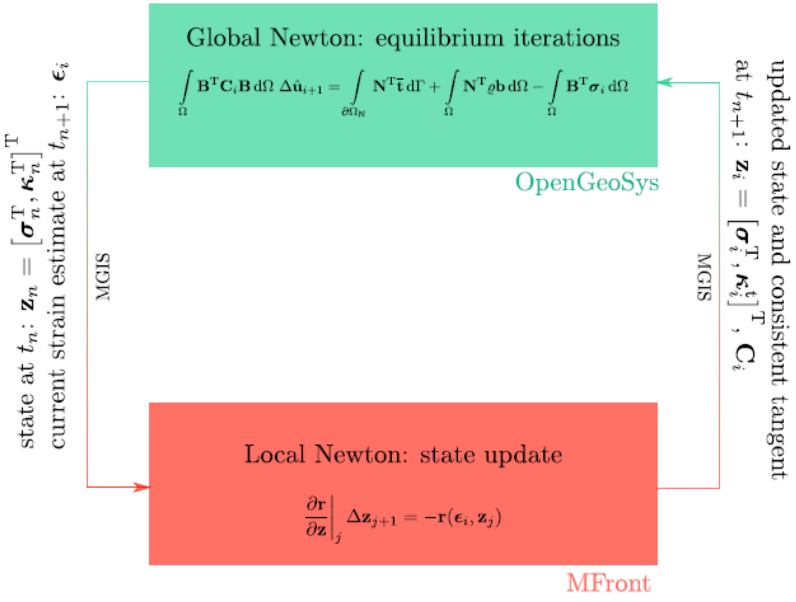
Mašín(2017)

BGE TEC
BGE TECHNOLOGY GmbH

Implementation in Mfront

- Conceptual approach

Model implementation in OGS



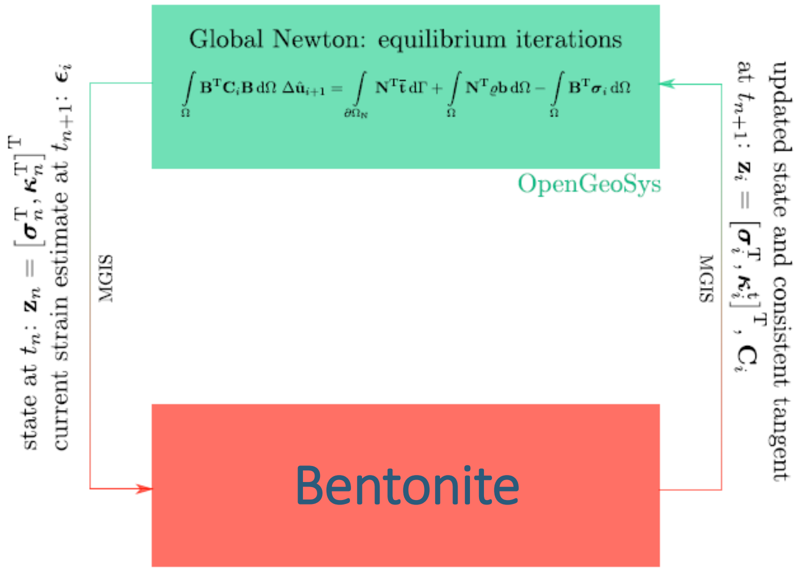
Actual implementation of the model in FE-Code SIFEL

FE Code: SIFEL

constitutive model can influence the finite element code timestep

Bentonite Model

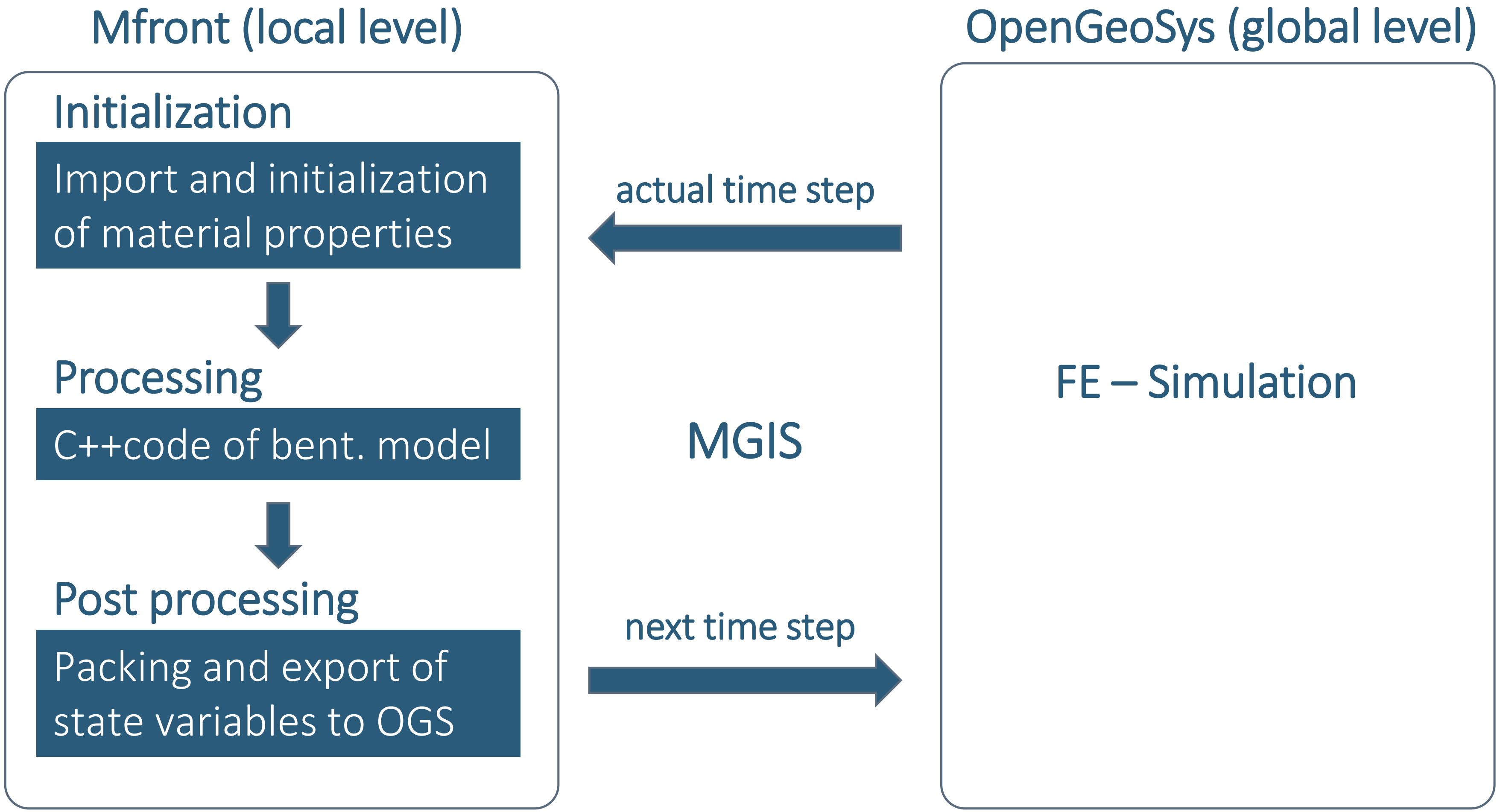
Integration of the bentonite model in Mfront



BGE TEC BGE TECHNOLOGY GmbH

Implementation in Mfront

- The available code of the bentonite model was included in Mfront as a C++Library



BGE TEC
BGE TECHNOLOGY GmbH

Implementation in Mfront

- Testing of the implementation: at local level

BGE TEC

Model development

Mfront as a Wrapper

↓

Finite element tester

Mtest

David Mašín (CU Prague)

Model development

C++

↓

Finite element tester

Triax

↘ ↙

Benchmark

Based on examples from (Mašín, 2013 & 2017)

BGE TEC
BGE TECHNOLOGY GmbH

Implementation in Mfront

- Testing of the implementation: at global level

BGE TEC

3D-Simulation

FE-Code: OGS

David Mašín (CU Prague)

3D-Simulation

FE-Code: SIFEL

Benchmark

Based on examples from (Mašín, 2013 & 2017)

First results

- Suction and axial stress were applied then saturation was calculated:

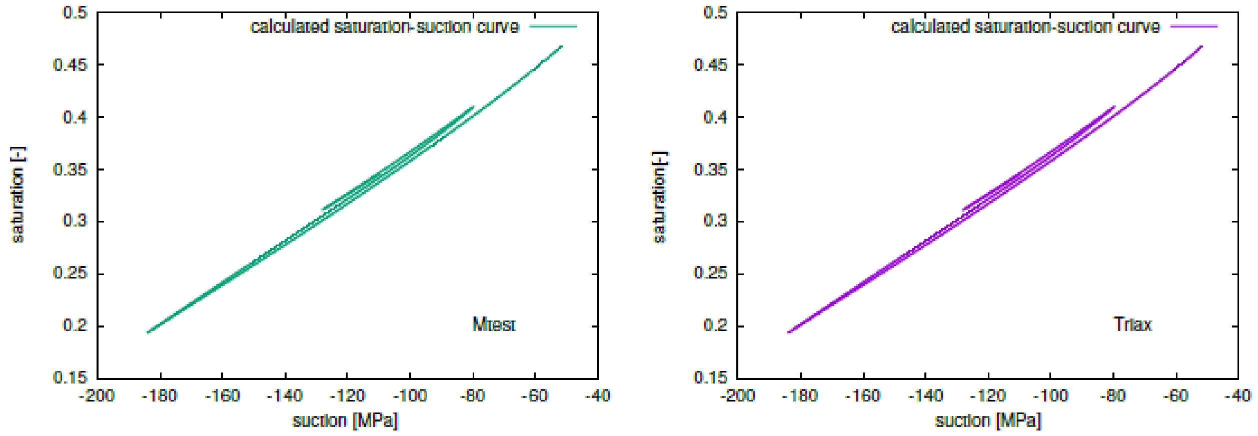


Figure 1: Comparison of the saturation computed with MTest and the saturation computed with TRIAX for the first test

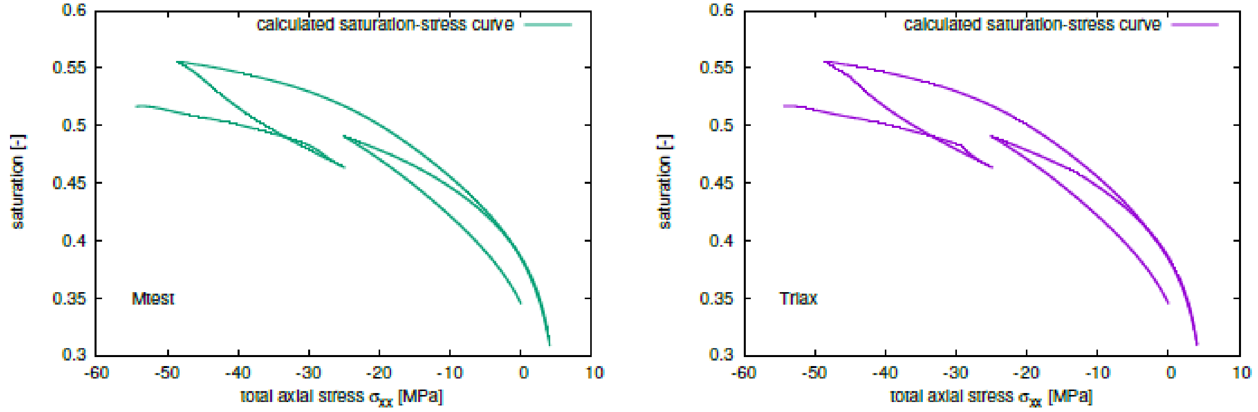


Figure 2: Comparison of the saturation computed with MTest and the saturation computed with TRIAX for the second test

A nonlocal HM-model for clay rocks

Miguel Mánica

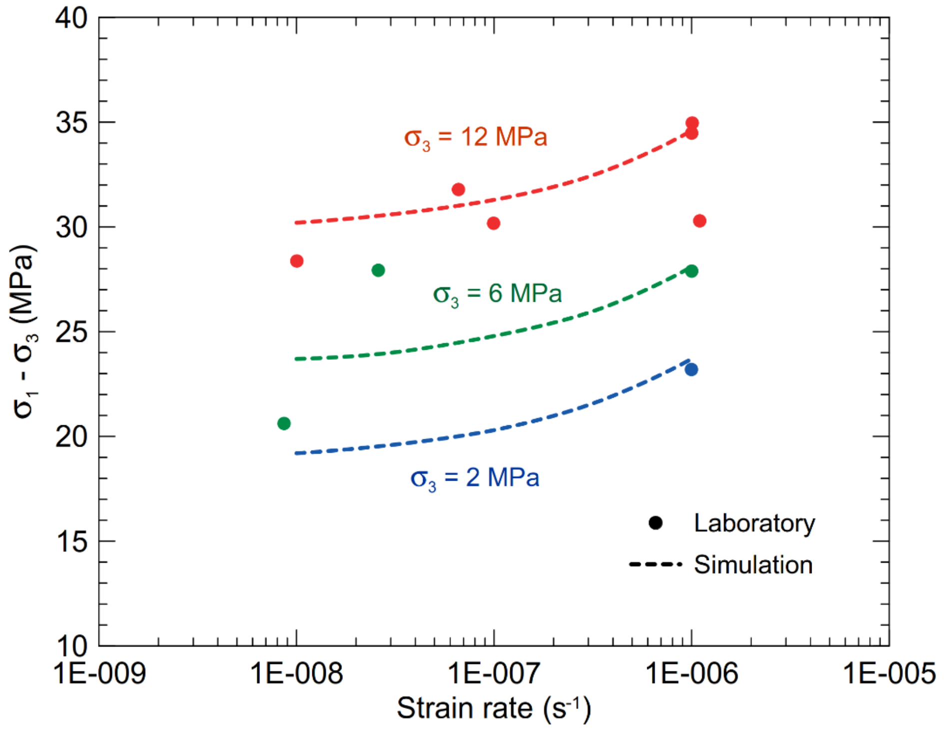
BGE TEC
BGE TECHNOLOGY GmbH

Material behaviour of claystone

- Observed behaviour:

Material behaviour of claystone

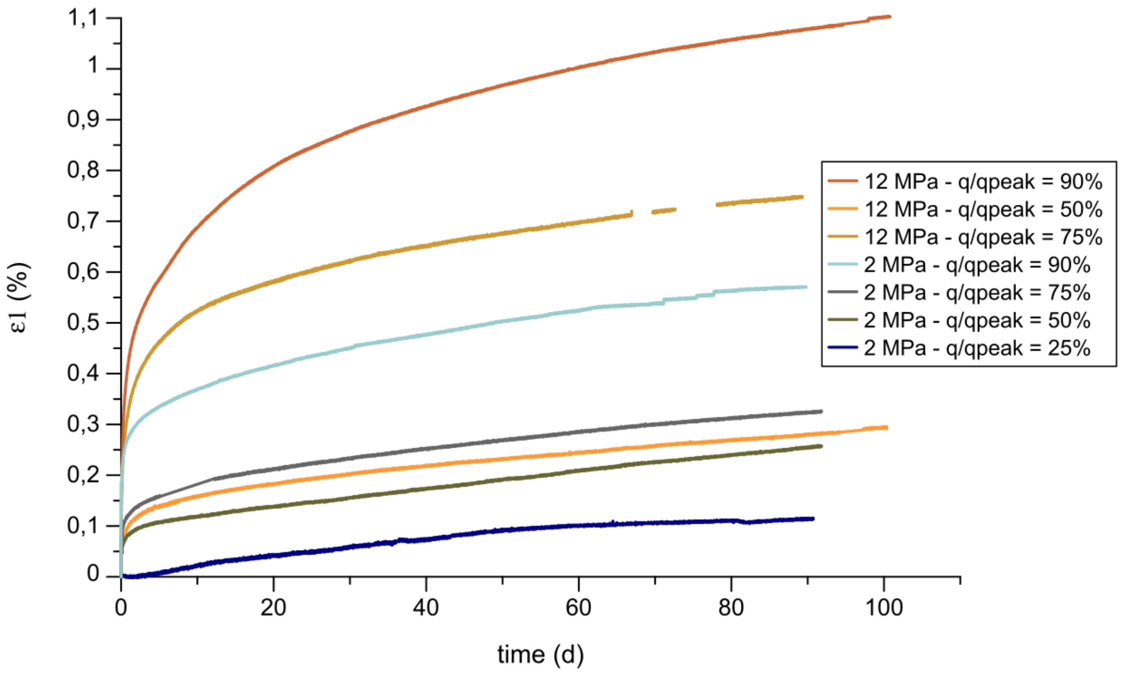
- Observed behaviour:
  - **Rate dependency**



Callovo-Oxfordian argillite
(Armand et al., 2017)

Material behaviour of claystone

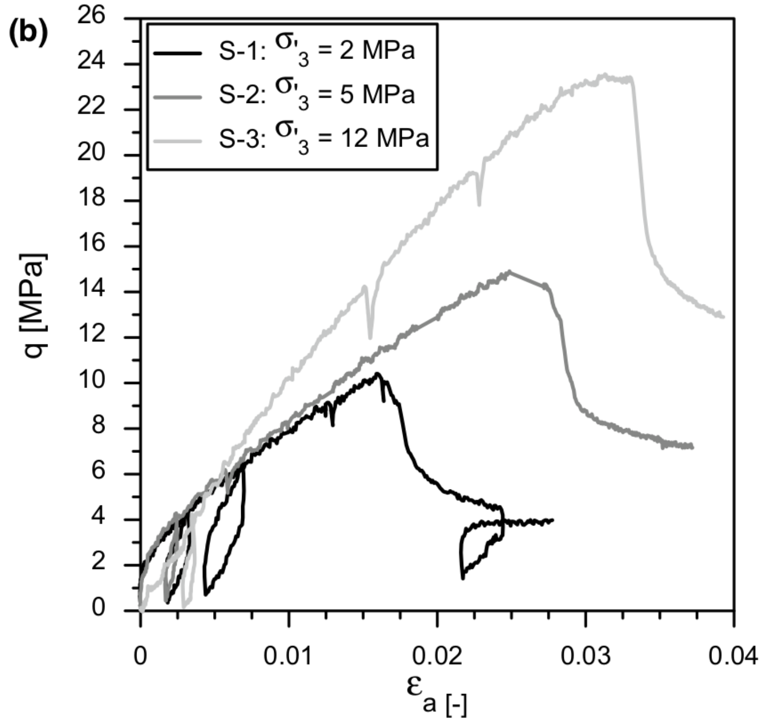
- Observed behaviour:
  - Rate dependency
  - **Creep**



Callovo-Oxfordian argillite
(Armand et al., 2017)

Material behaviour of claystone

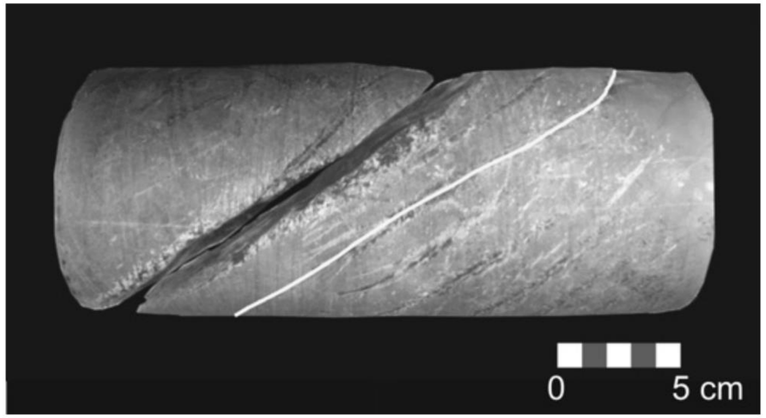
- Observed behaviour:
  - Rate dependency
  - Creep
  - **Significant softening**



Opalinus clay
(Favero et al., 2018)

Material behaviour of claystone

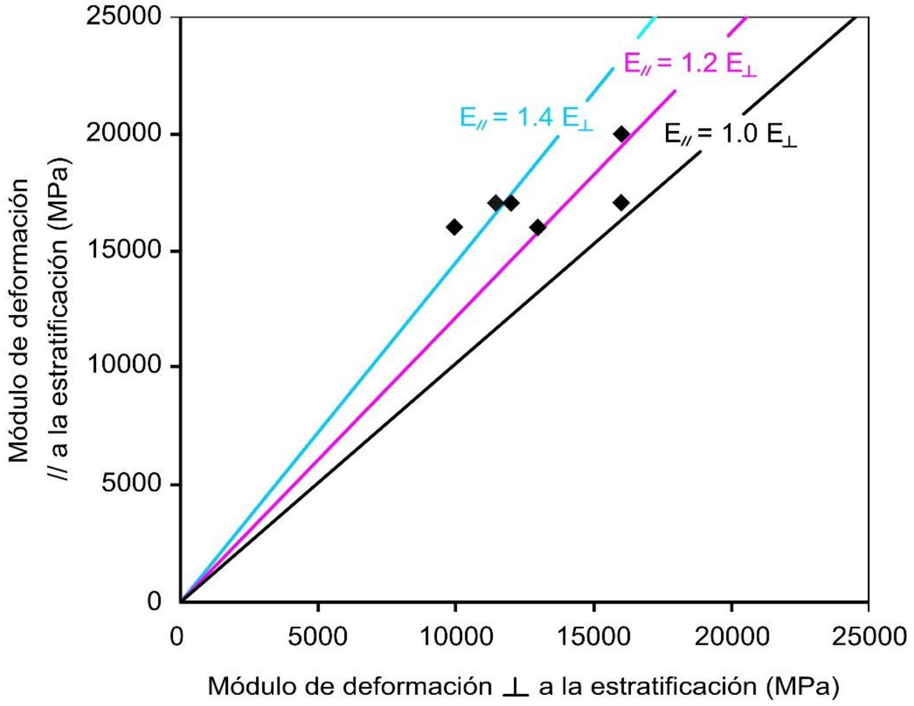
- Observed behaviour:
  - Rate dependency
  - Creep
  - Significant softening
  - **Localised deformations**



Opalinus clay
(Naumann et al., 2007)

Material behaviour of claystone

- Observed behaviour:
  - Rate dependency
  - Creep
  - Significant softening
  - Localised deformations
  - Anistropic properties:
    - **Stiffness**

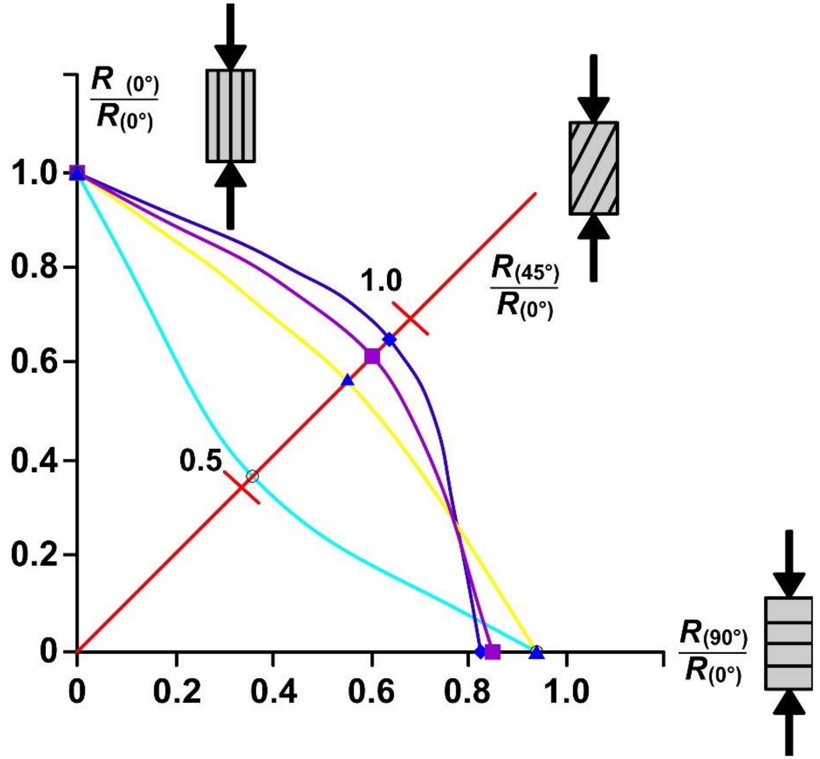


Callovo-Oxfordian argillite
(Auvray, 2004)

BGE TEC
BGE TECHNOLOGY GmbH

Material behaviour of claystone

- Observed behaviour:
  - Rate dependency
  - Creep
  - Significant softening
  - Localised deformations
  - Anistropic properties:
    - Stiffness
    - **Strength**

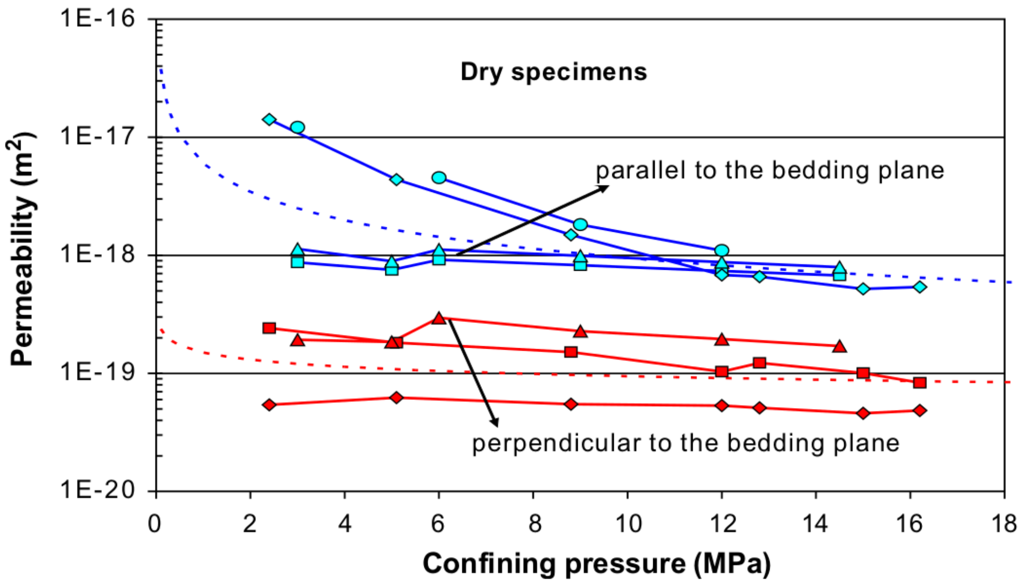


Callovo-Oxfordian argillite
(Auvray, 2004)

BGE TEC
BGE TECHNOLOGY GmbH

Material behaviour of claystone

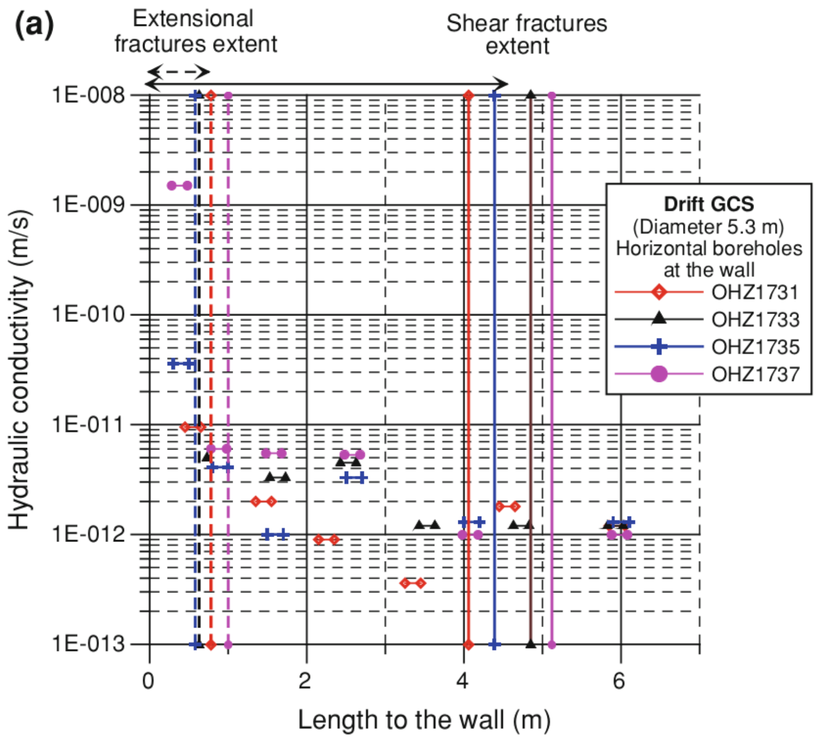
- Observed behaviour:
  - Rate dependency
  - Creep
  - Significant softening
  - Localised deformations
  - Anistropic properties:
    - ➢ Stiffness
    - ➢ Strength
    - ➢ **Permeability**



Callovo-Oxfordian argillite
(Zhang & Rothfuchs, 2004)

Material behaviour of claystone

- Observed behaviour:
  - Rate dependency
  - Creep
  - Significant softening
  - Localised deformations
  - Anistropic properties:
    - ➢ Stiffness
    - ➢ Strength
    - ➢ Permeability
  - **Increase of permeability with damage**



Callovo-Oxfordian argillite
(Armand et al., 2014)

Material behaviour of claystone

- Nonlocal elasto-viscoplastic constitutive model (Manica, 2018).
- Incorporates the mentioned behavioural features for indurated clayey materials.
- Implemented in the FEM code Plaxis.

Material behaviour of claystone

- Nonlocal elasto-viscoplastic constitutive model (Manica, 2018).
- Incorporates the mentioned behavioural features for indurated clayey materials.
- Implemented in the FEM code Plaxis.
- Is currently being implemented in **OpenGeoSys** trough **MFront.**

Material behaviour of claystone

- Nonlocal elasto-viscoplastic constitutive model (Manica, 2018).
- Incorporates the mentioned behavioural features for indurated clayey materials.
- Implemented in the FEM code Plaxis.
- Is currently being implemented in **OpenGeoSys** trough **MFront.**

Scientific open-source initiative for the numerical simulation of thermo-hydro-mechanical/chemical (THMC) processes in porous and fractures media (Kolditz, 1990; Wollrath, 1990; Kroehn, 1991; Helmig, 1993; Kolditz et al., 2012; Bilke et al., 2019)

https://www.opengeosys.org/

BGE TEC
BGE TECHNOLOGY GmbH

Material behaviour of claystone

- Nonlocal elasto-viscoplastic constitutive model (Manica, 2018).
- Incorporates the mentioned behavioural features for indurated clayey materials.
- Implemented in the FEM code Plaxis.
- Is currently being implemented in **OpenGeoSys** trough **MFront.**

Scientific open-source initiative for the numerical simulation of thermo-hydro-mechanical/chemical (THMC) processes in porous and fractures media (Kolditz, 1990; Wollrath, 1990; Kroehn, 1991; Helmig, 1993; Kolditz et al., 2012; Bilke et al., 2019)

https://www.opengeosys.org/

No introduction required here ;)
(Helfer et al., 2015)

http://tfel.sourceforge.net/

Brief description of the formulation

Description	Equation	Parameters
Strain decomposition	$\mathrm{d}\boldsymbol{\epsilon} = \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{e}} + \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{vp}} + \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{c}}$	-

Brief description of the formulation

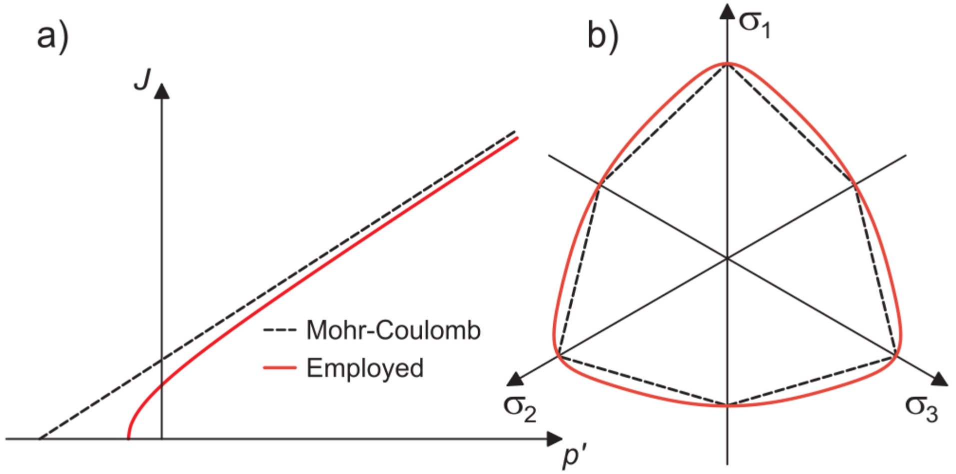
Description	Equation	Parameters
Strain decomposition	$\mathrm{d}\boldsymbol{\epsilon} = \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{e}} + \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{vp}} + \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{c}}$	-
Elastic behaviour	$\mathrm{d}\boldsymbol{\sigma} = \hat{\mathbf{D}}^{\mathrm{e}} \mathrm{d}\boldsymbol{\epsilon}^{\mathrm{e}}$	E_1, E_2, G_2, ν_1, ν_2, α^{rot},
	$\hat{\mathbf{D}}^{\mathrm{e}} = \mathbf{T}^{\mathrm{T}} \mathbf{D}^{\mathrm{e}} \mathbf{T}$	β^{rot}

$$\mathbf{D}^{\mathrm{e}} = \begin{bmatrix} E_1 \dfrac{1-\bar{n}\nu_2^2}{(1+\nu_1)\bar{m}} & E_1 \dfrac{\nu_1+\bar{n}\nu_2^2}{(1+\nu_1)\bar{m}} & E_1 \dfrac{\nu_2}{\bar{m}} & 0 & 0 & 0 \\ E_1 \dfrac{\nu_1+\bar{n}\nu_2^2}{(1+\nu_1)\bar{m}} & E_1 \dfrac{1-\bar{n}\nu_2^2}{(1+\nu_1)\bar{m}} & E_1 \dfrac{\nu_2}{\bar{m}} & 0 & 0 & 0 \\ E_1 \dfrac{\nu_2}{\bar{m}} & E_1 \dfrac{\nu_2}{\bar{m}} & E_2 \dfrac{1-\nu_1}{\bar{m}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \dfrac{E_1}{2(1+\nu_1)} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & G_2 \end{bmatrix}$$

BGE TEC
BGE TECHNOLOGY GmbH

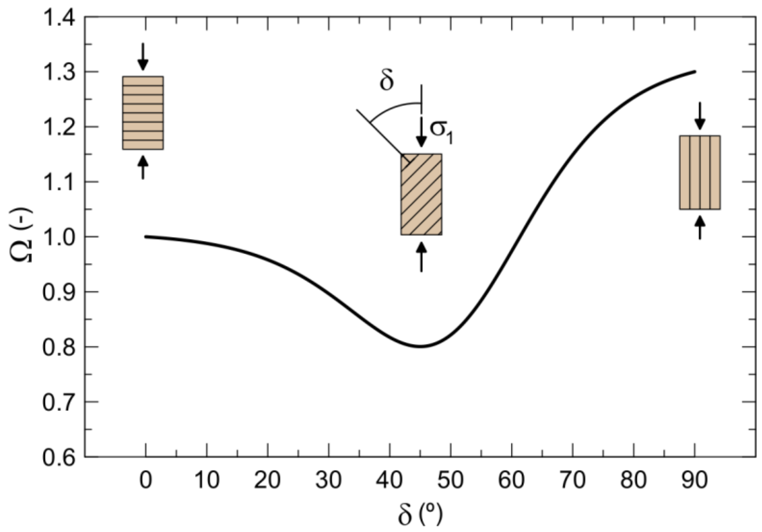
Brief description of the formulation

Description	Equation	Parameters
Strain decomposition	$d\boldsymbol{\epsilon} = d\boldsymbol{\epsilon}^{\mathrm{e}} + d\boldsymbol{\epsilon}^{\mathrm{vp}} + d\boldsymbol{\epsilon}^{\mathrm{c}}$	-
Elastic behaviour	$d\boldsymbol{\sigma} = \hat{\mathbf{D}}^{\mathrm{e}} d\boldsymbol{\epsilon}^{\mathrm{e}}$	$E_1,\ E_2,\ G_2,\ \nu_1,\ \nu_2,\ \alpha^{\mathrm{rot}},$
	$\hat{\mathbf{D}}^{\mathrm{e}} = \mathbf{T}^{\mathrm{T}}\mathbf{D}^{\mathrm{e}}\mathbf{T}$	β^{rot}
Yield criterion	$F = \sqrt{\frac{J_2}{f_{\mathrm{d}}(\theta)} + (c^* + p_t \tan\phi^*)^2} - (c^* + p' \tan\phi^*)$	α_{d}
	$f_{\mathrm{d}}(\theta) = \alpha_{\mathrm{d}}\,(1 + B_{\mathrm{d}} \sin 3\theta)^{n_{\mathrm{d}}}$	



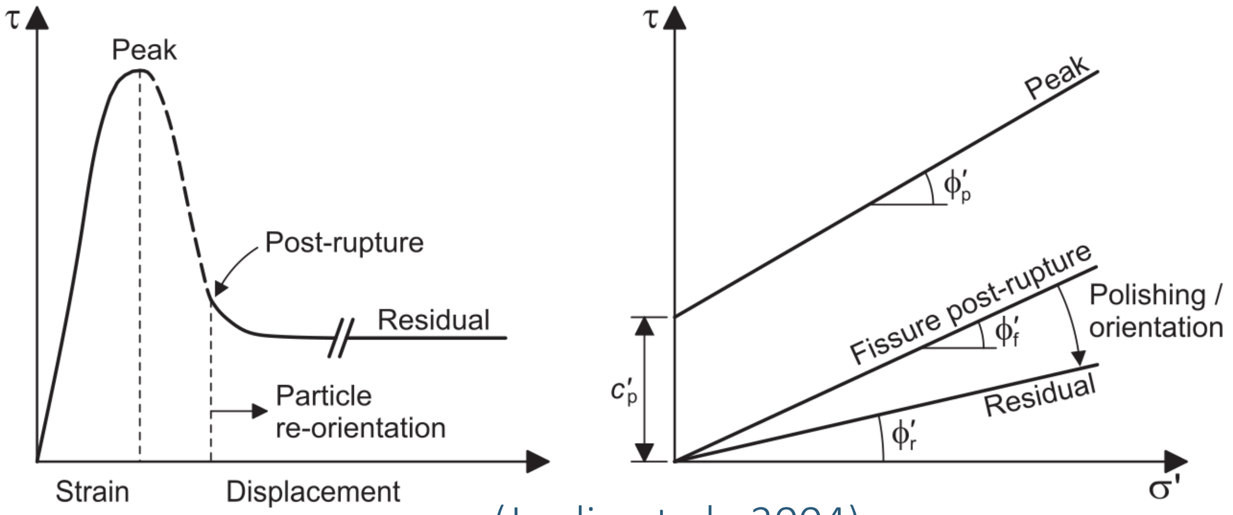
Brief description of the formulation

Description	Equation	Parameters
Strength anisotropy	$c^* = \Omega(\delta) c_0^*$	Ω_{90}, Ω_{m}, δ_{m}, n
	$p_t = \Omega(\delta) p_{t0}$	
	$\Omega = \frac{A \mathrm{e}^{(\delta_{\mathrm{m}} - \delta) n}}{\left[1 + \mathrm{e}^{(\delta_{\mathrm{m}} - \delta) n}\right]^2} + \frac{B}{1 + \mathrm{e}^{(\delta_{\mathrm{m}} - \delta) n}} + C$	
	$A = \frac{2(e_1+1)(e_2+1)(e_1 - e_2 + \Omega_{90} + e_1 e_2 + e_1 \Omega_{90} - e_2 \Omega_{90} - 2 e_1 \Omega_{\mathrm{m}} + 2 e_2 \Omega_{\mathrm{m}} - e_1 e_2 \Omega_{90} - 1)}{(e_1 - e_2)(e_1 - 1)(e_2 - 1)}$	
	$B = \frac{\Omega_{90} - \frac{A e_1}{(e_1+1)^2} + \frac{A e_2}{(e_2+1)^2} - 1}{\frac{1}{e_1+1} - \frac{1}{e_2+1}}$	
	$C = 1 - \frac{A e_2}{(e_2+1)^2} - \frac{B}{e_2+1}$	
	$e_1 = \mathrm{e}^{n(\delta_{\mathrm{m}} - 90)}$	
	$e_2 = \mathrm{e}^{n \delta_{\mathrm{m}}}$	



Brief description of the formulation

Description	Equation	Parameters
Softening laws	$\tan\phi^* = \tan\phi^*_{\text{peak}} - \left(\tan\phi^*_{\text{peak}} - \tan\phi^*_{\text{res}}\right)\left[1 - \mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}\right]$	$\phi^*_{\text{peak}},\ \phi^*_{\text{res}},\ c^*_{0\,\text{peak}},\ p_{t\,\text{peak}},$
	$c^*_0 = \left(c^*_{0\,\text{peak}} - c^*_{0\,\text{post}}\right)\mathrm{e}^{-b_{\text{post}}(\epsilon^{\text{p}}_{\text{eq}})} + c^*_{0\,\text{post}}\mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}$	$r_{\text{post}},\ b_{\text{post}},\ b_{\text{res}}$
	$p_{t0} = \left(p_{t0\,\text{peak}} - p_{t0\,\text{post}}\right)\mathrm{e}^{-b_{\text{post}}(\epsilon^{\text{p}}_{\text{eq}})} + p_{t0\,\text{post}}\mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}$	
	$\epsilon^{\text{p}}_{\text{eq}} = \left(\boldsymbol{\epsilon}^{\text{p}} : \boldsymbol{\epsilon}^{\text{p}}\right)^{1/2}$	
	$\boldsymbol{\epsilon}^{\text{p}} = \boldsymbol{\epsilon}^{\text{vp}} + \boldsymbol{\epsilon}^{\text{c}}$	
	$r_{\text{post}} = \dfrac{c^*_{0\,\text{post}}}{c^*_{0\,\text{peak}}} = \dfrac{p_{t0\,\text{post}}}{p_{t0\,\text{peak}}}$	



(Jardin et al., 2004)

Brief description of the formulation

Description	Equation	Parameters
Softening laws	$\tan\phi^* = \tan\phi^*_{\text{peak}} - \left(\tan\phi^*_{\text{peak}} - \tan\phi^*_{\text{res}}\right)\left[1 - \mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}\right]$	$\phi^*_{\text{peak}},\ \phi^*_{\text{res}},\ c^*_{0\,\text{peak}},\ p_{t\,\text{peak}},$
	$c^*_0 = \left(c^*_{0\,\text{peak}} - c^*_{0\,\text{post}}\right)\mathrm{e}^{-b_{\text{post}}(\epsilon^{\text{p}}_{\text{eq}})} + c^*_{0\,\text{post}}\mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}$	$r_{\text{post}},\ b_{\text{post}},\ b_{\text{res}}$
	$p_{t0} = \left(p_{t0\,\text{peak}} - p_{t0\,\text{post}}\right)\mathrm{e}^{-b_{\text{post}}(\epsilon^{\text{p}}_{\text{eq}})} + p_{t0\,\text{post}}\mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}$	
	$\epsilon^{\text{p}}_{\text{eq}} = \left(\boldsymbol{\epsilon}^{\text{p}} : \boldsymbol{\epsilon}^{\text{p}}\right)^{1/2}$	
	$\boldsymbol{\epsilon}^{\text{p}} = \boldsymbol{\epsilon}^{\text{vp}} + \boldsymbol{\epsilon}^{\text{c}}$	
	$r_{\text{post}} = \dfrac{c^*_{0\,\text{post}}}{c^*_{0\,\text{peak}}} = \dfrac{p_{t0\,\text{post}}}{p_{t0\,\text{peak}}}$	
Plastic potential	$\dfrac{\partial G}{\partial \boldsymbol{\sigma}'} = \omega\dfrac{\partial F}{\partial p}\dfrac{\partial p}{\partial \boldsymbol{\sigma}'} + \dfrac{\partial F}{\partial J_2}\dfrac{\partial J_2}{\partial \boldsymbol{\sigma}'} + \dfrac{\partial F}{\partial \theta}\dfrac{\partial \theta}{\partial \boldsymbol{\sigma}'}$	ω

BGE TEC
BGE TECHNOLOGY GmbH

Brief description of the formulation

Description	Equation	Parameters
Softening laws	$\tan\phi^* = \tan\phi^*_{\text{peak}} - \left(\tan\phi^*_{\text{peak}} - \tan\phi^*_{\text{res}}\right)\left[1 - \mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}\right]$	$\phi^*_{\text{peak}},\ \phi^*_{\text{res}},\ c^*_{0\,\text{peak}},\ p_{t\,\text{peak}},$
	$c^*_0 = \left(c^*_{0\,\text{peak}} - c^*_{0\,\text{post}}\right)\mathrm{e}^{-b_{\text{post}}(\epsilon^{\text{p}}_{\text{eq}})} + c^*_{0\,\text{post}}\mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}$	$r_{\text{post}},\ b_{\text{post}},\ b_{\text{res}}$
	$p_{t0} = \left(p_{t0\,\text{peak}} - p_{t0\,\text{post}}\right)\mathrm{e}^{-b_{\text{post}}(\epsilon^{\text{p}}_{\text{eq}})} + p_{t0\,\text{post}}\mathrm{e}^{-b_{\text{res}}(\epsilon^{\text{p}}_{\text{eq}})}$	
	$\epsilon^{\text{p}}_{\text{eq}} = \left(\boldsymbol{\epsilon}^{\text{p}} : \boldsymbol{\epsilon}^{\text{p}}\right)^{1/2}$	
	$\boldsymbol{\epsilon}^{\text{p}} = \boldsymbol{\epsilon}^{\text{vp}} + \boldsymbol{\epsilon}^{\text{c}}$	
	$r_{\text{post}} = \dfrac{c^*_{0\,\text{post}}}{c^*_{0\,\text{peak}}} = \dfrac{p_{t0\,\text{post}}}{p_{t0\,\text{peak}}}$	
Plastic potential	$\dfrac{\partial G}{\partial \boldsymbol{\sigma}'} = \omega\dfrac{\partial F}{\partial p}\dfrac{\partial p}{\partial \boldsymbol{\sigma}'} + \dfrac{\partial F}{\partial J_2}\dfrac{\partial J_2}{\partial \boldsymbol{\sigma}'} + \dfrac{\partial F}{\partial \theta}\dfrac{\partial \theta}{\partial \boldsymbol{\sigma}'}$	ω
Visco-plasticity	$\mathrm{d}\boldsymbol{\epsilon}^{\text{vp}} = \dfrac{\langle\Phi(F)\rangle}{\eta}\dfrac{\partial G}{\partial \boldsymbol{\sigma}'}\,\mathrm{d}t$	$N,\ \eta$
	$\Phi(F) = \left(\dfrac{F}{p_{\text{atm}}}\right)^N$	

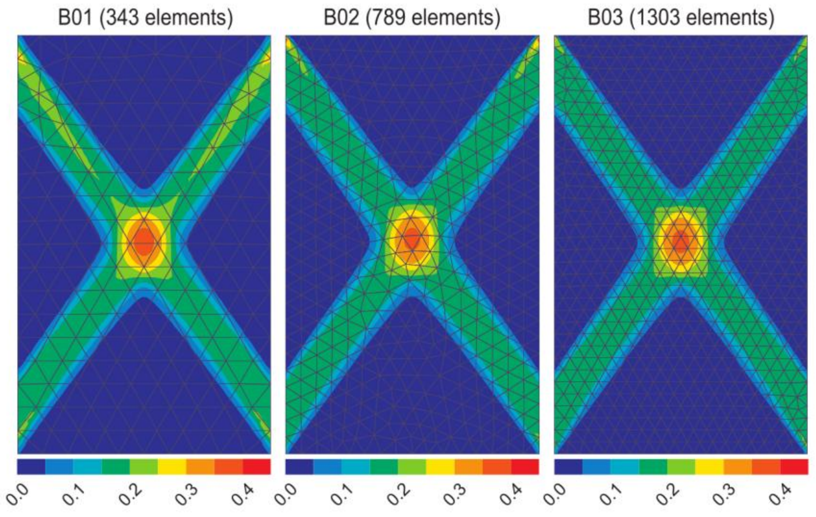
Brief description of the formulation

Description	Equation	Parameters
Creep deformations	$\mathrm{d}\boldsymbol{\epsilon}^{\mathrm{c}} = \dot{\boldsymbol{\epsilon}}^{\mathrm{c}}\mathrm{d}t$ $\dot{\boldsymbol{\epsilon}}^{\mathrm{c}} = \begin{cases} \mathbf{0} & \text{if } \epsilon^{\mathrm{p}}_{\mathrm{eq}} \leq \epsilon_{\mathrm{thr}} \\ \gamma \mathrm{e}^{(-m\epsilon^{\mathrm{c}}_{\mathrm{eq}})} (\mathbf{s} + \mu p' \mathbf{I}) & \text{if } \epsilon^{\mathrm{p}}_{\mathrm{eq}} > \epsilon_{\mathrm{thr}} \end{cases}$ $\epsilon^{\mathrm{c}}_{\mathrm{eq}} = (\boldsymbol{\epsilon}^{\mathrm{c}} : \boldsymbol{\epsilon}^{\mathrm{c}})^{1/2}$	γ, μ, m, ϵ_{thr}

BGE TEC BGE TECHNOLOGY GmbH

Brief description of the formulation

Description	Equation	Parameters
Creep deformations	$\mathrm{d}\boldsymbol{\epsilon}^{\mathrm{c}} = \dot{\boldsymbol{\epsilon}}^{\mathrm{c}}\mathrm{d}t$ $\dot{\boldsymbol{\epsilon}}^{\mathrm{c}} = \begin{cases} \mathbf{0} & \text{if } \epsilon^{\mathrm{p}}_{\mathrm{eq}} \leq \epsilon_{\mathrm{thr}} \\ \gamma \mathrm{e}^{\left(-m\epsilon^{\mathrm{c}}_{\mathrm{eq}}\right)}\left(\mathbf{s} + \mu p' \mathbf{I}\right) & \text{if } \epsilon^{\mathrm{p}}_{\mathrm{eq}} > \epsilon_{\mathrm{thr}} \end{cases}$ $\epsilon^{\mathrm{c}}_{\mathrm{eq}} = \left(\boldsymbol{\epsilon}^{\mathrm{c}} : \boldsymbol{\epsilon}^{\mathrm{c}}\right)^{1/2}$	$\gamma,\ \mu,\ m,\ \epsilon_{\mathrm{thr}}$
Nonlocal regularisation	$\bar{\epsilon}^{\mathrm{p}}_{\mathrm{eq}}(\mathbf{x}) = \int_V w\left(\mathbf{x}, \boldsymbol{\xi}\right) \epsilon^{\mathrm{p}}_{\mathrm{eq}}\left(\boldsymbol{\xi}\right) d\boldsymbol{\xi}$ $w\left(\mathbf{x}, \boldsymbol{\xi}\right) = \frac{w_0(\lVert\mathbf{x}-\boldsymbol{\xi}\rVert)}{\int_V w_0(\lVert\mathbf{x}-\boldsymbol{\zeta}\rVert)d\boldsymbol{\zeta}}$ $w_0 = \frac{\lVert\mathbf{x}-\boldsymbol{\xi}\rVert}{l_{\mathrm{s}}}\mathrm{e}^{-\left(\frac{\lVert\mathbf{x}-\boldsymbol{\xi}\rVert}{l_{\mathrm{s}}}\right)^2}$	l_{s}



BGE TEC
BGE TECHNOLOGY GmbH

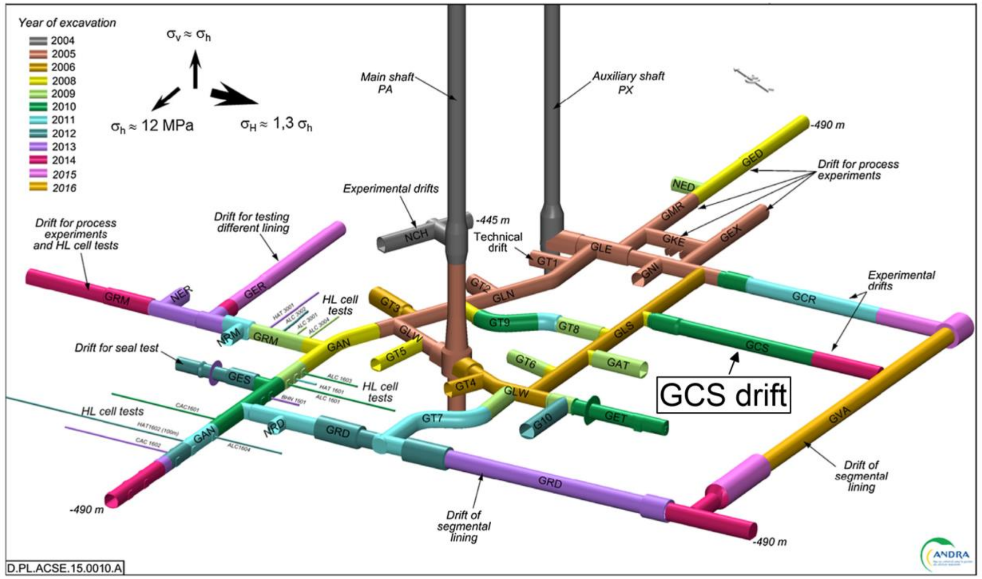
Brief description of the formulation

Description	Equation	Parameters
Hydro-mechanical coupling	$\boldsymbol{\sigma}' = \boldsymbol{\sigma} + S_\mathrm{e} s B \mathbf{I}$ $S_\mathrm{e} = \frac{S_\mathrm{l} - S_\mathrm{lr}}{S_\mathrm{ls} - S_\mathrm{lr}} = \left[1 + \left(\frac{s}{P}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda}$ $\mathbf{q} = -\frac{\mathbf{k} k_\mathrm{r}}{\mu_\mathrm{w}} \left(\nabla p_\mathrm{l} - \rho_\mathrm{w} \mathbf{g}\right)$ $k_\mathrm{r} = S_\mathrm{e}^{\frac{1}{2}} \left[1 - \left(1 - S_\mathrm{e}^{\frac{1}{\lambda}}\right)^{\lambda}\right]^2$ $\mathbf{k} = \mathbf{k}_0 \left[1 + \beta \left(\epsilon^\mathrm{p}_\mathrm{eq}\right)^3\right]$	$B,\ \lambda,\ P,\ \beta,\ k_\mathrm{h},\ k_\mathrm{v}$

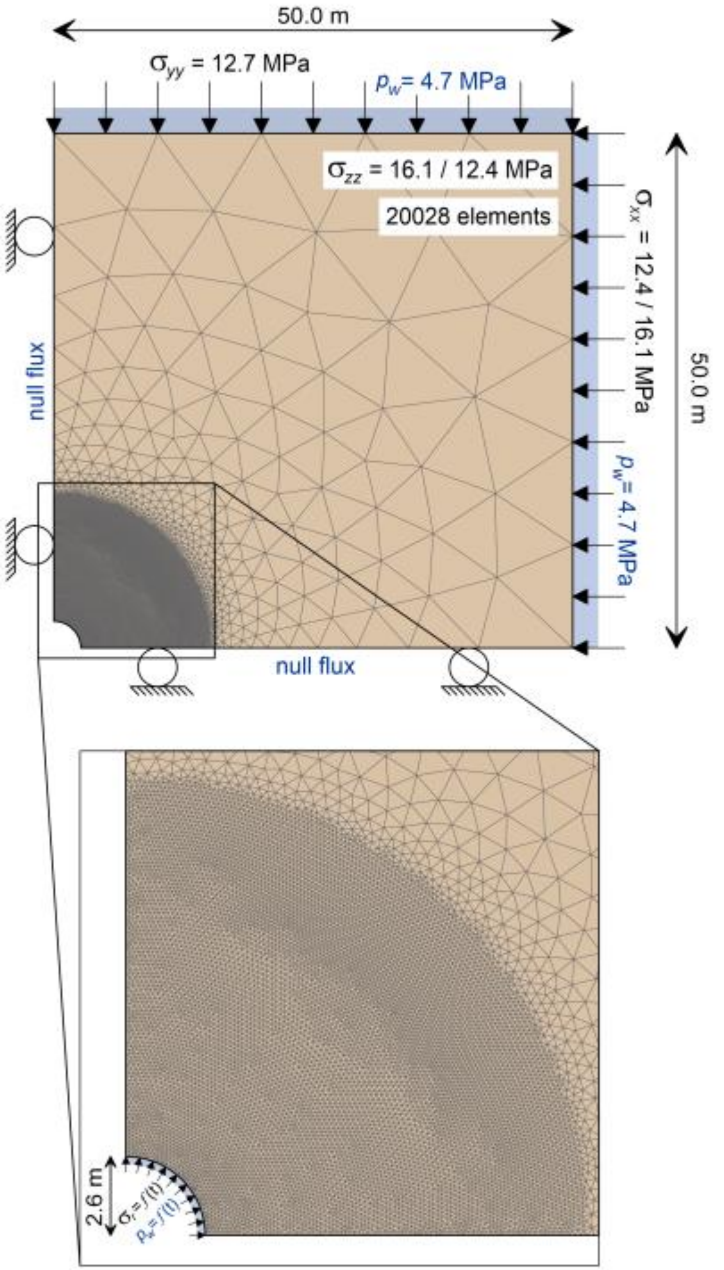
BGE TEC
BGE TECHNOLOGY GmbH

Application example

- Simulation of drifts at the Meuse/Haute Marne Underground Research Laboratory.



(Seyedi et al., 2017)

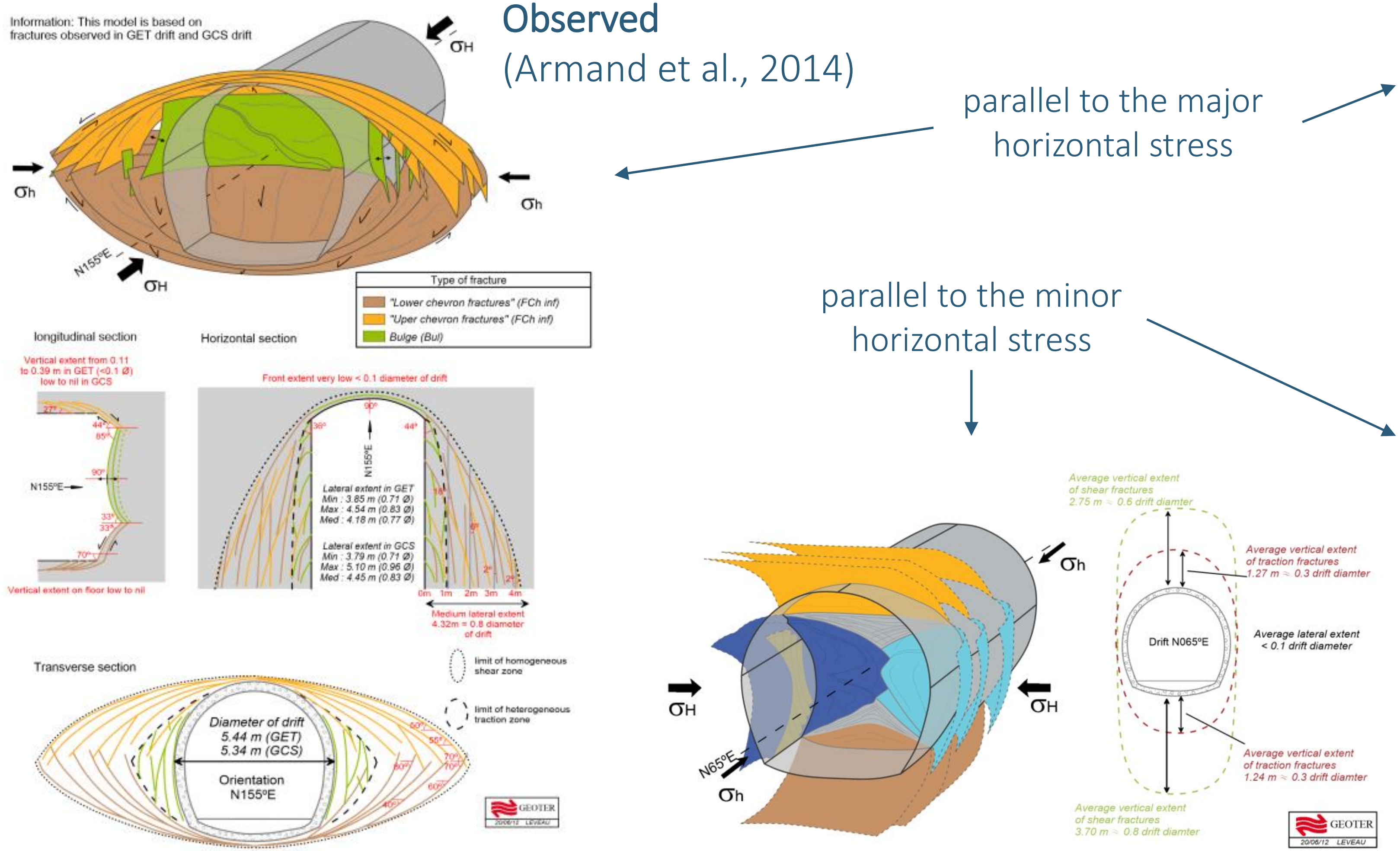


Details in: Mánica M (2018) Analysis of underground excavations in argillaceous hard soils–weak rocks. Technical University of Catalonia, PhD.

Application example

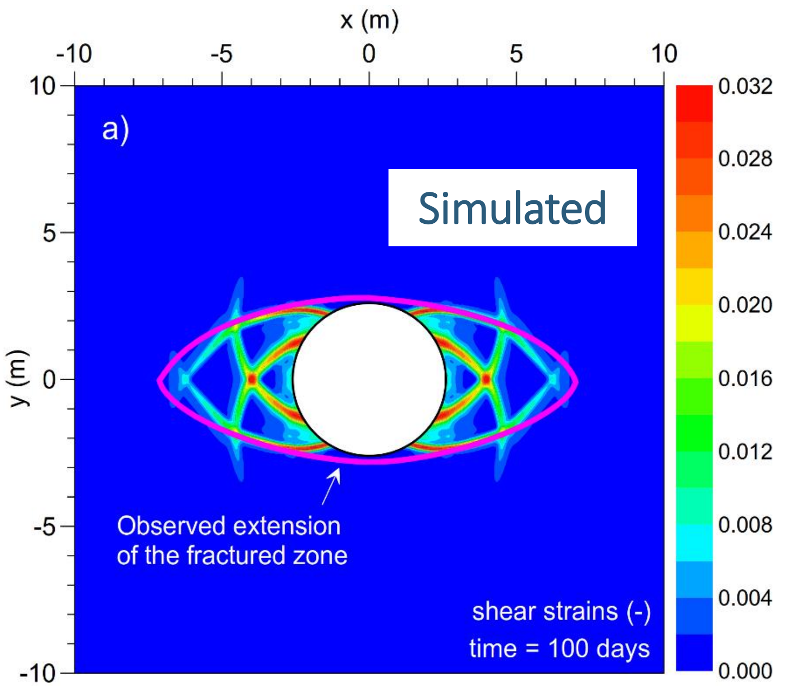
- Obtained results – damaged zone

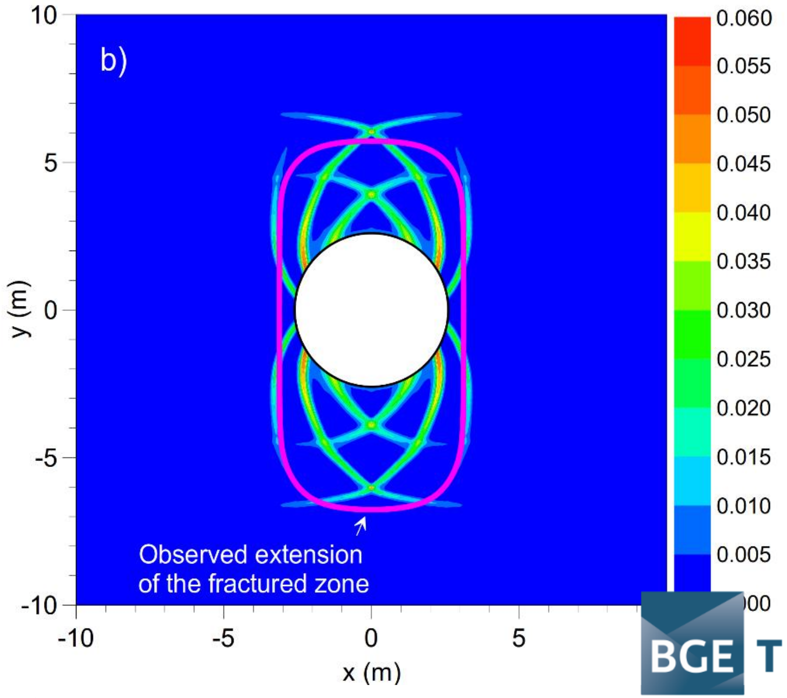
Observed
(Armand et al., 2014)



parallel to the major horizontal stress

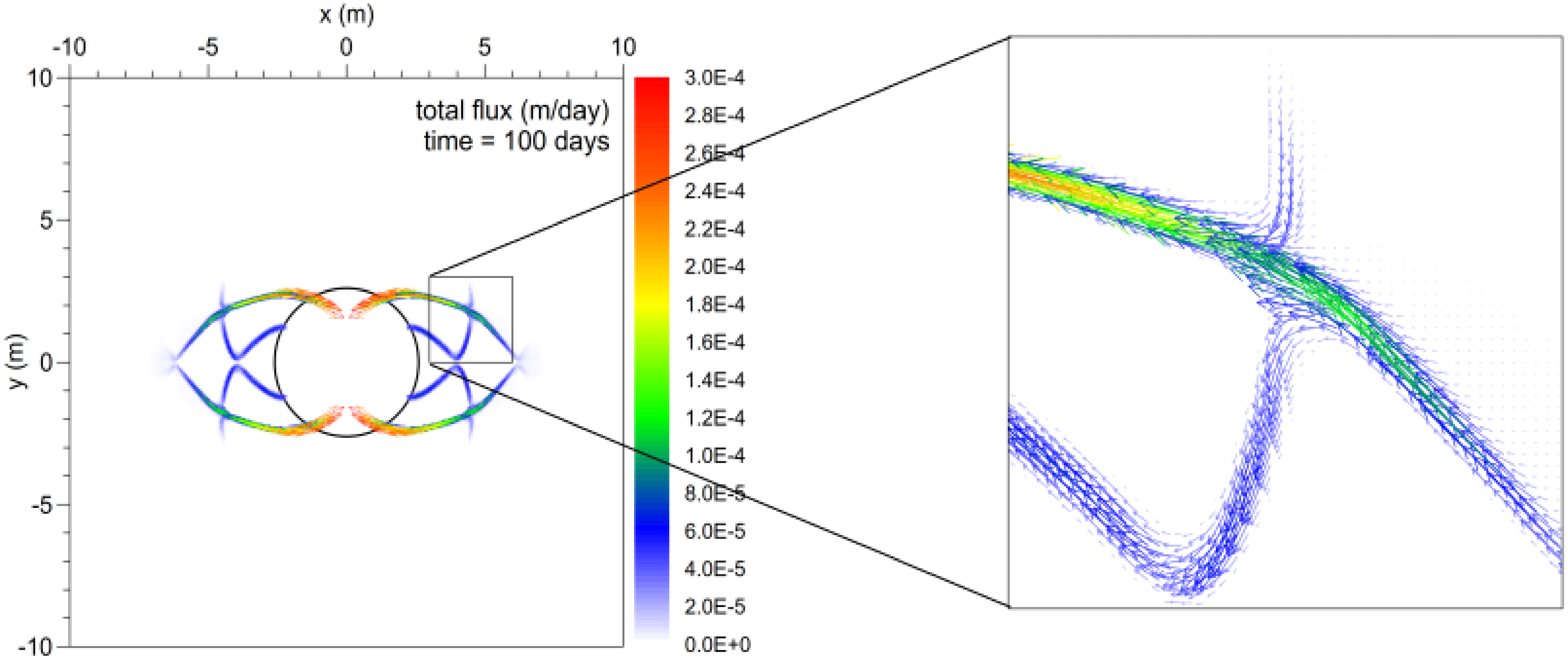
parallel to the minor horizontal stress





Application example

- Obtained results – localized water flow

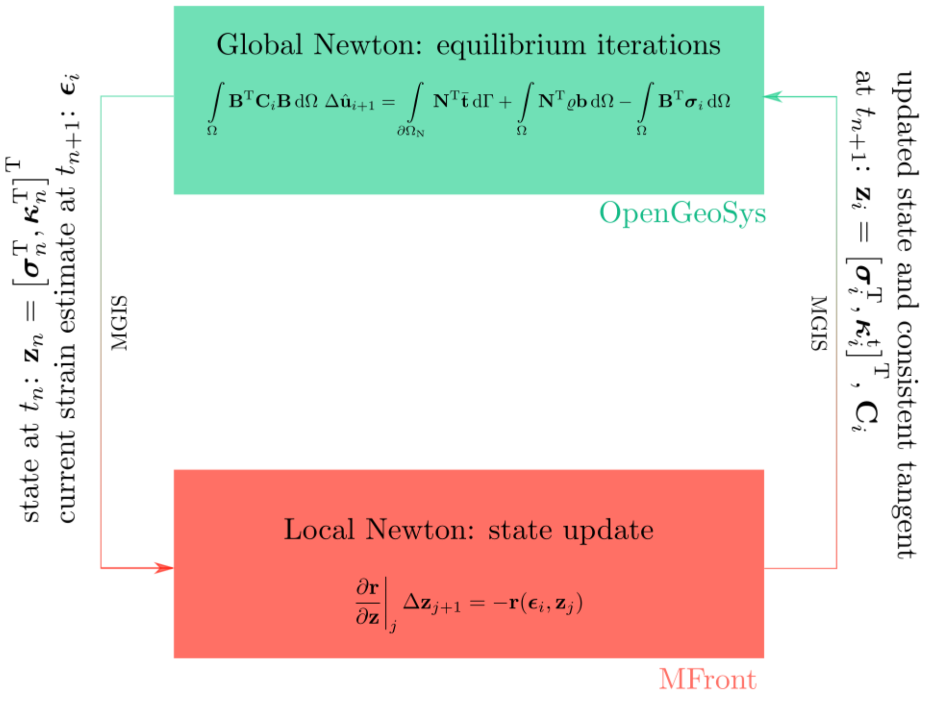


BGE TEC
BGE TECHNOLOGY GmbH

Implementation - MFront

- Implementation of the described model in **OpenGeoSys**: recently started project.

Implementation - MFront

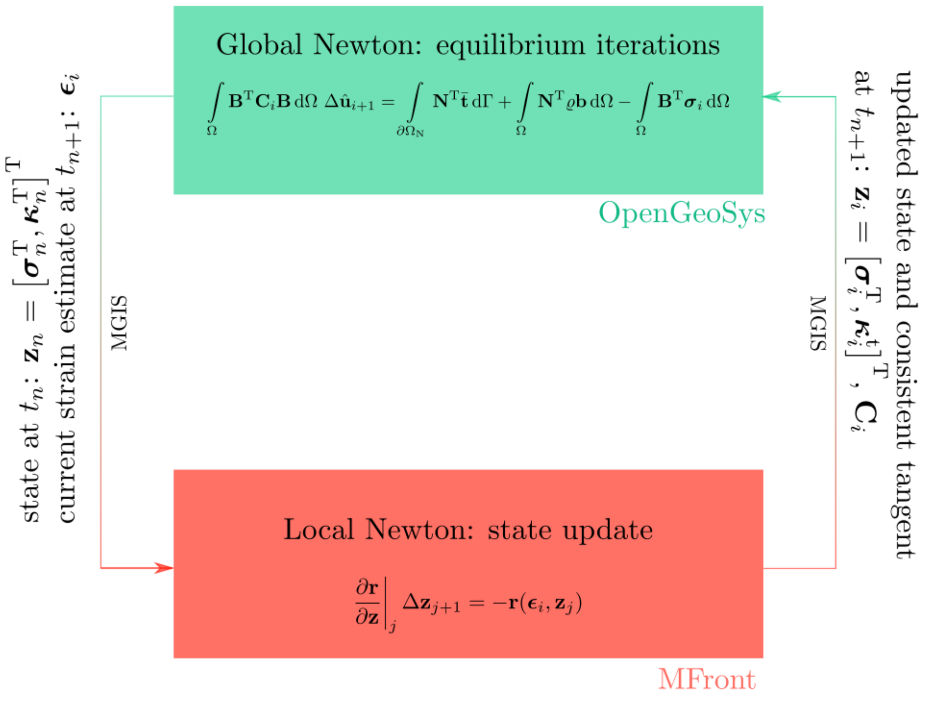


(Nagel et al., 2019)

- Implementation of the described model in **OpenGeoSys**: recently started project.
- Support for **MFront** already provided in **OpenGeoSys** (Nagel et al., 2019) trough the MFrontGenericInterfaceSupport (**MGIS**) library (Helfer et al., 2020).

BGE TEC BGE TECHNOLOGY GmbH

Implementation - MFront

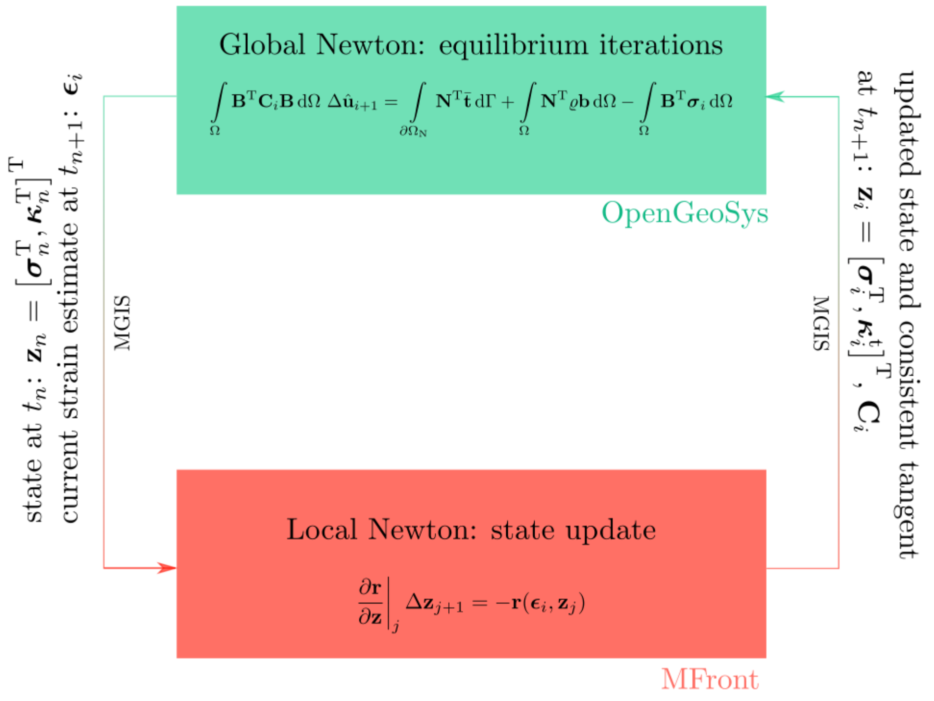


(Nagel et al., 2019)

- Implementation of the described model in **OpenGeoSys**: recently started project.
- Support for **MFront** already provided in **OpenGeoSys** (Nagel et al., 2019) trough the MFrontGenericInterfaceSupport (**MGIS**) library (Helfer et al., 2020).
- Local version of the model straightforward.

BGE TEC BGE TECHNOLOGY GmbH

Implementation - MFront



(Nagel et al., 2019)

- Implementation of the described model in **OpenGeoSys**: recently started project.
- Support for **MFront** already provided in **OpenGeoSys** (Nagel et al., 2019) trough the MFrontGenericInterfaceSupport (**MGIS**) library (Helfer et al., 2020).
- Local version of the model straightforward.
- Nonlocal version – more challenging:
  - Already exists a native implementation in **OGS** (Parisio et al., 2019).
  - Main requirement – access to state variables from neighboring Gauss points.
  - It could be directly addressed in **MFront**.

Next steps

- **Bentonite model:**
  - Development work in OpenGeoSys to considered the generalized state variable vector for THM-simulation
  - Numerical tests and Benchmarks in OpenGeoSys and SIFEL

- **Clay stone model**
  - Implementation of the local model in Mfront
  - Theoretical work to deal with nonlocal plasticity in Mfront

Thank you for your attention!