Rock physics-guided seismic survey optimization for CO2 injection monitoring - model building

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Summary

Taking advantage of advances in data processing capability, the CLEAN4D project aims to relax geometric repeatability requirement in seismic time-lapse data acquisition, thereby significantly reducing the cost and the environmental impact of acquisition while maintaining or improving data quality for time-lapse monitoring. In the first project phase, we have designed a workflow for building a model of a deep saline aquifer for CO2 storage embedded in a realistic 3D geological background model. The model is designed to generate seismic data using finite-difference modelling containing a realistic level of complexity which might compromise seismic time-lapse imaging and inversion of reservoir properties. Modelled data illustrate the realistic degree of complexity which is well suited to evaluate how well different combinations of acquisition and processing techniques can resolve the known time-lapse signal while accounting for uncertainties in reservoir behaviour. This will lead to the development of acquisition design strategies optimizing the trade-off between added value and cost, a contribution to the design of effective monitoring strategies for CO2 storage.

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Introduction

Repeated seismic surveying and data analysis (time-lapse seismic) is a key technique in monitoring and optimizing the depletion of hydrocarbon reservoirs and it will play a similar key role in monitoring future CO_2 and energy storage projects. Traditional time-lapse seismic acquisition and processing for reservoir monitoring typically requires close repetition of the acquisition geometry. We started a project (CLEAN4D) that aims to relax the need for strong repeatability which will benefit traditional hydrocarbon, CO_2, and energy storage monitoring. Taking advantage of advances in data processing capability, we aim to relax geometric repeatability requirement in data acquisition, thereby significantly reducing the cost and the environmental impact of acquisition while maintaining or improving data quality for time-lapse monitoring. The CLEAN4D project focuses on extensive modelling and processing of synthetic data to evaluate how well different combinations of acquisition and processing techniques can resolve the known time-lapse signal while accounting for uncertainties in reservoir behaviour. This will lead to the development of acquisition design strategies optimizing the trade-off between added value and cost, including the contribution to reducing CO_2 emissions related to time-lapse seismic acquisition.

The first project phase focused on building suitable realistic models for synthetic data generation. In this paper, we describe the process of building a model comprising a representative deep saline aquifer CO_2 storage reservoir embedded in a full 3D geological model, based on settings found on the Norwegian continental shelf. To be suitable for our project objectives, the model needs to be large enough for full-scale 3D seismic survey modelling and needs to contain realistic geologic complexity to generate data with typical processing challenges that might compromise inversion and monitoring of reservoir properties.

Model building

The model is loosely based on the Sleipner CO_2 storage site in the North Sea with several modifications. We pushed the reservoir deeper to a measured depth of about 1200 m at top reservoir to be better aligned with depths of future storage sites while keeping modelling cost manageable. The necessary pressure adjustment is considered in the reservoir simulations. We increased water depth to about 200 m. The remaining depth difference between the original Sleipner setting and our synthetic model was accounted for by vertical stretching of all the elements that contribute to the overburden model building process: seismic data, interpreted horizons, and well logs. The overall lateral dimensions of the model are 9 x 11.1 km and it is 1850 m thick. This is large enough for modelling surveys with 50-60 km^2 full-fold area on top of the injection point. The reservoir model properties, after CO_2 injection simulation, are up-scaled from the laterally large and vertically thin grid cells within the reservoir simulation software to the finite-difference grid with a regular grid cell size of 5 m x 5 m x 5 m, preserving the kinematics of wave propagation. The up-scaled reservoir model properties are seamlessly integrated into a background model which is built from well log information giving realistic velocity distribution, interpreted horizons for geologically consistent distribution of said velocities, and seismic data introducing structural complexity and heterogeneity.

Finite difference (FD) modelling is our method of choice for synthesising seismic data that contain the full wavefield generated by structurally complex geology. Visco-acoustic, isotropic modelling is chosen for balancing realistic modelling against computing cost. Efficient cloud computing resources are employed. To enable consistent data comparisons with potential visco-elastic modelling, the model grids are generated in a way that compressional waves have identical kinematics in both modelling schemes by taking the shear modulus and shear wave attenuation into account when generating P-wave velocity and attenuation grids for visco-acoustic modelling. The implementation of visco-elasticity follows the theory developed in Emmerich and Korn (1987) with a single Maxwell body for every grid cell and a single fixed relaxation frequency for the entire model. The limitation to a single fixed relaxation frequency poses a challenge for integrating representative background attenuation in the entire model without CO_2 injection and injection-related attenuation due to wave induced fluid flow (WIFF) in the reservoir.

Following typical amplitude decay observations in this field (e.g., Rossi et al., 2011), we assume a laterally and vertically moderately varying background P-wave attenuation in the entire model (water column excluded), prevailing in both baseline (i.e., fully brine-saturated reservoir) and monitor (i.e., CO_2-brine-saturated reservoir) scenarios. This attenuation mechanism is independent of the CO_2 saturation state of the medium. We model these effects using a single Maxwell body that produces an average spectral slope, comparable to that of a constant-Q model, in the frequency range between 1 and 125 Hz for the Q value in each finite-difference block. The relaxation frequency for the single Maxwell body is set to 400 Hz. For the reservoir sandstone, the P-wave attenuation maximum is set to Q_P=172 to mimic a background constant Q of 150. Similarly, we assume S-wave attenuation comparable to a constant-Q model of about Q=100. The attenuation maximum for S-waves at 400 Hz is set to Q_S=115 for the reservoir sandstone. Based on the principle of causality, this implies that the bulk and shear moduli of the rock are frequency dependent. Figure 1 shows a comparison between the amplitude decay exhibited by a P-wave and a S-wave over 1000 m propagation distance when considering a constant-Q model and the single Maxwell bodies described above.

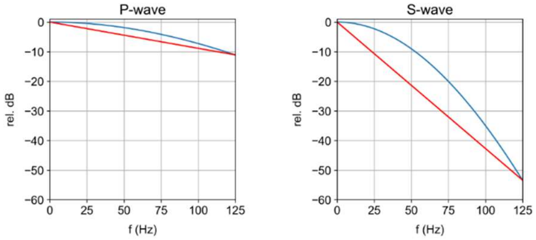

Figure 1 *Amplitude decay in a constant Q model (red) and attenuation modelled by a Maxwell body (blue). Constant Q is 150 for compressional waves and 100 for shear waves.*

To predict time-lapse saturation effects on seismic velocity and attenuation when CO_2 is injected, we consider a partial saturation (i.e., two or more immiscible fluids) poroelastic model. When a seismic wave propagates through a partially saturated medium, pressure gradients are created between the regions saturated with different fluids. The resulting WIFF during pressure equilibration manifests as seismic attenuation and velocity dispersion. We are mainly interested in heterogeneities in the rock caused by spatial variations in saturating pore fluids (e.g., CO_2, brine) and thus consider the poroelastic formulation of the White-Dutta-Odé patchy saturation model (Dutta and Odé, 1979). In this model, partial saturation is conceptualized as a regular distribution of spherical CO_2-saturated regions surrounded by brine-saturated rock. To compute the frequency-dependent P-wave velocity and attenuation predicted by the White-Dutta-Odé model for different petrophysical properties, we use the Python-based open-source library "rockphypy" (Yu et al., 2023) using rock physics properties representative of the Utsira sands reservoir according to the work of Dupuy et al. (2017). In addition, we define a characteristic patch size (i.e., sphere radius of the porous medium saturated with CO_2) and overall gas saturation S_g. Using a patchy saturation model, Dupuy et al. (2017) found that S_g values of up to 40% were associated with patch sizes oscillating around 5 cm with an uncertainty of 2 cm. We use these values to get a realistic range of patch sizes to be used in the White-Dutta-Odé model. Finally, gas saturation, which can vary between 0 and 100%, is determined by reservoir flow simulations.

In the case of partial saturation, the two attenuation and dispersion mechanisms described above must be combined. Under the assumption that the associated mechanisms do not affect each other, we first add the attenuation predicted by both models. Next, assuming a Maxwell body model, we can obtain the corresponding elastic modulus dispersion from the frequency-dependent attenuation and the modulus value at the low-frequency limit (Emmerich and Korn, 1987). The latter can be computed using the Gassmann-Wood limit, which coincides with the low-frequency limit of the White-Dutta-Odé model. Figure 2 illustrates the frequency-dependent P-wave attenuation and velocity dispersion predicted by the background and WIFF models as well as their combined effects in the frequency range of interest. The curves correspond to a patch size of 5 cm and CO_2 saturation equal to 5%. To numerically implement the attenuation and modulus dispersion, we find a Maxwell body that best reproduces the expected effects over the modelling bandwidth of interest (up to 125 Hz). The finite difference implementation allows only a single fixed relaxation frequency for the entire model. We found that a relaxation frequency of 400 Hz allowed us to fit patch sizes around 5 cm with good accuracy. Then, given the resonance frequency and assuming a low-frequency modulus given by the Gassmann-Wood limit, we determine the attenuation maximum that optimizes the fit of dispersion and attenuation for each CO_2 saturation in the model. Figure 2 shows the fitting results, which are in very good agreement with the predicted response of the background+WIFF model within the frequency range of interest.

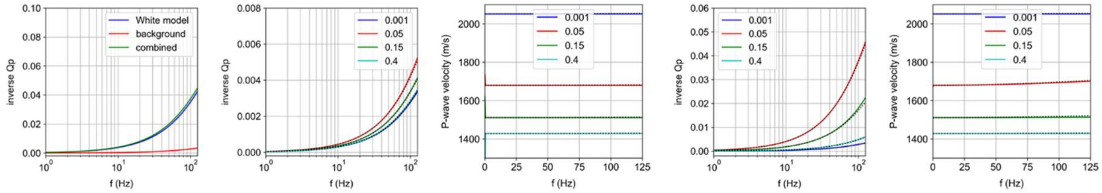

Figure 2 *From left to right: Frequency dependent P-wave attenuation for background model (red), WIFF model (blue), and combined attenuation models (green). Frequency dependent P-wave attenuation and phase velocity for combined attenuation effects (colored) and best fit model (black dotted) for different CO2 saturations (color coded). Figures 2 and 3 from the left show values for 1 cm patch size, figures 4 and 5 show values for 5 cm patch size.*

Modelling results

The baseline survey has been modelled using a vessel towing ten dual-sensor streamers spaced 50 m apart, measuring both pressure and particle motion, and four sources at zero inline offset spaced 62.5 m apart in the crossline direction. This acquisition configuration is representative of modern seismic experiments to establish a baseline for monitoring future CO_2 injection. A streamer length of four kilometres is sufficient to record reflected and refracted energy from the reservoir at all offsets. The data is modelled with 4 ms temporal sampling. Figure 3 shows a common channel section (11.1 km lateral extent) of the baseline survey after receiver motion correction, receiver-side wavefield separation, source-side deghosting, and designature. The storage complex sits between 1.2 s and 1.5 s. Lateral reflectivity variations and complex diffraction and multiple patterns caused by model heterogeneities demonstrate that the model generates realistic challenges in time-lapse data processing and imaging. Model slices (Figure 3) show the lateral heterogeneity.

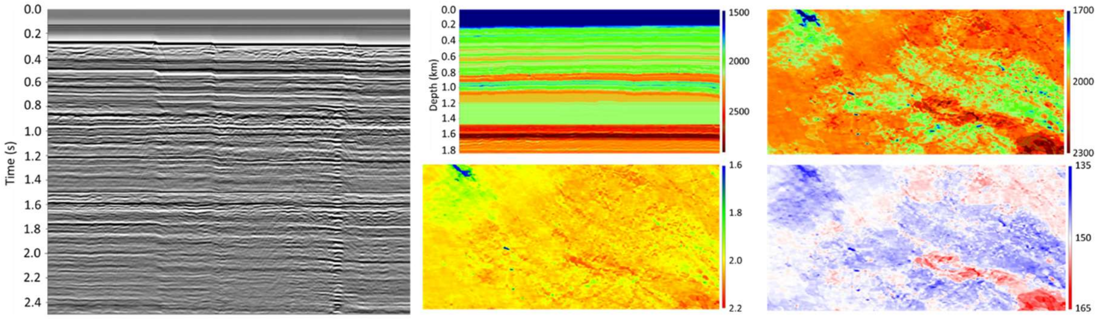

Figure 3 *Left: Common channel section of baseline survey after pre-processing steps (T^2-gain applied). Right: Vertical section through V_P model (top left, in m/s) and depth slices (800 m) through the full model area of V_P (top right, in m/s), density (bottom left, in g/cm^3), and Q_P (bottom right).*

Before large scale modelling of monitor data with different acquisition layouts, we predicted expected 4D attributes at various CO_2 saturations to ensure that the model will yield realistic 4D results. Figure 4 shows expected normalized root-mean-square (NRMS) amplitude differences and 4D time shifts at different CO_2 saturations for a 10% increase of CO_2 saturation between base and monitor. The values have been computed by propagating a 0-3-100-125 Hz Hanning bandpass filter through 60 m of reservoir rock using patch sizes of 1 cm and 5 cm. These levels of patchy saturation introduce differences in 4D response below about 25% CO2 saturation. Differences in expected broadband NRMS differences are explained by increased high frequency attenuation for larger patch sizes biasing the bandwidth towards lower frequencies with corresponding decrease in NRMS difference. Differences in 4D time shift are less pronounced.

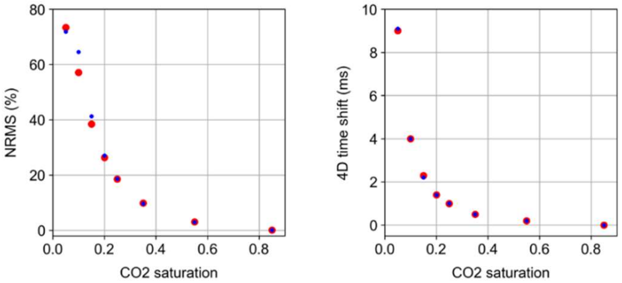

Figure 4 *Predicted NRMS difference (left) and 4D time shift (right) at different CO2 saturations for an increase in CO2 saturation of 10% between base and monitor surveys. Red: 5 cm patch size. Blue: 1 cm patch size.*

Conclusions

We demonstrated the seamless integration of a realistic geological background and a reservoir simulation model into visco-elastic property grids for finite difference modelling. A general background attenuation of P- and S-waves has been combined with reservoir specific attenuation effects due to WIFF using a single Maxwell body in each finite difference grid cell. Modelled baseline data show a realistic level of complexity, and we predict realistic 4D attributes. This model will allow a realistic assessment of the impact of different acquisition geometries and techniques in different time-lapse monitoring scenarios for deep saline aquifer CO_2 storage. With that solid foundation, further work in the CLEAN4D project aims to demonstrate that 4D repeatability requirements in time-lapse surveying can be relaxed while optimizing the value of time lapse seismic for different monitoring objectives.

Acknowledgements

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