A NUMERICAL STUDY OF GEOLOGICAL CO_2 SEQUESTRATION IN A MULTI-COMPARTMENT RESERVOIR OFFSHORE THE NORTHERN ADRIATIC SEA, ITALY

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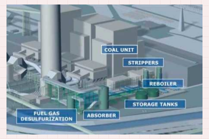
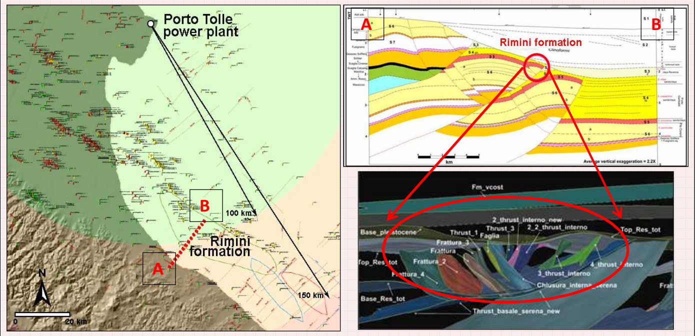
1. STUDY SITE: PORTO TOLLE [3]

- Power generation: 660 MWe
- Primary fuel: bituminous coal
- Secondary fuel: biomass
- CO_2 capture technology: post-combustion capture with amine
- % of the flue gas treated: 40%
- Stored CO_2: up to 1Mt/year for 10 years



(left) Satellite image of the Po River delta in Northern Italy with the location of the Porto Tolle power plant. (right) A photo of the plant from which the CO_2 will be produced

2. GEOLOGICAL SETTINGS



(left) Map of the zone of interest for CO_2 injection with the existing wells the location of Porto Tolle power plant and of the Rimini injection area. (right, top) Geological section along the AB alignment and (right, bottom) 3D reconstruction by seismic survey of the multi-compartment structure of the Rimini reservoir

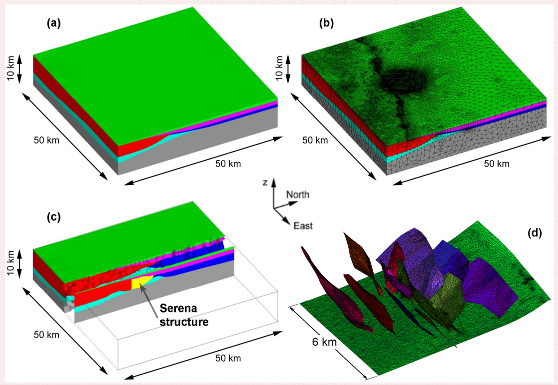
ABSTRACT

It is widely recognized that fossil fuel power plants will continue to play an important role in the energy supply for a large number of countries in the decades to come. The implementation of suitable CCS technologies is a mandatory requirement for abating the GHG emissions into the atmosphere and obtaining a sustainable power generation from fossil fuels, especially coal. At present, carbon dioxide sequestration in saline aquifers is indicated as one of the most promising techniques which, however, implies a complex multidisciplinary effort involving a number of hydrological, geomechanical and geochemical issues.

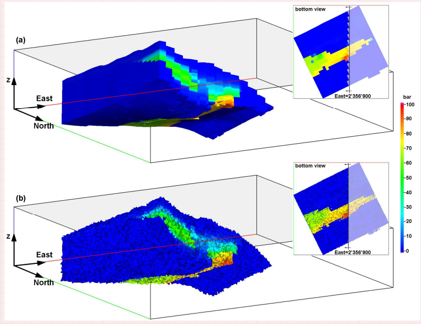
In the present contribution a geomechanical modeling study of the CO_2 disposal into a deep saline aquifer located at about 1500 m depth in the Northern Adriatic Sea, Italy, is discussed. The model makes use of a **3D structural non-linear Finite Element (FE)** code (GEPS3D) allowing for the assessment of the geomechanical safety of the sequestration and the prediction of the expected land uplift with the potential related hazards. The caprock sealing capacity and the injected formation integrity are investigated by two safety factors that account for a shear and a tensile failure mechanism, respectively. The land surface stability is also addressed in terms of absolute and differential displacements, the latter being the key factor controlling the safety of the existing ground structures and infrastructures. Moreover, the possible fault activation is modelled with the aid of **special Interface Finite Elements (IFE), specifically designed for the simulation of fault slippage and opening** [1].

The geological structure of the storage unit is very complex due to the **presence of several faults and thrusts** that partition the injectable porous volume into different blocks, possibly disconnected from the hydraulic point of view. Based on a detailed interpretation of a 3D seismic survey, a FE-IFE model that accurately reproduces the geology of the selected site has been developed. A hypoplastic constitutive law derived from radioactive marker measurements carried out in the Adriatic Sea [2] is selected for the geomechanical characterization of the porous formation. Several scenarios are addressed according to different distributions of the petrophysical properties, i.e. permeability and porosity, rock compressibility and initial in-situ stress and pore pressure. A set of simulations is performed with **CO_2 injected at a rate of 1 Mton/year** through two vertical wells. A sensitivity analysis on the parameters defining the yield surface, i.e. friction angle and cohesion in the Mohr-Coulomb criterion, shows that only a 4- to 7-year injection period appears to be safe in relation to any risk of potential shear and tensile failure.

3. GEOMECHANICAL FE-IFE MODEL AND INTERFACE WITH THE FLUID-DYNAMIC MODULE



3D static model for geomechanical simulation: (a) 3D volume, (b) 3D FE grid, (c) vertical section of the domain through the Rmini structure, and (d) discretization of the faults/thrusts within the Rimini structure by IFEs
[# nodes: 463,783; # FEs: 2,868,292; # IFEs: 50,789]



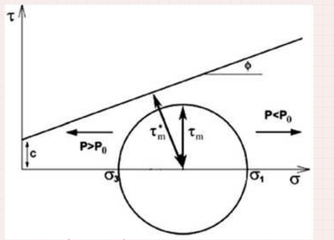
Pore overpressure (a) provided by COORES simulator[4] on the structured finite difference grid and (b) transformed into tetrahedral source of strength as input to GEPS3D

4. FORMATION AND CAPROCK FAILURE

Gas injection into a geological reservoir generally increases the risk of shear and tensile failures. The rock can fail with the generation of a number of local fractures, a sharp increase of the hydraulic conductivity and a significant reduction of the stress bearing capacity, thus potentially impacting on both the CO_2 plume motion and the porous medium deformation. The failure mechanism can be understood with the aid of the schematic Mohr representation of the stress state. During the reservoir depletion the pore pressure p decreases ($p < p_0$) while the effective stress increases. Hence the Mohr's circle moves rightward, i.e. farther from the failure line bounding the envelope of the allowable stress states. By contrast, during gas injection the pore pressure raises possibly exceeding the original pressure p_0. In this case the effective stress decreases with the Mohr's circle moving leftward, i.e. toward the failure line. Two failure mechanisms can be envisaged [5]:

1. if the stress state is such that the Mohr's circle touches the failure line a shear failure may occur. The distance from such occurrence can be measured by the safety factor χ:
$$\chi = 1 - \frac{\tau_m}{\tau_m^*}$$
where $\tau_m = (\sigma_1 - \sigma_3)/2$ and $\tau_m^* = [c\cos\phi + 0.5\,(\sigma_1 - \sigma_3)\sin\phi]$ are the current largest and maximum allowable shear stress, respectively, with c the cohesion and ϕ the friction angle. Wherever χ becomes zero a shear failure is likely to occur.

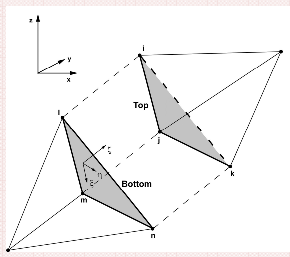
2. if the Mohr's circle crosses the s-axis a tensile failure takes place. The failure condition is simply $\sigma_3 \le 0$, with the safety factor ψ defined as:
$$\psi = \frac{\sigma_3}{\sigma_{3,0}}$$
with $\sigma_{3,0}$ the undisturbed initial minimum principal stress. Similarly to χ, wherever ψ becomes zero a tensile failure is likely to occur.



Example of a Mohr's circle representing the porous medium stress state.

5. INTERFACE FINITE ELEMENTS

Interface Elements: special zero or finite thickness elements able to describe slippage or opening of contact surfaces [1]



Mohr-Coulomb failure criterion as yield surface:

$$F = |\tau_s| + \sigma_n \tan\varphi - c \ge 0 \qquad \sigma_n < 0$$
$$F = |\tau_s| - c \ge 0 \qquad \sigma_n \ge 0$$

φ: friction angle
c: cohesion

$F \Rightarrow$ slippage $\Rightarrow K_s=0 \Rightarrow \tau_s$ no longer transferred

$F \Rightarrow$ opening $\Rightarrow K_n=0 \Rightarrow \sigma_n$ no longer transferred

slippage $\Rightarrow K_s=0 \Rightarrow \tau_s$ no longer transferred

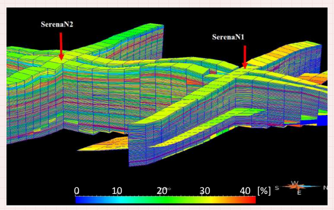
6. INVESTIGATED GEOMECHANICAL ISSUES AND SIMULATION SCENARIOS

A number of geomechanical issues must be addressed in a project of geological CO_2 sequestration in a saline aquifer or depleted reservoir:

- analysis of the stress-strain conditions of the injected formation and the aquifer/reservoir with the potential for large plastic deformations, fracturing and instabilities;
- possible activation of the pre-existing faults intersecting or close to the formation;
- related motion of the sea bottom and the coastline.

The geomechanical analyses are performed for the four following scenarios:

- **#1**: base scenario characterized by the more realistic dataset in relation to the petrophysical model (porosity, horizontal and vertical permeability), most probable number of injection wells (2 boreholes injecting 0.5×10^6 tons/year per well), together with the more conservative assumptions (impermeable lateral boundaries and sealing faults);
- **#2**: the same as #1 except for a more pessimistic petro-physical model in term of porosity and permeability;
- **#3**: the same as #1 with one injection well only injecting 1.0×10^6 tons/year;
- **#4**: the same as #1 with open lateral boundaries for the fluid-dynamic model.

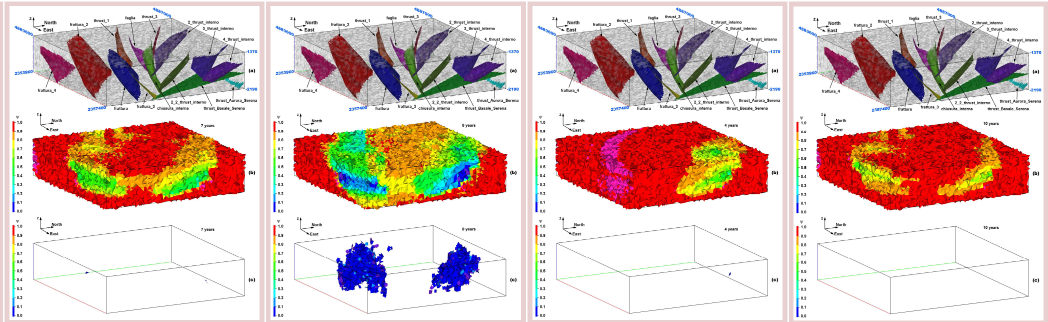


Petrophysical model for scenarios #1, #3,#4: porosity distribution (cross - section through wells) [4]

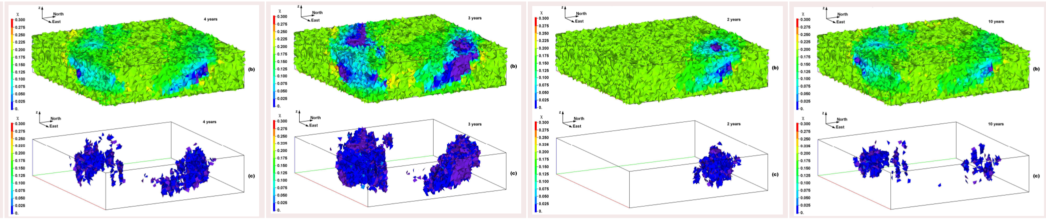
7. RESULTS

	#1	#2	#3	#4

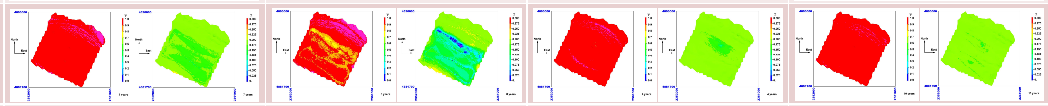
(a) portion of the FE grid where the stress field generated by the CO_2 injection is investigated. The thrusts and faults are shown with different colors.
(b) Safety factor ψ in the selected portion of the Serena structure at time = T_{flow}.
(c) FE where $\psi \cong 0$, i.e. tensile failure is likely to occur



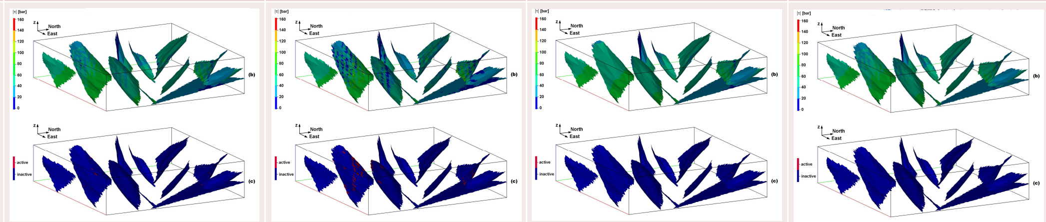
(b) Safety factor χ in the selected portion of the Serena structure at time = T_{geom}.
(c) FE where $\chi \cong 0$, i.e. shear failure is likely to occur



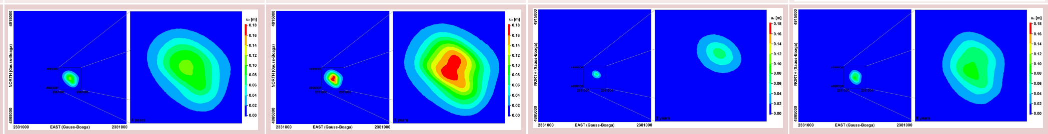
Horizontal view of the safety factors ψ (left) and χ (right) at the bottom of the caprock sealing the Serena structure at time = T_{flow}



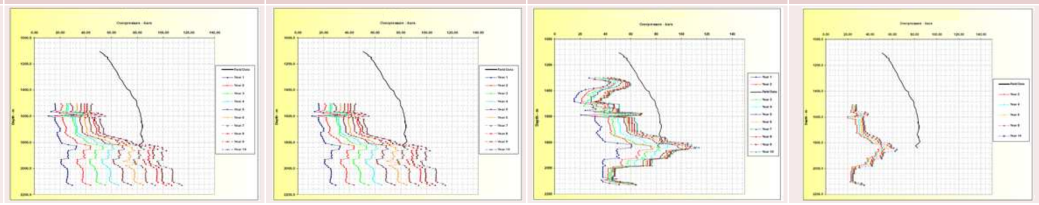
(b) Modulus of the stress τ_s tangential to the fault and thrust surfaces at time = T_{flow}.
(c) Active (red) and inactive (blue) IE: red elements slip due to the stress change induced by the injection



Uplift at the sea bottom/land at time = T_{geom}



Comparison betweent the maximum allowed overpressure (continuous black profile) and the expected overpressure distribution at the injection well (dotted profile) after different times of CO_2 injection



8. CONCLUSIONS

Scenario	Years (T_{geom}) of safe injection from a geomechanical points of view	Years (T_{flow}) of safe injection from a flowdynamic point of view	Geomechanical problems detected at T_{flow}			
			formation integrity	caprock integrity	fault activation	differential displacements
#1	4	7	Yes	No	Probable	No (3.5×10^{-5})
#2	3	8	Yes	Yes	Probable	No (9.2×10^{-5})
#3	2	4	Yes	No	Probable	No (3.8×10^{-5})
#4	10	10	No	No	No	No (4.0×10^{-5})

9. REFERENCES

[1] M. Ferronato, G. Gambolati, C. Janna, P. Teatini. Numerical modeling of regional faults in land subsidence prediction above gas/oil reservoirs. **International Journal for Numerical and Analytical Methods in Geomechanics**, 32, 633-657, 2008.
[2] D. Bau', M. Ferronato, G. Gambolati and P. Teatini. *Basin-scale compressibility of the Northern Adriatic by the radioactive marker technique.* **Géotechnique**, 52(8), 605-616, 2002.
[3] M. Politi. *I progetti CCS dell'ENEL: metodologie di analisi e individuazione dei siti di stoccaggio della CO_2*(in Italian). In: Geofluid 2010, drilling and foundations, Piacenza, Italy, 2010.
[4] D. Bossie-Codreanu, O.Vincke. *Part 3 – Porto Tolle Simulation Study – Final report*. IFP Energies nouvelles, 92 pp., 2011.
[5] M. Ferronato, G. Gambolati, C. Janna, P. Teatini. *Geomechanical issues of anthropogenic CO_2 sequestration in exploited gas fields.* **Energy Conversion and Management**, 51, 1918-1928, 2010.

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