KEM01
SAFE OPERATIONAL BANDWIDTH OF GAS STORAGE RESERVOIRS


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Project aims

Project structure

Literature review (WP1)
  - in The Netherlands
  - in Italy

Model set-up (WP2)

Sensitivity & Scenarios (WP3-WP5-WP6)

Outcome analysis (WP4-WP7)
  - comparing
  - ranking
  - guidelines for safe operational bandwidths

Ongoing and planned research on the topic addressed by KEM01
Project Aims

INVESTIGATE:

- the geomechanical hazards and risks associated with gas storage in Underground Gas Storage (UGS) reservoirs
- how possible drivers of fault reactivation can combine in UGS to increase the hazard of (significant) seismic events and/or even induced "un-expected" (micro-) seismicity

“EXPECTED” INDUCED SEISMICITY

- primary production (PP) with large pressure drop
- fluid injection (CO₂ sequestration, waste water disposal, fracking) with significant pressure increase

“UN-EXPECTED” INDUCED SEISMICITY

- when the pressure is within a range already experienced (UGS with p<p<sub>initial</sub>)
PHASE 1:

- **WP1** – Bibliographic review: inventory of possible mechanisms of fault reactivation induced by fluid injection/production in UGS

- **WP2** – Conceptual model and definition of the potential driving mechanisms (simplified representative geological setting of Dutch UGS)

- **WP3** – Modelling scenarios and mechanisms of fault reactivation proposed in WP2 investigated using M3E_GEPS3D

- **WP4** – Analysis of modelling results: (i) ranking the simulated scenarios (ii) weighting the critical factors

PHASE 2 (Phase 1 follow-up):

- **WP5** – Testing the proposed updates. The effect of the various modifications has been tested and the updated “reference” scenario has been defined

- **WP6** – Modelling scenarios. The scenarios investigated in WP3 have been re-evaluated taking into account the pressure change within the faults and the updated features of the salt caprock. A few more combined mechanisms have been investigated

- **WP7** – Final report. Based on the previous outcomes, in particular the numerical results provided in WP3, WP5 and WP6, the report aims at providing a few general rules to define a “safe operational bandwidth of gas storage reservoirs”
<table>
<thead>
<tr>
<th>RESERVOIR LOCATION</th>
<th>TYPE</th>
<th>STAGE</th>
<th>ACTIVATED FAULT GEOMETRY</th>
<th>DEPTH below reservoir</th>
<th>MAGNITUDE ≤1</th>
<th>1 - 3</th>
<th>≥3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norg</td>
<td>The Netherlands</td>
<td>UGS</td>
<td>PP; UGS, slip motion on a sub-vertical NW-SE fault (PP) and a sub-vertical compressive SW-NE fault (UGS)</td>
<td>x</td>
<td></td>
<td>x (2)</td>
<td></td>
</tr>
<tr>
<td>Grijpskerk</td>
<td>The Netherlands</td>
<td>UGS</td>
<td>large uncertainty to locate active faults</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bergermeer</td>
<td>The Netherlands</td>
<td>UGS</td>
<td>PP; CG; UGS, strike: SSW; dip: 60-65</td>
<td>x</td>
<td>x (1 - CG)</td>
<td></td>
<td>x (4 - PP)</td>
</tr>
<tr>
<td>Duvernay Formation</td>
<td>Canada</td>
<td>HF</td>
<td>PT, strike-slip motion on subvertical, ~S/E-W oriented faults</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x (4.1)</td>
</tr>
<tr>
<td>Castor</td>
<td>Spain</td>
<td>UGS</td>
<td>PT, secondary fault was activated during the 2013 earthquake sequence instead of the Amposta fault</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x (4.3)</td>
</tr>
</tbody>
</table>

Inventory of induced seismicity cases according to reservoir development stage, event focal mechanism and magnitude, and hypocenter location with respect to the developed formation and the fault geometry. PP=primary production; UGS=underground gas storage; CG=cushion gas; PT=post-treatment; HF=hydraulic fracturing
<table>
<thead>
<tr>
<th>RESERVOIR</th>
<th>LOCATION</th>
<th>TYPE</th>
<th>STRESS REGIME</th>
<th>SEISMIC NETWORK</th>
<th>RESERVOIR INFO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norg</td>
<td>The Netherlands</td>
<td>UGS</td>
<td>( \sigma_v = 25 \text{ Mpa}; \sigma_h \text{_{min}} = 9 \text{ Mpa (effective stress)} )</td>
<td>micro-seismic network in deep wells</td>
<td>primary production started in 1983 until 1995 with a max DP of about 117 bar; UGS started in 1995-1997 with a DP for cycle of about 57 bar</td>
</tr>
<tr>
<td>Grijskerk</td>
<td>The Netherlands</td>
<td>UGS</td>
<td>( \sigma_v = 25 \text{ Mpa}; \sigma_h \text{_{min}} = 9 \text{ Mpa (effective stress)} )</td>
<td>micro-seismic network in deep wells</td>
<td>primary production started in 1993 until 1994 with a max DP of about 53 bar; UGS started in 1997 with a DP for cycle of about 127 bar</td>
</tr>
<tr>
<td>Bergermeer</td>
<td>The Netherlands</td>
<td>UGS</td>
<td>( \sigma_v = 25 \text{ Mpa}; \sigma_h \text{_{min}} = 9 \text{ Mpa (effective stress)} )</td>
<td>down-hole micro-seismic network</td>
<td>primary production started in 1971 until 2006 with a max DP of about 213 bar; no activity between 2007 and 2010; cushion gas injection between 2010 and 2012; UGS started in 2013</td>
</tr>
<tr>
<td>Duvernay Formation</td>
<td>Canada</td>
<td>HF</td>
<td>strike-slip regime, oriented at (-45^\circ)</td>
<td>regional &amp; local networks</td>
<td>average mean injection pressure = 62.5 Mpa</td>
</tr>
<tr>
<td>Castor</td>
<td>Spain</td>
<td>UGS</td>
<td>graben structure with two families of active faults; the maximum horizontal stress equal to the vertical stress and points to the NE; the minimum horizontal stress equal to (0.7 \times \text{vertical stress})</td>
<td>Spanish National Network</td>
<td>initial reservoir pressure = 190 bar; max Dp during primary production = 5 bar. During the injection period the maximum pressure increase observed in the Castor field was 7.6 bar above the initial formation pressure</td>
</tr>
</tbody>
</table>
four blocks separated by minor non-sealing faults

the virgin average pressure in Block no. 2 was 327 bar, with a minimum value around 190 bar recorded in 1995

the first seismic event occurred in 1993 during the primary production, while the second one was recorded in 1999 soon after the beginning of the UGS operations

gradient for the vertical stress is estimated at 2.16 bar/10 m, the minimum / maximum horizontal stress at 1.63 bar/10 m and 1.92 bar/10 m

Pressure evolution in time at the Norg UGS field. The location of the two seismic events in 1993 and 199 are reported
two seismic events have been detected, the first in 1997 (M=1.3) and the second in 2015 (M=1.5)

both events occurred during the production phase at an average pressure of about 280 bar and at a flow rate of 9 million m³/day

large uncertainties associated with the hypocenter location

Pressure evolution in time at the Grijpskerk UGS field. The location of the two seismic events in 1997 and 2015 are reported
The gas field consists of two reservoir blocks, which are intersected by a partially sealing Central fault.

4 seismic events have been detected in 1994 and 2001 during primary production phase. The events are of magnitude in the range 3.0-3.5 and located at the tip of the central fault.

during injection of cushion gas some small seismic events were detected with a largest magnitude of M=0.7 recorded in 2013.

during annual cycles of gas injection and production, the Central fault is not critically stressed and the predicted stress changes lie in the elastic region. The fault slip is deemed to be unlikely.

Map of the Bergermeer UGS field. The location of the seismic events from 1994 and 2013 are reported.
WP1 – A UGS case study in Italy

Depth of the reservoir top

Seismic section

Can UGS activities be responsible for the recorded seismicity?

Micro-seismicity recorded by the local micro-seismic borehole network in the area surrounding the Emilia field from 1979 to July 2013
Axonometric view of the 3D mesh. The vertical exaggeration is 5

354,611 nodes
2,154,316 FEs
26,274 IEs

(a) Axonometric detail and (b) vertical southwest-northeast cross-section of the 3D FE-IE model of the Emilia gas field showing different portions of the geologic system.

Grid plane view. The trace of the field (in red) and the faults (in green) confining northward and crossing the reservoir and the waterdrive are highlighted.

WP1 – A UGS case study in Italy
Average pore pressure behavior in the A layer

(a) Pore pressure decline (bars) in level A at the end of the field production life (1971) and (b) pore pressure increase during a UGS injection cycle from April to November 2006
(a) Vertical and (b) west-east horizontal displacements (mm) as measured by PSInSAR above the Emilia field from 11/2004 to 04/2005. Match of the simulated (c) vertical and (d) horizontal movement with the satellite displacement.

**Basin-scale constitutive relationship (anisotropy):**

\[ c_M = 0.01241 \sigma_z^{-1.1342} \]

from RMT (virgin loading condition)

\[ \sigma_z^* = 0.12218 |z|^{1.0766} \]

from density logs

\[
\begin{align*}
\beta & \quad v_h & \quad v_z & \quad \gamma & \quad s \\
3.0 & 0.15 & 0.25 & 1.0 & 5.0
\end{align*}
\]

\[ \beta = \frac{E_h}{E_z} \quad \gamma = \frac{G_h}{G_z} \quad s = \frac{c_M}{c_{MH}} \]

from calibration (PSInSAR)
Land subsidence (cm) at the end the Emilia field production life (1971) as predicted by the FE-IE model

Normal stress variations (bar) in level A and in a vertical cross-section through the top of the Emilia gas field along (a) the west-east ($\Delta \sigma_x$), (b) north-south ($\Delta \sigma_y$), and (c) vertical ($\Delta \sigma_z$) directions in 1971, i.e. at the end of the field production life
Scenario A
- cohesion $c = 10$ bar on the fault surface;
- friction angle = 30°;
- initial stress regime: compressive regime $\sigma_{h1} = \sigma_v v_h / (1 - \nu_z) = 0.3 \sigma_v$
  $\sigma_{h2} = (\sigma_v + \sigma_{h1})/2 = 0.65 \sigma_v$
- $c = 0$ bar;
- friction angle = 30°;
- initial stress regime: normal regime, $\sigma_{h1} = \sigma_{h2} = \sigma_v v_h / (1 - \nu_z) = 0.3 \sigma_v$

Scenario B
- friction angle = 30°;
- initial stress regime: normal regime, $\sigma_{h1} = \sigma_{h2} = \sigma_v v_h / (1 - \nu_z) = 0.3 \sigma_v$
- $c = 0$ bar;
- friction angle = 30°;
- initial stress regime: compressive regime

(a) Direction of the maximum horizontal stress in the horizontal plane $\sigma_{h2}$. (b) Initial normal and tangential stress and potential stress drop on the faults with scenario A
WP1 – A UGS case study in Italy

Perspective view on the fault discretization with the cumulative slip between 1959 and 1971, i.e. during the primary production life of the Emilia reservoir, as computed by the IE solution in (a) scenario A and (b) scenario (B). Vertical exaggeration is 5.

Area A, and average ($s_a$) and maximal ($s_{max}$) yearly slip of the activated portion of the faults during the primary development of the Emilia reservoir for the three scenarios addressed by the study.

activation at the reservoir depth only
WP2 - Model set-up

Norg: sketch of the main faults

Bergermeer: sketch of the main faults

Representative geometrical configuration
WP2 - Modelling Approach

Mohr-Coulomb Failure criterion:

\[ \tau_L = c - \sigma_n \tan \phi \]

TOP - BOTTOM IE displacements \([u^{T,B} ; v^{T,B}]\)

\[ \delta = S u \]

fault opening \(\delta_n\)

slippage \(\delta_s\)

interface normal stress \(\sigma_n\)

shear stress \(\tau_s\)

Perspective view of possible IE elements in a 3D setting

Sealing or non-sealing faults

Perspective view of possible IE elements in a 3D setting

\[ Pf \neq 0 \]
FE – IE mesh (253'165 nodes, 236'208 FEs, 5215 IEs)
Pore pressure change in the reservoir compartments 1 and 2

Mohr-Coulomb criterion with a criticality index $\chi$

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>RANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3 dip</td>
<td>90°</td>
<td>+65° – -65°</td>
</tr>
<tr>
<td>Dislocation</td>
<td>0 m</td>
<td>100 – 200 m</td>
</tr>
<tr>
<td>$\theta$</td>
<td>0°</td>
<td>90°</td>
</tr>
<tr>
<td>$M_1$</td>
<td>0.74</td>
<td>0.42</td>
</tr>
<tr>
<td>$M_2$</td>
<td>0.83</td>
<td>0.45</td>
</tr>
<tr>
<td>Cohesion</td>
<td>20 bar</td>
<td>0 – 10 – 100 m bar</td>
</tr>
<tr>
<td>Static friction angle</td>
<td>30°</td>
<td>10° – 20° + weakening</td>
</tr>
<tr>
<td>$E_{\text{reservoir}}$</td>
<td>11 GPa</td>
<td>8 – 20 GPa</td>
</tr>
<tr>
<td>$E_{\text{Zechstein &lt; 1800 m}}$</td>
<td>20 GPa</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{Zechstein &gt; 1800 m}}$</td>
<td>35 GPa</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{overburden}}$</td>
<td>10 GPa</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{underburden}}$</td>
<td>30 GPa</td>
<td></td>
</tr>
<tr>
<td>Zechstein</td>
<td>linear elastic</td>
<td>viscous (Maxwell $\mu = 10^{17}$ Pa·s)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.86</td>
<td>1.0</td>
</tr>
<tr>
<td>$\nu_{\text{reservoir}}$</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\text{Zechstein}}$</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\text{overburden}}$</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>$\nu_{\text{underburden}}$</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Pf</td>
<td>average between $\Delta P$ at the two sides of the fault</td>
<td>sealing Pf=0</td>
</tr>
</tbody>
</table>

Model parametrization for the “reference” and the investigated ranges
SIMULATED SCENARIOS

1) sensitivity to $\Delta P_f$ ($=0 \rightarrow$ sealing ; $0.5(\Delta P_1 + \Delta P_2)$)
2) sensitivity to Biot's coefficient (1.0 instead of the actual value);
3) sensitivity to reservoir and fault geometry (F3 dip angles $+65^\circ$ and $-65^\circ$, offset equal to 100 m and 200 m);
4) sensitivity to initial stress regime ($\theta=90^\circ$; $M_1 = 0.40$ and $M_2 = 0.47$);
5) sensitivity to fault Mohr-Coulomb parameters ($c=0$ bar; $\varphi_s=20^\circ$; $\varphi_d=10^\circ$ and $d_c=2$ mm; $\varphi_d=20^\circ$ and $d_c=20$ mm);
6) sensitivity to reservoir stiffness ($E=8$ bar; $E=20$ bar);
7) sensitivity to the differential pore pressure in the reservoir compartments ($\Delta P_1=-100$ bar and $\Delta P_2=0$ bar; $\Delta P_1=-100$ bar and $\Delta P_2=-200$ bar);
8) sensitivity to caprock rheology (viscous instead of elastic).

+ COMBINATIONS (of previous simulated scenarios)
FAULT F3 GEOMETRY

a) dip angle = $+65^\circ$
b) dip angle = $-65^\circ$
c) dislocation = 100 m
d) dislocation = 200 m

Maximum elemental value of $\chi$: comparison with the reference case
Scenario d: $|\tau|$ and (node-based) $\chi$ at the end of primary production
Fault activation during PP leads to a stress redistribution and a new (deformed) "equilibrated" configuration that is newly loaded, in the opposite direction, when the pressure variation changes the sign.

(a) Distribution of the shear stress $\tau$ for a few representative loading steps on fault F2 (dip = 10°).

(b) Time behavior of $\tau$ for the nodes shown in (a) located at the top (T), center (C), and bottom (B) of the reservoir.

(c) Sketches representing the reservoir deformation, shear stress direction, and inactive/active portions of the fault at the loading steps shown in (a).
Scenarios a-d: maximum sliding $\delta_{\text{max}}$ versus time
MOHR-COULOMB PARAMETERS

a) \( c = 0 \) bar
b) \( \varphi_s = 20^\circ \)
c) \( \varphi_d = 10^\circ \) and \( d_c = 2 \) mm
d) \( \varphi_d = 20^\circ \) and \( d_c = 20 \) mm

Maximum elemental value of \( \chi \): zoom over CG and UGS

Maximum elemental value of \( \chi \): comparison with the reference case
Stress path $|\tau|$ vs $\sigma$ for the F2 fault node 2665. The red line represents the yield bound and the numbers the various loading steps. Different colours are used for primary production (PP, loading steps #1 – 10), cushion gas (CG, loading steps #11 – 12), and underground gas storage (UGS, loading steps #12.1 – 13).

$\phi_s = 30^\circ$

$\phi_s = 20^\circ$

$\phi_d = 10^\circ$, $d_c = 2$ mm

Location of the node used to represent the stress path
MOST CRITICAL COMBINATION

- static friction angle = 20°;
- F3 dip angle = +65°;
- viscous caprock;
- compartment offset = 100 m
- other parameters: reference case

Maximum elemental value of $\chi$: comparison with the reference case
WP3-WP5-WP6 - Sensitivity & Scenarios

**Maximum sliding $\delta_{\text{max}}$ versus time**

**Stress path $|\tau|$ vs $\sigma$ for the F2 fault node 1920**
$t_{80}$ time behaviors obtained for fault F3 for scenarios with asymmetry in the geological setting and/or stress driving forces
Scenarios are ranked following these nested criteria:

- (a) element-based $\chi_{\text{max}}$ during UGS; or
- (b) $\chi^* = \sum_{\text{element}} (t_e \cdot \chi | \chi > 0.8)$ normalized over $\max(\chi^*)$|scenarios where $t_e$ is the element thickness (more generally the element area if a non-regular discretization is used);

- maximum value of average sliding ($\delta_{\text{avg}}$), evaluated on active elements only;

- loading step of activation.

### BOUNDING FAULT

<table>
<thead>
<tr>
<th>Scenario #</th>
<th>Parameter / Mechanism</th>
<th>$\chi_{\text{max}}$ UGS</th>
<th>Maximum $\delta_{\text{avg}}$</th>
<th>Activation L.S.</th>
<th>$\chi^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5c</td>
<td>$\phi_d = 10^\circ$; $d = 2$ mm</td>
<td>1.00</td>
<td>0.026</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>7b</td>
<td>$\Delta P1 = -100$ bar; $\Delta P2 = -200$ bar</td>
<td>0.97</td>
<td>0.010</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>3b</td>
<td>$d = 100$ m</td>
<td>0.96</td>
<td>0.018</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>5b</td>
<td>$\phi_d = 20^\circ$</td>
<td>0.84</td>
<td>0.008</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>3c</td>
<td>$d = 100$ m</td>
<td>0.81</td>
<td>0.010</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>6a</td>
<td>$E = 8$ GPa</td>
<td>0.80</td>
<td>0.007</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>5a</td>
<td>$c = 0$ bar</td>
<td>0.79</td>
<td>0.010</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>5b</td>
<td>$\phi_s = 20^\circ$</td>
<td>0.78</td>
<td>0.008</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>4b</td>
<td>$M1-M2$ lower</td>
<td>0.78</td>
<td>0.007</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>7a</td>
<td>$\Delta P1 = -100$ bar; $\Delta P2 = 0$ bar</td>
<td>0.78</td>
<td>0.007</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>UGS $\Delta P1 = \Delta P2 = -150$ bar</td>
<td>0.78</td>
<td>0.007</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>3a/b</td>
<td>$F3$ dip = $65^\circ$</td>
<td>0.77</td>
<td>0.007</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Biot = 1.0</td>
<td>0.76</td>
<td>0.008</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>4a</td>
<td>$\phi_s = 20^\circ$</td>
<td>0.74</td>
<td>0.007</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>viscous salt caprock</td>
<td>0.70</td>
<td>0.009</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>5d</td>
<td>$\phi_d = 20^\circ$; $d = 20$ mm</td>
<td>0.70</td>
<td>0.009</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>6b</td>
<td>$E = 20$ GPa</td>
<td>0.78</td>
<td>0.005</td>
<td>-</td>
<td>0.79</td>
</tr>
</tbody>
</table>
### WP4-WP7 - Ranking scenarios

#### Scenario # | Parameter / Mechanism | $\chi_{\max}$ UGS | Maximum $\delta_{reg}$ | Activation L.S. | $\chi_{max}$
--- | --- | --- | --- | --- | ---
3d | disl = 200 m | 0.84 | 0.033 | 7 | -
3c | disl = 100 m | 0.81 | 0.007 | - | 0.85
7a | $\Delta P_1 = -100$ bar; $\Delta P_2 = 0$ bar | 0.53 | 0.000 | - | 0.53
7b | $\Delta P_1 = -100$ bar; $\Delta P_2 = -200$ bar | 0.53 | 0.000 | - | 0.53
3a/b | F3 dip = 65° | 0.32 | 0.000 | - | 0.46
2 | Biot | 0.00 | 0.000 | - | 0.00
4a | theta = 90° | 0.00 | 0.000 | - | 0.00
4b | M1-M2 lower | 0.00 | 0.000 | - | 0.00
5a | c = 0 bar | 0.00 | 0.000 | - | 0.00
5b | $\phi_{s} = 20^\circ$ | 0.00 | 0.000 | - | 0.00
5c | $\phi_{s} = 10^\circ$; $d_1 = 2$ mm | 0.00 | 0.000 | - | 0.00
5d | $\phi_{s} = 20^\circ$; $d_1 = 20$ mm | 0.00 | 0.000 | - | 0.00
6a | $E = 8$ GPa | 0.00 | 0.000 | - | 0.00
6b | $E = 20$ GPa | 0.00 | 0.000 | - | 0.00
8 | UGS $\Delta P_1 = \Delta P_2 = -150$ bar (mech 04) | 0.00 | 0.000 | - | 0.00
9 | salt caprock | 0.00 | 0.000 | - | 0.00

#### INTRA-RESEVOIR FAULT

**Faults bounding the reservoir**

During UGS the stability is manly jeopardized by:

- an initial stress regime with small horizontal principal components,
- failure criterion with **low friction angle**,
- large pressure change because of production/injection,
- significant **contrast** between the reservoir and the over- side- and underburden stiffness.

**Intra-reservoir faults**

During UGS the stability is manly jeopardized by:

- dislocation of the reservoir compartments,
- different pressure change in the two compartments,
- fault dip.
The numerous scenarios investigated within the study have clearly revealed that fault reactivation can occur during CG and UGS, more likely if:

i) seismicity has been recorded during PP and
ii) when the reservoir pressure is approaching or reaches \( P_{\text{max,CG}} \), \( P_{\text{max,UGS}} \), and \( P_{\text{min,UGS}} \).

A few qualitative guidelines have been produced to bound \( P_{\text{max,CG}} \), \( P_{\text{max,UGS}} \), and \( P_{\text{min,UGS}} \) depending on \( P_{\text{seis,PP}} \) and \( P_{\text{min,PP}} \).
If seismicity has been recorded during PP, $P_{\text{max,CG}}$ and $P_{\text{max,UGS}}$ must be smaller than $P_i$; a rough rule could be to keep the pressure recovery smaller than:

$$\min[\theta |P_i-P_{\text{seis,PP}}| ; |P_i-P_{\min,PP}|] , \ 1 \leq \theta \leq 2$$

If seismicity has been recorded during PP, $P_{\text{min,UGS}}$ must be larger than $P_{\min,PP}$; a rough rule could be to keep $P_{\text{min,UGS}}$ larger than the reservoir pressure at the time of seismic occurrence;

If seismicity has been recorded during PP, avoid during CG and UGS to cause a pressure change between various reservoir compartments larger than that at the time of seismic occurrence;

If no seismicity has been recorded during PP, $P_{\text{max,CG}}$ can safely be equal to $P_i$;

If no seismicity has been recorded during PP and CG, UGS pressure change can safely span the whole pressure change between $P_i$ and $P_{\min,PP}$.
SEISMIC DATA ASSIMILATION IN GEOMECHANICAL MODELING

- Sensitivity analysis via Sobol’ indices
- Bayesian update of FE-IE geomechanical model (MCMC)
- Forward full model is approximate via surrogate solution (generalized polynomial chaos expansion)
- Assimilation of seismic moment $M_0$
- $N = 5000$ realizations
- Effective constrain of parameters $\tau_0$ and $M_2$

Sensitivity analysis via Sobol’ indices

Prior and POSTERIOR cumulative DISTRIBUTIONS of $\tau_0$, $\phi$, $M_2$

Surrogate vs forward model outcomes
MODEL APPROXIMATIONS BY ML TECHNIQUES

- **Gradient boosting tree**: machine learning technique, an ensemble-based tree method
- Investigations of the relationship between a set of input combinations and output space
- Application to ground ruptures due to the excessive groundwater pumping
- Analysis of relative importance of geometry, compressibility, pore pressure

Sequential evolution of fissure for the 5th, 8th and 10th loading steps

Sequential evolution of dimensionless horizontal stress for the 5th, 8th and 10th loading steps

Individual conditional expectation for the aquifer $C_m$
COUPLED MODEL OF CONTACT MECHANICS AND FLUID FLOW: PENNY-SHAPED CRACK

Sketch and mesh used in the analytical 3D example with flow

Comparison in terms of opening (w), pressure (p) and fracture radius (R)
IMPROVING THE CODE NUMERICS FOR COMPLEX REAL APPLICATIONS

**HI24L**: complex real-world case with **32 faults** intersecting in various ways, discretized with more than **5M elements**. It is located in the Gulf of Mexico, offshore the Texas coastline.

*Views of the normal component of the traction field on the fracture surfaces*

*FE – IE mesh*
STORING GREEN ENERGY UNDERGROUND: H2 POTENTIAL IN ITALY

S1. Criteria for identification of possible geologic structures for UHS

S2. Identification and characterization of reservoirs in Italy most promising for UHS

S3. H2 fate in subsurface reservoirs

S4. Hazards related to UHS

S5. H2 – subsurface environment interactions

S6. Guidelines on incentives strategies needed to make UHS competitive

S7. UHS risk perception and social aspects

- Relationships linking the change of geomechanical properties to chemical H2-CH4-rock interactions and microbial activity will be implemented in GEPD3D to quantify the effects of these processes on the mechanical safety of UHS;

- Investigation of parameter-related model uncertainties via Sobol' indices in a generalized Polynomial Chaos Expansion (gPCE) framework. Application to outcomes of GEPS3D with quasi-static seismological relationships (Zoccarato et al, 2019);
Thank you for the attention

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