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SAFE OPERATIONAL BANDWIDTH OF GAS STORAGE RESERVOIRS
WP4 - FINAL REPORT

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1. Introduction

The project “Safe operational bandwidth of gas storage reservoirs” is aimed at investigating the geomechanical hazards and risks associated with gas storage in Underground Gas Storage (UGS) reservoirs. In particular, the aim of the research activities is to investigate 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.

The report summarizes the main achievements obtained by the whole study. The outcomes of the various scenarios performed in WP3 have been processed with the aim of:

- ranking the simulated scenarios in relation to their possibility of inducing unexpected seismic events during cushion gas injection and UGS cycles;
- weighting the critical factors (drivers / settings) influencing fault activation during UGS cycles; i.e., understanding which are the mechanisms most prone to cause unexpected seismic events during UGS activities;
- developing guidelines for safe operational bandwidths based on the outcome of the points above and proposing ideas to improve monitoring, modelling, and mitigation strategies.

If the first three issues are presented with a certain detail, the analyses carried out until allow only anticipating a few preliminary notes concerning the last item.

2. Ranking scenarios

A first task concerns the possibility of ranking the mechanisms, geological settings, geomechanical and production parameters in relation to their potentiality of inducing “unexpected” seismic events. The sensitivity scenarios and the various mechanisms have been ranked following these nested criteria:

1. Loading step of activation;
2. Maximum value of average sliding (δ_{avg}), evaluated on active elements only;
3. (a) χ_{max} during UGS; or (b) $\chi^* = \sum_{\text{element}}(t_e \cdot \chi|_{\chi>0.8})$ normalized over $\max(\chi^*)|_{\text{scenarios}}$ where t_e is the element thickness (more generally the element area if a non-regular discretization is used).

The analysis has been carried for the central fault F3, which is the most stressed in realistic conditions, and fault F2 that is representative of the discontinuities bounding the reservoir. Notice that fault F3 is inactive in some of the investigated scenarios because of symmetry in the geological setting and stress driving forces. The results of the two ranking procedures are reported in Table 1 and Table 2 for faults F2, and in Table 3 and Table 4 for fault F3. A classification has been also carried for the three combination scenarios, see Table 5 and Table 6.

The modelling study reveals that seismicity may occur unexpectedly during cushion gas (CG) and UGS phase, following more expected seismicity during primary production (PP). Generally, scenarios more prone to activation during PP are also the most critical ones during GC and UGS.

During UGS, fault activation may be induced more often at the end of the injection phase (i.e., at $P=P_{initial}$) and, secondarily, at the end of the production phase (at P_{min}). Notice that during UGS/CG the fault activates on a portion of the element patch that already slides during PP. However, sliding in CG/UGS usually occurs in the opposite direction compared to PP, following reservoir expansion.

Table 1 Fault F2: ranking on the simulated scenarios from the most to the least prone to induce subsidence during CG and UGS phases using criterion 3(a)

Parameter / Mechanism	χ_{max}	activation L.S.	Maximum δ_{avg}	L.S. of maximum δ_{avg}	χ_{max} UGS	UGS - L.S. / δmax
M1-M2 lower	1	4	0.019	end CG	0.95	-
salt caprock	1	4	0.010	end PP	1.00	12.5/0.002
E = 8 GPa	1	5	0.013	end CG	0.95	-
c = 0 bar	1	5	0.011	end CG	0.95	-
φ_s = 20°	1	5	0.011	end CG	0.95	-
φ_d = 10° ; d_c = 2 mm	1	6	0.020	end CG	1.00	12.1/0.008 ; 12.5/0.001; 13.0/0.002
offset = 200 m	1	6	0.011	end CG	0.95	-
φ_d = 20° ; d_c = 20 mm	1	6	0.009	end PP-CG	0.92	-
E_{II}/E_I = 2.5	1	6	0.009	end PP	0.93	-
offset = 100 m	1	6	0.008	end PP	0.95	-
F3 dip = 65°	1	6	0.008	end PP	0.90	-
reference (Table 2)	1	6	0.008	end PP	0.89	-
ΔP1 = -100 bar; ΔP2 = 0 bar	1	6	0.008	end PP	0.89	-
ΔP1 = -100 bar; ΔP2 = -200 bar	1	6	0.008	end PP	0.89	-
UGS ΔP1 = ΔP2 = -150 bar (mech 04)	1	6	0.008	end PP	0.89	-
uneven UGS pressure (mech 02)	1	6	0.008	end PP	0.86	-
theta = 90°	1	6	0.007	end PP	0.75	-
reference_PF	1	8	0.006	end PP	0.67	-
E = 20 GPa	1	8	0.003	end PP	0.52	-
c = 100 bar	1	10	0.004	end PP	0.53	-

Table 2 Fault F2: ranking on the simulated scenarios from the most to the least prone to induce subsidence during CG and UGS phases using criterion 3(b)

Parameter / Mechanism	χ_{max}	activation L.S.	Maximum δ_{avg}	L.S. of maximum δ_{avg}	χ_*
M1-M2 lower	1	4	0.019	end CG	0.67
salt caprock	1	4	0.010	end PP	0.55
E = 8 GPa	1	5	0.013	end CG	0.33
c = 0 bar	1	5	0.011	end CG	0.33
φ_s = 20°	1	5	0.011	end CG	0.67
φ_d = 10° ; d_c = 2 mm	1	6	0.020	end CG	1.00
offset = 200 m	1	6	0.011	end CG	0.33
φ_d = 20° ; d_c = 20 mm	1	6	0.009	end PP-CG	0.31
E_{II}/E_I = 2.5	1	6	0.009	end PP	0.33
offset = 100 m	1	6	0.008	end PP	0.33
ΔP1 = -100 bar; ΔP2 = -200 bar	1	6	0.008	end PP	0.67
F3 dip = 65°	1	6	0.008	end PP	0.32
reference (Table 2)	1	6	0.008	end PP	0.31
ΔP1 = -100 bar; ΔP2 = 0 bar	1	6	0.008	end PP	0.31
UGS ΔP1 = ΔP2 = -150 bar (mech 04)	1	6	0.008	end PP	0.31
uneven UGS pressure (mech 02)	1	6	0.008	end PP	0.30
theta = 90°	1	6	0.007	end PP	0.00
reference_PF	1	8	0.006	end PP	0.00
E = 20 GPa	1	8	0.003	end PP	0.00
c = 100 bar	1	10	0.004	end PP	0.00

Table 3 Fault F3: ranking on the simulated scenarios from the most to the least prone to induce subsidence during CG and UGS phases using criterion 3(a)

Parameter / Mechanism	χ_{max}	activation L.S.	Maximum δ_{avg}	L.S. of maximum δ_{avg}	χ_{max} UGS
offset = 200 m	1	3	0.080	end CG	0.95
offset = 100 m	1	5	0.038	end CG	0.95
M1-M2 lower	1	9	fault opening	-	0.00
F3 dip = 65°	1	10	0.016	end PP	0.58
ΔP1 = -100 bar; ΔP2 = -200 bar	0.92	-	0.000	-	0.92
ΔP1 = -100 bar; ΔP2 = 0 bar	0.59	-	0.000	-	0.59
uneven UGS pressure (mech 02)	0.08	-	0.000	-	0.08
reference (Table 2)	0	-	0.000	-	0.00
salt caprock	0	-	0.000	-	0.00
E = 8 GPa	0	-	0.000	-	0.00
c = 0 bar	0	-	0.000	-	0.00
φ_s = 20°	0	-	0.000	-	0.00
φ_d = 10° ; d_c = 2 mm	0	-	0.000	-	0.00
φ_d = 20° ; d_c = 20 mm	0	-	0.000	-	0.00
E_{II}/E_I = 2.5	0	-	0.000	-	0.00
UGS ΔP1 = ΔP2 = -150 bar (mech 04)	0	-	0.000	-	0.00
theta = 90°	0	-	0.000	-	0.00
E = 20 GPa	0	-	0.000	-	0.00
c = 100 bar	0	-	0.000	-	0.00
reference_PF	0	-	0.000	-	0.00

Table 4 Fault F3: ranking on the simulated scenarios from the most to the least prone to induce subsidence during CG and UGS phases using criterion 3(b)

Parameter / Mechanism	χ_{max}	**activation L.S.**	**Maximum δ_{avg}**	**L.S. of maximum δ_{avg}**	χ_*
offset = 200 m	1	3	0.080	end CG	0.95
offset = 100 m	1	5	0.038	end CG	1.00
M1-M2 lower	1	9	fault opening	-	0.00
F3 dip = 65°	1	10	0.016	end PP	0.00
ΔP1 = -100 bar; ΔP2 = -200 bar	0.92	-	0.000	-	0.97
ΔP1 = -100 bar; ΔP2 = 0 bar	0.59	-	0.000	-	0.00
uneven UGS pressure (mech 02)	0.08	-	0.000	-	0.00
reference (Table 2)	0	-	0.000	-	0.00
salt caprock	0	-	0.000	-	0.00
E = 8 GPa	0	-	0.000	-	0.00
c = 0 bar	0	-	0.000	-	0.00
φ_s = 20°	0	-	0.000	-	0.00
φ_d = 10° ; d_c = 2 mm	0	-	0.000	-	0.00
φ_d = 20° ; d_c = 20 mm	0	-	0.000	-	0.00
E_{II}/E_I = 2.5	0	-	0.000	-	0.00
UGS ΔP1 = ΔP2 = -150 bar (mech 04)	0	-	0.000	-	0.00
theta = 90°	0	-	0.000	-	0.00
E = 20 GPa	0	-	0.000	-	0.00
c = 100 bar	0	-	0.000	-	0.00
reference_PF	0	-	0.000	-	0.00

Table 5 Faults F2 and F3: ranking on the combination scenarios from the most to the least prone to induce subsidence during CG and UGS phases using criterion 3(a)

	combination	χ_{max}	**activation L.S.**	**Maximum δ_{avg}**	**L.S. of maximum δ_{avg}**	**χ_{max} UGS**	**UGS - L.S. / δmax**
Fault F2	2	1	3	0.021	mid CG	1.00	13.0/0.001
	2_PF	1	3	0.021	mid CG	1.00	13.0/0.001
	1	1	5	0.014	end CG	0.95	-
	3	1	5	0.012	end CG	0.79	-
	1_PF	1	6	0.006	end PP	0.97	-
Fault F3	1	1	4	0.064	mid CG	0.95	-
	2	1	4	0.024	mid CG	1.00	12.4/0.002 ; 12.5/0.002 ; 13.0/0.001
	2_PF	1	4	0.012	end PP	1.00	12.4/0.001; 12.5/0.003; 13.0/0.001
	3	1	5	0.058	mid CG	0.70	-
	1_PF	1	5	0.016	l.s. 9	0.95	-

Table 6 Faults F2 and F3: ranking on the combination scenarios from the most to the least prone to induce subsidence during CG and UGS phases using criterion 3(b)

	combination	χ_{max}	**activation L.S.**	**Maximum δ_{avg}**	**L.S. of maximum δ_{avg}**	χ_*
Fault F2	2	1	3	0.021	mid CG	0.52
	2_PF	1	3	0.021	mid CG	0.52
	1	1	4	0.064	mid CG	0.26
	3	1	4	0.024	mid CG	1.00
	1_PF	1	4	0.012	end PP	0.67
Fault F3	1	1	5	0.058	mid CG	0.94
	2	1	5	0.016	l.s. 9	0.98
	2_PF	1	5	0.014	end CG	0.98
	3	1	5	0.012	end CG	0.91
	1_PF	1	6	0.006	end PP	1.00

3. Weighting the critical factors

Inspection of Table 1-Table 6 reveal that the critical factors (drivers/settings) influencing fault activation during CG and UGS cycles arranges differently for the boundary and central faults, F2 and F3.

On fault F2, i.e. for the faults bounding the reservoir, Table 1 and Table 2 reveal that the stability is manly jeopardized by the initial stress regime of the system, the presence of the viscous caprock, the geomechanical properties of the system (e.g., reservoir stiffness) and the faults (cohesion, static friction angle, presence of fault weakening). However, offset and differential pore pressure of the reservoir compartments might also threaten the fault stability.

Due to symmetry conditions of fault F3 for most of the scenarios, the major influencing drivers to fault instability are given by geometrical parameters characterizing the fault/reservoir system (Table 3 and Table 4). Offset of the reservoir compartments, initial stress regime, and fault dip are the most prone to threat the stability of the fault F3. Subsequent, the criticality is enhanced by differential pore pressure within the two compartments, again removing the symmetry of the system deformation. The maximum average sliding of F3 is always computed at the end of the primary production or cushion gas phase, never within the UGS cycle. Notice that the condition $P_f \neq 0$ within the faults generally enhances their stability by increasing the normal stress, thus the limit shear stress used in the failure criterion.

Overall, ranking criteria 3(a) and 3(b) give almost the same results without significant differences. This is also partly due to the fact that this is the last criterion within the proposed nested rule.

4. Developing guidelines for safe operational bandwidths

Although qualitative because of the theoretical/general framework of the modelling applications and the “partial completeness” of the investigated scenarios, preliminary “safe operation bandwidths” can be sketched to avoid potential induced seismicity during CG and UGS.

A limitation on the maximum pressure P_{max} (below the initial pore pressure) should be prescribed depending the geometry of the fault/reservoir: the presence of sloped faults, offset of the reservoir compartments, differential pore pressure between adjacent reservoir compartments and within each reservoir block are criticality factors to be accounted for to define safe P_{max} bound. The Zechstein caprock formation and high reservoir compressibility are also criticality factors that can threaten the fault stability. In these conditions, limitations on the operational pressure fluctuation during a UGS cycle and on the rate of pressure recovery during CG injection should be properly prescribed depending on the specific reservoir features.

Specific investigations are also fundamental to characterize the reservoir setting and, therefore to avoid or reduce the risk of critical operations. In particular, importance should be given to improve the knowledge on (from the most to the least importance):

- the initial stress regime on the faulting system;
- the reservoir compressibility;
- the geomechanical parameters of the faults (failure criterion);
- the reservoir permeability (or, equivalently, the pore pressure distribution within the reservoir compartment).