A temperature-dependent constitutive model for argillaceous hard soils - weak rocks

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Content

1. Introduction
2. Implementation of thermal effects
   - Volumetric yield function
   - Temperature dependence of the **deviatoric** yield surface
   - Temperature dependence of the **volumetric** yield surface
   - Additional convergence checks
3. Coupled THM BVP simulation
4. Conclusions

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Deep geological disposal of nuclear waste

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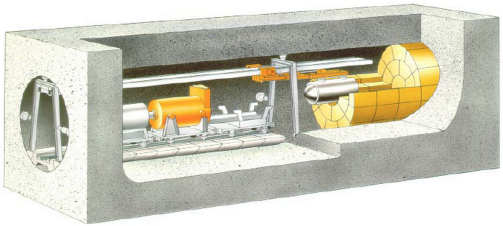

(Gens, 2004)

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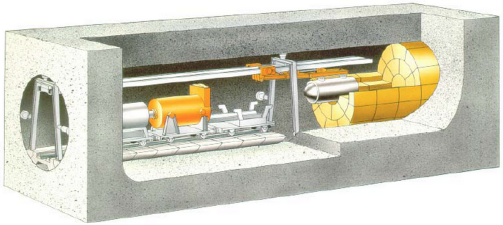

(Gens, 2004)

- Possible geological barriers:
  - Salt rocks
  - Argillaceous rocks
  - Limestones
  - Granite rock
  - Basalt rock
  - Volcanic tuff

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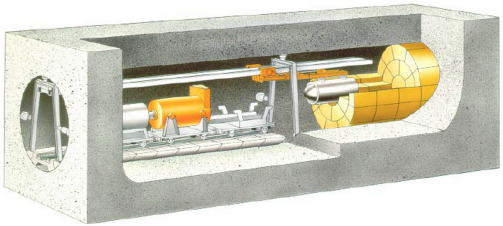

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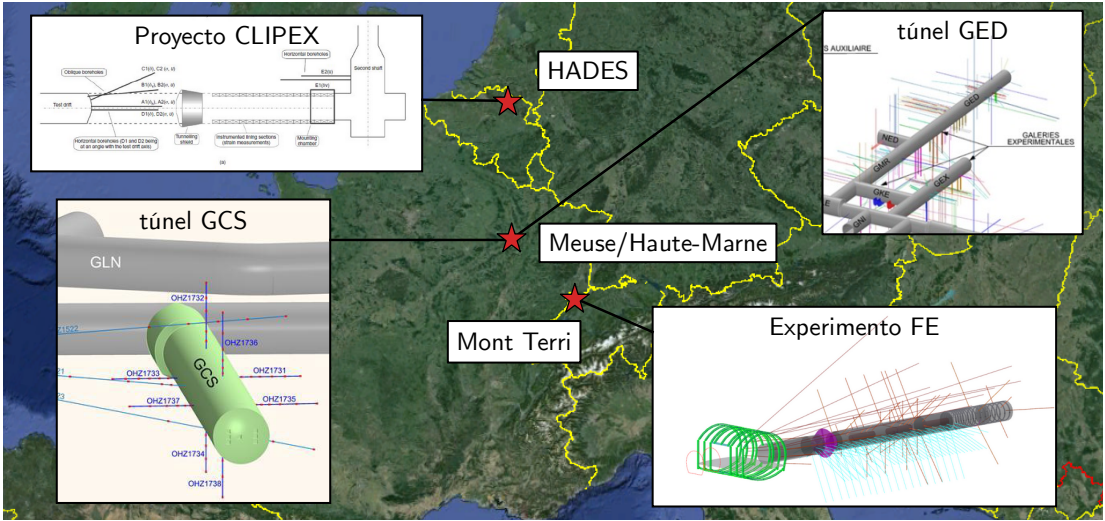


Introduction - Constitutive model for the host rock

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 (cross-anisotropy)

$$\mathrm{d}\boldsymbol{\sigma} = \hat{\mathbf{D}}^{\mathrm{e}}\mathrm{d}\boldsymbol{\epsilon}^{\mathrm{e}}$$
$$\hat{\mathbf{D}}^{\mathrm{e}} = \mathbf{T}^{\mathrm{T}}\mathbf{D}^{\mathrm{e}}\mathbf{T}$$

Yield criterion

$$f = \sqrt{\frac{J_2}{f_{\mathrm{d}}(\theta)} + (c^* + p_{\mathrm{t}}\tan\phi^*)^2} - \left(c^* + p'\tan\phi^*\right)$$
$$f_{\mathrm{d}}(\theta) = \alpha_{\mathrm{d}}\left(1 + B_{\mathrm{d}}\sin 3\theta\right)^{n_{\mathrm{d}}}$$

Strength anisotropy

$$p_{\mathrm{t}} = \Omega(\delta)p_{\mathrm{t0}}$$
$$\Omega = \frac{A\mathrm{e}^{(\delta_{\mathrm{m}}-\delta)n}}{\left[1+\mathrm{e}^{(\delta_{\mathrm{m}}-\delta)n}\right]^2} + \frac{B}{1+\mathrm{e}^{(\delta_{\mathrm{m}}-\delta)n}} + C$$

Softening laws

$$\tan\phi^* = \tan\phi^*_{\mathrm{peak}} - \left(\tan\phi^*_{\mathrm{peak}} - \tan\phi^*_{\mathrm{res}}\right)\left[1 - \mathrm{e}^{-b_{\mathrm{res}}(\epsilon^{\mathrm{p}}_{\mathrm{eq}})}\right]$$
$$c^*_0 = \left(c^*_{0\,\mathrm{peak}} - c^*_{0\,\mathrm{post}}\right)\mathrm{e}^{-b_{\mathrm{post}}(\epsilon^{\mathrm{p}}_{\mathrm{eq}})} + c^*_{0\,\mathrm{post}}\mathrm{e}^{-b_{\mathrm{res}}(\epsilon^{\mathrm{p}}_{\mathrm{eq}})}$$
$$p_{\mathrm{t0}} = \left(p_{\mathrm{t0\,peak}} - p_{\mathrm{t0\,post}}\right)\mathrm{e}^{-b_{\mathrm{post}}(\epsilon^{\mathrm{p}}_{\mathrm{eq}})} + p_{\mathrm{t0\,post}}\mathrm{e}^{-b_{\mathrm{res}}(\epsilon^{\mathrm{p}}_{\mathrm{eq}})}$$
$$\epsilon^{\mathrm{p}}_{\mathrm{eq}} = (\boldsymbol{\epsilon}^{\mathrm{p}} : \boldsymbol{\epsilon}^{\mathrm{p}})^{1/2} \qquad \boldsymbol{\epsilon}^{\mathrm{p}} = \boldsymbol{\epsilon}^{\mathrm{vp}} + \boldsymbol{\epsilon}^{\mathrm{c}}$$

Flow rule

$$\frac{\partial G}{\partial \boldsymbol{\sigma}'} = \omega\frac{\partial F}{\partial p}\frac{\partial p}{\partial \boldsymbol{\sigma}'} + \frac{\partial F}{\partial J_2}\frac{\partial J_2}{\partial \boldsymbol{\sigma}'} + \frac{\partial F}{\partial \theta}\frac{\partial \theta}{\partial \boldsymbol{\sigma}'}$$

Visco-plasticity

$$\mathrm{d}\boldsymbol{\epsilon}^{\mathrm{vp}} = \frac{\langle\Phi(F)\rangle}{\eta}\frac{\partial G}{\partial \boldsymbol{\sigma}'}\,\mathrm{d}t$$
$$\Phi(F) = \left(\frac{F}{p_{\mathrm{atm}}}\right)^N$$

Creep deformations

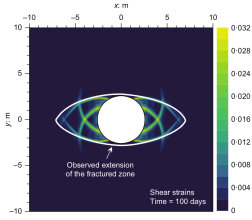
$$\mathrm{d}\boldsymbol{\epsilon}^{\mathrm{c}} = \dot{\boldsymbol{\epsilon}}^{\mathrm{c}}\mathrm{d}t$$
$$\dot{\boldsymbol{\epsilon}}^{\mathrm{c}} = \begin{cases} \mathbf{0} & \text{if } \epsilon^{\mathrm{p}}_{\mathrm{eq}} \le \epsilon_{\mathrm{thr}} \\ \gamma\mathrm{e}^{(-m\epsilon^{\mathrm{c}}_{\mathrm{eq}})}\left(\mathbf{s} + \mu p'\mathbf{I}\right) & \text{if } \epsilon^{\mathrm{p}}_{\mathrm{eq}} > \epsilon_{\mathrm{thr}} \end{cases}$$
$$\epsilon^{\mathrm{c}}_{\mathrm{eq}} = (\boldsymbol{\epsilon}^{\mathrm{c}} : \boldsymbol{\epsilon}^{\mathrm{c}})^{1/2}$$

Nonlocal regularisation

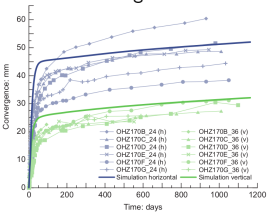
$$\bar{\epsilon}^{\mathrm{p}}_{\mathrm{eq}}(\mathbf{x}) = \int_V w\left(\mathbf{x}, \boldsymbol{\xi}\right)\epsilon^{\mathrm{p}}_{\mathrm{eq}}\left(\boldsymbol{\xi}\right)d\boldsymbol{\xi}$$
$$w\left(\mathbf{x}, \boldsymbol{\xi}\right) = \frac{w_0(\|\mathbf{x}-\boldsymbol{\xi}\|)}{\int_V w_0(\|\mathbf{x}-\boldsymbol{\zeta}\|)d\boldsymbol{\zeta}}$$
$$w_0 = \frac{\|\mathbf{x}-\boldsymbol{\xi}\|}{l_{\mathrm{s}}}\mathrm{e}^{-\left(\frac{\|\mathbf{x}-\boldsymbol{\xi}\|}{l_{\mathrm{s}}}\right)^2}$$

Introduction

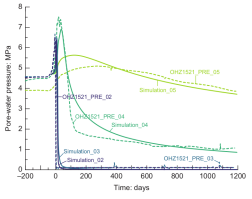
- *Hydromechanical behaviour of excavations*



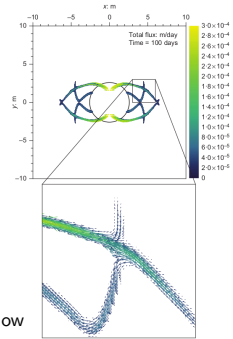
damage zone



horizontal and vertical convergences



water pressures



localised water flow

(Mánica et al., 2022)

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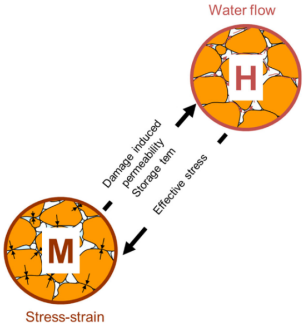

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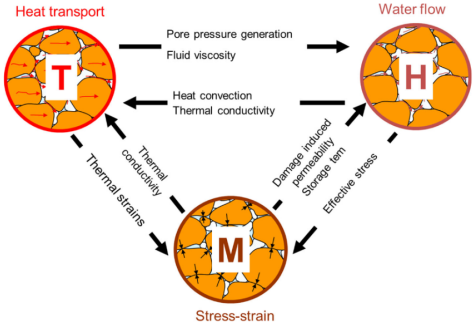

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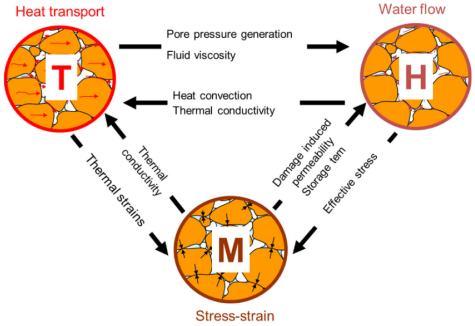

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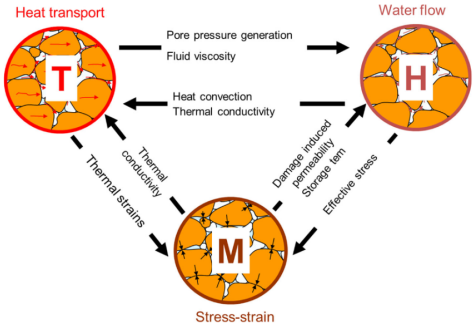

- The main objective is to incorporate thermal effects into the constitutive description of the host rock.

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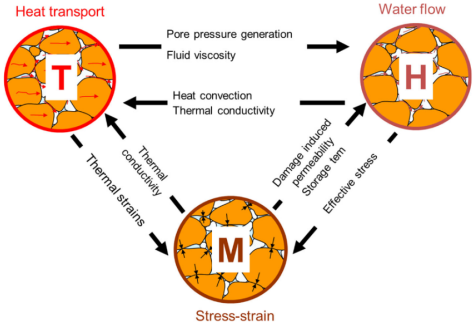

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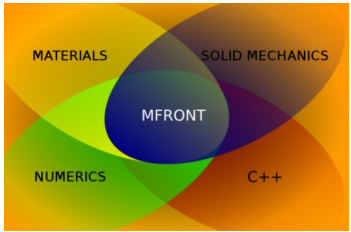
- Implementation of the constitutive model through **MFront**.



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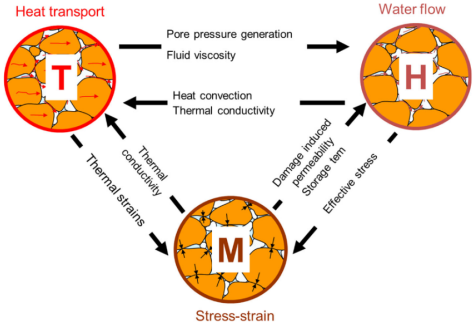

- The main objective is to incorporate thermal effects into the constitutive description of the host rock.
- Implementation of the constitutive model through **MFront**.
- To be used in coupled THM simulations using the finite element code **OpenGeoSys**

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OpenGeoSys
OPEN-SOURCE MULTI-PHYSICS

Introduction

Thermal behaviour of argillaceous hard soils - weak rocks

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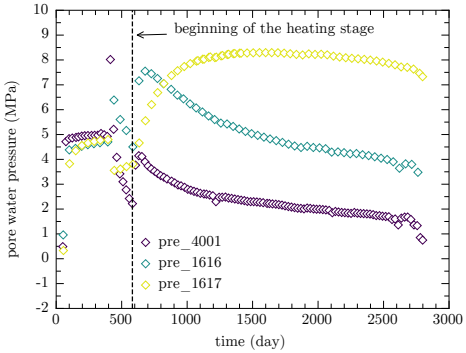
- **Thermal pressurisation**

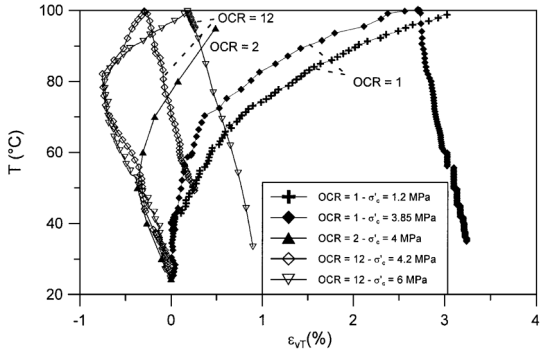


COx claystone (Bumbieler et al., 2021)

Introduction

Thermal behaviour of argillaceous hard soils - weak rocks

- Thermal pressurisation
- **Thermal volume changes**



Boom clay (Sultan et al., 2002)

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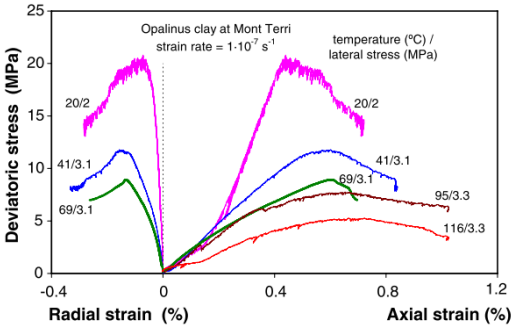
Thermal behaviour of argillaceous hard soils - weak rocks

- Thermal pressurisation
- Thermal volume changes
- **Variation of mechanical properties**



Opalinus clay (Zhang et al., 2007)

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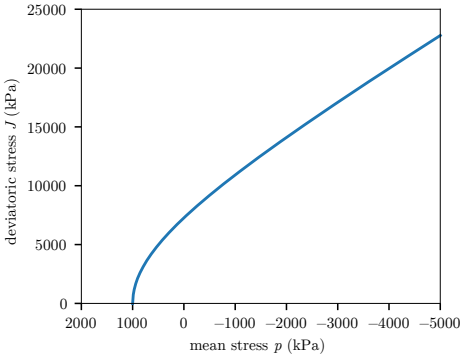
Volumetric yield function

- Originally only a deviatoric yield mechanism was considered:

$$f_1 = \sqrt{\frac{J_2}{f_{\mathrm{d}}(\theta)} + (c^* + p_{\mathrm{t}} \tan\phi^*)^2} - (c^* + p' \tan\phi^*)$$



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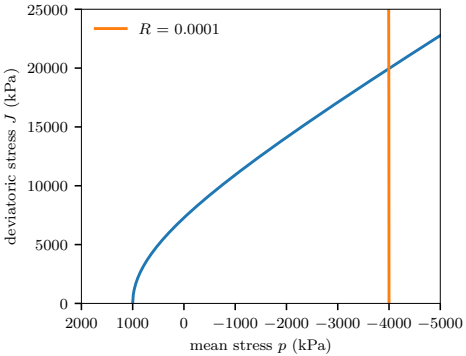
$$f_2 = R^2 J^2 + p_c - p'$$



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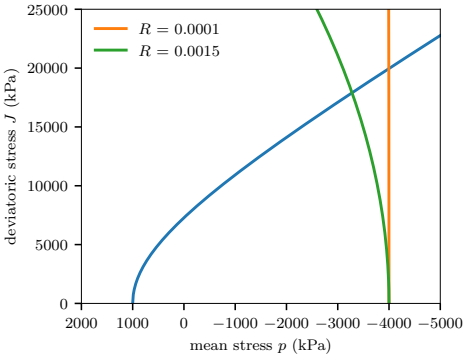

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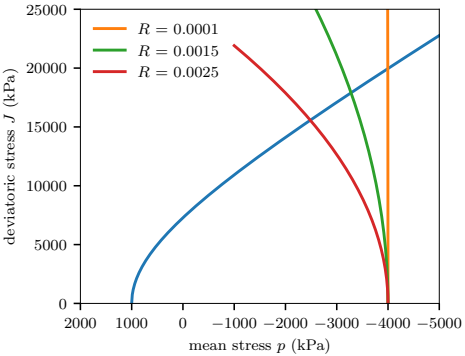

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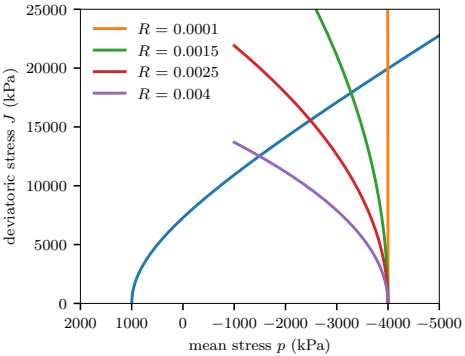

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$$f_2 = R^2 J^2 + p_c - p'$$

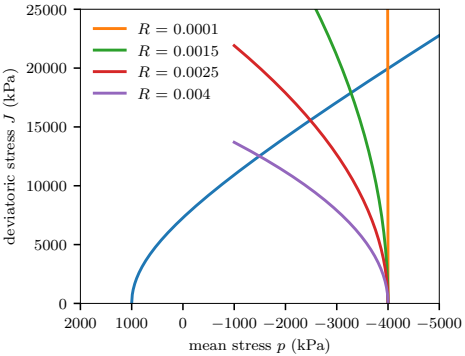
- Multi-surface plasticity framework:

$$\mathcal{E} = \{\boldsymbol{\sigma} \mid F_i(\boldsymbol{\sigma},\ \boldsymbol{\alpha}_i) < 0,\ i = 1, ..., n\}$$

$$F_i(\boldsymbol{\sigma}, \boldsymbol{\alpha}_i) = 0$$

$$\Delta\boldsymbol{\epsilon}^{\mathrm{p}} = \sum_{i=1}^{n} \Delta\lambda_i \frac{\partial g_i}{\partial \boldsymbol{\sigma}}$$

$$F_i \leq 0, \quad \Delta\lambda_i \geq 0, \quad F_i \Delta\lambda_i = 0$$



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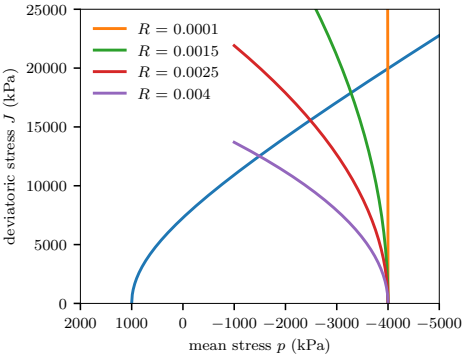

- Linear hardening law:

$$\frac{\partial p_{\mathrm{c}}}{\partial \epsilon_{\mathrm{v}}^{\mathrm{p}}} = \frac{K^{\mathrm{ep}} K^{\mathrm{e}}}{K^{\mathrm{ep}} - K^{\mathrm{e}}}$$

Volumetric yield function

System of equations

Activation only of the **deviatoric** yield surface.

```
feel    += dlambda*d_g_d_sig + dt*epsc_rate;
flambda =  (f - p_atm*pow(dlambda*eta_pz/dt, (1.0/N_pz)))/D(0,0);
fepsp   =  depsp - dlambda*d_g_d_sig - dt*epsc_rate;
fepsc   =  depsc - dt*epsc_rate;
```

Volumetric yield function

System of equations

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feel    += dlambda*d_g_d_sig + dt*epsc_rate;
flambda =  (f - p_atm*pow(dlambda*eta_pz/dt, (1.0/N_pz)))/D(0,0);
fepsp   =  depsp - dlambda*d_g_d_sig - dt*epsc_rate;
fepsc   =  depsc - dt*epsc_rate;
```

Activation only of the **volumetric** yield surface.

```
feel     += dlambda2*d_f2_d_sig + dt*epsc_rate;
fpc      =  dpc + (K_ep*K_ave)/(K_ep-K_ave)*dlambda2*d_f2_d_p +
            (K_ep*K_ave)/(K_ep-K_ave)*(id|(dt*epsc_rate));
flambda2 =  (f2 - p_atm*pow(dlambda2*eta_pz/dt, (1.0/N_pz)))/D(0,0);
fepsp    =  depsp - dlambda2*d_f2_d_sig - dt*epsc_rate;
fepsc    =  depsc - dt*epsc_rate;
```

Volumetric yield function

System of equations

Activation of both the **deviatoric** and **volumetric** yield surfaces.

```
feel      += dlambda*d_g_d_sig + dt*epsc_rate + dlambda2*d_f2_d_sig;
flambda   =  (f - p_atm*pow(dlambda*eta_pz/dt, (1.0/N_pz)))/D(0,0);
flambda2  =  (f2 - p_atm*pow(dlambda2*eta_pz/dt, (1.0/N_pz)))/D(0,0);
fepsp     =  depsp - dlambda*d_g_d_sig - dlambda2*d_f2_d_sig - dt*epsc_rate;
fepsc     =  depsc - dt*epsc_rate;
fpc       =  dpc + (K_ep*K_ave)/(K_ep-K_ave)*dlambda2*d_f2_d_p +
             (K_ep*K_ave)/(K_ep-K_ave)*(id|(dt*epsc_rate));
```

Volumetric yield function

System of equations

Activation of both the **deviatoric** and **volumetric** yield surfaces.

```
feel      += dlambda*d_g_d_sig + dt*epsc_rate + dlambda2*d_f2_d_sig;
flambda   =  (f - p_atm*pow(dlambda*eta_pz/dt, (1.0/N_pz)))/D(0,0);
flambda2  =  (f2 - p_atm*pow(dlambda2*eta_pz/dt, (1.0/N_pz)))/D(0,0);
fepsp     =  depsp - dlambda*d_g_d_sig - dlambda2*d_f2_d_sig - dt*epsc_rate;
fepsc     =  depsc - dt*epsc_rate;
fpc       =  dpc + (K_ep*K_ave)/(K_ep-K_ave)*dlambda2*d_f2_d_p +
             (K_ep*K_ave)/(K_ep-K_ave)*(id|(dt*epsc_rate));
```

None of the yield surfaces are active but **creep** have been activated:.

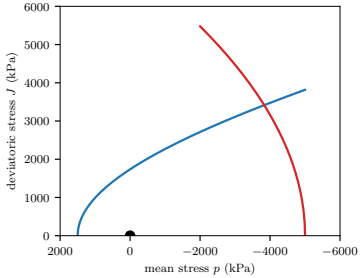
```
feel  += dt*epsc_rate;
fepsp =  depsp - dt*epsc_rate;;
fepsc =  depsc - dt*epsc_rate;
```

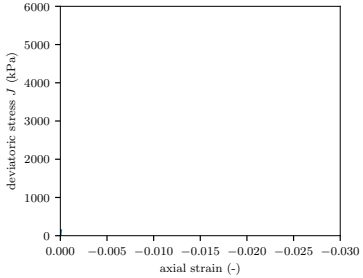
Volumetric yield function

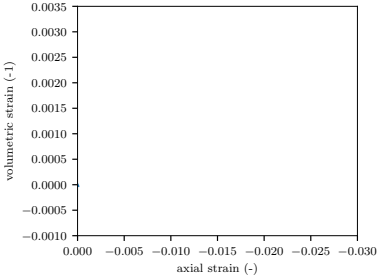
*Mobilisation only of the **deviatoric** yield surface*

Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

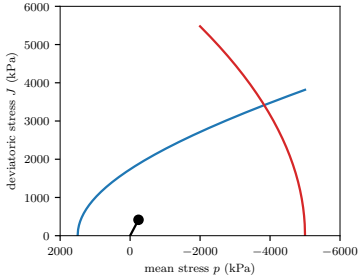


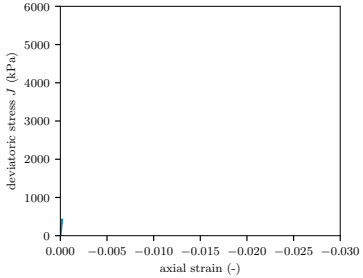


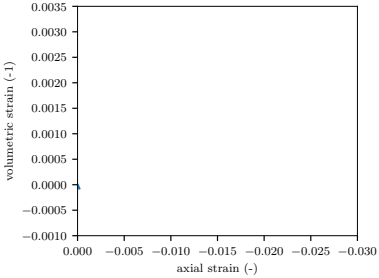


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

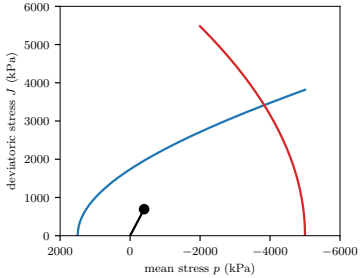


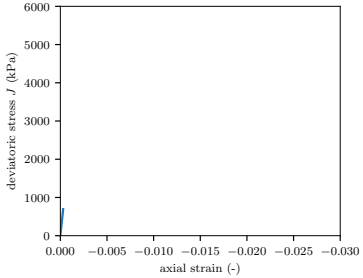


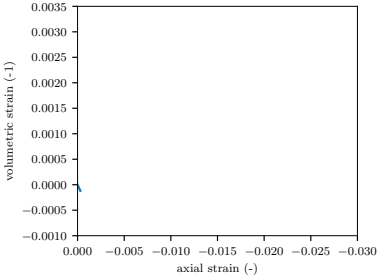


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

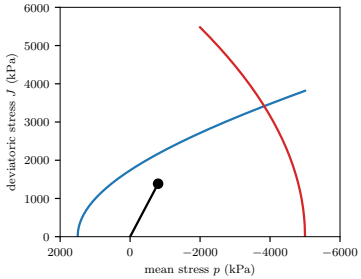


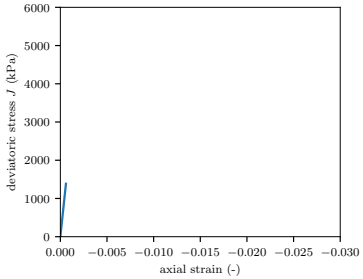


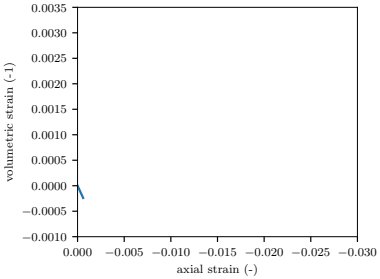


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

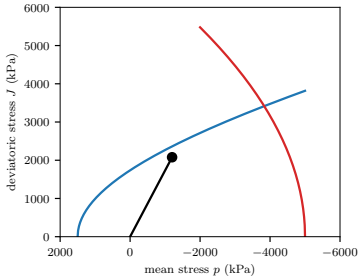


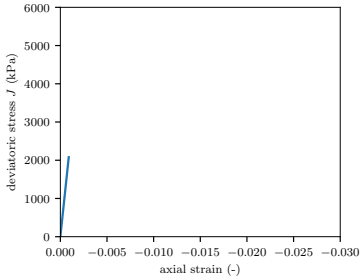


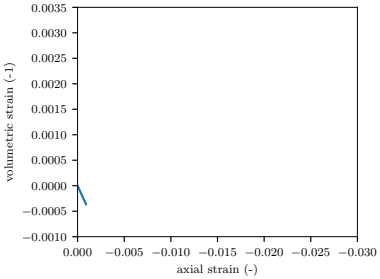


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

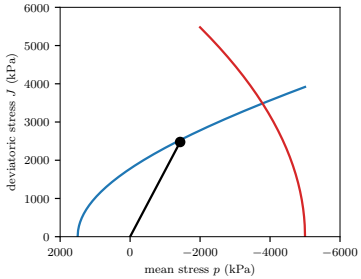


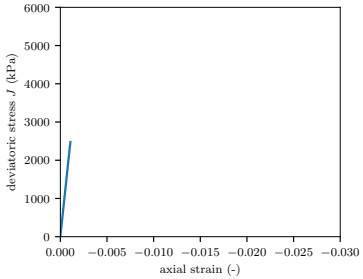


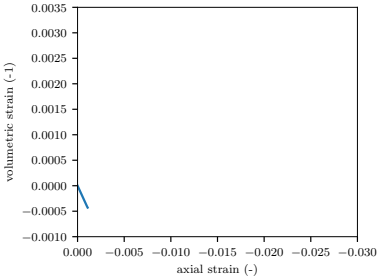


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

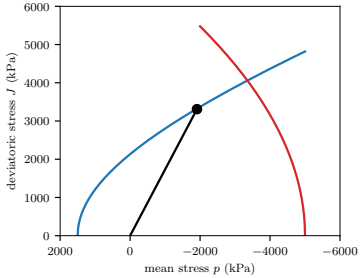


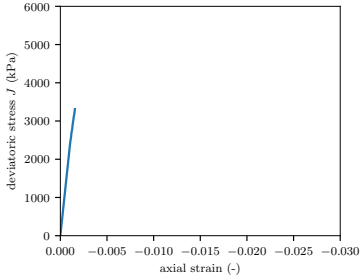


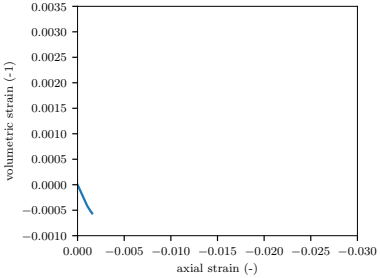


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

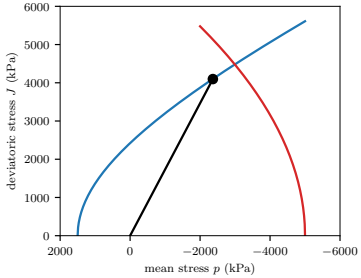


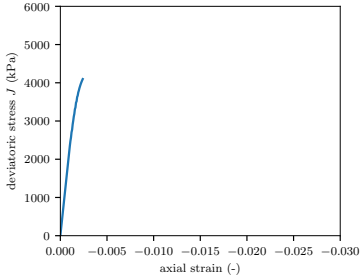


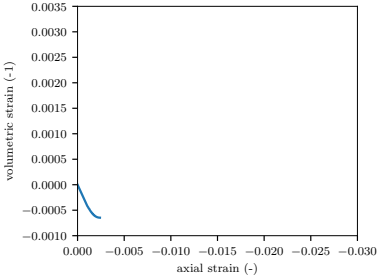


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

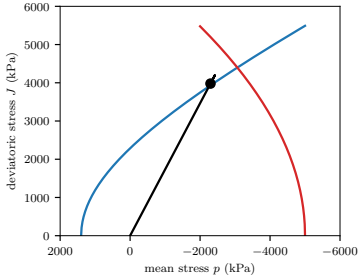


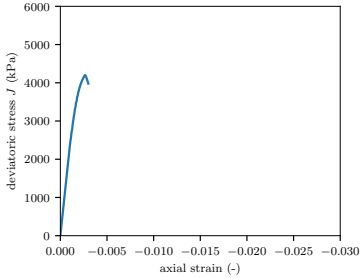


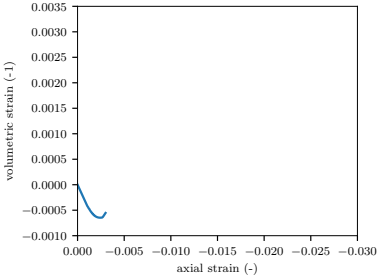


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

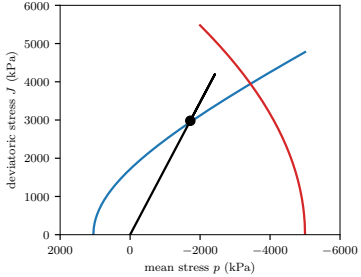


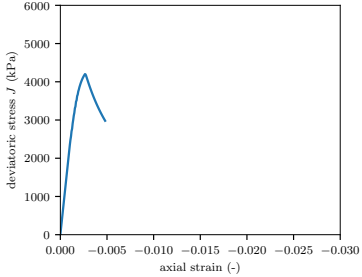


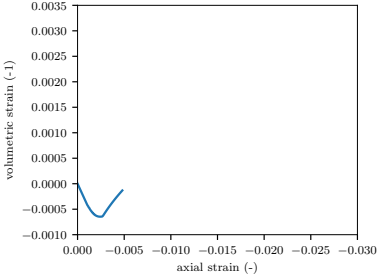


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

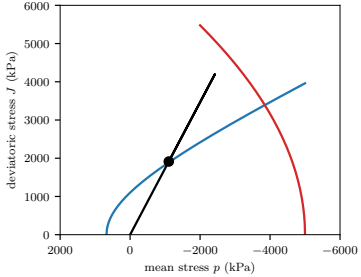


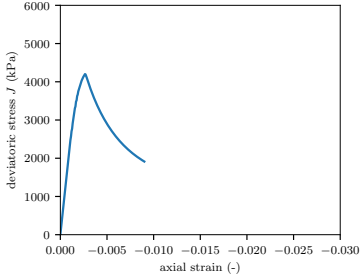


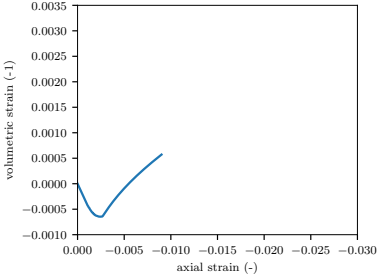


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

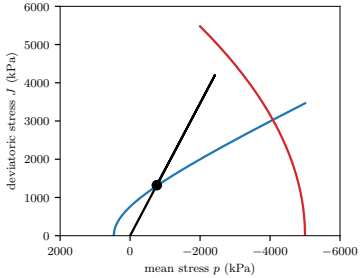


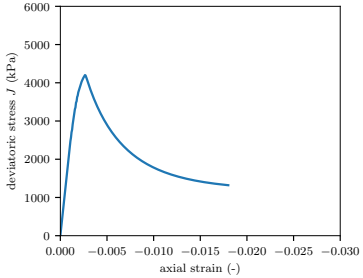


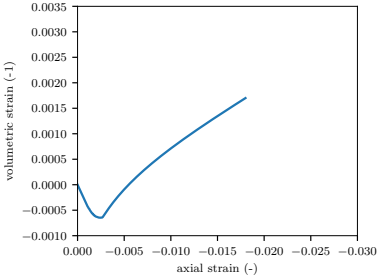


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*

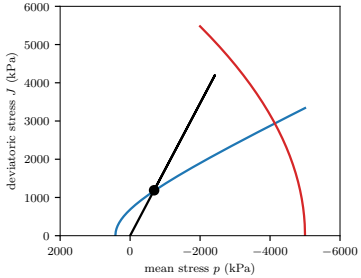


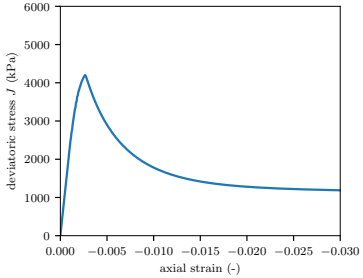


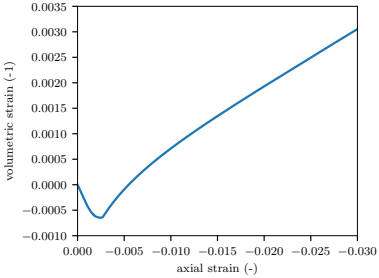


Volumetric yield function

*Mobilisation only of the **deviatoric** yield surface*





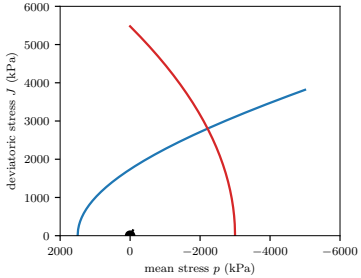


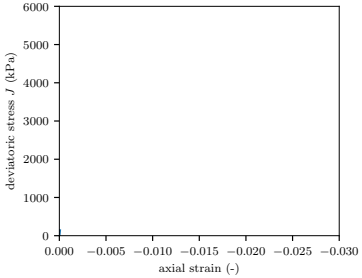
Volumetric yield function

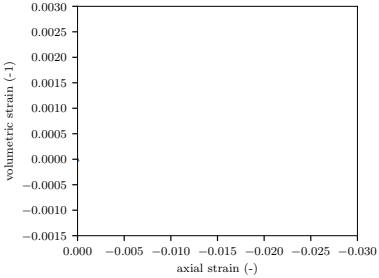
*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

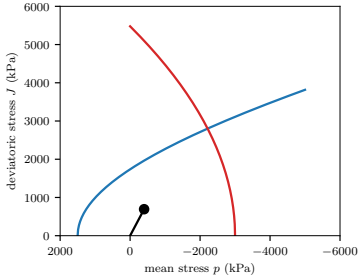


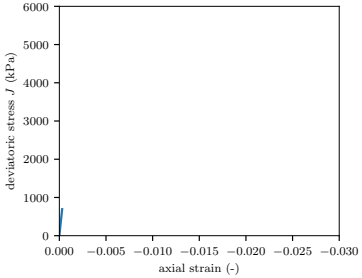


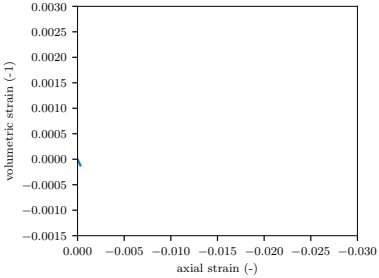


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

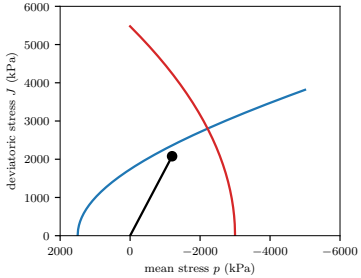


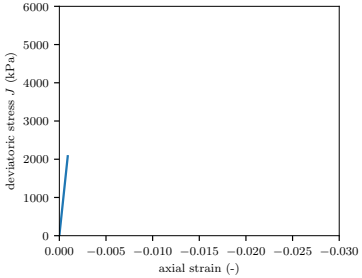


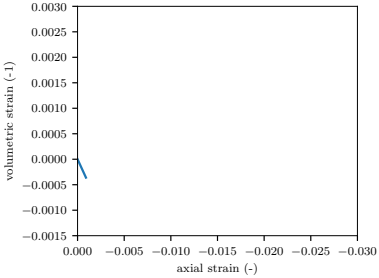


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

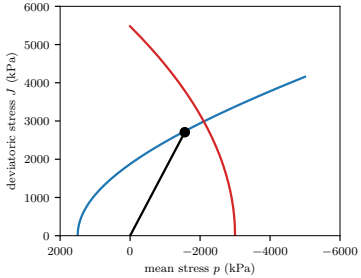


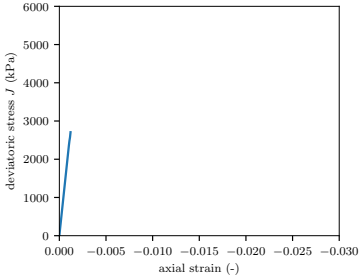


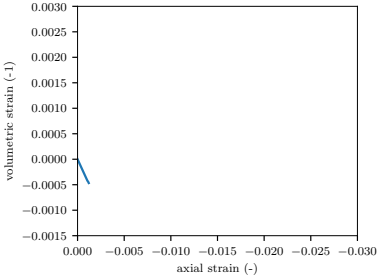


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

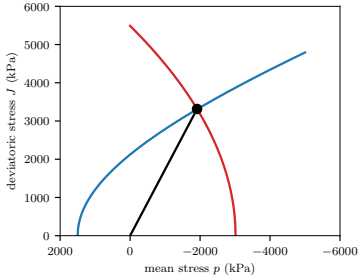


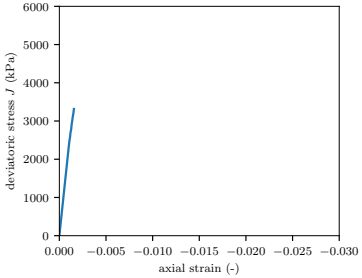


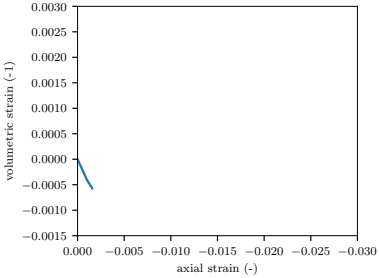


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

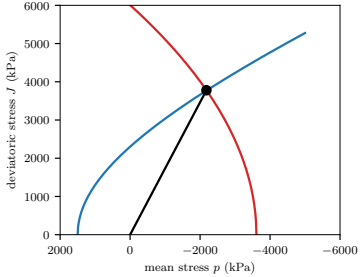


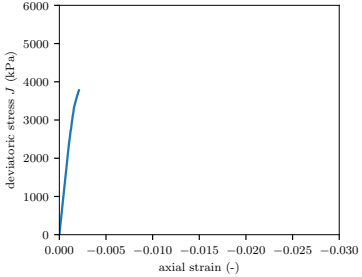


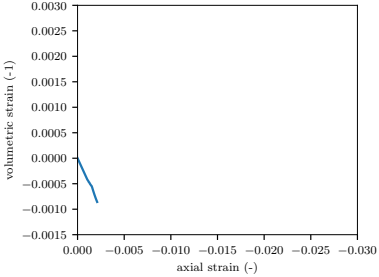


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

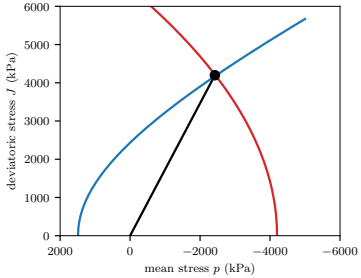


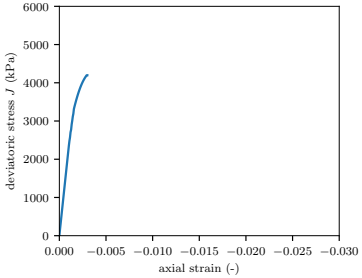


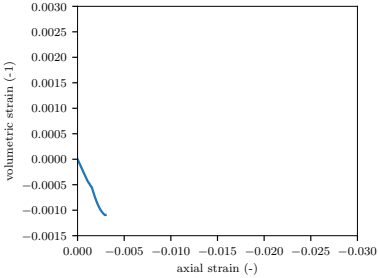


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*

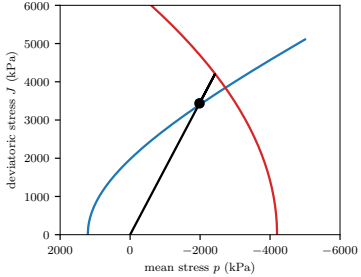


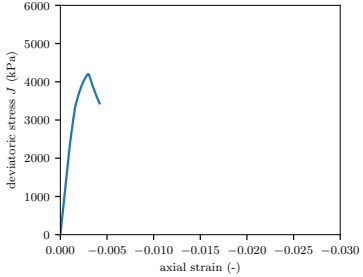


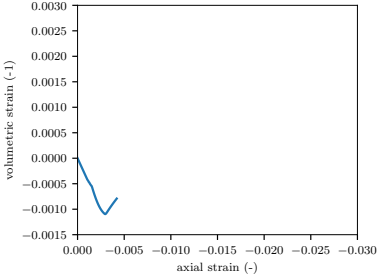


Volumetric yield function

*Mobilisation first of the **deviatoric** yield surface and then the **volumetric** yield surface*







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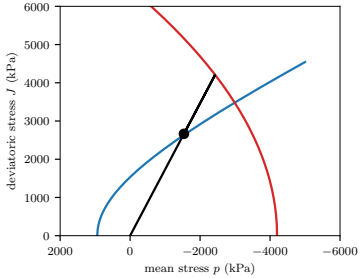

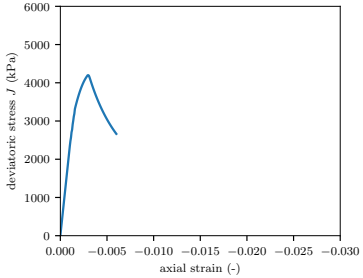

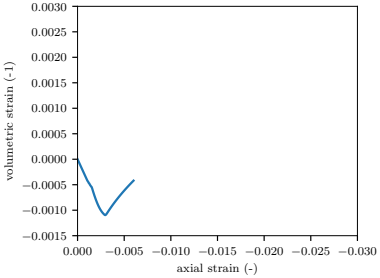

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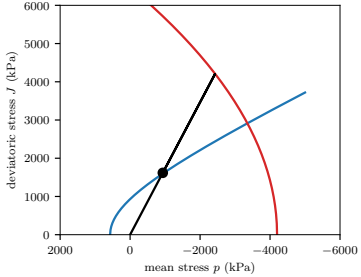

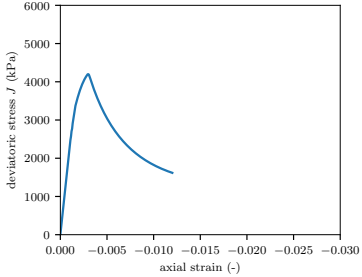

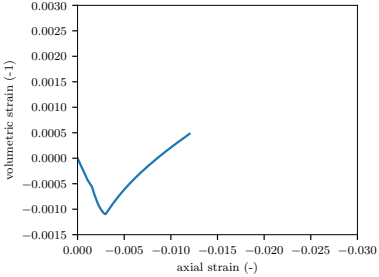

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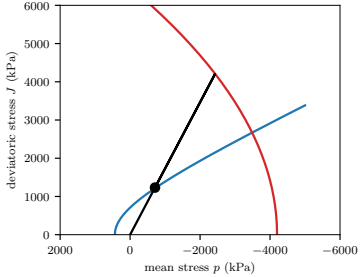

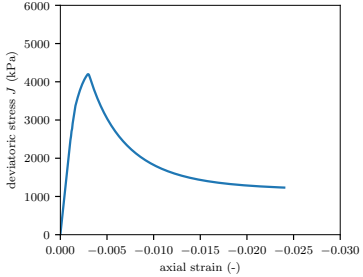

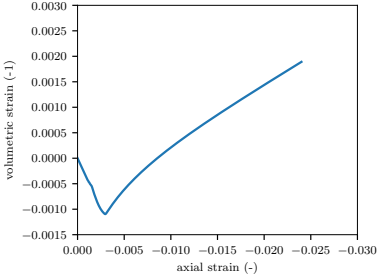

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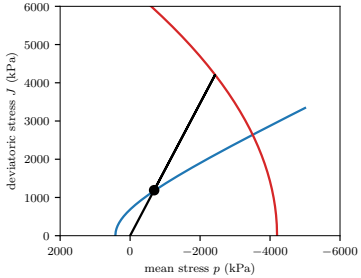

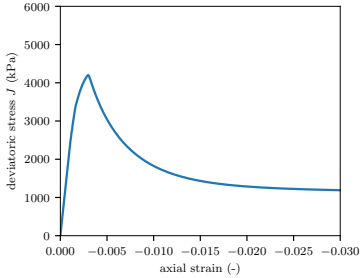

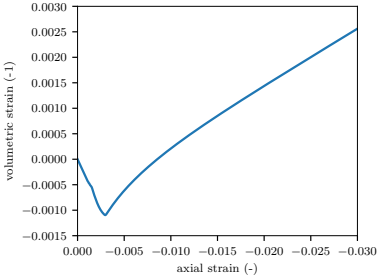

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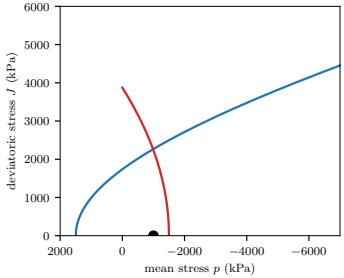

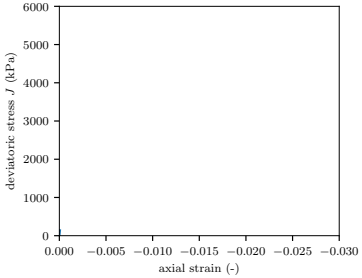

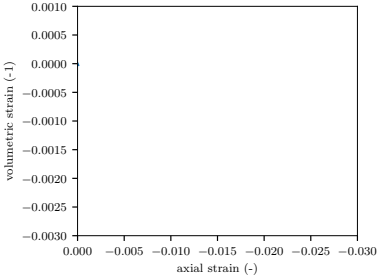

Volumetric yield function

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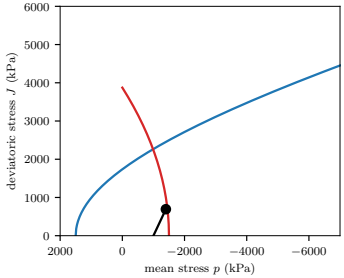

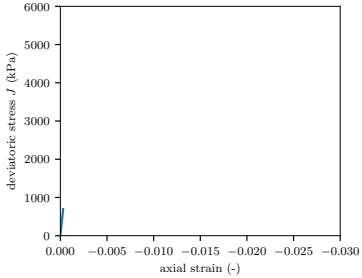

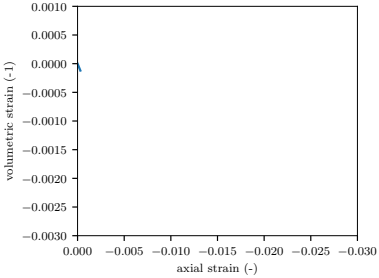

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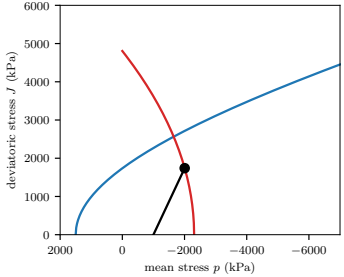

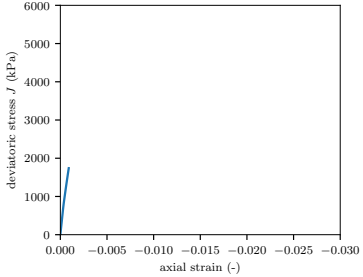

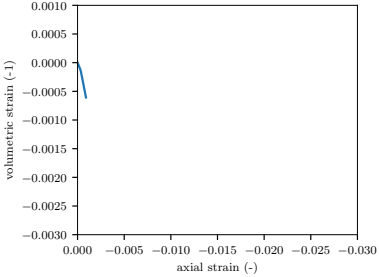

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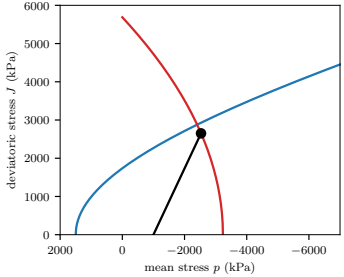

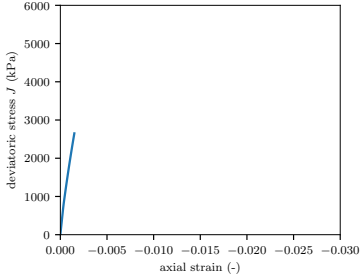

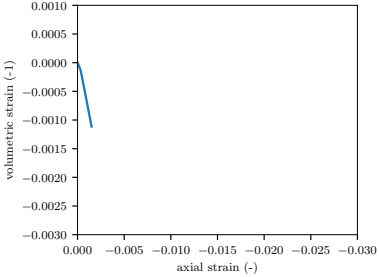

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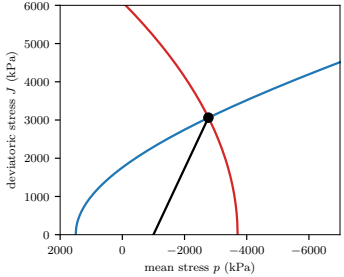

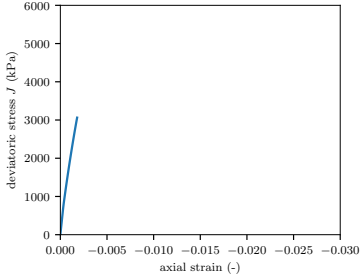

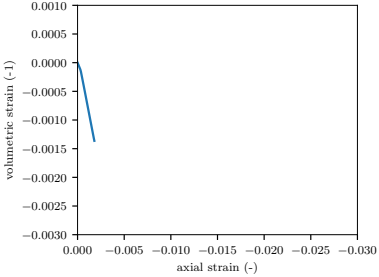

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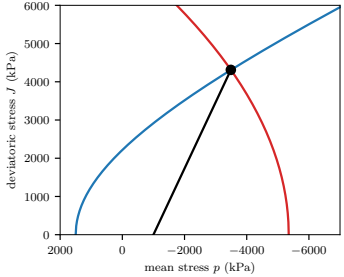

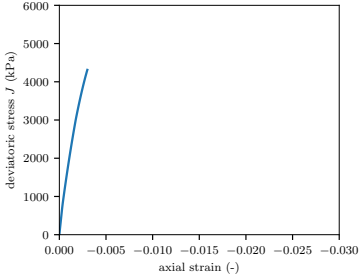

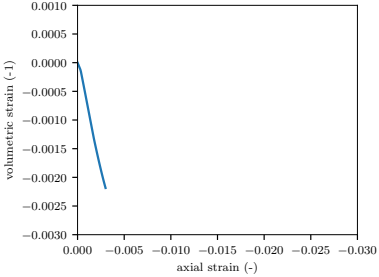

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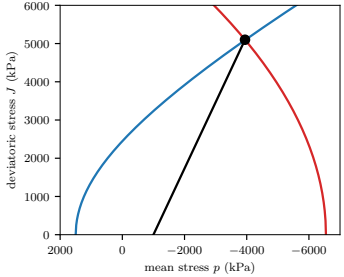

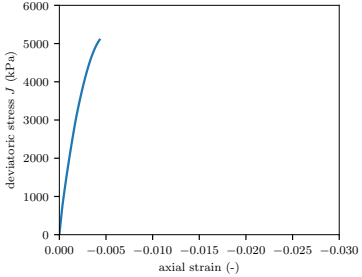

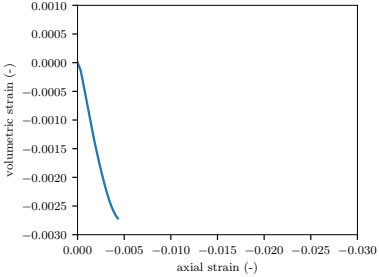

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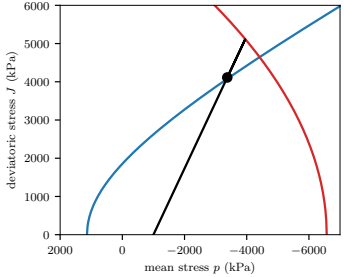

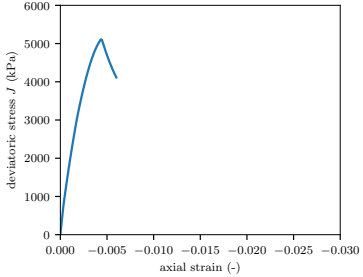

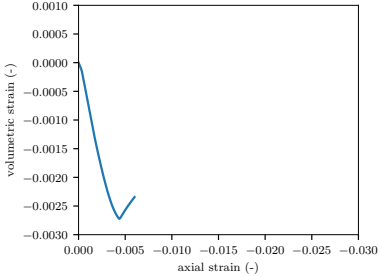

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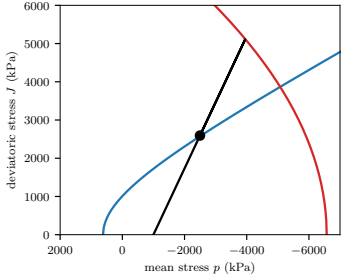

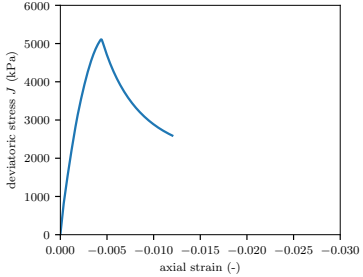

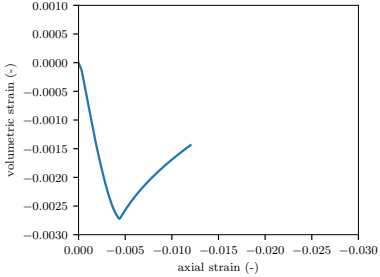

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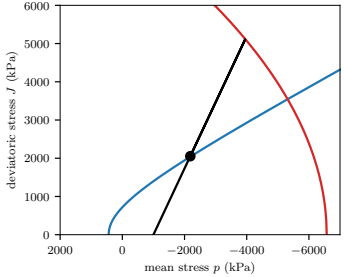

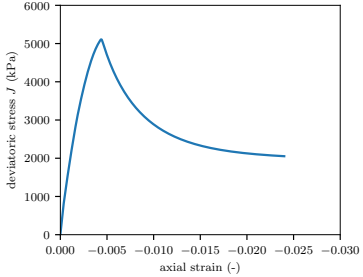

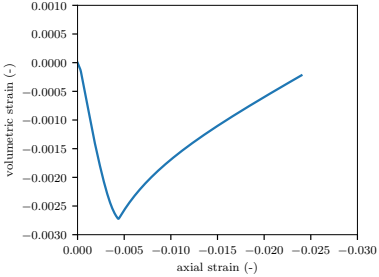

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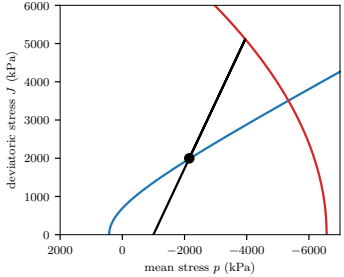
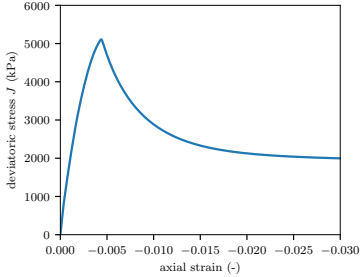
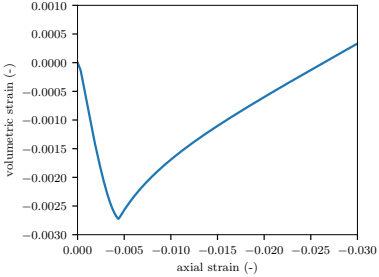






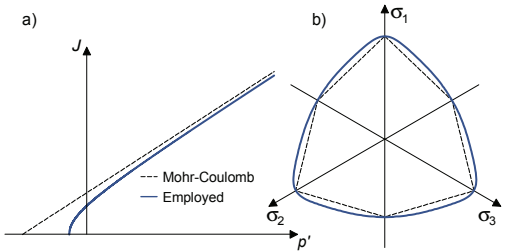
Content

1. Introduction
2. Implementation of thermal effects
   - Volumetric yield function
   - Temperature dependence of the **deviatoric** yield surface
   - Temperature dependence of the **volumetric** yield surface
   - Additional convergence checks
3. Coupled THM BVP simulation
4. Conclusions

Temperature dependence of the **deviatoric** yield surface

- Deviatoric yield surface:

$$f = \sqrt{\frac{J_2}{f_{\mathrm{d}}(\theta)} + \left(c^* + p_{\mathrm{t}} \tan\phi^*\right)^2} - \left(c^* + p' \tan\phi^*\right)$$



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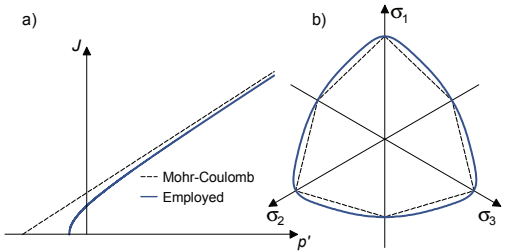
- Temperature dependence through the strength parameters (Tourchi et al., 2023):

$$\phi^*(T) = \phi^*_{T_0} \left[1 - \mu_\phi \ln\left(T/T_0\right)\right]$$

$$c^*(T) = c^*_{T_0} \left[1 - \mu_c \ln\left(T/T_0\right)\right]$$

$$p_t(T) = p_{t\,T_0} \left[1 - \mu_c \ln\left(T/T_0\right)\right]$$



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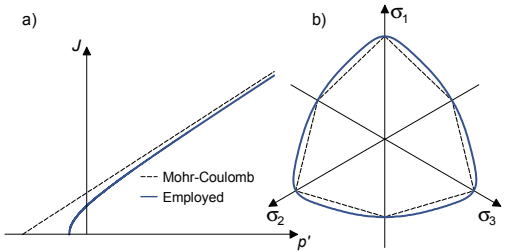

Temperature dependence of the **deviatoric** yield surface

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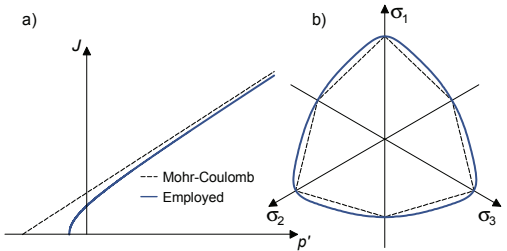

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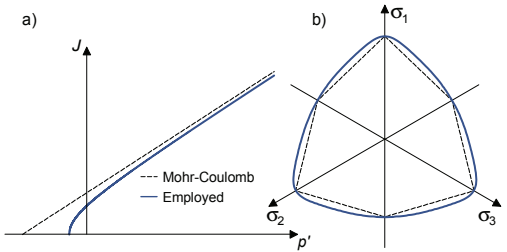

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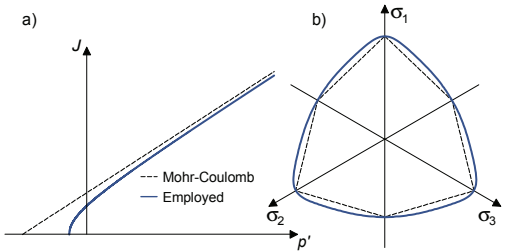

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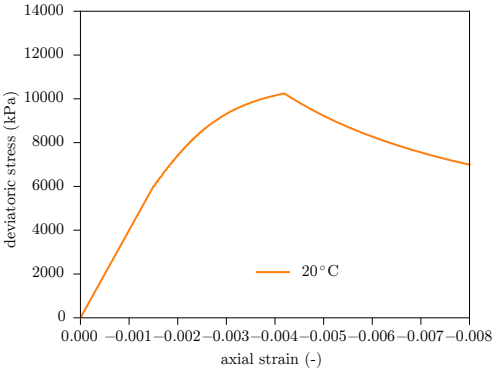

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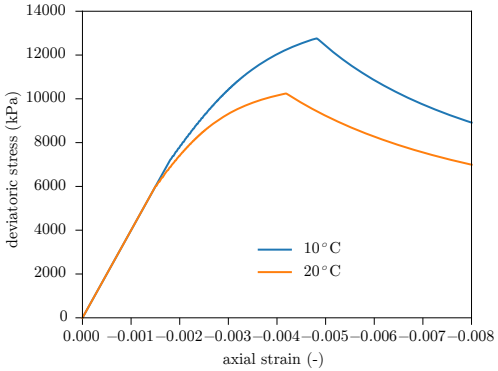

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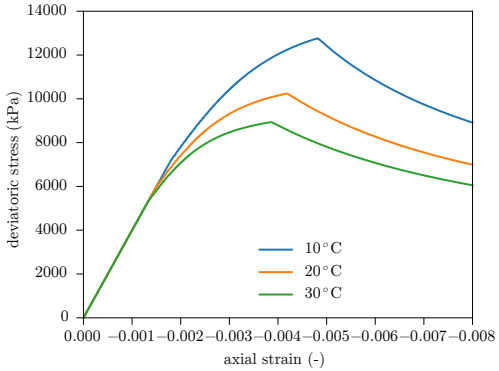

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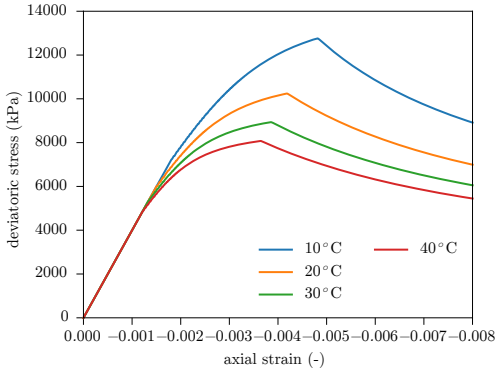

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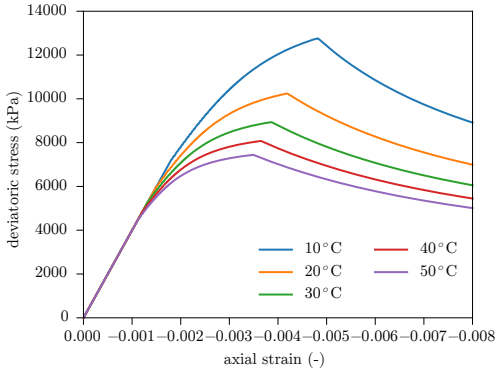

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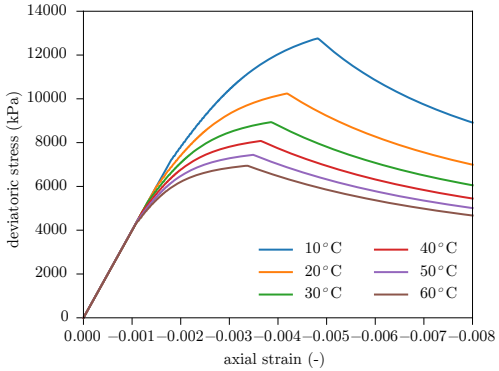

Content

1. Introduction
2. Implementation of thermal effects
   - Volumetric yield function
   - Temperature dependence of the **deviatoric** yield surface
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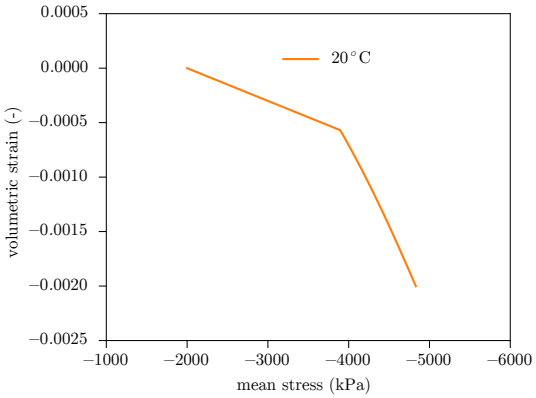

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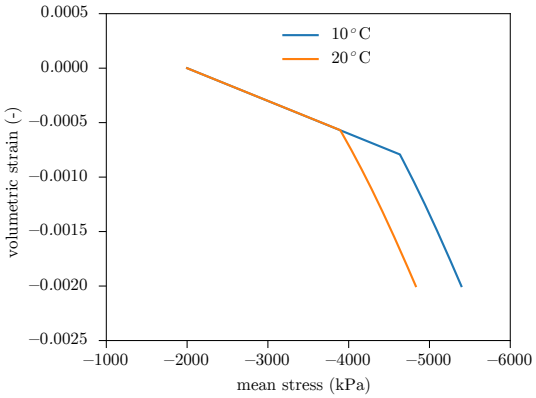

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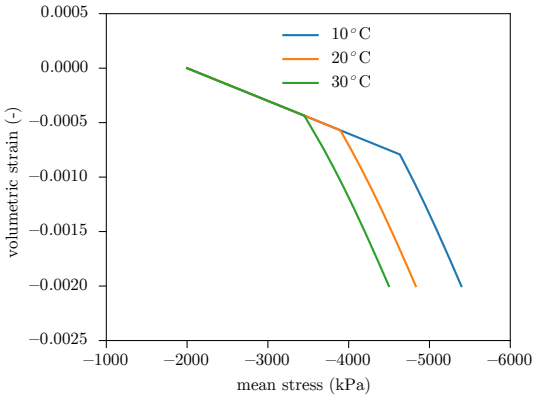

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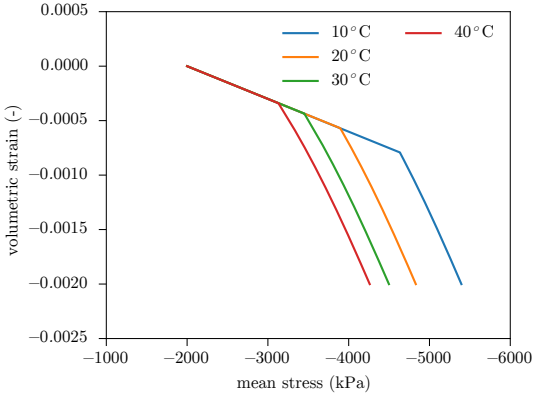

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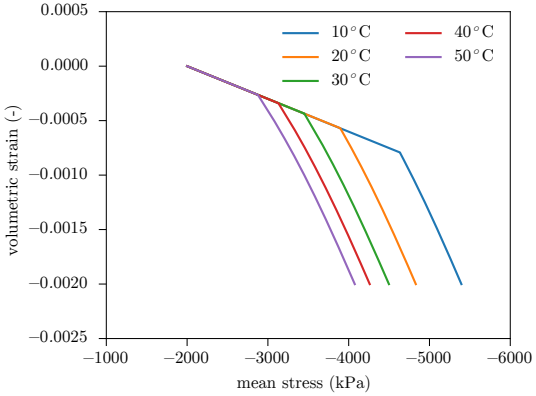

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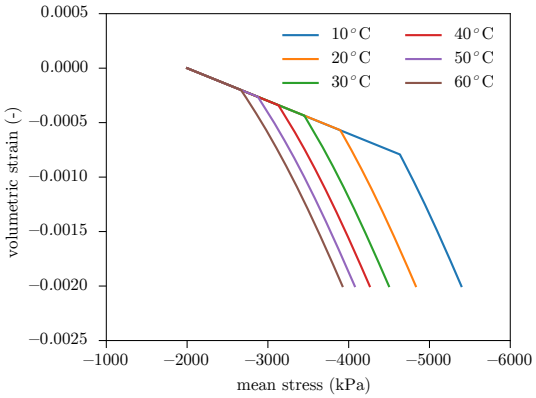

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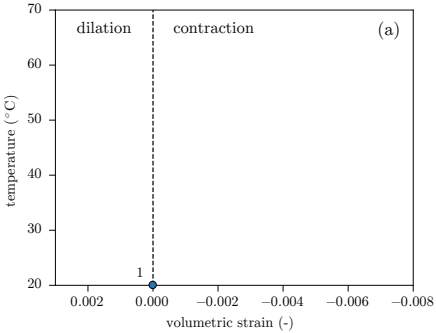

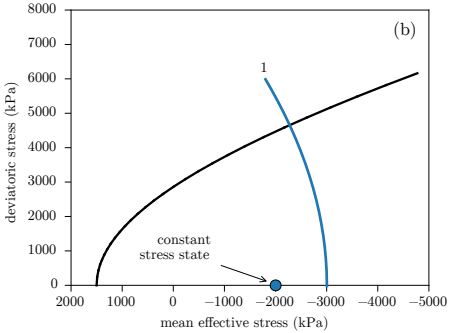

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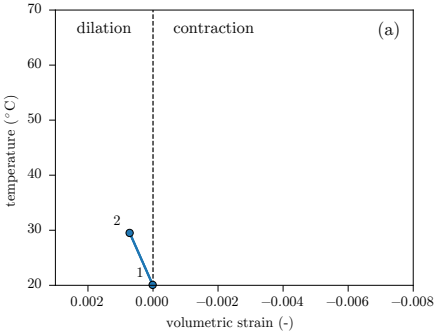

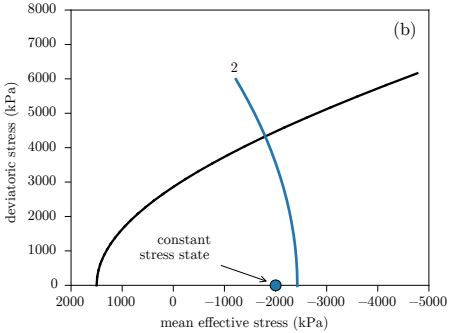

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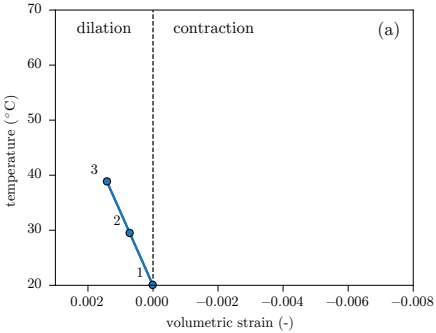

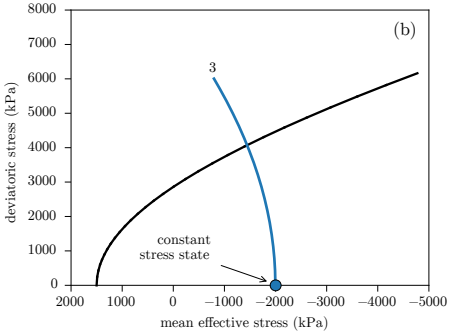

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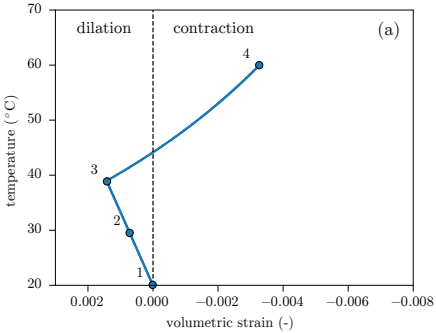

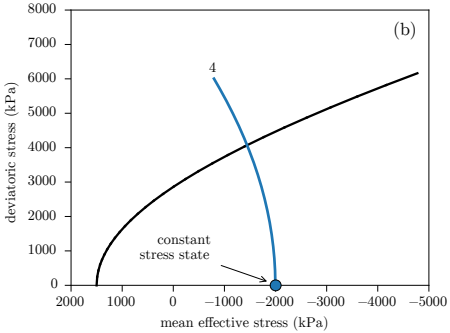

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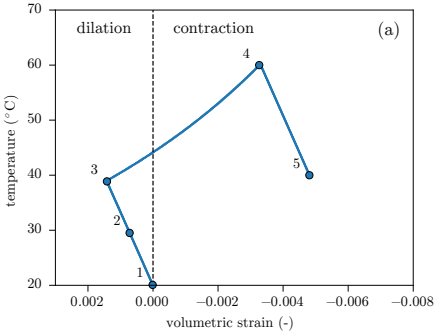

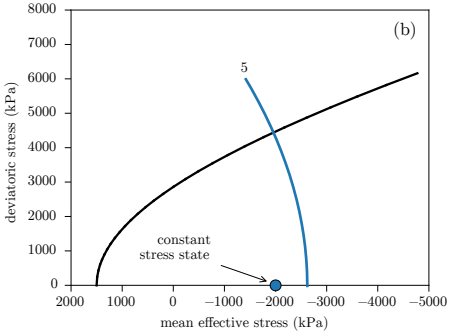

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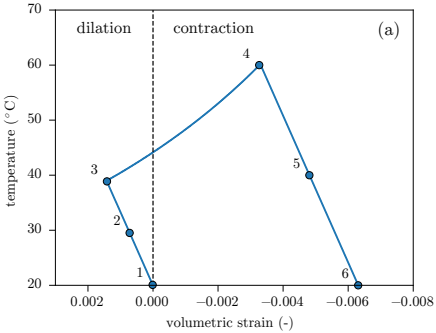

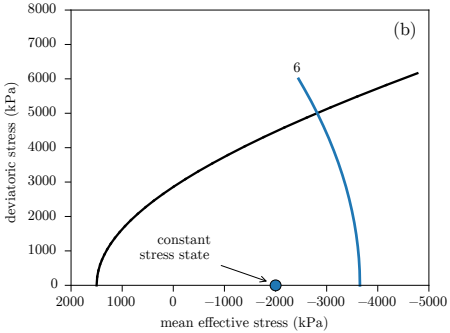

Content

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Additional convergence checks

```
@AdditionalConvergenceChecks{
  // check integration type
  bool int_check = false;
  if((f > 0.0) && (f2 < 0.0) && (int_type_1 == false)){int_check = true;}
  if((f < 0.0) && (f2 > 0.0) && (int_type_2 == false)){int_check = true;}
  if((f > 0.0) && (f2 > 0.0) && (int_type_3 == false)){int_check = true;}
  if((f < 0.0) && (f2 < 0.0) && (int_type_4 == false)  && (eps_eq_p > eps_thr)){
      int_check = true;}
  if(int_check){
    converged = false;
    int_type_1 = false;
    int_type_2 = false;
    int_type_3 = false;
    int_type_4 = false;
    if((f > 0.0) && (f2 < 0.0)){int_type_1 = true;}
    if((f < 0.0) && (f2 > 0.0)){int_type_2 = true;}
    if((f > 0.0) && (f2 > 0.0)){int_type_3 = true;}
    if((f < 0.0) && (f2 < 0.0) && (eps_eq_p > eps_thr)){int_type_4 = true;}
  }
}
```

Content

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2. Implementation of thermal effects
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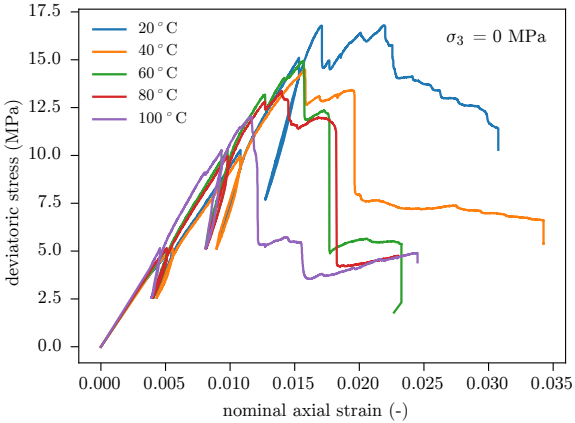

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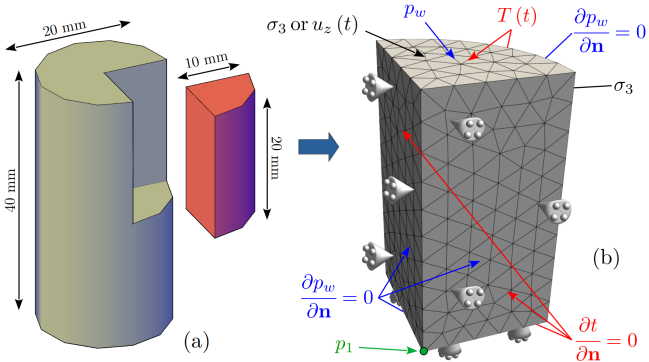
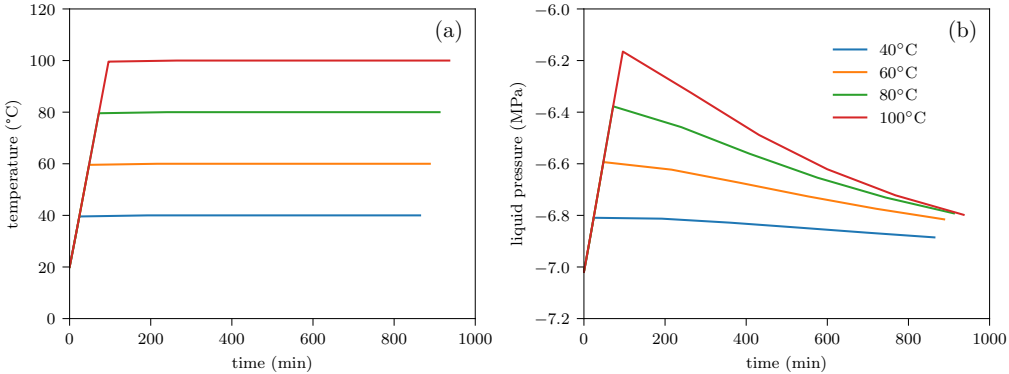


Coupled THM BVP simulation

Obtained results



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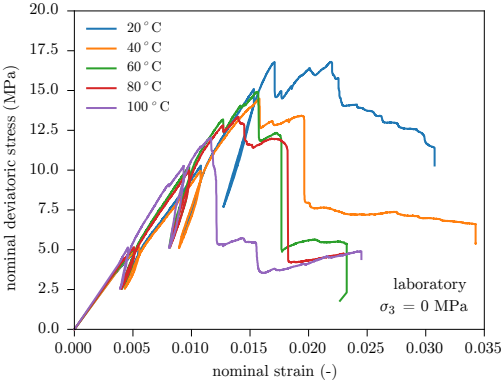

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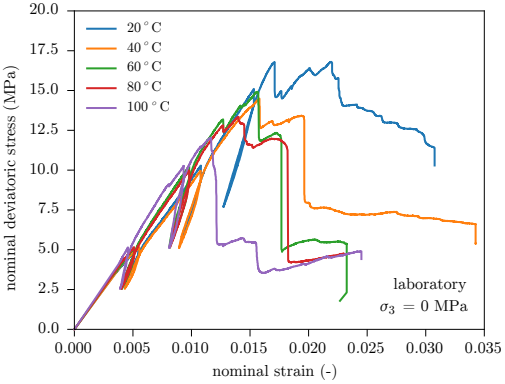
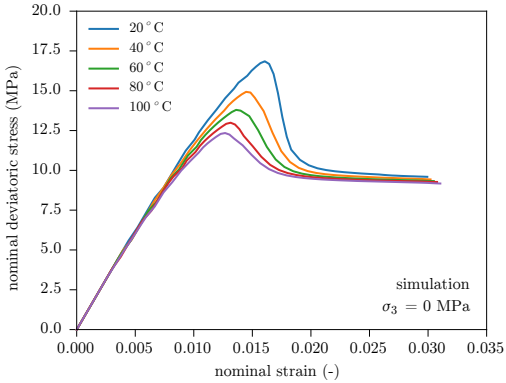
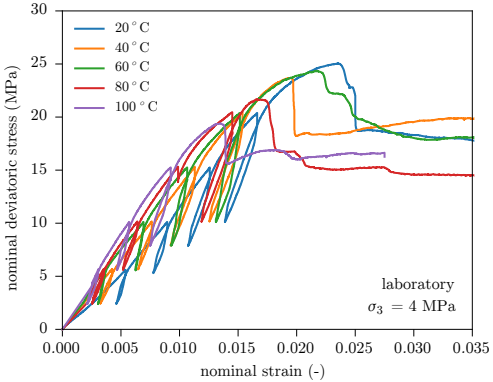
Obtained results





Coupled THM BVP simulation

Obtained results



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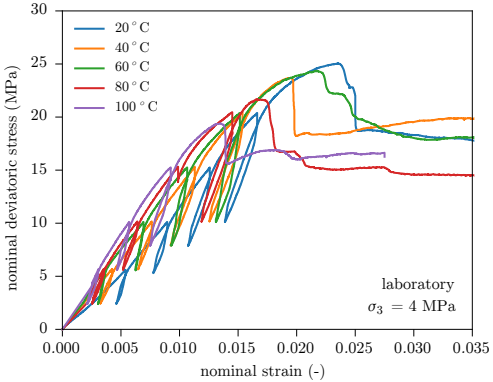

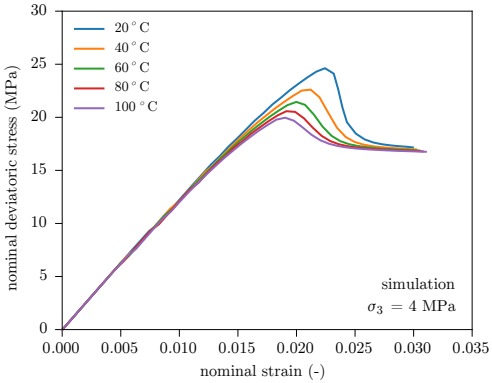

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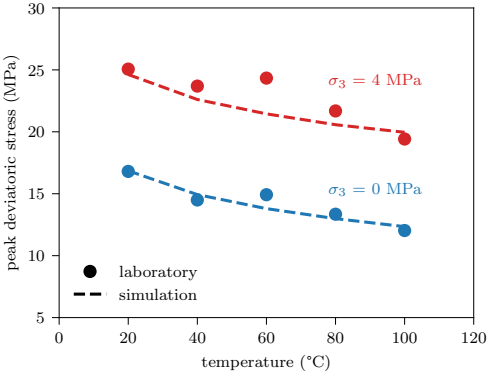

Content

1. Introduction

2. Implementation of thermal effects
   - Volumetric yield function
   - Temperature dependence of the **deviatoric** yield surface
   - Temperature dependence of the **volumetric** yield surface
   - Additional convergence checks

3. Coupled THM BVP simulation

4. Conclusions

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- Including the expansion-contraction transition observed as the temperature is increased in temperature-controlled constant stress tests.

¡Thank you for your attention!

References

Bumbieler, F., Plúa, C., Tourchi, S., Vu, M. N., Vaunat, J., Gens, A., and Armand, G. (2021). Feasibility of constructing a full-scale radioactive high-level waste disposal cell and characterization of its thermo-hydro-mechanical behavior. *International Journal of Rock Mechanics and Mining Sciences*, 137(October 2020).

Mánica, M. A., Gens, A., Vaunat, J., Armand, G., and Vu, M. N. (2022). Numerical simulation of underground excavations in an indurated clay using non-local regularisation. Part 1: formulation and base case. *Geotechnique*, 72(12):1092–1112.

Resende, L. and Martin, J. B. (1985). Formulation of Drucker-Prager cap model. *Journal of Engineering Mechanics*, 111(7):855–881.

Sultan, N., Delage, P., and Cui, Y. J. (2002). Temperature effects on the volume change behaviour of Boom clay. *Engineering Geology*, 64(2-3):135–145.

Zhang, C. L., Rothfuchs, T., Su, K., and Hoteit, N. (2007). Experimental study of the thermo-hydro-mechanical behaviour of indurated clays. *Physics and Chemistry of the Earth*, 32(8-14):957–965.