Hydrogen storage in salt caverns: evolution of salt permeability and hydromechanical modelling at the cavern scale under cycling conditions.

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Funding: ROSTOCK-H Geodénergies project, Grand Est Region Council, Carnot ICEEL
Hydrogen: versatile and promising carrier for energy transition

Currently produced from fossil fuels but from renewable energies in the future (green hydrogen)

Clean hydrogen (green and/or blue) should play a key role in the world transition to achieve carbon neutrality before 2050

- large-scale electricity storage
- decarbonize uses that are difficult to electrify
- use in industrial processes
GENERAL CONTEXT: massive H₂ storage

Storing hydrogen in large quantities is the best option

Massive Storage  ➔  Underground storage

2 solutions

- Storage in deep aquifers
- Storage in salt caverns

Storage in salt cavern

Most secure and economical solution for large volumes of H₂

Only 4 salt caverns in operation worldwide (e.g., Spindletop USA, Teeside UK...)

but many industrial pilot sites in preparation worldwide (e.g., Etrez, France)
PROBLEM

Specific constraints compared to conventional gas storage

- High danger and mobility of H\textsubscript{2} (low density and viscosity, high diffusion)
- Need to accurately predict the extent of potential leaks of H\textsubscript{2} to ensure safe storage: sealing of salt?

Strong temperature (0-50 °C) and gas pressure (2-6 MPa for a 350 m deep cavern) variations in the salt cavern depending on the injection-production cycles (depends on usage)

→ Thermo-mechanical damage of rock salt in the near field (close to the wall) → permeability

FOCUS OF THE STUDY

Characterize the ThermoHydroMechanical behaviour of rock salt

- Mechanical properties of initial material
- Impact of damage processes on rock salt permeability
- Viscoplasticity effect (self-healing process)
- Impact of mechanical (static and dynamic) and thermal (dynamic) fatigue

MATERIALS AND METHODS

Rock salt samples

- Salt bed of the Alsace potash mines (530 m depth) in the East region of France (Stocamine site for ultimate waste storage)
- Sannoisian-Oligocene (Cenozoic) geological stage
- Considered as a natural analogue of salt caverns used for in-situ H₂ storage
- Very low initial porosity (~ 1%) composed mainly of infrapores (nanometric size) that connect dispersed cracks and macropores

Experimental device

- Large scale triaxial compression cell
- Continuous measurement of deformations (strain gages)
- Continuous measurement of gas (He) permeability with the steady-state method
- Pressures controlled with precision syringe pumps
Characterisation of the mechanical behaviour

- Hydrostatic compression tests
- Uniaxial and triaxial compression tests

→ Characterization of short-term deformation mechanisms (plasticity, micro-cracking damage)

Gas permeability measurements

- Under hydrostatic loading and triaxial loading with different confining pressures

→ Analyse the impact of the deformation mechanisms on permeability
  - At different gas pressures

→ Analyse the slippage (Klinkenberg) effect and obtain the intrinsic gas permeability
  - Under dynamic (cyclic) and static (creep test) triaxial loading, and under dynamic thermal loading

→ Analyse the impact of mechanical and thermal fatigue
**MECHANICAL BEHAVIOUR OF ROCK SALT**

**Under hydrostatic loading**

- **Isotropic** mechanical behaviour
- The behaviour is **elastic** (irreversible) and linear up to 30 MPa
  → No large initial cracks
- No poromechanical coupling (Biot’s coefficient ~ 0)

**Stress-strain curves of an hydrostatic compression test**

**Under deviatoric loading**

- **Very low elastic limit** (yield strength)
- Crack initiation and dilatancy thresholds increase with the confining pressure (Pc)
- Dilatant and irreversible microcracking damage develops at low Pc (0 and 1 MPa)
- Behaviour becomes **fully plastic** (ductile) at high Pc (5 MPa)
- Dilatancy threshold ↔ important increase of permeability due to cumulated microcracking damage

**Stress-strain curves of of uniaxial (left) and triaxial (right) compression tests**
Klinkenberg (slippage) effect

- **Klinkenberg effect** (i.e., decrease of permeability with the increase in gas pressure) only observed for the less permeable (and then less initially damaged) samples.
- When it appears, the gas flow falls in **transitional regime** in weakly damaged rock salt.

**Evolution of apparent permeability** $k_a$ as a function of mean gas pressure at different deviatoric stress levels during triaxial compression tests.

Initial permeability

- The initial intrinsic permeability of the studied rock salt ranges over more than 4 orders of magnitude: $10^{-16}$ to $5 \times 10^{-21}$ m$^2$.
- Wide permeability range of the as-received samples due to the presence of cracks caused by the stress relaxation (induced by core drilling or cavity excavation) and sample preparation.

**Voids (cracks) distribution in a rock salt sample from X-ray tomography.**
Under deviatoric loading

- At low confining pressure (1 MPa): small increase in gas permeability from the dilatancy threshold due to microcracking damage.
- At high confining pressure (5 MPa): no increase in permeability because the material becomes fully plastic which practically eliminates microcracking and thus dilatancy.

Under hydrostatic loading

- Gas permeability decreases because of the closure of voids (cracks and pores).
- Decrease is irreversible if time of run is high enough.
- Due to the self-healing process (irreversible closure of cracks).
  → Restoration of the permeability of undisturbed natural rock salt.

Evolution of apparent permeability $k_a$ as a function of deviatoric stress.

Evolution of apparent permeability $k_a$ as a function of confining pressure $P_c$ and time.
Static (creep test) and dynamic (cyclic) mechanical fatigue

- Volumetric dilatancy (microcracking damage) develops and increases slightly the permeability during dynamic fatigue
- Self-recovery reduces damage and decreases slightly the permeability during static fatigue (creep)

→ Different mechanisms involved in rock salt deformation during dynamic and static fatigue act in a competitive way to **annihilate any significant permeability evolution**
Cyclic thermal fatigue

- Small permeability increase due to the microcracking damage that develops at the microscopic scale
- Due to the anisotropy of the thermal deformation of rock forming minerals and to the polycrystalline nature of rock salt
  → Deformation heterogeneities and then differential thermal stresses and microcracking damage

Evolution of volumetric deformation $\varepsilon_v$ as a function of time during the thermal cyclic fatigue test

Evolution of apparent permeability $k_a$ as a function of mean gas pressure, before and after the thermal cyclic fatigue test

Intrinsic permeability
Before test: $2.7 \times 10^{-20}$ m$^2$
After test: $4.9 \times 10^{-20}$ m$^2$
The different mechanisms (viscoplasticity with strain hardening, microcracking and cracks healing) involved in rock salt deformation act in a competitive way to annihilate any significant permeability evolution. 

→ Strong confidence in the H₂ storage in salt caverns which remains by far the SAFEST SOLUTION
Numerical modeling of hydrogen storage in salt cavern

• From available experimental results on salt rock, propose/develop a rheological model that reproduces the main features of short and long term behavior
• Validation based on experimental tests and application(s) to salt cavern
• Analysis of the impact of the operational phase:
  ✓ Mechanical behaviour of the salt cavern
  ✓ $\text{H}_2$ leakage through the cavern wall (extent of the dissolved $\text{H}_2$ plume)

• **HydroMechanical model**: viscoplastic and damage model


• **ThermoHydroMechanical model**: Previous model + fatigue + healing + thermal coupling
Elastoplastic and damage model

Elastic tensor

\[ C_{ijkl} = (1 - d) C_{ijkl}^0 \]
\[ d = d_i + d_f + d_t - h \]
\[ d_i: \text{instantaneous damage} \]
\[ d_f: \text{fatigue damage} \]
\[ d_t: \text{tertiary damage} \]
\[ h: \text{healing} \]

\[ d: \text{total damage} \]

Mohr-Coulomb yield surface

\[ f_p = q + p M_p - N_p \]
\[ M_p = \eta_p(\gamma^p) \frac{\sin \phi}{(\frac{\cos \theta}{\sqrt{3}} - \frac{1}{3} \sin \theta \sin \phi)} \]
\[ N_p = \eta_p(\gamma^p) \frac{(1 - d_i - d_f + h) c \cos \phi}{(\frac{\cos \theta}{\sqrt{3}} - \frac{1}{3} \sin \theta \sin \phi)} \]

Hardening rule

\[ \eta_p(\gamma^p) = 1 - (1 - \eta_p^0) \exp \left\{ -\alpha_p \gamma^p \right\} \]
Elastoplastic and damage model

Plastic potential

\[ g = q + \beta(\gamma^p) \rho \]

\[ \beta(\gamma^p) = \begin{cases} 
\beta_m - (\beta_m - \beta_0) \exp(-b_\beta \gamma^p) & ; \quad \gamma^p < \gamma^p_{ult} \\
\beta_{ult} \exp\left(1 - \frac{\gamma^p}{\gamma^p_{ult}}\right) & ; \quad \gamma^p \geq \gamma^p_{ult}
\end{cases} \]

\[ \beta_m = \begin{cases} 
\beta_m^0 \exp(a_p \sigma_1) & ; \quad \sigma_1 < 0 \\
\beta_m^0 & ; \quad \sigma_1 \geq 0
\end{cases} \]

\( \beta(\gamma^p) \) : dilatancy coefficient

\( \beta_0 (\beta_0 < 0) \) is the initial volumetric contraction, \( \beta_m (\beta_m > 0) \) is the volumetric dilatancy at large deformation.

We have volumetric contraction when \( \beta < 0 \), whereas the plastic strains evolve towards volumetric dilatancy if \( \beta > 0 \).
Elastoplastic and damage model

Instantaneous damage ($d_i$) (Mazars 1984)

\[ f_d = d_i^{\text{max}} \{1 - \exp[-b_d (Y_d - Y_0)]\} - d_i \leq 0 \ ; \quad d_i \in [0; d_i^{\text{max}}] \]

\[ d_i^{\text{max}} = \begin{cases} 
    d_{i0}^{\text{max}} \exp(a_d \sigma_1) & ; \quad \sigma_1 < 0 \\
    d_{i0}^{\text{max}} & ; \quad \sigma_1 \geq 0 
\end{cases} \]

\[ Y_d = \sqrt{\langle \varepsilon \rangle : \langle \varepsilon \rangle} ; \quad \varepsilon \text{ is the principal strain value of the elastic and plastic strains} \]

\[ a_d : \text{parameter describing the effect of confining stress} \]

Fatigue damage ($d_f$) (Zhang et al. 2023)

\[ \dot{d}_f = \frac{b_f}{T_f} (d_f^{\text{max}} - d_f) \quad ; \quad d_f \in [0; d_f^{\text{max}}] \]

\[ d_f^{\text{max}} = d_{f0}^{\text{max}} \eta_p \left( 1 + b_{f2} \frac{Y_d - Y_d^c}{Y_d^c} \right) \]

Assumption: The value of instantaneous damage is constant during the fatigue test.
Elastoplastic and damage model

Creep strain rate

**Transient creep**
(Kelvin-Voigt model)

\[
\dot{\varepsilon}_{ij}^C = \frac{1}{\bar{\tau}_k^*} (q^* - \tilde{G}_k^* \varepsilon_{tr}) + A_N \exp \left( -\frac{B_N}{T} \right) \left( \frac{q^*}{\sigma_{ref}} \right)^{n_N} \frac{3}{2} \frac{s_{ij}}{q}
\]

\[\tilde{G}_k^* = G_k \exp (k_1 q^*) \quad \bar{\tau}_k^* = \tau_k \exp (k_2 q^*)\]

**Steady-state creep**
(Norton law)

\[q^*_{\text{Mises stress undamaged}} \quad q^*_{\text{Mises stress damaged}}\]

\[q^* = \frac{q}{1 - d}\]

\[q^*_{\text{Mises stress undamaged}} \quad q^*_{\text{Mises stress damaged}}\]

Damage is activated and increases if the damage limit (dilatance criterion) is exceeded.

**Tertiary damage** ($d_t$)

(Hou et al. 2003)

\[d_t = A_T \frac{A_T}{1 - d} n_T \left( \frac{f_{ds}}{\sigma_{ref}} \right)^n_T\]

Healing ($h$)

\[h = \frac{d}{h_1} \left( -\frac{f_{ds}}{\sigma_{ref}} \right)\]

**Assumption**: The healing boundary and the damage threshold are identical.

![Graph showing tertiary creep zone](image)
Mathematical formulation

Thermo-hydro-mechanical coupling

\[ \nabla \left[ C : \varepsilon^e - b (p - p_{ref}) I - \alpha C : (T - T_{ref}) I \right] + \rho_m \ddot{g} = 0 \]

\[ \rho b \frac{\partial \varepsilon_v}{\partial t} + \frac{\rho_f \partial p}{M \partial t} + \nabla (\rho_f \ddot{q}) - 3 \rho_f \alpha_m \frac{\partial T}{\partial t} = 0 \]

\[ \rho C_p \frac{\partial T}{\partial t} + \rho_f C_p \ddot{q} \cdot \nabla T - \nabla \cdot (\lambda \nabla T) = 0 \]

Where:

\[ C = (1 - d) C^0 \]
\[ \rho_m = (1 - n) \rho_s + n \rho_f \]
\[ \ddot{q} = -\frac{k}{\mu_f(T)} (\nabla p + \rho_f \ddot{g}) \]

\[ \frac{1}{M} = \frac{n}{K_f} + \frac{(1 - b)(b - n)}{K_d} \]

\[ \alpha_m = (b - n) \alpha + n \alpha_f(T) \]

\[ k = k_0 10^{4k \cdot d} \quad (Gawin et al. 2002) \]

- Fully water-saturated material
- Two-phase flow not considered
- Dissolved H\(_2\) transport by advection and diffusion
- The value of the Biot coefficient is 0.3 if material is damaged
Storage in salt cavern: case study
boundary and initial conditions

Model geometry

<table>
<thead>
<tr>
<th>Depth</th>
<th>Cavern A</th>
<th>Cavern B</th>
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<tbody>
<tr>
<td>m</td>
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<table>
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<td>910 800</td>
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<th>Pmin - H₂</th>
<th>MPa</th>
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<tbody>
<tr>
<td>Cavern A</td>
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<td>2</td>
<td></td>
</tr>
<tr>
<td>Cavern B</td>
<td>20</td>
<td>6</td>
<td></td>
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H₂ Conditions

Cycling scenarios:
- **Seasonal**
  - For 50 years
- **Daily**
  - For 100 days

Analysis cases

- **Elastic** (To verify the HM model: realised)
- Cavern A (seasonal & daily)
- Cavern B (seasonal & daily)
Storage in salt cavern: case study

Cavern geometry, boundary and initial conditions and properties
\begin{align*}
\sigma \cdot \mathbf{n} &= p_{\text{atm}} z \\
p_f &= p_{\text{atm}} \\
T &= 25^\circ \\
\vec{n} \cdot (\nabla c_{\text{H}_2}) &= 0
\end{align*}

Initial stresses and pore pressure (MPa):

- \( \sigma_\nu \)
- \( \sigma_r \)
- \( p \)
- \( T \)

Temperature (°C):

- Temperature profile over depth.

Graphs showing:
- Depth vs. Radial Distance
- Depth vs. Temperature
- Depth vs. Pore Pressure
Storage in salt cavern: case study
Cavern geometry, boundary and initial conditions and properties

### Short-term numerical values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<td>/MPa</td>
<td>$d_f^0$</td>
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<td>$b_d$</td>
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<td></td>
<td>$b_{f_1}$</td>
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<td>s</td>
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<tr>
<td>$c$</td>
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<td>MPa</td>
<td>$\beta_m$</td>
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<td>$\gamma_{\text{ult}}$</td>
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<td>$R_f$</td>
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<td>MPa</td>
<td>$T_f$</td>
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### Long-term numerical values

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<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Parameter</th>
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<td>MPa</td>
<td>$\eta_l$</td>
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<td>1/K</td>
<td>$A_N$</td>
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<td>K</td>
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<td>1/MPa</td>
<td>$n_{N_T}$</td>
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<td>$h_1$</td>
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<td>d</td>
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<td>1/d</td>
<td>$\beta_{n}$</td>
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Storage in salt cavern: case study

Cavern geometry, boundary and initial conditions and properties

<table>
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<th>Parameter</th>
<th>Value</th>
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<td>$\mu_t$</td>
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<td>Pa.s</td>
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<tr>
<td>$\eta$</td>
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<td></td>
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<tr>
<td>$b$</td>
<td>0.012</td>
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<tr>
<td>$K_t$</td>
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<td>Pa</td>
</tr>
<tr>
<td>$\rho_t$</td>
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<table>
<thead>
<tr>
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<th>Unit</th>
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<td>$\lambda$</td>
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<td>$\alpha$</td>
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<tr>
<td>$C_p$</td>
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</tr>
<tr>
<td>$\alpha_f$</td>
<td>$f(T)$</td>
<td>1/K</td>
</tr>
<tr>
<td>$D^*$</td>
<td>6.0E-9</td>
<td>m²/s</td>
</tr>
</tbody>
</table>

Graph showing linear thermal expansion of water and dynamic viscosity of water as functions of temperature.
Hydro-mechanical results

Stress path at the bottom of the cavern (Deviatoric stress projected to the plane $\theta=\pi/6$)

- Relaxation of deviatoric stresses over time
- **Seasonal and cavern A:** in the first extraction it exceeds the elastic limit. For the following cycles this limit is not exceeded due to creep. In **cavern B** the dilatancy criterion is reached
Hydro-mechanical results

Plastic and damage zone

 Around **cavern A** there is a small extension of the plastic zone, in the lower and lateral part of the cavern.

 Around **cavern B**, the damage zone is initially located at the bottom. The plastic zone is all around the cavern and is more extensive for daily cycling.
Hydro-mechanical results

Cavern wall displacements

Around **cavern A**, the displacements are small and in the order of 26 mm.

Around **cavern B**, the displacements are important for seasonal cyclage. Maximum displacement of 3.6 m on the lateral side.
For both caverns, a similar hydrogen extension is estimated around the cavern. Almost 2.5 m for a daily cycling and almost 15 m for a seasonal cycling. **Gas transport mainly by diffusion.**
Thermo-hydro-mechanical results

Plastic and damage zones around cavern

Zones at 33 years for (a) Case 1: HM (b) Case 2: THM (c) Case 3: THM (without healing)

- Before the operation phase, only plastic zones are calculated in the analysis cases
- At 3.5 years (first minimum gas pressure), the damage zone appears, and the plastic zone increases.
- In the following years, damage zones increased slightly in extension, while the plastic zone increased more.
Thermo-hydro-mechanical results

Net damage at the bottom of the cavern

Note: Net damage is defined as $d = d_i + d_f + d_t - h$
Thermo-hydro-mechanical results
Cavern wall displacements

(a) Cavern wall displacements (scaled by a factor of 2.5), (b) horizontal and (c) vertical displacements for Case 1: HM

- Case 1 has more displacements than Cases 2 and 3 because it has a larger extent of the plastic zone around the cavern.
- Cases 2 (THM) and 3 (THM without healing) exhibit similar displacements.
- Important horizontal displacements are calculated on the bottom wall of the cavern, while significant vertical displacements are calculated on the floor of the cavern.
Thermo-hydro-mechanical results

Pore pressure distribution

Pore pressure distribution around salt cavern at 32.5 years for:
(a) Case 1: HM (b) Case 2: THM (c) Case 3: THM (without healing)

- Pore pressure distributions for Cases 2 and 3 show more modification around the cavern compared to Case 1, due to the temperature effect.
Thermo-hydro-mechanical results

Hydrogen leakage

Hydrogen extension around salt cavern at 33 years for:
- (a) Case 1: HM
- (b) Case 2: THM
- (c) Case 3: THM (without healing)

Hydrogen extensions are similar for the three cases due to transport properties, modified only near the cavern wall.
Conclusions

• A THM model describing the main key features of the rock salt behavior has been developed
  ✓ Short term model takes into account elastoplastic and instantaneous damage behaviors
  ✓ For the long-term behavior, the three creep phases generally observed on creep tests are considered
  ✓ Fatigue damage and healing have been also implemented
  ✓ Thermal coupling and hydrogen transport are considered

• Numerical simulation results
  • The deep cavern is more susceptible to mechanical stability problems.
  • The daily scenario is also more detrimental to the stability.
  • Even if damage occurs, the extent of damage zone is limited
  • the amount of gas leakage is also limited and both caverns lead to almost the same plume size because of diffusion which is preponderant.
  • Healing contributes to annihilate any significant damage evolution
Thank you for your attention!
Main assumptions of the model

- Rock salt is considered as an isotropic material
- Its elastic limit is very low - The initial yield strength is assumed to be a fraction of the peak strength criterion
- It has a **hardening deformation mechanism** and shows a more **ductile response** than most other rocks
- **Ductile behaviour**: increasing confining stress
- Significant dilatancy at low confining stresses - To define the dilatancy criterion
- we use the plastic potential: volumetric plastic strain \(\varepsilon^p_v\)
- if \(\varepsilon^p_v > 0\): we suppose that the material is in volumetric dilatancy

**Damage initialisation**: volumetric dilatation, due to microcracking, lead to a significant increase in the permeability of rock salt

- Damage initiation is characterised macroscopically by dilatancy
- The maximum achievable damage is reduced with increasing confining stress, because there is no volumetric dilatancy → ductile behaviour
- Based on continuum of damage mechanics - CDM, an **isotropic damage** variable is considered, in first approximation, which modifies the elasticity and strength parameters
Proposed elastoplastic damage model

Full model equations (compressive stresses are negative and $\sigma_1 \leq \sigma_2 \leq \sigma_3$)

**M-C yield surface:**

$$f_p = q + p M_p - N_p$$

$$M_p = \eta^p (\gamma_p) \left( \frac{\sin \phi}{\left( \frac{\cos \theta}{\sqrt{3}} - \frac{1}{3} \sin \theta \sin \phi \right)} \right) ; \quad N_p = \eta^p (\gamma_p) \left( \frac{(1 - d) c_i \cos \phi}{\left( \frac{\cos \theta}{\sqrt{3}} - \frac{1}{3} \sin \theta \sin \phi \right)} \right)$$

**Hardening variable:**

$$\eta^p (\gamma_p) = \left\{ \eta_o^p + \left( 1 - \eta_o^p \right) \frac{\gamma_p}{\alpha^p + \gamma_p} \right\}$$

(Chiarelli et al. 2003, Zhou et al. 2011)

**Plastic potential:**

$$g = q + \beta (\gamma_p) p$$

(Chiarelli et al. 2003, Souley et al. 2017)

$$\beta (\gamma_p) = \begin{cases} \beta_m - (\beta_m - \beta_0) \exp (-b_\beta \gamma_p) & ; \quad \gamma_p < \gamma_{ult} \\ \beta_{ult} \exp \left( 1 - \frac{\gamma_p}{\gamma_{ult}} \right) & ; \quad \gamma_p \geq \gamma_{ult} \end{cases}$$

$$\beta_m = \beta_{m0} \exp (a_d \sigma_3)$$
Rock salt behaviour in long-term

\[ \varepsilon_{ij}^c = \left( \frac{1}{\bar{\eta}_k^*} (q^* - \bar{G}_k^* \varepsilon_{tr}) + A_N \left( \frac{q^*}{\sigma_{ref}} \right)^{n_N} \right) \frac{3}{2} s_{ij} \]

\[ \bar{G}_k^* = G_k \exp(k_1 q^*) \]

\[ \bar{\eta}_k^* = \eta_k \exp(k_2 q^*) \]

**Transient creep**
(Kelvin-Voigt model)

**Steady-state creep**
(Norton law)

**Tertiary creep**
(Hou et al. 2003)

\[ \dot{d}_t = A_T \left( \frac{f_{ds}}{\sigma_{ref}} \right)^{n_T} \]

Parameters: \( G_k, k_1, \eta_k \) and \( k_2 \)
(Heussermann et al. 2003)

Parameters: \( A_N \) and \( n_N \)

\[ q^* = \frac{q}{1 - d_t} \]

\( q^* \): Mises stress undamaged
\( q \): Mises stress damaged

Damage is activated and increases if the damage limit (dilatance criterion) is exceeded

**Numerical uniaxial creep test**

![Numerical uniaxial creep test diagram](image)
Full model equations

(compressive stresses are negative and $\sigma_1 \leq \sigma_2 \leq \sigma_3$)

**Damage:**

$$f_d = d_{\text{max}} \{1 - \exp(-b_d (Y_d - Y_0))\} - d \leq 0$$

$$Y_d = \sqrt{\langle\epsilon\rangle: \langle\epsilon\rangle}$$

(Mazars 1984)

$Y_0$ = value of $Y_d$ at $\beta (\gamma_p^*) = 0 \Rightarrow f_{ds}$

$$d_{\text{max}} = d_{\text{max}}^0 \exp(a_d \sigma_3)$$

$a_d$: parameter describing the effect of confining stress

$d_{\text{max}}$ decreases from its maximum value due to confinement effect

**Dilatance criterion**

$$\beta (\gamma_p^*) = 0; \quad \gamma_p^* = -\frac{1}{b_\beta} \ln \left( \frac{\beta_m}{\beta_m - \beta_0} \right) \quad \Rightarrow \eta^p (\gamma_p^*)$$

$$f_{ds} = q + p M_{ds} - N_{ds}$$

$$M_{ds} = \eta^p (\gamma_p^*) \frac{\sin \phi}{\cos \theta - \frac{1}{3} \sin \theta \sin \phi}$$

$$N_{ds} = \eta^p (\gamma_p^*) \frac{c_i \cos \phi}{\cos \theta - \frac{1}{3} \sin \theta \sin \phi}$$

**Parameters:**

$E, \nu$
$c_i, \phi, \eta_0^p, \alpha^p, \beta_0, \beta_m, b_\beta, d_{\text{max}}^0, b_d, a_d$

Thorel 1994: $c_i, \phi, d_{\text{max}}^0, b_d, a_d$
Dragan et al. 2021: $E, \nu, \beta_0, \beta_m, b_\beta$
Numerical verification of triaxial tests

Short-term parameters values used

![Graphs showing experimental and numerical deviatoric stress and volumetric strain curves compared to theoretical criteria.](image)