Transversal action " Models “

Phase 3 : Underground structure modelling

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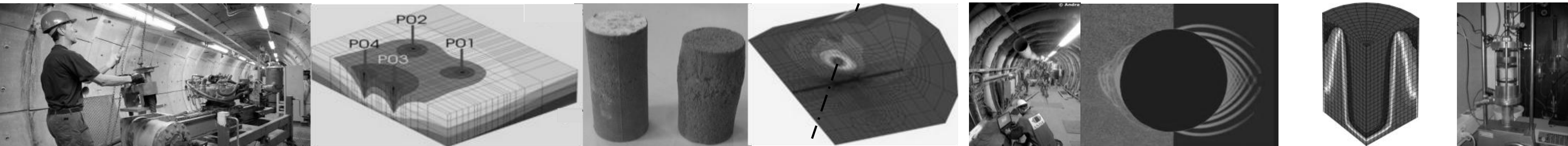


Outline

1. CONSTITUTIVE MODELS AND FITTING

2. NUMERICAL MODELLING

3. OUTLOOKS

Outline

1. **CONSTITUTIVE MODELS AND FITTING**

2. NUMERICAL MODELLING

3. OUTLOOKS

1. Constitutive models and fitting

Balance equations (LAGAMINE FE code) :

Momentum :

$$div(\sigma_{ij}) = 0$$

Bishop's effective stress :

$$\sigma_{ij} = \sigma'_{ij} - bS_{rw} p_w \delta_{ij}$$

Water mass :

$$\frac{\partial}{\partial t}\left(\rho_w \Phi S_{r,w}\right) + div\left(\rho_w \underline{q}_w\right) = 0$$

Flow model :

Advection of liquid phase (Darcy's flow) :

$$\underline{q}_w = -\frac{K_w(S_{r,w})}{\mu_w} \underline{\nabla} p_w$$

Water retention and permeability curves (Van Genuchten's model) :

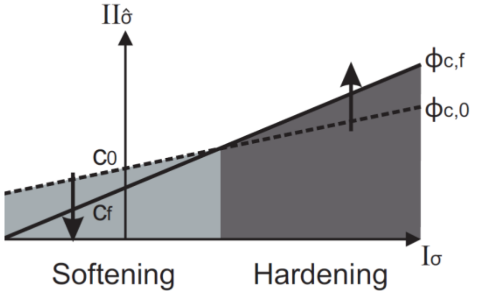
$$S_{r,w} = S_{res} + \left(S_{\max} - S_{res}\right)\left[1 + \left(\frac{p_c}{P_r}\right)^n\right]^{-m}$$

$$k_{r,w} = \sqrt{S_{r,w}}\left[1 - \left(1 - S_{r,w}^{1/m}\right)^m\right]^2$$

Symbol	Name	Value	Unit
$k_{hor,//}$	Horizontal intrinsic water permeability	$4\ 10^{-20}$	m²
$k_{vert,\perp}$	Vertical intrinsic water permeability	$1.33\ 10^{-20}$	m²
Φ	Porosity	0.173	-
m	Van Genuchten coefficient	0.33	-
n	Van Genuchten coefficient	1.49	MPa
P_r	Van Genuchten parameter	15	MPa

1. Constitutive models and fitting

Mechanical model :



- Non-associated, elasto-viscoplastic, internal friction model : $\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{vp}$

- Van Eeckelen yield surface : $F \equiv II_{\hat{\sigma}} - m\left(I_{\sigma} + \frac{3c}{\tan\phi_C}\right) = 0$

- Hardening/softening of φ/c as a function of the Von Mises equivalent plastic strain :

$$\varepsilon_{eq}^{p} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}^{p}\hat{\varepsilon}_{ij}^{p}} \qquad if\ \varepsilon_{eq}^{p} > dec_{\phi} : \phi_C = \phi_{C0} + \frac{\left(\phi_{Cf} - \phi_{C0}\right).\left(\varepsilon_{eq}^{p} - dec_{\phi}\right)}{B_{\phi} + \left(\varepsilon_{eq}^{p} - dec_{\phi}\right)}$$

- Viscoplasticity : loading surface of the viscoplastic flow : $f_{vp} = \sqrt{3}II_{\hat{\sigma}} - \alpha_{vp}R_c\sqrt{A\left(C_s + \frac{I_{\sigma}}{3R_c}\right)} \geq 0$

viscoplastic hardening function : $\alpha_{vp} = \alpha_{vp,0} + \left(1 - \alpha_{vp,0}\right)\frac{\gamma_{vp}}{B_{vp} + \gamma_{vp}}$

equivalent viscoplastic shear strain : $\dot{\gamma}_{vp} = \sqrt{\frac{2}{3}\dot{e}_{ij}^{vp}\dot{e}_{ij}^{vp}}$

from Zhou et al. (2008), Jia et al. (2008)

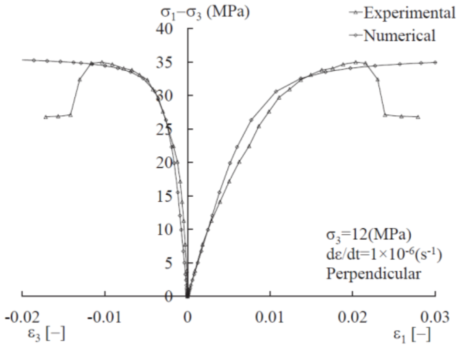
1. Constitutive models and fitting

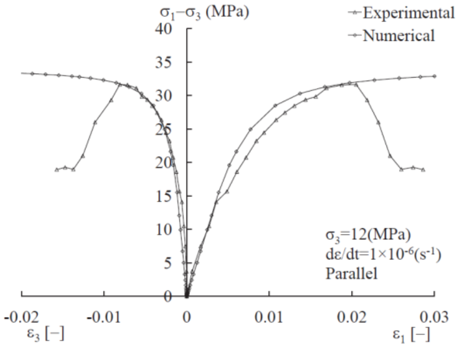
Fitting :

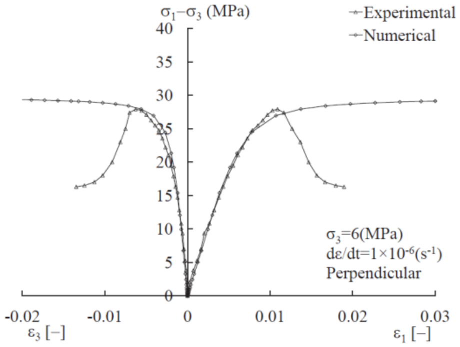
1. Triaxial compression tests :

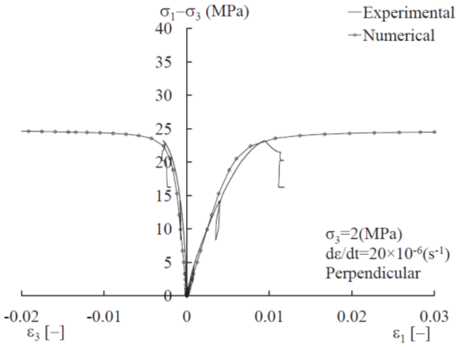
elastoplastic, undrained condition

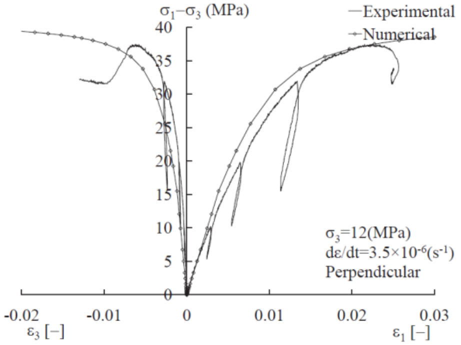
Symbol	Name	Value	Unit
E	Young’s modulus	4000	MPa
ν	Poisson’s ratio	0.3	-
b	Biot’s coefficient	0.6	-
ρ_s	Specific mass	2750	kg/m³
ψ	Dilatancy angle	0.5	°
φ_{c0}	Initial compression friction angle	10	°
φ_{cf}	Final compression friction angle	23	°
B_φ	Friction angle hardening coefficient	0.001	-
dec_φ	Friction angle hardening shifting	0	-
c	Cohesion	4.2	MPa











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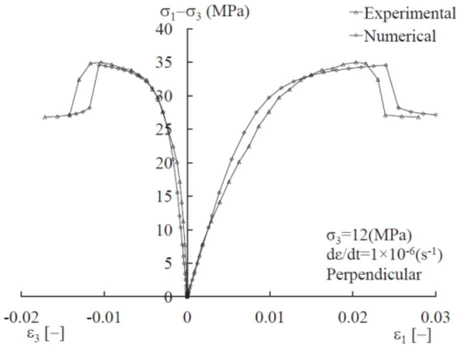
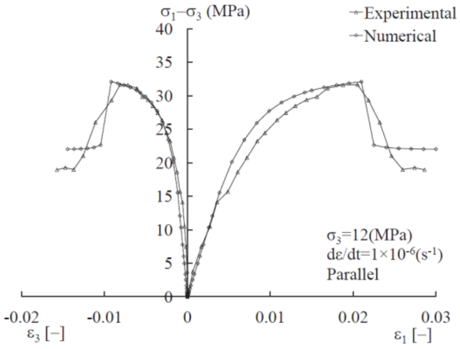
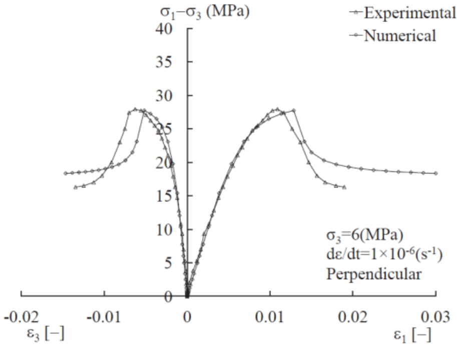
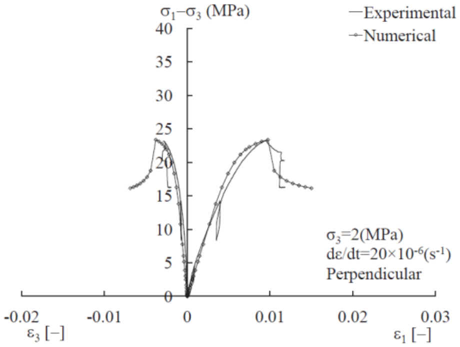
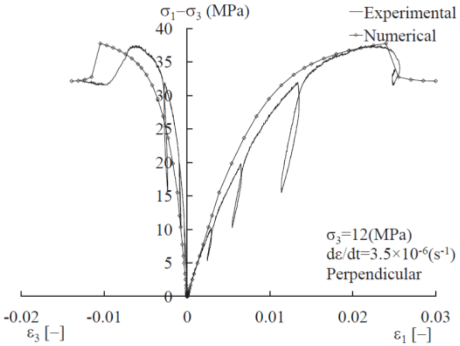
ρ_s	Specific mass	2750	kg/m^3
ψ	Dilatancy angle	0.5	°
φ_{c0}	Initial compression friction angle	10	°
φ_{cf}	Final compression friction angle	23	°
B_φ	Friction angle hardening coefficient	0.001	-
dec_φ	Friction angle hardening shifting	0	-
c_0	Initial cohesion	4.2	MPa
c_f	Final cohesion	0.04-2	MPa
B_c	Cohesion softening coefficient	0.001	-
dec_c	Cohesion softening shifting	0.011	-











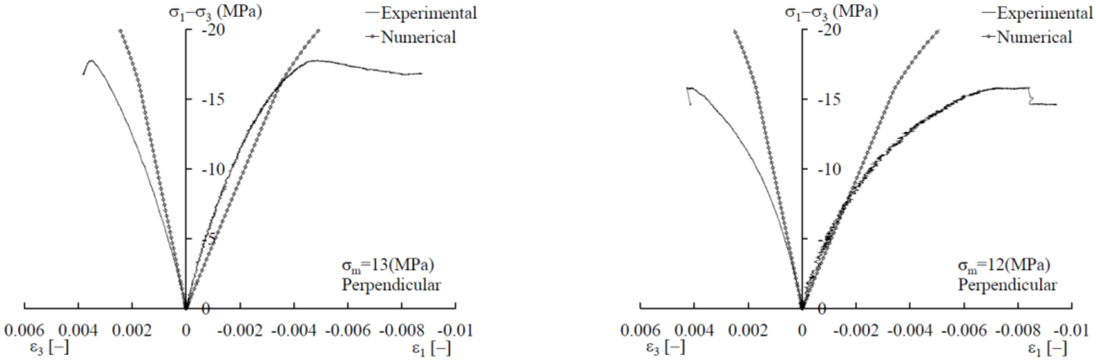
1. Constitutive models and fitting

Fitting :

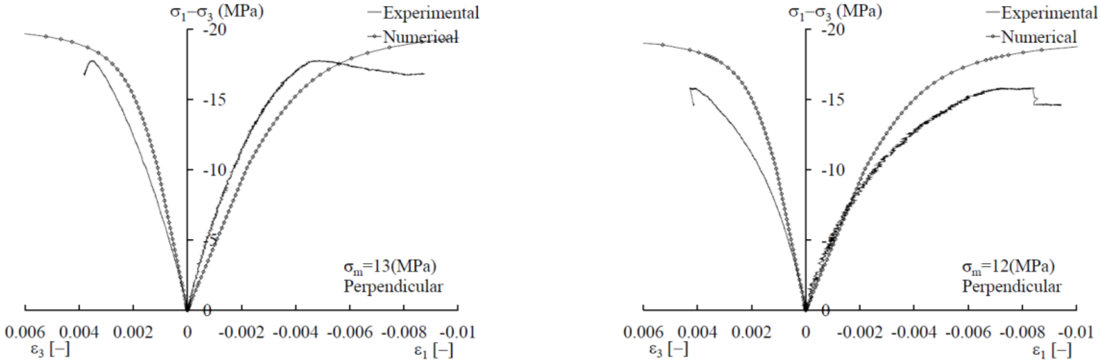
2. Triaxial extension tests :

elastoplastic, undrained condition,
p=cst, extension axiale

Symbol	Name	Value	Unit
E	Young’s modulus	4000	MPa
ν	Poisson’s ratio	0.3	-
b	Biot’s coefficient	0.6	-
ρ_s	Specific mass	2750	kg/m³
ψ	Dilatancy angle	0.5	°
φ_{c0}	Initial compression friction angle	10	°
φ_{cf}	Final compression friction angle	23	°
φ_{e0}	Initial extension friction angle	7	°
φ_{ef}	Final extension friction angle	23	°
B_φ	Friction angle hardening coefficient	0.001	-
dec_φ	Friction angle hardening shifting	0	-
c_0	Initial cohesion	4.2	MPa



Drucker-Prager



Van Eeckelen

Lower resistance in extension

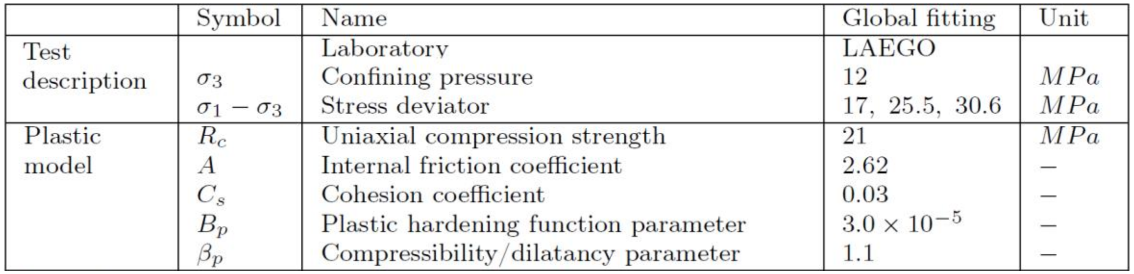
1. Constitutive models and fitting

Fitting :

3. Creep tests :

elasto-viscoplastic, drained condition

from Zhou et al. (2008), Jia et al. (2008)



	Symbol	Name	Global fitting	Unit
Test description		Laboratory	LAEGO	
	σ_3	Confining pressure	12	MPa
	$\sigma_1 - \sigma_3$	Stress deviator	17, 25.5, 30.6	MPa
Plastic model	R_c	Uniaxial compression strength	21	MPa
	A	Internal friction coefficient	2.62	–
	C_s	Cohesion coefficient	0.03	–
	B_p	Plastic hardening function parameter	3.0×10^{-5}	–
	β_p	Compressibility/dilatancy parameter	1.1	–

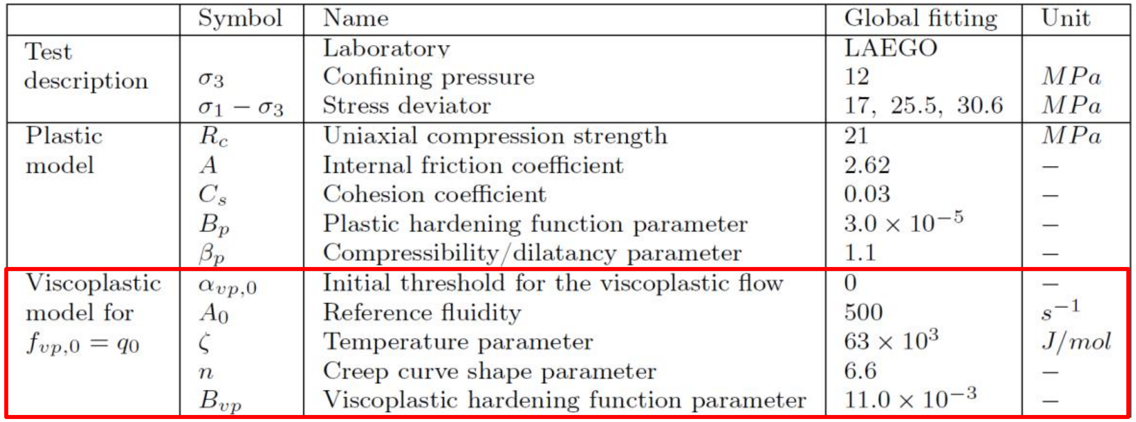
1. Constitutive models and fitting

Fitting :

3. Creep tests :

elasto-viscoplastic, drained condition

$\alpha_{vp,0}=0$



	Symbol	Name	Global fitting	Unit
Test description		Laboratory	LAEGO	
	σ_3	Confining pressure	12	MPa
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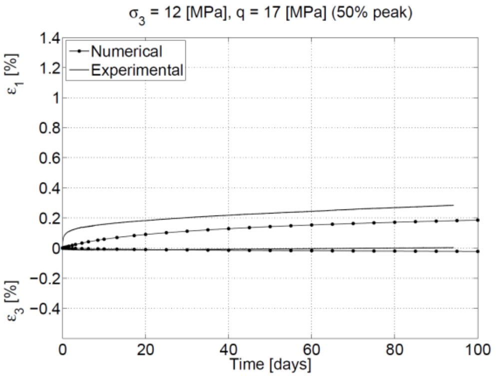
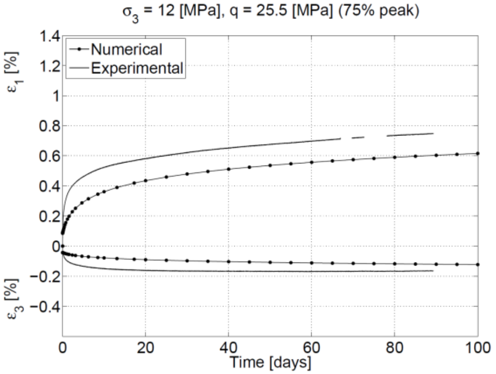
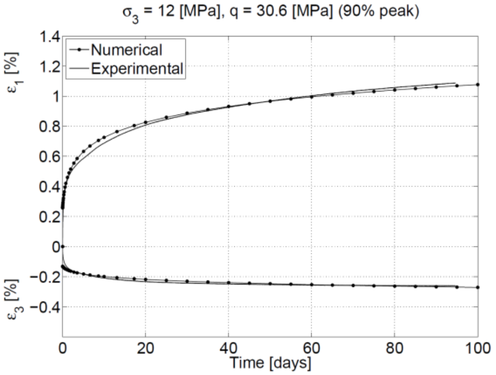
Plastic model	R_c	Uniaxial compression strength	21	MPa
	A	Internal friction coefficient	2.62	–
	C_s	Cohesion coefficient	0.03	–
	B_p	Plastic hardening function parameter	3.0×10^{-5}	–
	β_p	Compressibility/dilatancy parameter	1.1	–
Viscoplastic model for $f_{vp,0}=q_0$	$\alpha_{vp,0}$	Initial threshold for the viscoplastic flow	0	–
	A_0	Reference fluidity	500	s^{-1}
	ζ	Temperature parameter	63×10^3	J/mol
	n	Creep curve shape parameter	6.6	–
	B_{vp}	Viscoplastic hardening function parameter	11.0×10^{-3}	–







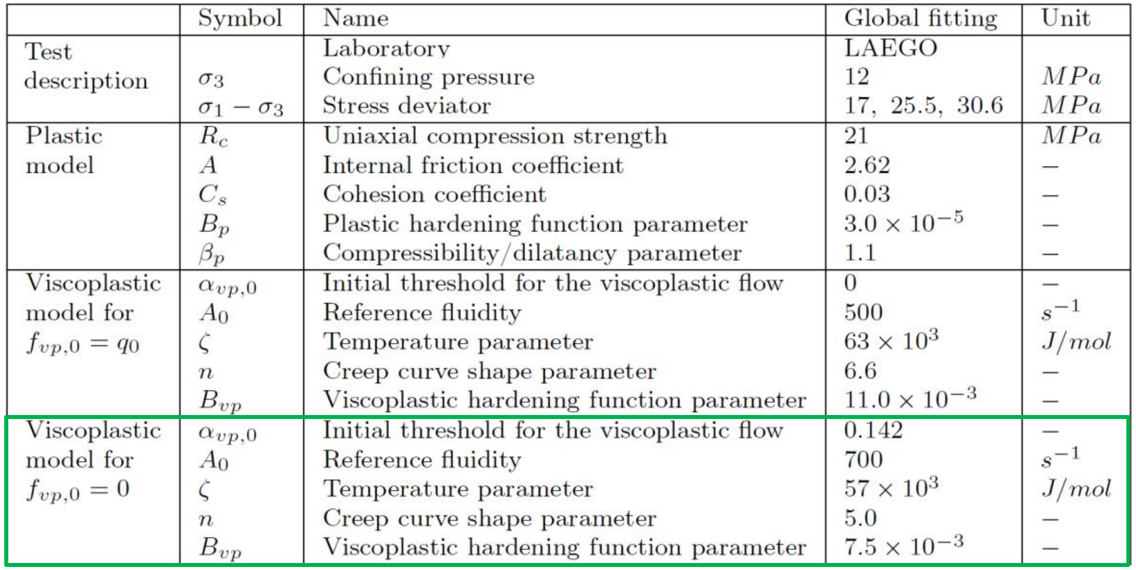
1. Constitutive models and fitting

Fitting :

3. Creep tests :

elasto-viscoplastic, drained condition

$f_{vp,0}=0$



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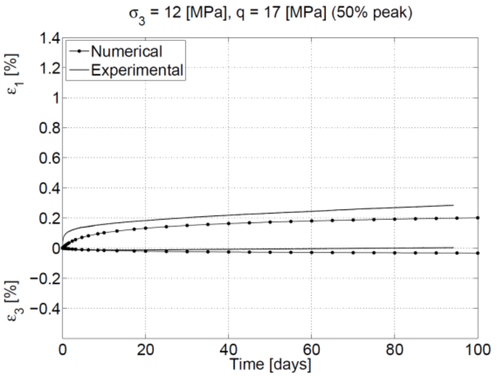
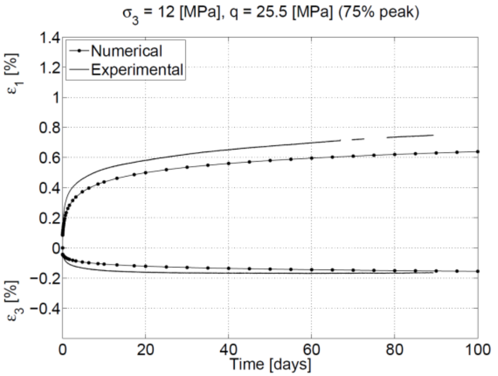
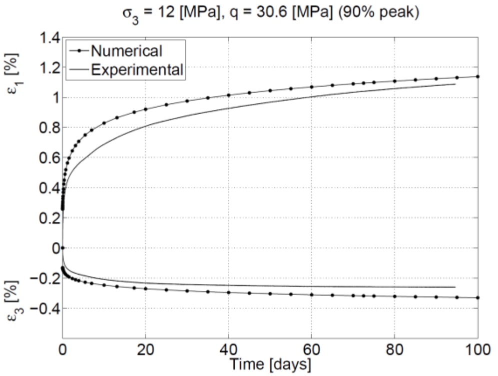
Viscoplastic model for $f_{vp,0}=q_0$	$\alpha_{vp,0}$	Initial threshold for the viscoplastic flow	0	–
	A_0	Reference fluidity	500	s^{-1}
	ζ	Temperature parameter	63×10^{3}	J/mol
	n	Creep curve shape parameter	6.6	–
	B_{vp}	Viscoplastic hardening function parameter	11.0×10^{-3}	–
Viscoplastic model for $f_{vp,0}=0$	$\alpha_{vp,0}$	Initial threshold for the viscoplastic flow	0.142	–
	A_0	Reference fluidity	700	s^{-1}
	ζ	Temperature parameter	57×10^{3}	J/mol
	n	Creep curve shape parameter	5.0	–
	B_{vp}	Viscoplastic hardening function parameter	7.5×10^{-3}	–







Outline

1. CONSTITUTIVE MODELS AND FITTING

2. NUMERICAL MODELLING

3. OUTLOOKS

2. Numerical modelling – Galery type 1

2.1. Mesh / Boundary conditions / Initial conditions :

- Mesh :

By symmetry: quarter of the gallery.
Modelling in 2D plane strain state.
Gallery radius = 2.6 m.

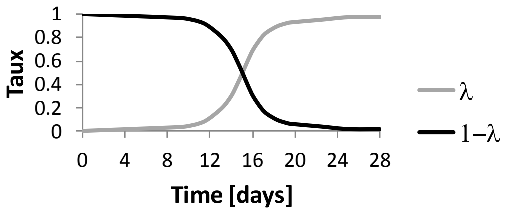
- Initial anisotropic stress state :

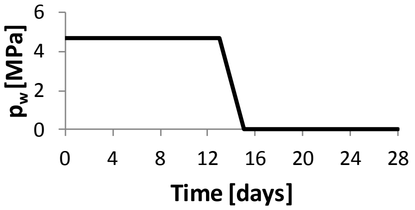
$p_{w,0} = 4.7$ [Mpa]
$\sigma_h = \sigma_z = 12.40$ [MPa]
$\sigma_v = \sigma_y = 12.70$ [MPa]
$\sigma_H = \sigma_x = 1.3\ \sigma_h = 16.12$ [MPa]

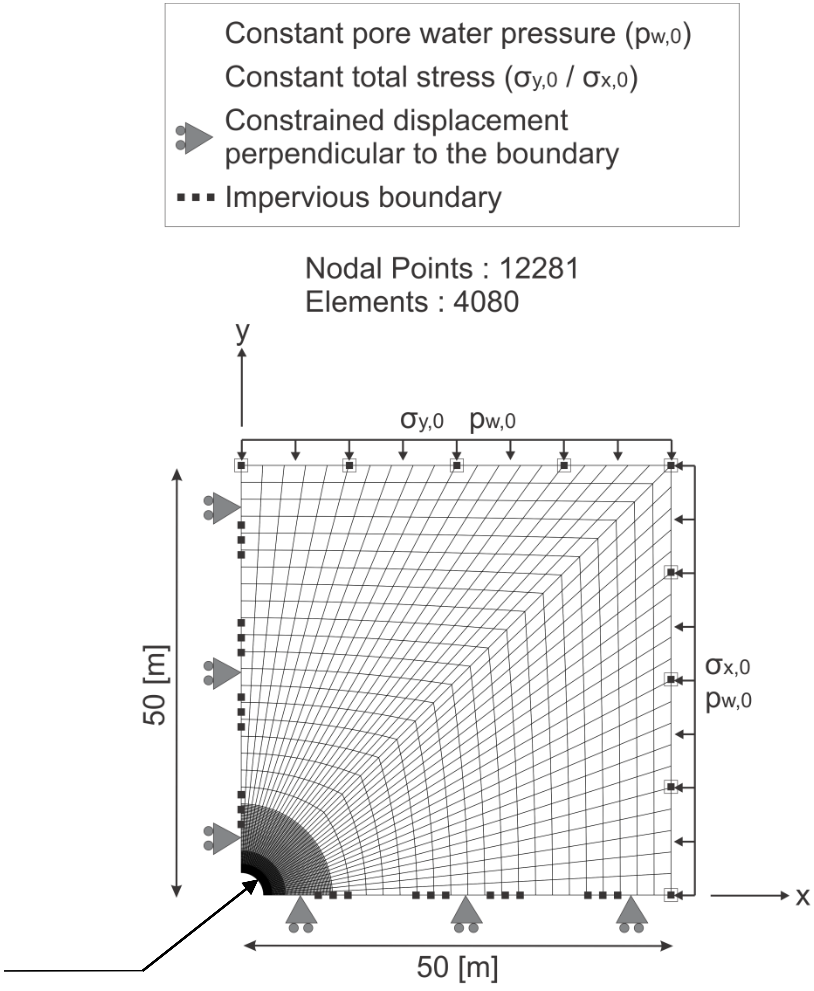
- Hydraulic permeability anisotropy

$k_{hor/vert} = 4\ 10^{-20} / 1.33\ 10^{-20}$ [m²]

- Excavation :







Nodal Points : 12281
Elements : 4080

2. Numerical modelling – Galery type 1

2.2. Hydromechanical modelling, case 1.3 :

- Convergence + Influence of viscosity :

(a) no viscosity

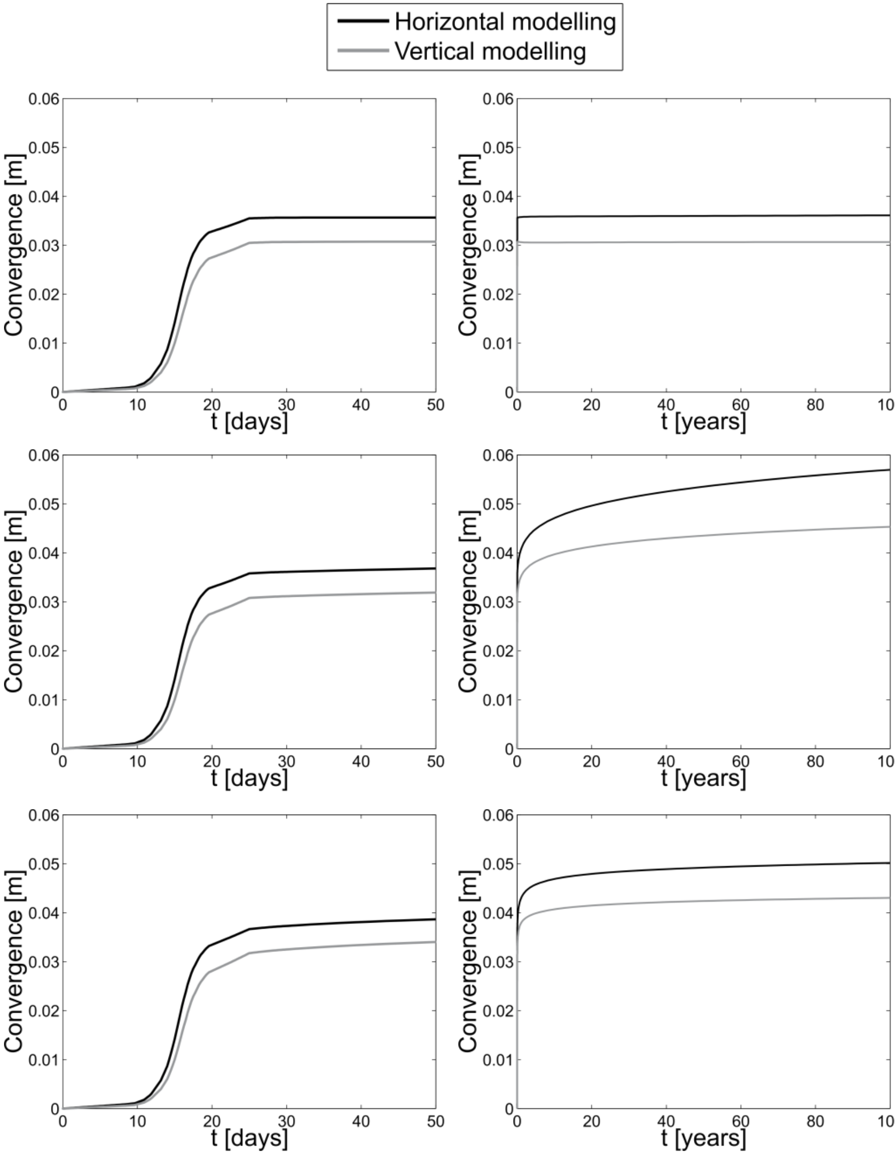
No evolution of deformation in the long term.

(b) viscosity without initial threshold, $\alpha_{vp,0}=0$

Viscosity increases the convergence in the long term.

(c) viscosity with initial threshold, $\boxed{f_{vp,0}=0}$

No initial viscoplastic flow decreases the convergence in the long term.



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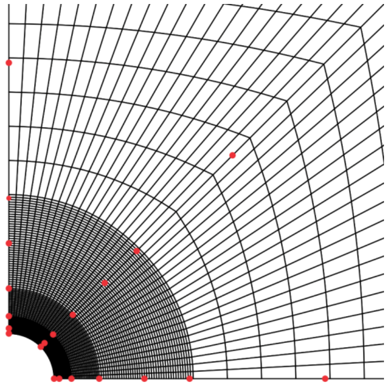
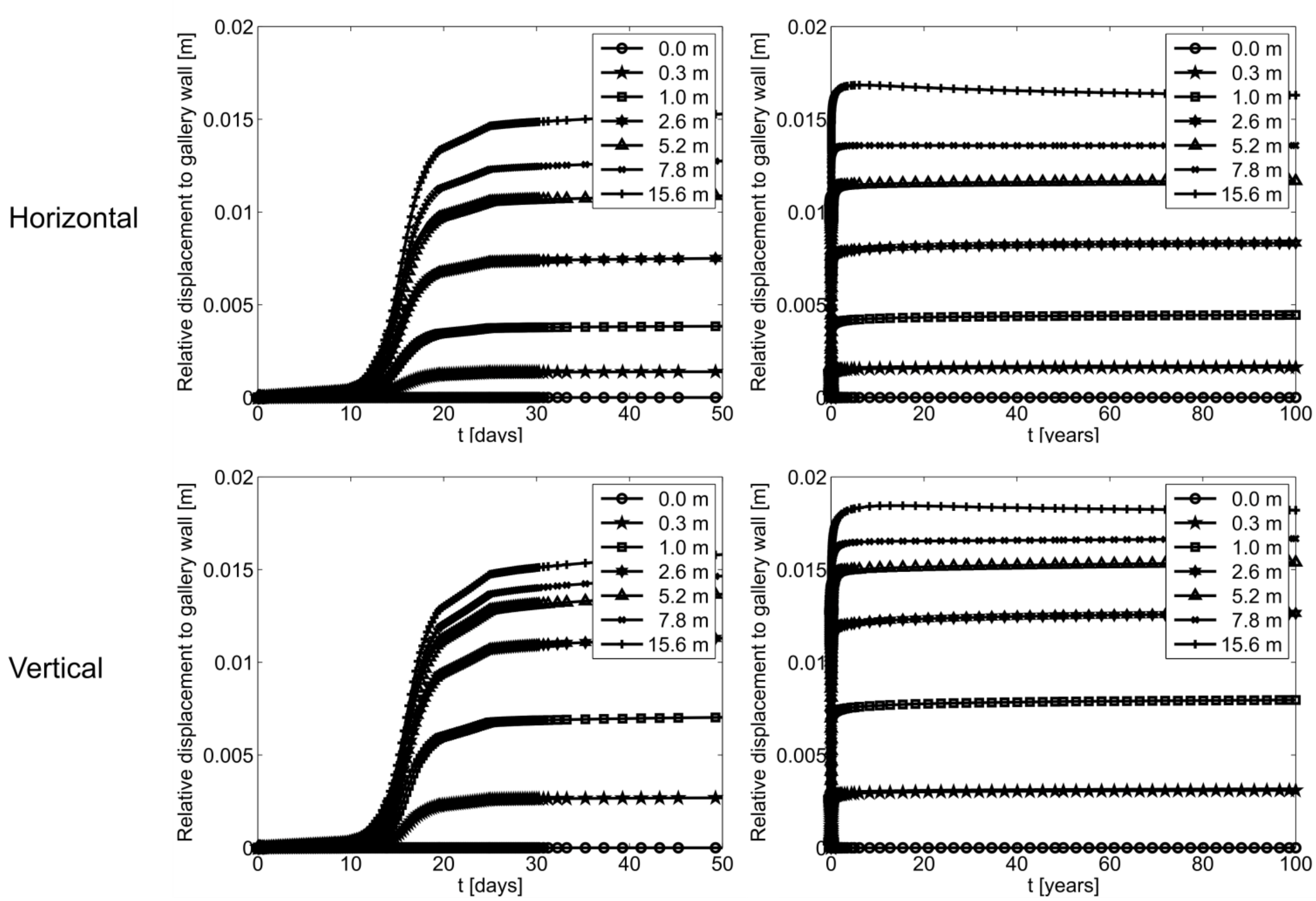


<u>2.2. Hydromechanical modelling, case 1.3 :</u> $f_{vp,0}=0$

- Relative displacement to gallery wall :

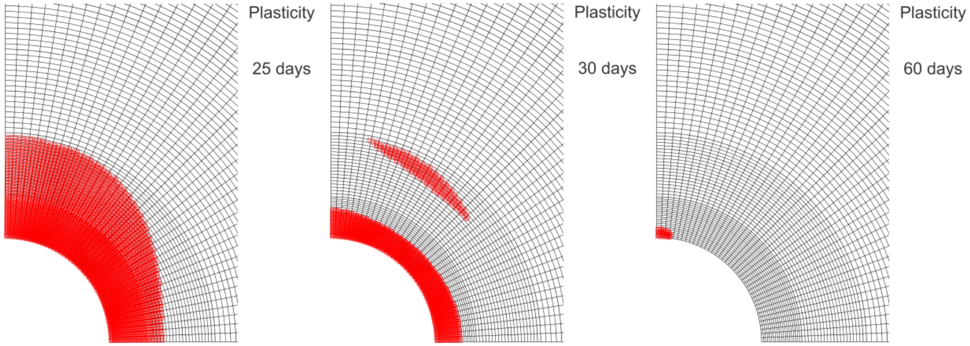


2. Numerical modelling – Galery type 1

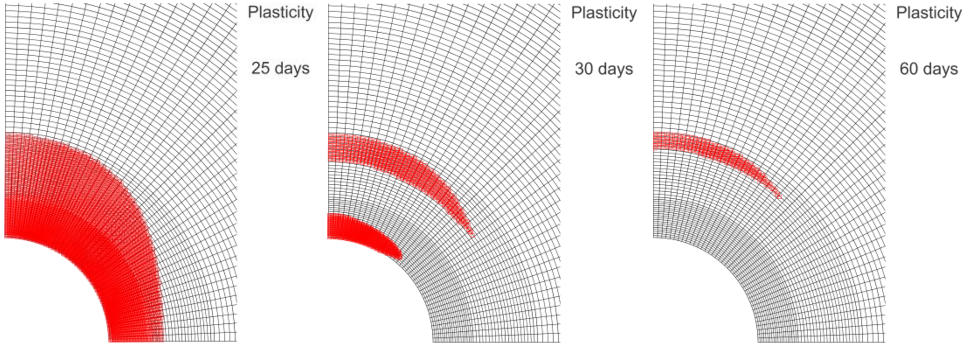
2.2. Hydromechanical modelling, case 1.3 :

- Plastic zone + influence of viscosity :

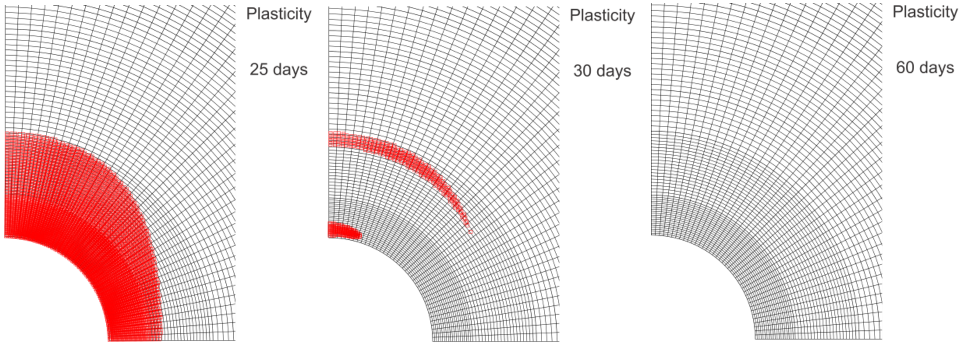
(a) no viscosity



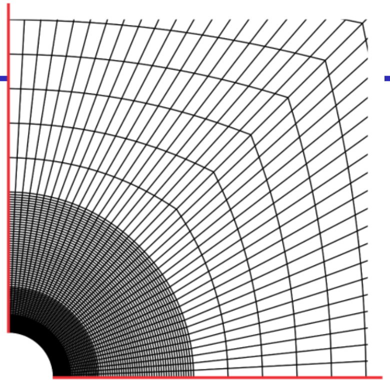
(b) viscosity without initial threshold, $\alpha_{vp,0}=0$



(c) viscosity with initial threshold, $\boxed{f_{vp,0}=0}$

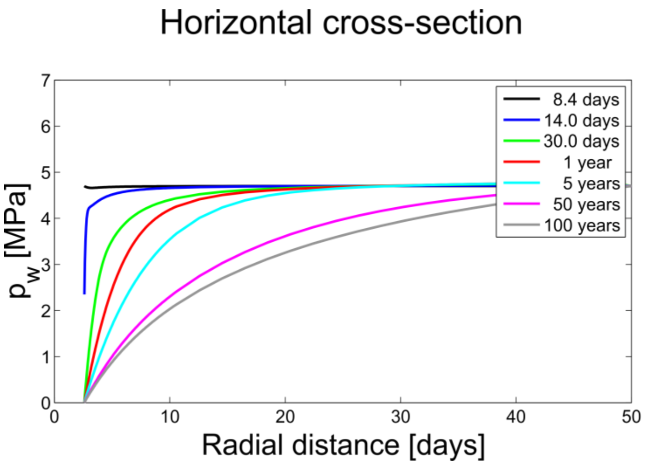


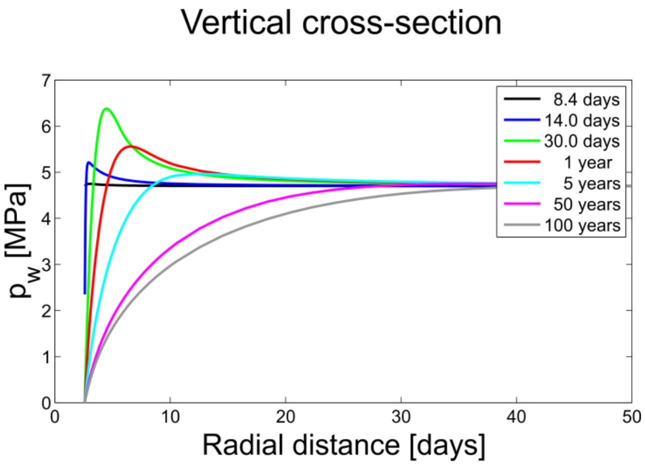
2. Numerical modelling – Galery type 1



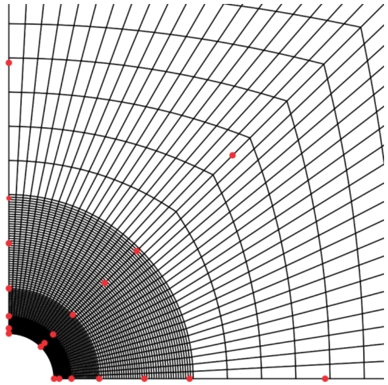
2.2. Hydromechanical modelling, case 1.3 : $f_{vp,0}=0$

- Pore water pressure :


Horizontal cross-section


Vertical cross-section

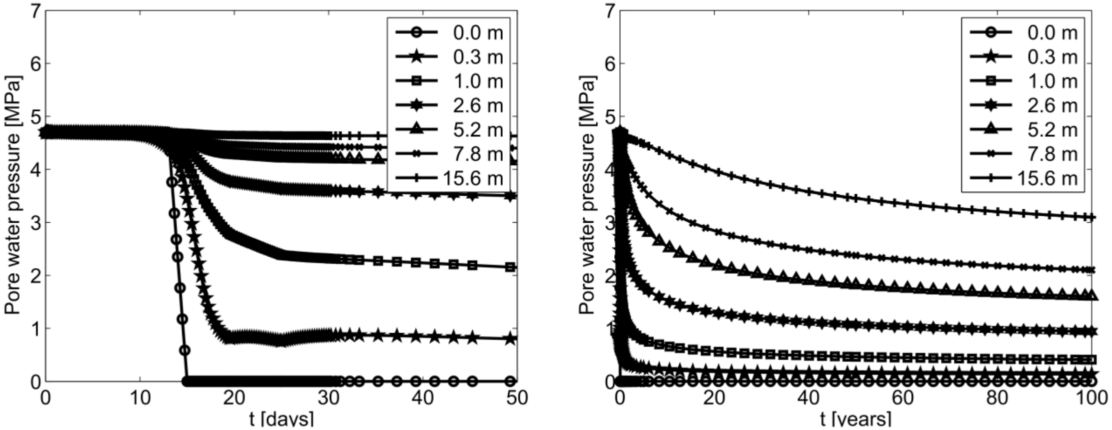
2. Numerical modelling – Galery type 1



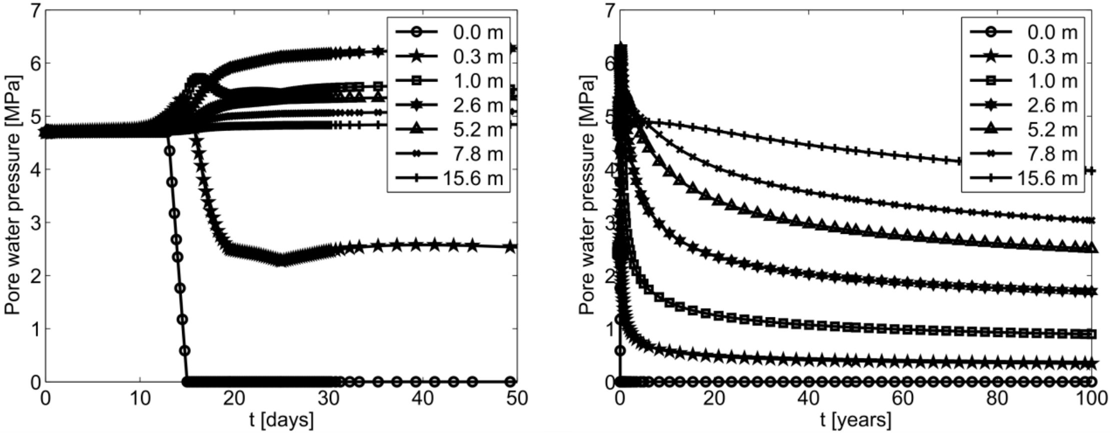
2.2. Hydromechanical modelling, case 1.3 : $f_{vp,0}=0$

- Pore water pressure :

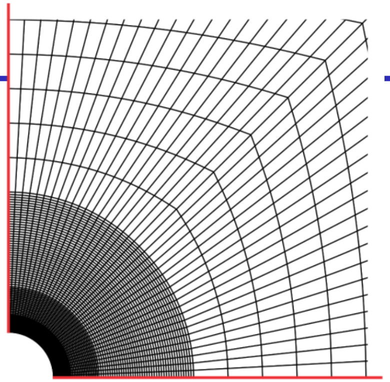
Horizontal



Vertical



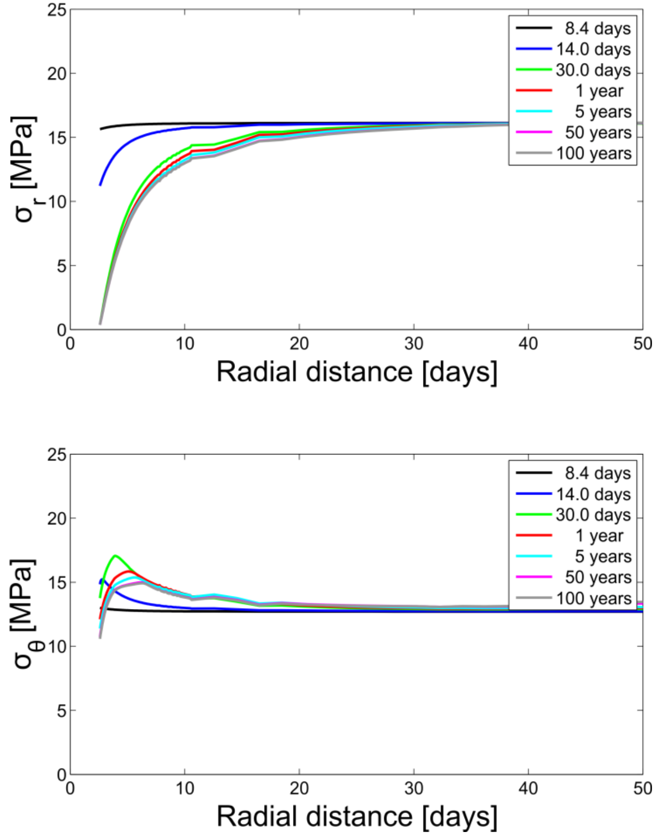
2. Numerical modelling – Galery type 1



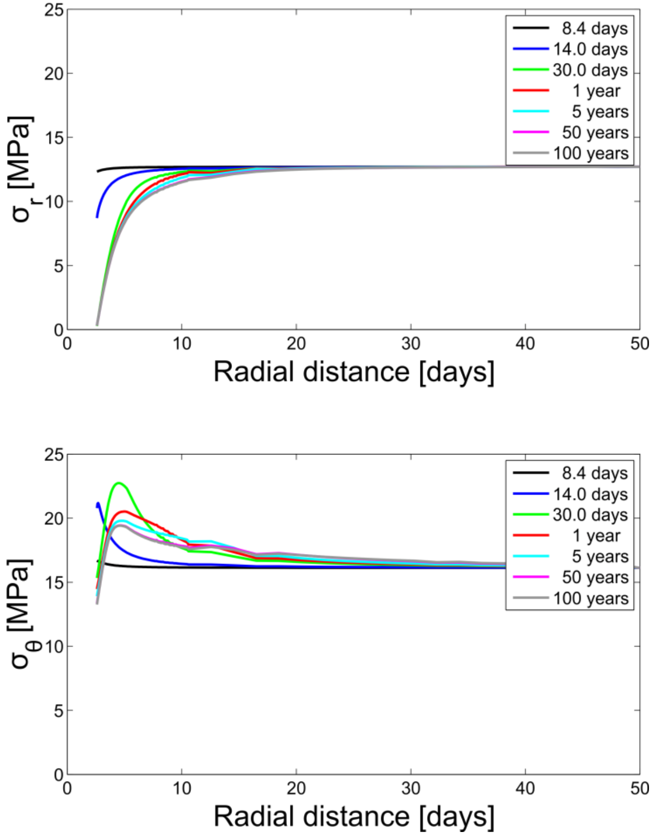
2.2. Hydromechanical modelling, case 1.3 : $f_{vp,0}=0$

- Radial and orthoradial total stress :

Horizontal cross-section



Vertical cross-section



2. Numerical modelling – Galery type 1

2.3. Mechanical modelling, case 1.1 and 1.2 : $f_{vp,0}=0$

- Convergence + influence of the support :

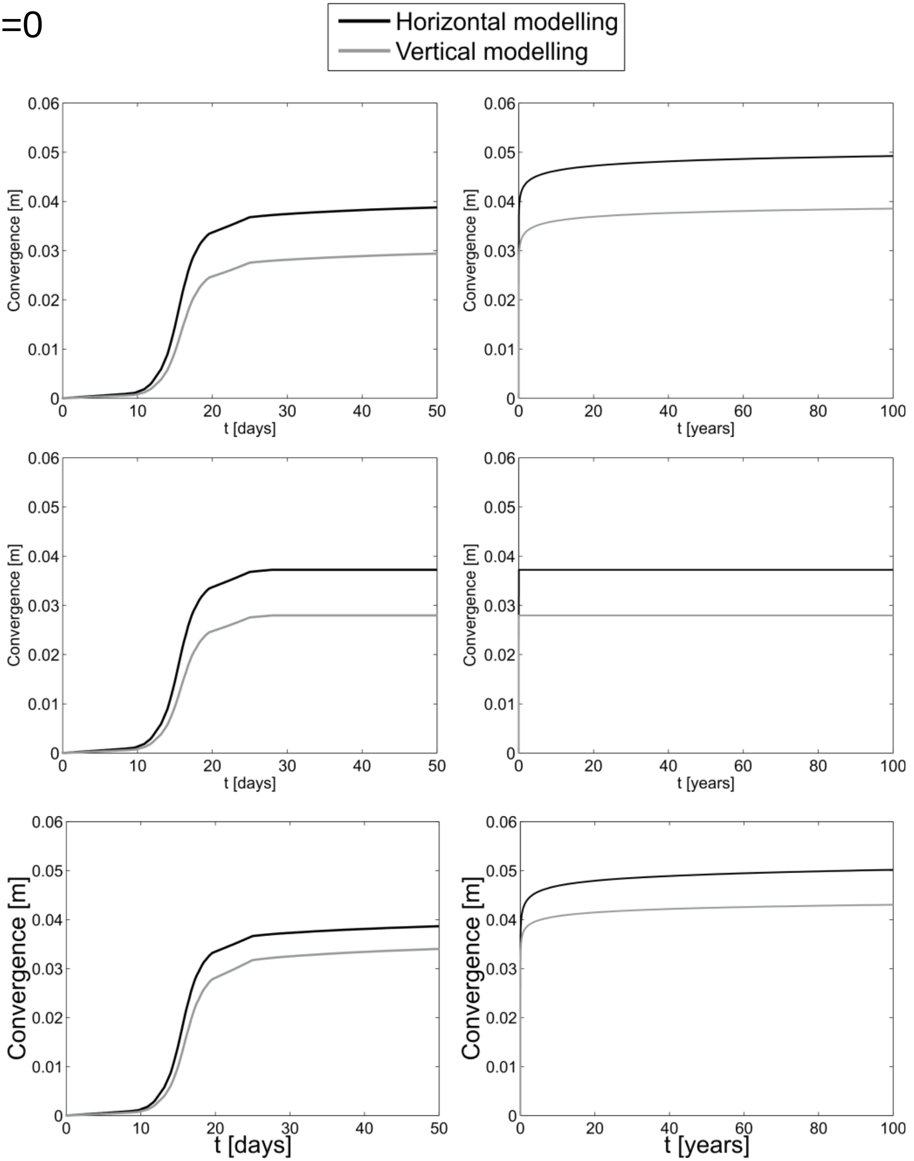
(a) Case 1.1, flexible liner

(b) Case 1.2, rigid liner

Stops the convergence after the excavation.

(c) Case 1.3, flexible liner, HM modelling

Similar to mechanical modelling in the long term.
Vertical convergence slightly greater.

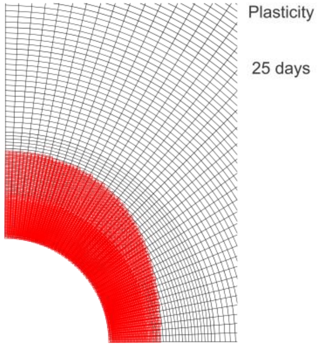


2. Numerical modelling – Galery type 1

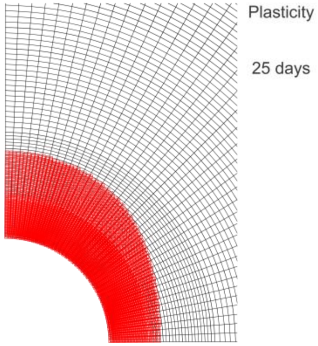
2.3. Mechanical modelling, case 1.1 and 1.2 : no viscosity

- Plastic zone + influence of the support :

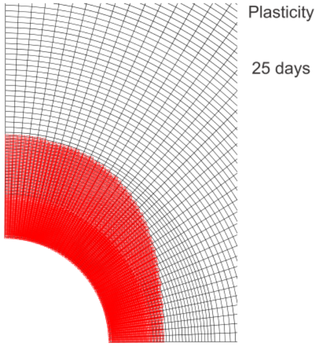
(a) Case 1.1, flexible liner

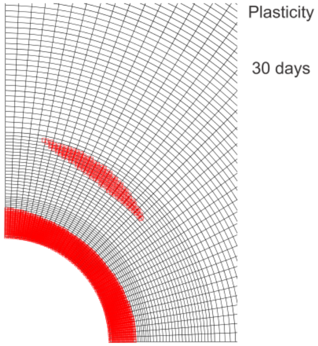


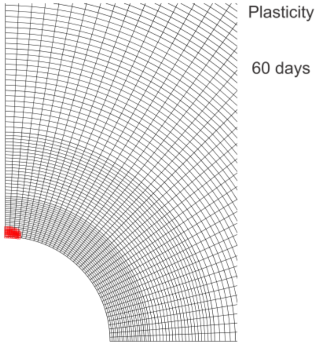
(b) Case 1.2, rigid liner



(c) Case 1.3, flexible liner, HM modelling





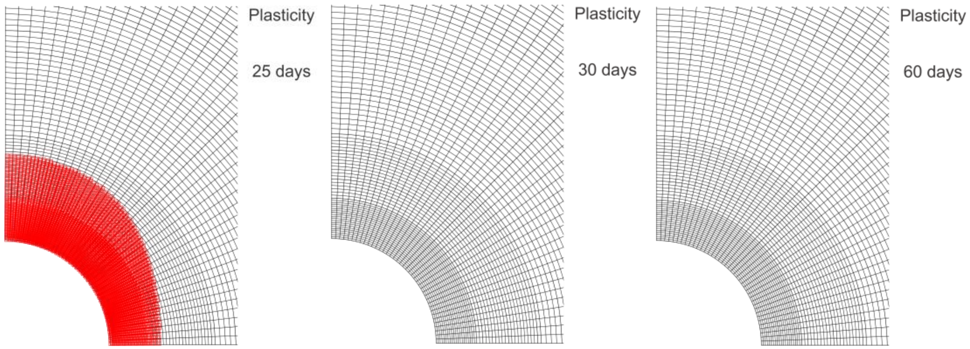


2. Numerical modelling – Galery type 1

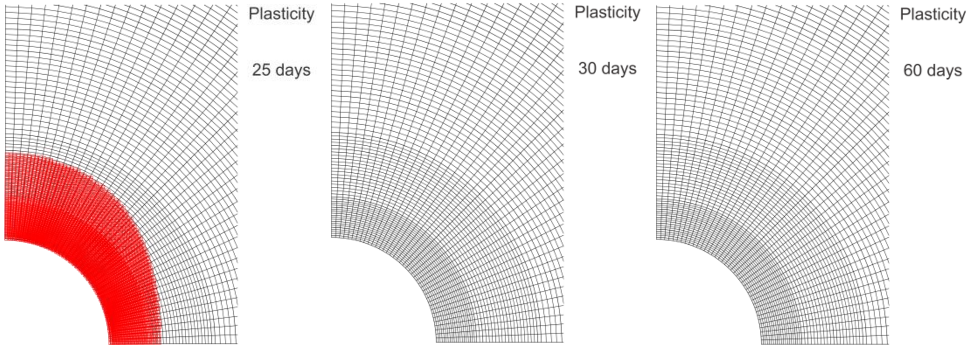
2.3. Mechanical modelling, case 1.1 and 1.2 : $f_{vp,0}=0$

- Plastic zone + influence of the support :

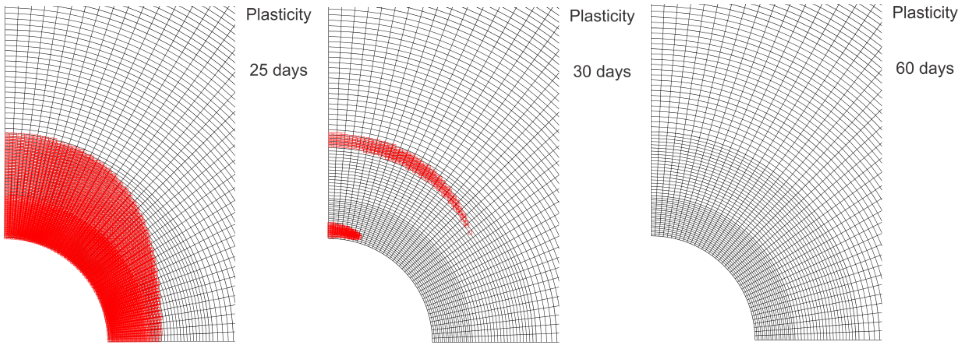
(a) Case 1.1, flexible liner



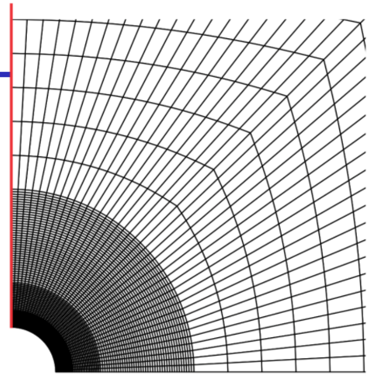
(b) Case 1.2, rigid liner



(c) Case 1.3, flexible liner, HM modelling



2. Numerical modelling – Galery type 1

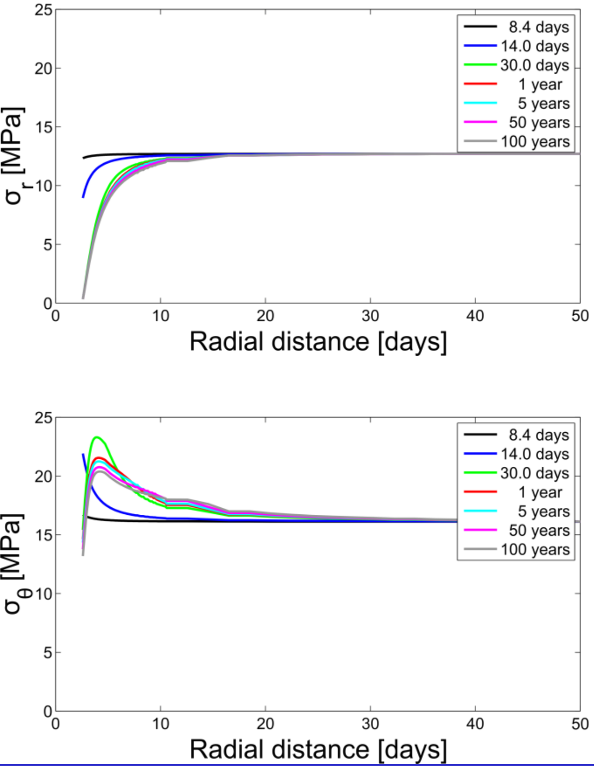


2.3. Mechanical modelling, case 1.1 and 1.2 : $f_{vp,0}=0$

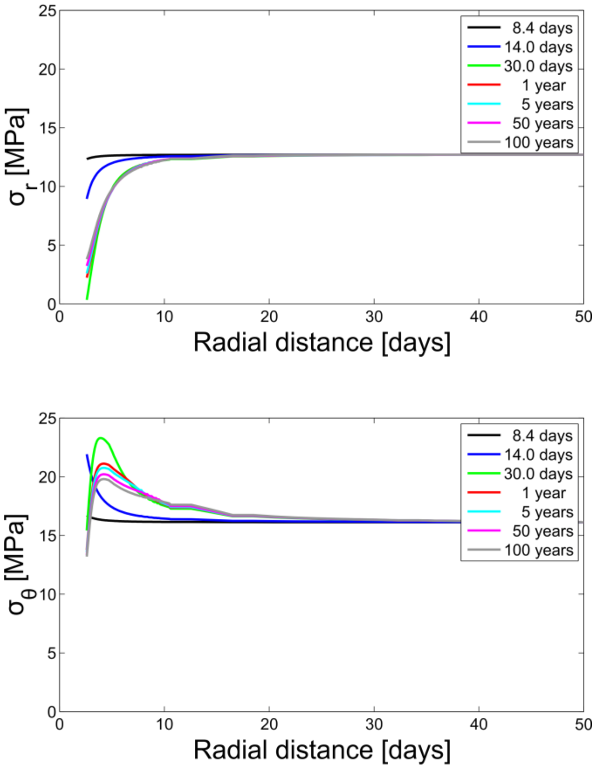
- Radial and orthoradial total stress :

  Vertical cross-section

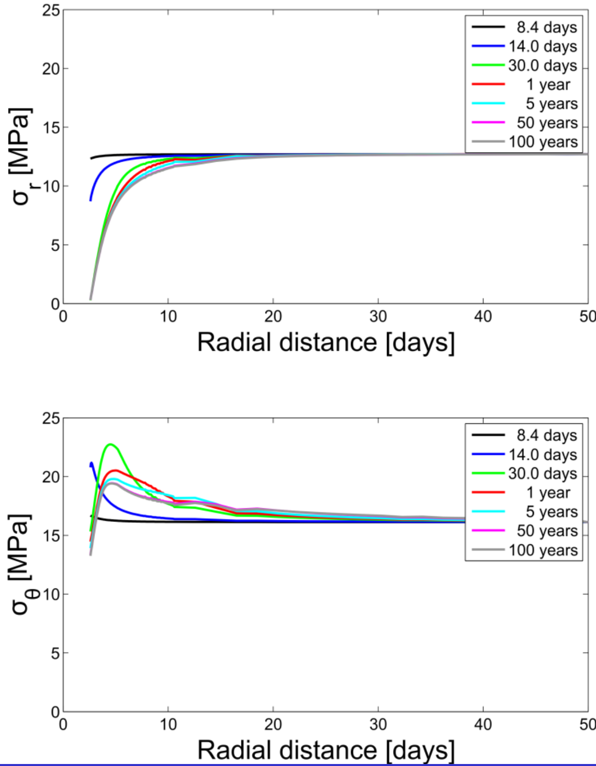
(a) Case 1.1, flexible liner
H modelling



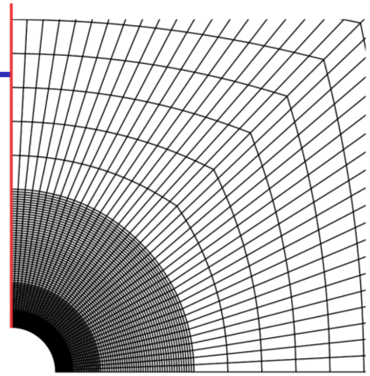
(b) Case 1.2, rigid liner
H modelling



(c) Case 1.3, flexible liner
HM modelling



2. Numerical modelling – Galery type 1



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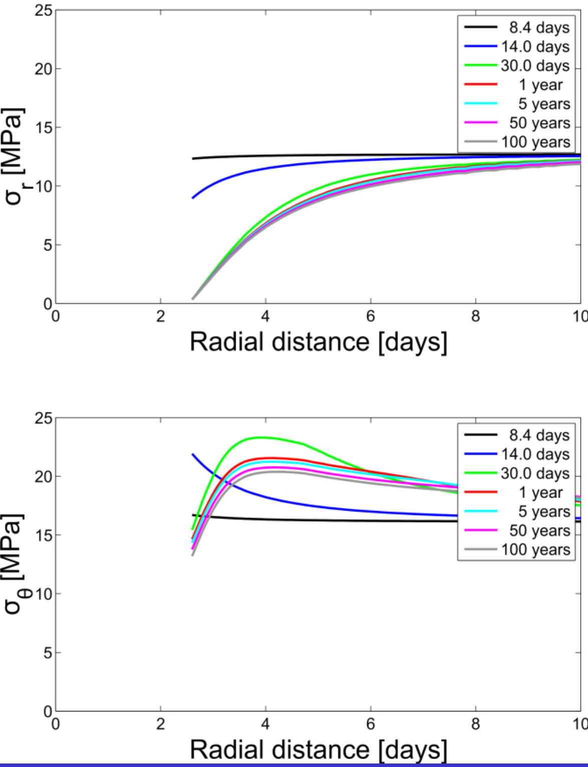
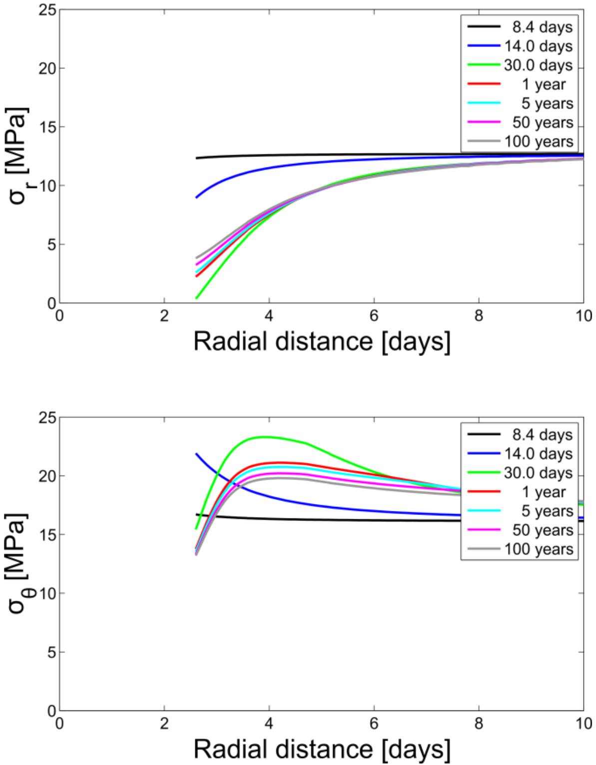
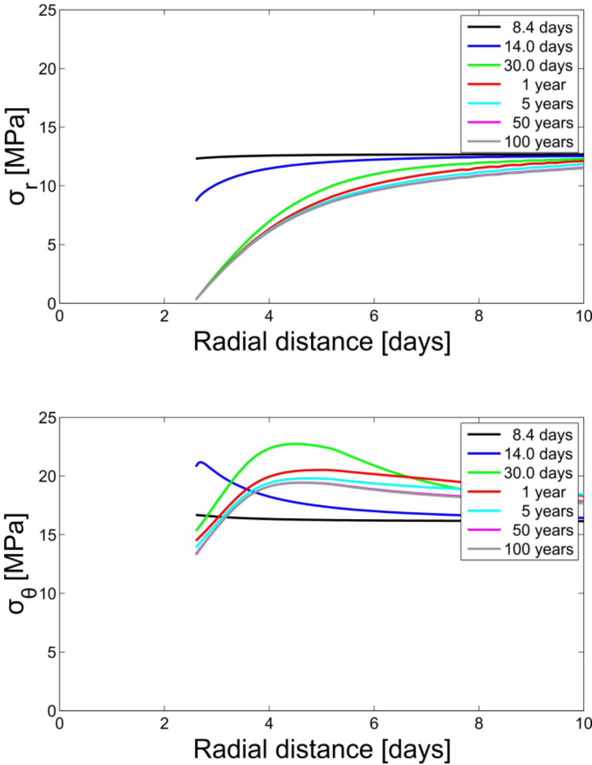


(a) Case 1.1, flexible liner
H modelling



(b) Case 1.2, rigid liner
H modelling



(c) Case 1.3, flexible liner
HM modelling

Outline

1. CONSTITUTIVE MODELS AND FITTING

2. NUMERICAL MODELLING

3. **OUTLOOKS**

   - Anisotropy : E, ν, c, b
   - Test case 2, strain localisation

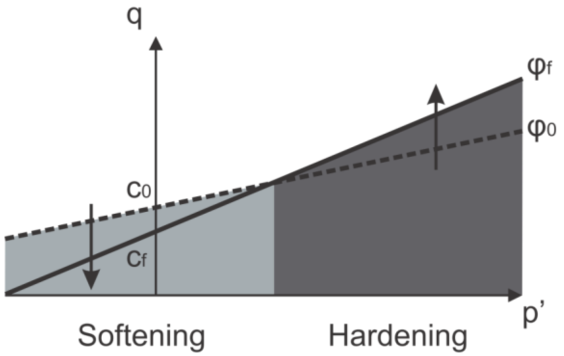
1. Constitutive models and fitting

Mechanical model :

The constitutive mechanical law for the clayey rock is :

- a non-associated elasto-plastic internal friction model, with a Van Eeckelen yield surface

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

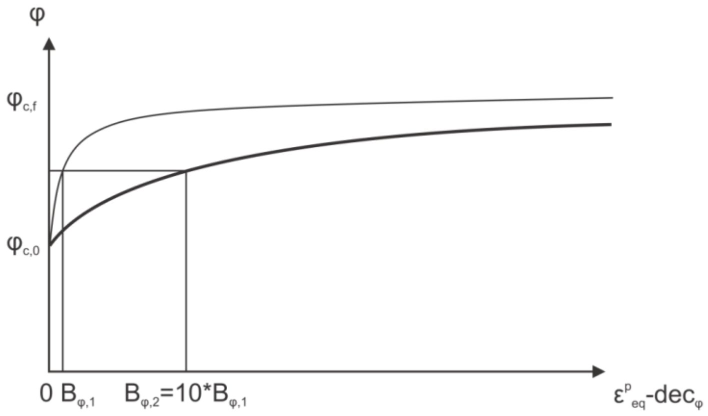


- allowing hardening/softening of φ and/or c as a function of the Von Mises equivalent plastic strain ε^p_{eq}

$$\varepsilon^p_{eq} = \sqrt{\frac{2}{3} \hat{\varepsilon}^p_{ij} \hat{\varepsilon}^p_{ij}}$$

$$if\ \ \varepsilon^p_{eq} \le dec_{\phi} : \phi_C = \phi_{C0}$$

$$if\ \ \varepsilon^p_{eq} > dec_{\phi} : \phi_C = \phi_{C0} + \frac{\left(\phi_{Cf} - \phi_{C0}\right).\left(\varepsilon^p_{eq} - dec_{\phi}\right)}{B_{\phi} + \left(\varepsilon^p_{eq} - dec_{\phi}\right)}$$



1. Constitutive models and fitting

Mechanical model :

Viscoplasticity : $\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{vp}$

from Zhou et al. (2008) and Jia et al. (2008)

- loading surface of the viscoplastic flow :

$$f_{vp} = q - \alpha_{vp} R_c \sqrt{A\left(C_s + \frac{p}{R_c}\right)} \geq 0$$

- viscoplastic potential :

$$Q_{vp} = q - \left(\alpha_{vp} - \beta_p\right)\left(p + C_s R_c\right)$$

- viscoplastic hardening function :

$$\alpha_{vp} = \alpha_{vp,0} + \left(1 - \alpha_{vp,0}\right)\frac{\gamma_{vp}}{B_{vp} + \gamma_{vp}}$$

- viscoplastic flow rule :

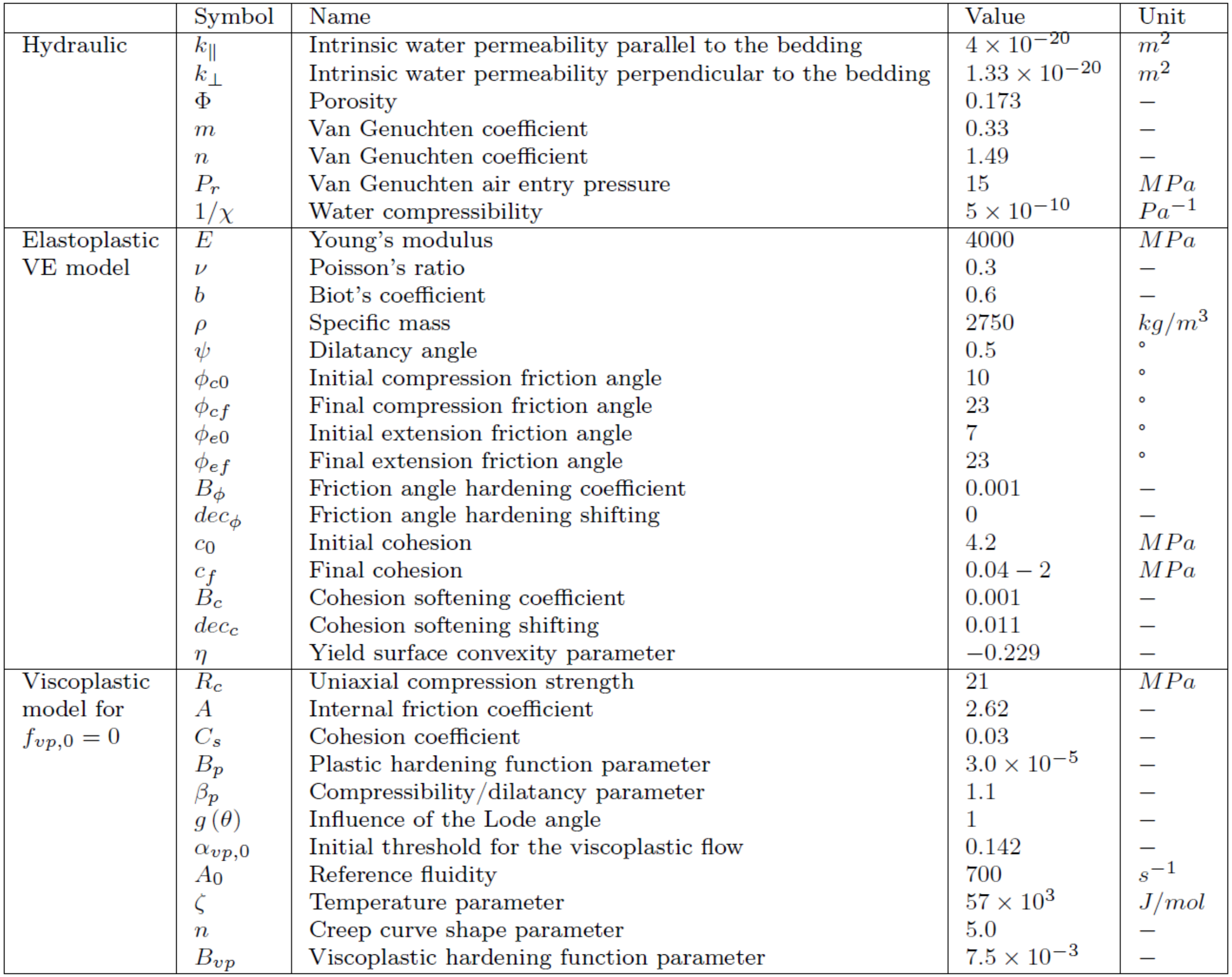
$$\dot{\gamma}_{vp} = \sqrt{\frac{2}{3}\dot{e}_{ij}^{vp}\dot{e}_{ij}^{vp}} \qquad \dot{e}_{ij}^{vp} = \dot{\varepsilon}_{ij}^{vp} - \dot{\varepsilon}_{kk}^{vp}\delta_{ij}$$

$$\dot{\varepsilon}_{ij}^{vp} = A(T)\left\langle \frac{f_{vp}}{R_c} \right\rangle^{n} \frac{\partial Q_{vp}}{\partial \sigma_{ij}} \qquad A(T) = A_0 \exp\left(-\frac{\zeta}{RT}\right)$$

γ_{vp}	is the equivalent plastic shear strain (function of viscoplastic deviatoric strain)
$\alpha_{vp,0}$	is initial threshold for the viscoplastic flow
B_{vp}	is a parameter controlling the evolution of α_{vp} and f_{vp}
A	is a internal friction coefficient defining the curvature of the failure surface
C_s	is a cohesion coefficient, the material cohesion in saturated condition
β_p	is a parameter which defines the transition from compressibility ($\alpha_{vp} < \beta_p$) to dilatancy ($\alpha_{vp} > \beta_p$)
$\dot{e}_{ij}^{vp}$	viscoplastic deviatoric strain
$A(T)$	is the fluidity coefficient
n	is a parameter which describes the shape of the creep curve
A_0	is the fluidity value
ζ	is a parameter controlling the influence of temperature on the material viscosity

1. Constitutive models and fitting

Parameters for COX : (Charlier et al. 2012) + fitting



	Symbol	Name	Value	Unit
Hydraulic	$k_{\parallel}$	Intrinsic water permeability parallel to the bedding	4×10^{-20}	m^2
	$k_{\perp}$	Intrinsic water permeability perpendicular to the bedding	1.33×10^{-20}	m^2
	Φ	Porosity	0.173	–
	m	Van Genuchten coefficient	0.33	–
	n	Van Genuchten coefficient	1.49	–
	P_r	Van Genuchten air entry pressure	15	MPa
	$1/\chi$	Water compressibility	5×10^{-10}	Pa^{-1}
Elastoplastic VE model	E	Young's modulus	4000	MPa
	ν	Poisson's ratio	0.3	–
	b	Biot's coefficient	0.6	–
	ρ	Specific mass	2750	kg/m^3
	ψ	Dilatancy angle	0.5	°
	ϕ_{c0}	Initial compression friction angle	10	°
	ϕ_{cf}	Final compression friction angle	23	°
	ϕ_{e0}	Initial extension friction angle	7	°
	ϕ_{ef}	Final extension friction angle	23	°
	B_{ϕ}	Friction angle hardening coefficient	0.001	–
	dec_{ϕ}	Friction angle hardening shifting	0	–
	c_0	Initial cohesion	4.2	MPa
	c_f	Final cohesion	$0.04 - 2$	MPa
	B_c	Cohesion softening coefficient	0.001	–
	dec_c	Cohesion softening shifting	0.011	–
	η	Yield surface convexity parameter	-0.229	–
Viscoplastic model for $f_{vp,0} = 0$	R_c	Uniaxial compression strength	21	MPa
	A	Internal friction coefficient	2.62	–
	C_s	Cohesion coefficient	0.03	–
	B_p	Plastic hardening function parameter	3.0×10^{-5}	–
	β_p	Compressibility/dilatancy parameter	1.1	–
	$g(\theta)$	Influence of the Lode angle	1	–
	$\alpha_{vp,0}$	Initial threshold for the viscoplastic flow	0.142	–
	A_0	Reference fluidity	700	s^{-1}
	ζ	Temperature parameter	57×10^3	J/mol
	n	Creep curve shape parameter	5.0	–
	B_{vp}	Viscoplastic hardening function parameter	7.5×10^{-3}	–