ANALYSIS OF SURFACE MOVEMENT THROUGH CONCEPTUAL AND COUPLED FLOW-GEOMECHANICS MODELS
AN EXAMPLE OF SURFACE MONITORING ASSESSMENT FOR CCS PROJECT

Sarah Bouquet[1*], Jeremy Frey[1], Iryna Malinouskaya[1], Antoine Soulat[1], Audrey Estublier[1], André Fourno[1], SENSE Consortium

[1] IFP Energies Nouvelles, 1 et 4 avenue de Bois-Préau, 92852 Rueil-Malmaison, France

* Corresponding author e-mail: sarah.bouquet@ifpen.fr

Abstract

Monitoring of geological CO_2 storage sites is crucial for the widespread deployment of this technology to be accepted as a reliable method of reducing CO_2 emissions worldwide. The SENSE project aims to develop reliable, continuous and cost-effective monitoring based on ground motion detection combined with modelling and geomechanical inversion, using new technological developments, data processing optimization and interpretation algorithms. In this context, we present a methodology based on coupled flow/geomechanical simulations which, from the uncertainty on the subsurface properties and uncertainties on the measurements, can reproduce the measurements from different surface monitoring tools. By carrying out an uncertainty study on simulations results and taking into account the advantages and disadvantages of each of these tools, a monitoring strategy can be designed such that the tools will record potential displacements at the most sensitive periods and locations, taking into account their respective accuracies. If surface displacements are measurable and sufficiently sensitive to subsurface properties then this kind of monitoring will help to better constrain subsurface properties and possibly subsurface behavior such as plume migration, pressure propagation, and storage capacity. This methodology is applied to conceptual models in order to identify which conditions induce different surface displacements and thus may require specific surface monitoring strategy.

Keywords: *Surface displacement – Coupled flow-geomechanical simulation –CO_2 storage integrity – Cost-effective monitoring – conceptual models – subsurface uncertainties*

1. Introduction

For carbon dioxide capture and storage (CCS) to have a significant impact on climate objectives, significant quantities of CO_2, on the order of several gigatonnes per year, must be captured and stored. This means that the volume and number of injection sites must be rapidly increased, from today's isolated demonstrations pilots to large-scale storage sites. Monitoring of CO_2 geological storage sites is crucial to gain acceptance of the process as a reliable method of reducing CO_2 emissions, as well as to verify the behavior of the sites and to enable the closure of the storage sites in the long term. The SENSE project aims to develop reliable and cost-effective monitoring based on the combination of ground motion measurements with geomechanical modelling and inversion. The objective of this project is to demonstrate how surface displacements can be used in a monitoring program aimed at verifying the long-term integrity of a CO_2 geological storage site.

From numerical simulations of CO_2 injection for synthetic case studies, the objectives of this paper are :

- To identify whether surface displacements are likely to be "visible" by monitoring tools and for which resolution
- To identify which conditions impact surface displacements,
- Analyze the usefulness of various surface monitoring techniques (based on satellites, tiltmeters, GPS, etc.) and their ability to provide concrete information on subsurface behavior.

To achieve these objectives, numerical models coupling flow and geomechanics are developed for different key scenarios. For each specific surface displacement, the potential for surface monitoring in time and space can be evaluated.

For the identification of conditions inducing variations in surface displacements, we rely on the definition of different scenarios, representative of real potential storage sites. Thus, for each of these scenarios, a statistical analysis of the system responses is performed as a function of the a priori uncertain subsurface properties. If differences in observed surface displacements can be related to some model parameters (*e.g.* subsurface properties), then the measured surface displacements could help to characterize such subsurface properties.

2. Methods

2.1 Definition of conceptual models

Different structural models can be considered as potential structures for CO_2 storage. Here, an anticlinal structure without faults is modeled.

Several scenarios are considered to represent different types of sedimentary formations and therefore corresponding to different subsurface properties. These scenarios are defined to generate realistic intervals of uncertainty of the properties. This paper deals with a "carbonate" scenario based on data from the Brindisi carbonate formations [1] and those of the Michigan Basin (MRCSP Michigan Basin, [2]).

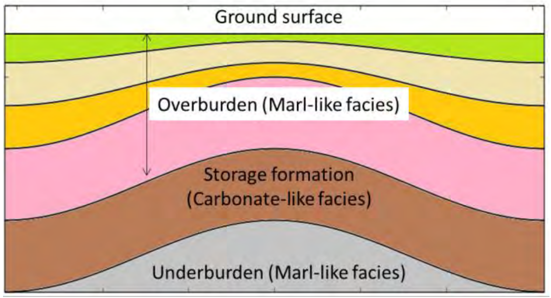

Figure 1 : Schematic representation of the geology of the "Carbonate", anticline model

Other scenarios based on sandstone formations data have also been defined but are beyond the scope of this paper.

Pressure and temperature conditions, salinity, storage depth and thickness, petrophysical properties, mechanical properties of the storage formation and of the overlying and underlying formations are defined from the collected data. Of these properties, nine are considered critical and uncertain in these scenarios. These include the porosity, permeability, Young's modulus and Poisson's ratio properties of the storage formation and overburden (caprock), as well as the capillary CO_2 entry pressure of the caprock. These uncertain parameters are defined through uncertainty intervals determined from the collected information. The a priori distribution of the parameter values corresponds to an uniform law on the defined uncertainty interval. Table 1 gives the range of values for those uncertain parameters for the "Carbonate" case.

Table 1**:** Uncertain parameters and related ranges of values for the "Carbonate" case.

Variables	Minimum	Maximum
Carbonate Porosity [-] (*Phi*)	0.15	0.25
Carbonate Permeability [mD] (*K*)	15	150
Carbonate Young Modulus [bar] (*E*)	250000	450000
Carbonate Poisson coefficient [-] (η)	0.15	0.25
Marl Porosity [-]	0.05	0.4
Marl Permeability [mD]	2e-3	6.e-2
Marl Entry Capillary Pressure [bar]	5	60
Marl Young Modulus [bar]	60000	550000
Marl Poisson coefficient [-]	0.15	0.35

2.1 Definition of surface monitoring tools and related limitations

Among the tools proposed for surface monitoring, two kind of tools are considered. For local measurements, and allowing fine temporal sampling, tools such as tiltmeters, GNSS, i.e. Geolocation and Navigation by Satellite System can be used. For covering large areas

but with a more limited resolution in displacement and time, scanning systems like InSAR can be used [3,4].
InSAR data can provide, after processing, displacement maps covering at least the entire storage area, at low cost and with low hardware constraints. However, the usefulness of these data may be limited by their spatial and temporal resolution, the duration of data processing and their sensitivity to land cover (*e.g.* vegetation). Typical limitation of displacement detection by InSAR will be 1 mm/yr. This may be improved with corner-reflectors installation in the area of interest.
Point measurements from tiltmeters provide spatially and temporally accurate but local, expensive information, with measurement accuracy (*e.g.* 5 to 50 nanorads) which can be affected by weather conditions and necessarily require the installation of surface tools.
From the uncertainty on the subsurface properties and the uncertainties on the measurements, predictive models (coupled flow-geomechanics simulations) can reproduce the expected measurements obtained with the different tools. By carrying out a sensitivity study and taking into account the advantages and disadvantages of each of those tools (including their respective accuracies), a design can be defined such that the tools will record potential displacements at the most sensitive periods and locations.

2.2 Coupled flow-geomechanics simulations

A coupled hydro-mechanical calculation was applied for estimating mechanical deformations during and after the injection process. It is based on a sequential coupling between the IFPEN Puma reservoir simulator [1], and the finite element code Code_Aster [2]. The simulation is divided into temporal sequences called "periods". Pressure results from the reservoir simulation are imposed as loading to Code_Aster in order to compute the corresponding displacements field. It should be noted that the flow and mechanical equations are solved independently and the mechanical behaviour is limited to linear elasticity.

A "one-way" coupling scheme was used as described on Figure 3.

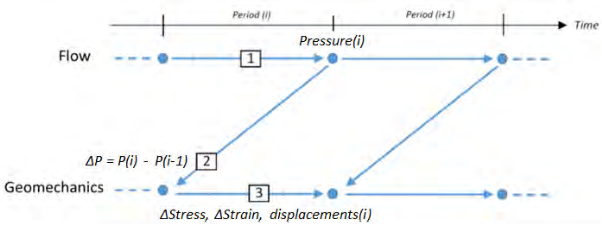

Figure 2: Schematic representation of the "one-way" coupling between flow and geomechanics simulations.

2.3 Statistical analysis methodology

The statistical analysis includes a sensitivity analysis and an uncertainty analysis on surface displacements. Uncertainty analysis consists of evaluating the uncertainty in the predictions of displacements given the a priori distribution of uncertain parameters (*e.g.* statistics of surface displacement maps). Sensitivity analysis is used to quantify the influence of model parameters on the model-simulated outputs of interest (*e.g.* Sobol index [5]). These analyses require a large sampling of combinations of parameters and outputs, too costly in computational time to be carried out from coupled flow/geomechanical simulations only.
The strategy used here consists first of defining the uncertain parameters and their uncertainty intervals (as described in paragraph 2.1.). Then a design of m experiments for the coupled simulation is built. This will be used as a learning sample for surrogate models. Surrogate models (or metamodels) are mathematical approximations of the responses of interest in studied parameters space, built based on simulated data [6].

3. Results

A single injector well is modeled, injecting CO_2 on the flank of the anticline, so as to facilitate the dissolution of CO_2 in the water during its migration to the top of the fold. CO_2 injection is controlled by a maximum pressure increase of 50 bar at the bottom of the well. The maximum injection rate is 1,500,000 m^3/day under surface conditions, or approximately 2800 t/day.

The extension of the model is about 60×60 km. The anticlinal structure is located in the center of the grid, the well is 6 km from the top of the fold (figure 2). The injection site is "onshore", the top of the storage formation is at a depth of about 1600 m, its thickness is 50 m. The pressure and temperature conditions are 160

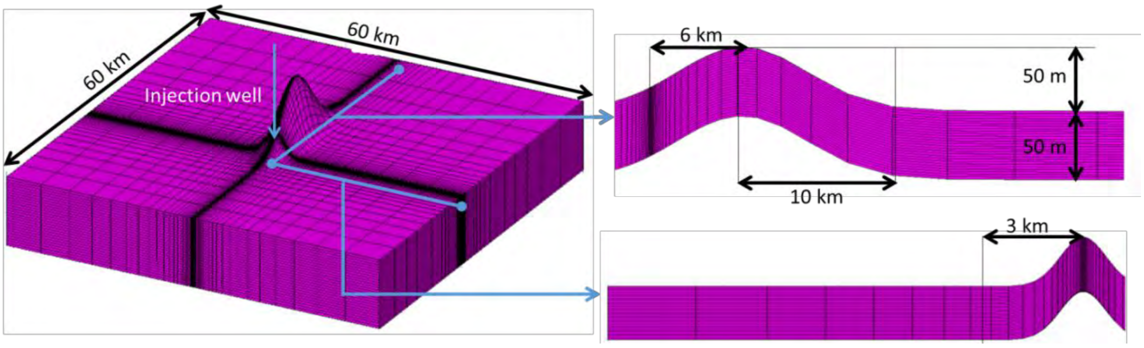

Figure 3: 3D model of the anticline structure and injection zone. Only storage formation (50 m thickness) is represented here. The coupled simulations are performed with 3D model from the surface to few meters of underburden (below the storage formation).

bar and 40°C, respectively. The salinity of the aquifer is 35,000 mg/L.

From the uncertainty intervals on the 9 parameters of interest (defined in Table 1), an LHS (Latin Hypercube Sampling, [7]) design of 115 simulations was built.

3.1 Storage capacity results

The storage capacity results for these 115 models, with the injection constraints described above, are shown in Figure 4; the evolution of the well pressure is shown in Figure 5. The differences in terms of injected volume (and therefore storage capacity) are mainly due to variations in formation properties from one case to another, knowing that the injected volume is constrained by a maximum bottom-hole pressure. According to the sensitivity study (with uncertain parameters as defined in Table 1), variations in the injected volume depend mainly on the permeability of the storage formation.

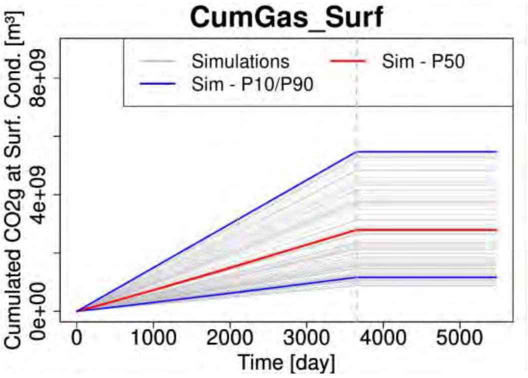

Figure 4: Cumulative volume of injected gas for each of the 115 simulations (in gray). In blue and red, the percentiles computed from these 115 simulations

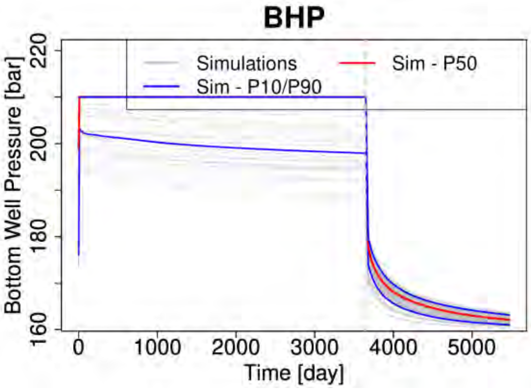

Figure 5: Bottom-Hole Pressure for each of the 115 simulations (in gray). In blue and red, the percentiles computed from these 115 simulations

3.2 Example of results from a given realization

The observation of results obtained from a particular example allows a better understanding of the physical mechanisms at work and links migration of the injected CO_2, pressure evolution in subsurface (Figure 6 and Figure 7), and the resulting surface displacement (Figure 8 - from the definition of our coupling, the surface displacement comes directly from the pressure variation observed in-situ).

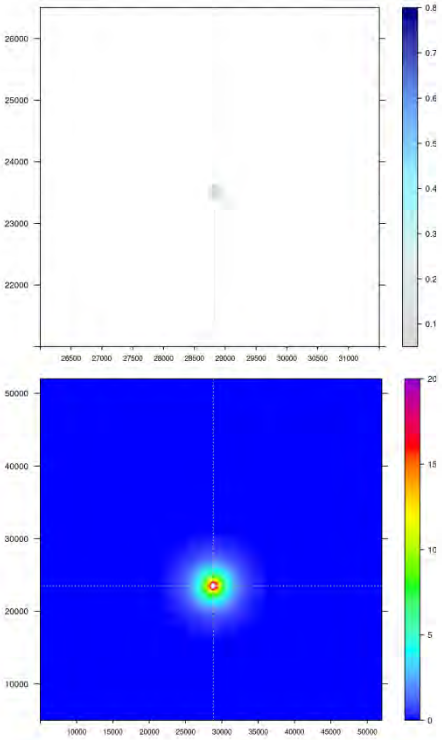

Figure 6: After 1 year of injection, (top) gas saturation at the and (bottom) pressure perturbations (i.e difference of pressure between the initial and current state, in bar) at the top of the storage formation for one realization. Spatial scales are different between gas saturation and pressure perturbations.

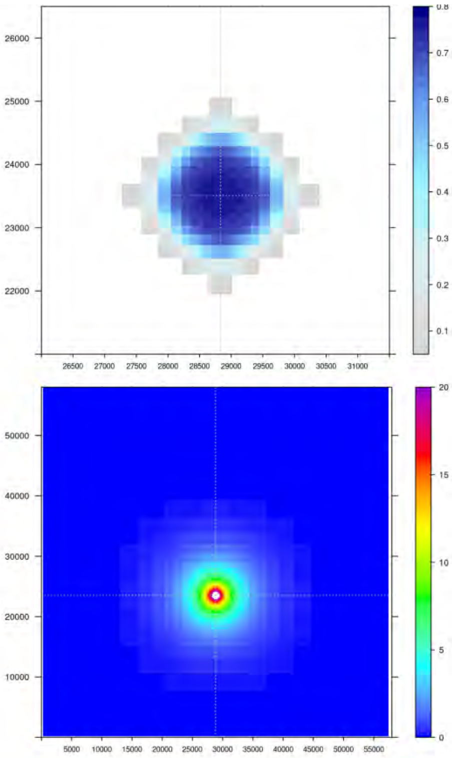

Figure 7: After 10 years of injection, (top) gas saturation and (bottom) pressure perturbations (i.e difference of pressure between the initial and current state, in bar) at the top of the storage formation for one realization. Spatial scales are different between gas saturation and pressure perturbations.

Thus, the largest pressure increases are located in the near-well, as are the highest vertical displacements at the surface. Furthermore, the shape and extent of the displacement also provides information on the properties of the deposit (here, its circular and uniform appearance reflects a low-slope structure made up of homogeneous materials). It should be noted that the propagation front of the pressure perturbation moves further than the saturation front at a given time.

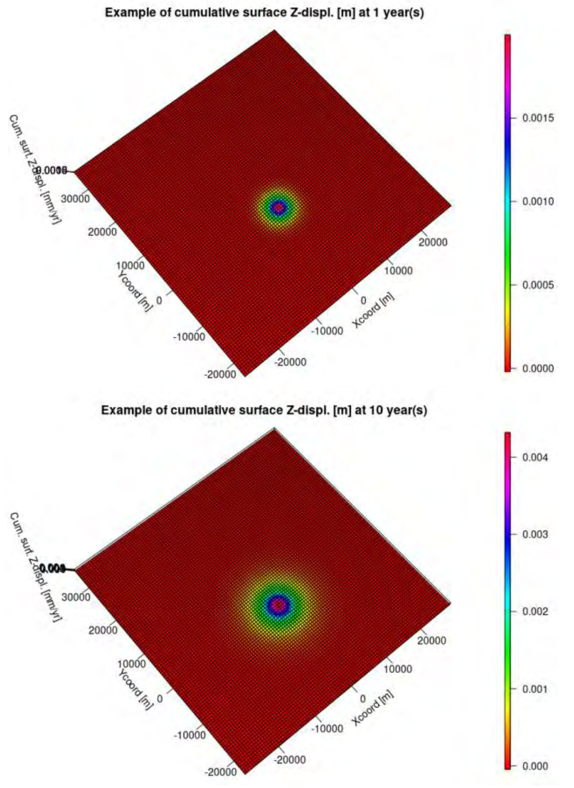

Figure 8: Maps of vertical displacements observed at the surface, cumulated (units in meters) (top) after 1 year of injection (bottom) after 10 years of injection for one realization.

3.3 Velocity of Displacement results and InSAR data

The surface displacements are analyzed here in terms of displacement velocities (mm/year) within the framework of InSAR measurements. The limit of detection of displacement velocities using InSAR methods is considered to be 1 mm/year, with +/- 1 mm/year accuracy.

Figure 9 and Figure 10 show statistical maps of surface displacement velocities after about half a year, and after 5 years of CO_2 injection respectively. If the displacement velocities are easily detectable at least until half a year of injection (minimum and maximum are above the detection limit), they are no longer detectable after 5 years with velocities below the InSAR detection threshold.

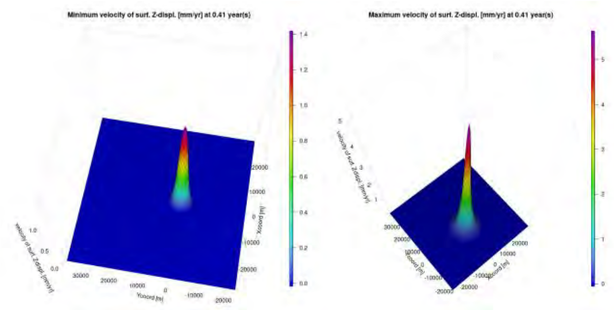

Figure 9: Minimum (left) and maximum (right) surface displacement velocities after about half a year of injection, based on 115 simulations.

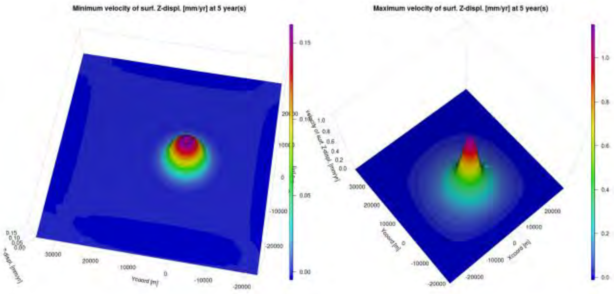

Figure 10: Minimum (left) and maximum (right) surface displacement velocities after five years of injection, based on 115 simulations.

For all simulations, the fastest vertical displacements velocities at the surface occur near the well. From the results of vertical displacements velocities over the well (Figure 11), one can distinguish the limits of the InSAR tool over time for this scenario. In the short term and up to about 2 years of injection, the InSAR data will detect displacements velocities. Beyond and until the end of the injection, the displacements velocities will not be measurable by InSAR anymore. On the other hand, post-injection displacements velocities could be detected by InSAR (see results post-injection, after 10 years in Figure 11).

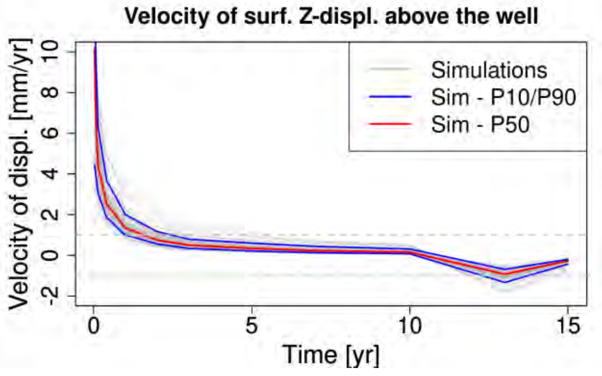

Figure 11: Simulations results of surface displacement velocities above the well function of time. In red, the median, in blue P10 and P90 percentiles of the 115 simulations (in grey).

Moreover, as results are X-symmetrical, one can simply analyze the results along the Y-axis. The statistical analysis performed on the metamodels from the 115 simulations (Figure 12) confirms that most of the displacements occur at the beginning of the injection: from the start of injection to about 2 years of injection (in more than 50% of the cases the displacements will not even be detectable at the wells after 2 years of injection). From the two-year injection period onwards, displacements velocities are no longer detectable via InSAR (less than 1 mm/year). It is also noted that these detectable displacements velocities will only be detectable over distances of less than 5 km around the well (in 90% of the cases at about half a year of injection), and given the limit of precision, the constraint brought by these data will be limited since the standard deviation is lower than the precision of the tool. InSAR measurements would only be of interest here if a high precision (1 mm/year) is required, over short periods (at the beginning of injection), and over a limited area around the well.

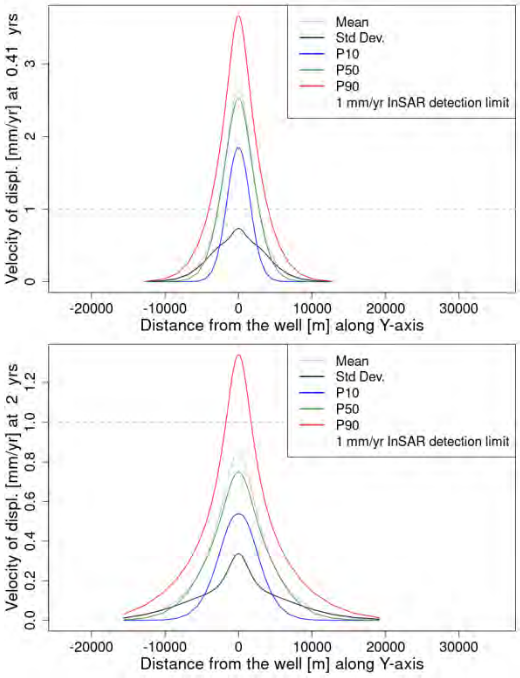

Figure 12: Uncertainties on the surface displacement velocities for the model studied (mean, standard deviation, median, quantiles 10% and 90%) related to the uncertainties on the subsurface properties. Statistical calculations performed from a Monte-Carlo sampling on metamodels built from the training sample. The detection threshold of the measurement is estimated at 1 mm/year. Beyond the two-year injection period, most of displacements are no longer detectable via InSAR.

The Shannon entropy [8, 9] calculation is carried out by classifying the displacements velocities values into five categories, in particular :

- Values below the detection threshold, i.e. of -1 to 1mm/year;
- Values from 1 to 3 mm/year, which, given the accuracy of the tool, globally represents a single type of measured value;
- Values from -1 to -3 mm/year;
- Values above 3 mm/year;
- Values under -3 mm/year.

The results obtained after one year of injection (Figure 13) make it possible to distinguish the zones of uncertainty where InSAR measurements could be useful.

The entropy is zero when the probability of obtaining a category of measurements is 1, *i.e.* when whatever the model parameters, the same category of measurement will always be obtained. For example, at one year of injection, there is a zero probability of obtaining displacements velocities above the detection threshold beyond 4 km distance from the well. Thus, there is no need to process InSAR measurements beyond 4 km from the well.

Entropy also drops when the probability of having a measurement between 1-3 mm/year is high, i.e. it becomes unlikely to obtain values outside this interval. The areas with high uncertainties, where the measurements could be most informative, correspond to the highest entropies (here, greater than 0.5).

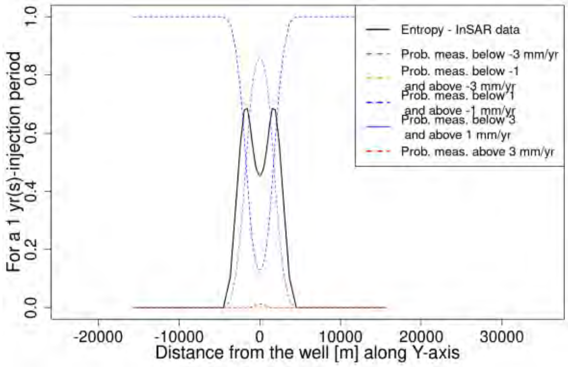

Figure 13: Shannon entropy for five categories of InSAR surface displacement velocity measurements after one year of injection. The measurement error is estimated at +/- 1mm/year.

Finally, here, surface monitoring by InSAR would be restricted to the short term at the beginning of injection or post-injection (*e.g.* one to two years after the start of injection) and over a 4 by 4 km zone around the well for this scenario. Given the small variations, it will be necessary to ensure the accuracy of the tool and to consider placing reflectors (which will improve the accuracy) in the areas of high uncertainties.

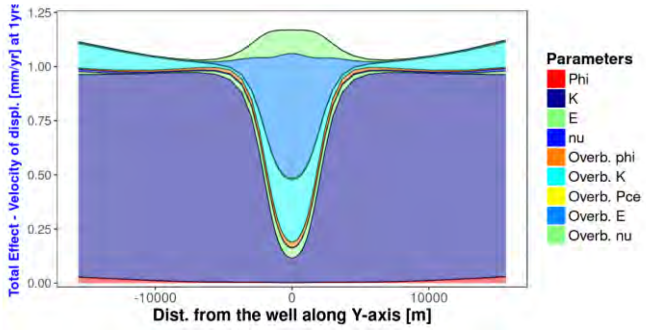

Figure 14: Total Sobol Indices calculated between uncertain parameters and surface displacements velocities variations after one year of injection.

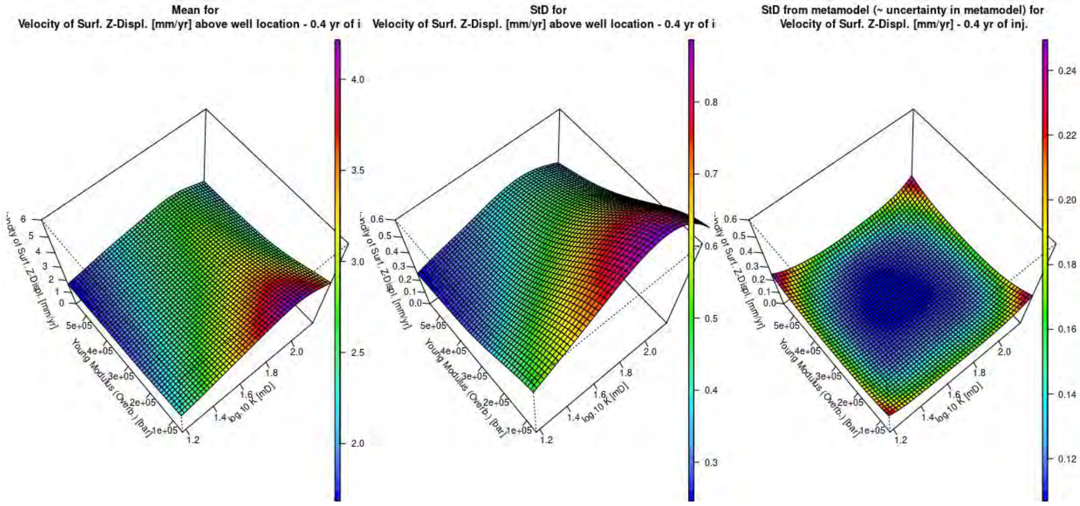

Figure 15: From metamodel: velocity of displacement above the well as a function of the Young's modulus value of the cover and the permeability of the storage formation, averaged with respect to the variations induced by the other parameters (left), the standard deviation associated with the variation of the other parameters (middle) and the uncertainty associated with the metamodel (right) used to evaluate these projections.

The results of the sensitivity analysis performed on the displacement velocities with respect to the model parameters (Figure 14) suggest a spatial and temporal variation of this sensitivity with a high sensitivity to the permeability value of the storage formation over the entire model and a significant sensitivity to the overburden parameters (mostly Young's modulus) near the well. Notice that the prior interval of the caprock Young’s modulus is far larger than the one from the storage formation (6-55 GPa *vs.* 25-45 GPa). This would partly explain why the response is more sensitive to the caprock Young modulus variations than the one from the storage formation. This also reflects the highest uncertainty that we often have in overburden properties compared to storage formation properties.

Thus, precise near-well displacement measurements would contribute over time to constrain mainly the model values of permeability and Young's modulus in the cap rock.

If we project the predictions of vertical displacement velocities over the well as a function of these two parameters, we see that this measurement could significantly constrain the values of this pair of parameters at short-term (Figure 15). Most of the variations e would be explained by these two parameters (between 2 and 4 mm/year) while the other parameters induce an average variation of an order of magnitude lower (between 0.3 and 0.8 mm/year).

3.4 Tilts variations and tiltmeters relevancy

Tiltmeter measurements are estimated by transforming the results into simulation displacements. Tilts are expressed in nanorad.

Due to its higher accuracy, the tiltmeter is both more sensitive in time and space to surface displacements induced by CO_2 injection, compared to InSAR data.

We obtain tilts variations of the order of a hundred nanorads at 1 year and of the order of ten nanorads at 5 years over distances of a few kilometers around the well (Figure 16). Consequently, if the precision of the tiltmeters is ensured at a minimum at about 10 nanorads, tiltmeters located few kilometers from the well would make it possible to follow the injection of CO_2 over time.

It is noted that near the well the tilts are null because the displacement is mostly vertical (no dip), so the tiltmeters should preferably be placed where vertical and horizontal displacements are expected.

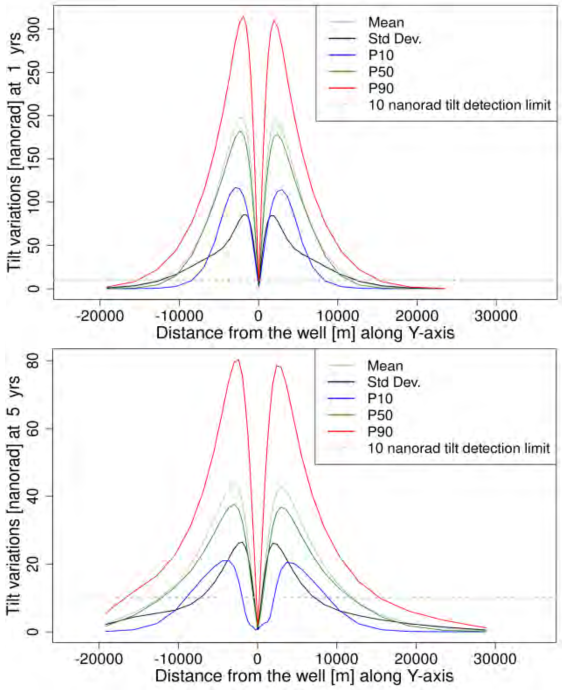

Figure 16: Uncertainties on the tilts measurements for the model studied (mean, standard deviation, median, quantiles 10% and 90%) relative to the uncertainties on the subsurface properties. Statistical calculations performed from a Monte-Carlo sampling on the metamodels built from the training sample. The detection threshold of the measurement is assumed at 10 nanorads.

For tiltmeters, the aim is to define a number of locations that would be informative, *i.e.* above the threshold of accuracy over time, and that would reduce the uncertainty in the model.

According to the entropy calculation (Figure 17), based on the definition of categories by precision limit, the uncertainties on the measurement of tilts are high on both sides of the well: between 800 and 2.5 km at one year and between 1 and 3 km at 5 years.

Considering the small variations in tilts away from the well with time, it would be recommended to place tiltmeter(s) about 1.5 km from the well for short- and long-term monitoring.

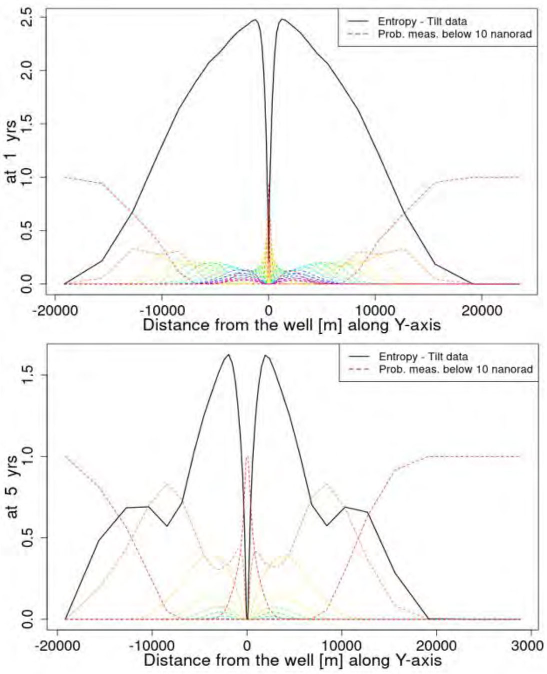

Figure 17: Shannon entropy for categorical tiltmeter data : the measurement error is assumed at +/- 10 nanorad, categories are defined from 10 nanorads up to 300 nanorads with an interval of 20 nanorads.

4. Conclusions

A methodology is proposed to define if these tools are relevant for CCS monitoring in specific conditions. This approach is based on coupled flow/geomechanical simulations reproduce the measurements from surface monitoring tools while taking into account the uncertainties on the subsurface properties. This is performed by carrying out an uncertainty study on simulations results and taking into account the advantages and disadvantages of each of those tools. Finally, a design can be defined such that the tools will record potential displacements at the most sensitive periods and locations, taking into account their respective accuracies. Measurable surface displacements could help to better constrain subsurface properties and behaviors such as plume migration, pressure propagation, and longer-term storage capacity. This methodology is applied here to a specific conceptual model but will be applied to other representative conceptual models (in particular models with fault zones) as well as models derived from actual storage sites in order to identify which conditions induce different surface displacements and thus may require specific surface monitoring strategy. An iterative coupling scheme would be considered for real cases to improve the accuracy of surface displacement estimation via simulations.

Acknowledgements

SENSE (Assuring integrity of CO$_2$ storage sites through ground surface monitoring) project No. 299664, has been subsidized through ACT (EC Project no. 691712) by Gassnova, Norway, United Kingdom Department for Business, Energy and Industrial Strategy, Forschungszentrum Jülich GMBH, Projektträger Jülich, Germany, The French Agency for the Environment and Energy Management, The United States Department of Energy and State Research Agency, Spain.

References

[1] Baroni, A., Estublier, A., Vincké, O., Delprat-Jannaud, F., Nauroy, J-F., (2015). Dynamic Fluid Flow and Geomechanical Coupling to Assess the CO$_2$ Storage Integrity in Faulted Structures. Oil & Gas Science and Technology - 70 (4), pp.729-751.

[2] Michael, K., Golab, A., Shulakova, V., Ennis-King, J., Allinson, G., Sharma, S., Aiken, T (2010). Geological storage of CO$_2$ in saline aquifers-A review of the experience from existing storage operations, International Journal of Greenhouse Gas Control, 4 (4), pp. 659-667. doi: 10.1016/j.ijggc.2009.12.011

[3] McColpin, G. (2009). Surface Deformation Monitoring As a Cost Effective MMV Method. Energy Procedia 1(1):2079-2086. DOI: 10.1016/j.egypro.2009.01.271

[4] Vasco, D., Ferretti, A., Rucci, A., Samsonov, S., & White, D. (2019). Monitoring the Deformation Associated with the Geological Storage of CO$_2$. In T. Davis, M. Landrø, & M. Wilson (Eds.), Geophysics and Geosequestration (pp. 93-114). Cambridge University Press. DOI 10.1017/9781316480724.007

[5] Sobol, I.M, (1993). Sensitivity analysis for non-linear mathematical models, Mathematical modelling and computational experiment (translated from Russian: I.M. Sobol', sensitivity estimates for nonlinear mathematical models. Matematicheskoe Modelirovanie 2 (1990), 112–118 407–414).

[6] Feraille, M., Marrel, A. (2012). Prediction under Uncertainty on a Mature Field. Oil & Gas Science and Technology – Rev. IFP Energies Nouvelles, Vol 67, No. 2, pp. 193-206. DOI: https://doi.org/10.2516/ogst/2011172

[7] McKay, M.D., Beckman, R., Conover, W. (1979). A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. In Technometrics, Vol. 21, No. 2, pp. 239-245. https://doi.org/10.1080/00401706.1979.10489755

[8] Leibovici D.G. (2009) Defining Spatial Entropy from Multivariate Distributions of Co-occurrences. In: Hornsby K.S., Claramunt C., Denis M., Ligozat G. (eds) Spatial Information Theory. COSIT 2009. Lecture Notes in Computer Science, vol 5756. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-03832-7_24

[9] Schweizer, D., Blum, P., Butscher, C. (2017). Data assimilation and uncertainty assessment in 3D geological modeling. Solid Earth Discussions, 1-23.