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Tracing back the pressure-impact zone of the CO_2 geological storage through a cyclic injection strategy

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Abstract

Industrial-scale CO2 injection into deep aquifers might induce far-field pressure perturbations on the basin scale, potentially impacting other underground uses present within the same aquifer formation. In the present paper, we investigate an approach to trace back the area of elevated pressure induced by CO_2 storage operations through an injection strategy in a cyclic manner over time. In this manner, the CO_2 injection-induced pressure field is characterized by a low magnitude harmonic signature very specific to the considered CO_2 storage, the frequency being chosen as different to naturally fluctuating phenomena or other anthropogenic underground activities. We rely on the combination of de-trending and FFT technique to detect the harmonic pattern associated the CO_2 storage injections. We apply the methodology on synthetic pressure signal numerically generated using a typical injection scenario in the Paris basin case. On this basis, we discuss how trace back the CO_2 storage site causing the pressure impact, in particular regarding the existing sources of noise.

Keywords: CO2 geological storage; Far-field pressure perturbation; cyclic injection; Time series analysis; Harmonic Pattern

1. Introduction

CO_2 capture and geological storage is seen as a promising technology in the portfolio of measures required to mitigate the effects of anthropogenic greenhouse gas emissions (IPCC [1]). Among the available geological targets, storage in deep aquifers is recognized to offer very large potential storage capacity with a broad distribution throughout the world in all sedimentary basins. Recently, the potential large-scale hydrodynamic impacts caused by CO_2 injections have been identified as a major limiting

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factor to the wide-scale deployment of this newcomer in the underground space use, see e.g., IEA-GHG [2]. Numerous studies modeling CO_2 injection in deep aquifers using either large-scale single phase or multiphase flow numerical simulations have shown that as injection progresses, pressure increases within the injection formation over a relatively large region (of the order of several tens of kilometers), see e.g., Zhou and Birkholzer [3]. The pressure pulse travels much faster than the CO_2 plume, which has the potential to displace reservoir fluids, far from the CO_2 plume itself, hence potentially impacting fresh groundwater resources at the aquifer outcrops (see e.g., IEA-GHG [4]) or potentially hampering the performance, in terms of extraction rates, pore space available, injectivity, etc., of other underground uses (e.g., hydrocarbon and geothermal activities).

However, in a context where multiple underground uses are present within the same aquifer formation, tracing back the underground activity causing the observed pressure impact can turn to be a tedious and difficult task. The deep saline aquifer of the Dogger formation in the Paris basin (France) provides a good example of an aquifer targeted for CO_2 storage (Grataloup et al. [5]), which is currently exploited by petroleum and geothermal activities. Another good example is provided by the Mount Simon Sandstone in the context of Illinois basin (USA), which presents multiple underground usages such as natural gas storage and potable water exploitation (e.g., Zhou and Birkholzer [3]).

A parallel can be drawn with the issue of distinguishing natural biogenic CO_2 fluxes, anthropogenic CO_2 fluxes from industrial plants and CO_2 leaking from underground sources (petrogenic). Recently, techniques based on the carbon isotopic signature of CO_2 have brought very promising results (e.g., Krevor et al. [6]). In the present paper, we aim at following the idea of a signature, but from a hydrodynamic perspective, i.e. by assigning to the injection-induced pressure field a signature of hydraulic nature. This hydraulic signature should be very specific to the considered CO_2 storage so that if detected, the CO_2 storage site causing the impact can be traced back.

In this view, we describe, in a first section, a strategy relying on a cyclic injection of CO_2 over time and on the detection of the induced cyclic pattern associated to the pressure evolution. To support the study, the hydrodynamic response of a deep aquifer formation during cyclic CO_2 injection is investigated through large-scale multi-phase flow transport numerical simulations using TOUGH2/ECO2n (Pruess [7]). The carbonate Dogger aquifer is used as an application case. Finally, we show in a third section how to trace back the CO_2 storage site causing the pressure impact (i.e. to monitor the pressure-impact zone of the CO_2 storage) and discuss how to use such information in case of conflict of use.

2. Cyclic injection strategy

2.1. Principles

The proposed methodology relies on the cyclic injection of CO_2 over time into the aquifer formation. In this preliminary study, we assume that CO_2 is injecting at a constant injection pressure P_0. A low-magnitude (δP_0 e.g., of a few bars), a harmonic pressure signal (of time period T) is then added, so that the pressure-controlled injection P_{inj} over time t can be expressed as:

$$P_{inj}=P_0+\delta P_0.\sin(2\pi.t/T) \quad (1)$$

The harmonic (cyclic) pressure signal of equation (1) is expected to propagate with the pressure pulse induced by the injection within the reservoir. The evidence of such a phenomenon is empirically supported by the observations of piezometric levels in the vicinity of seasonal natural gas storages in aquifers. For instance, in the case of the natural gas storages of Lussagnet and Izaute in South-West France, cyclic patterns in the temporal evolution of the piezometric level are both reported in the vicinity of the injection zone (of magnitude of the order of several tens of bars (1 bar = 10^5 Pa)), but also several tens of kilometers away from the injection wells with magnitude of the order of 1 bar, see Figure 3.5, page 64 in IEA-GHG [4]. Such cyclic patterns can be correlated to the cyclic injection / withdrawal operations.

The basic idea is then to detect and extract the harmonic signal from the pressure time series. The issues associated with the detection and extraction procedure are further discussed in section 4. Provided that the cyclic pattern is known to be very specific to the considered CO_2 storage site (see discussion below), then such a signal can be considered its signature.

2.2. Designing the cyclic injection

Designing such a cyclic injection implies dealing with two main issues.

On the one hand, the cyclic pattern extracted from the pressure measures should be distinguishable from other fluctuating phenomena, so that the cyclic pattern can be unambiguously recognized as the specific signature of the considered CO_2 storage site. This imposes choosing a time period T different from:

1. other anthropogenic underground activities such as cyclic groundwater pumping, seasonal natural gas storage, with usually 1-year periodicity;

2. naturally-fluctuating phenomena, which can take several forms. The most usual phenomena inducing water level fluctuations are the barometric pressure changes and earth tides (see e.g., Toll and Rasmussen [8]; Chang and Firoozabadi [9] and references therein) of periodicity ranging from 12 to 24 hours. Other more complex natural fluctuations exist such as those associated to aquifer recharge derived from snow melt and early spring rains.

On the other hand, the pressure signal magnitude δP_0 during one cycle should fulfill different requirements:

1. the maximum injection pressure $P_0+\delta P_0$ should not exceed the maximum sustainable injection pressure, i.e. without geomechanical degradation (such as micro-fracturing and/or fault reactivation) of the sealing structures (Rutqvist et al. [10]) or/and drive fluid through conductive features into shallow groundwater resources (such as reservoir brine, see e.g., Birkholzer et al. [11]). It is worth underlying that such a value should be estimated case by case.

2. the constraints on the injection process should be minimized. Imposing a time-varying injection pressure leads to a temporal variation of the total amount of injected CO_2 so that extra amount of CO_2 compared to the case of constant injection pressure is necessary. A possible option is to use a temporary storage unit (tank) at the surface. Their capacity as those commonly used in the domain of gas ship transport (see e.g., IEA-GHG [12]) range from 10,000 to 50,000 tonnes.

3. Synthetic application case

3.1. Model set-up and parameters

The described methodology is applied using the application case of the carbonate Dogger aquifer in the Paris basin. This formation has been targeted for potential host of CO_2 geological storage (Grataloup et al. [5]). The aquifer layer is assumed to be of very large spatial extent (>100 km). The system considers one layer with a thickness of 40 m (1D-axisymetrical model). A no-flow condition is assigned to the lateral boundary and the system is considered closed with no exchange of fluid or heat with the upper and lower layers. The grid includes series of refined zones from the injection zone with a minimum grid cell size of 0.2m, to the aquifer margins with a maximum grid cell size of 1 km. Using average values based on Andre et al. [13] and references therein, homogeneous and isotropic properties are assigned to the aquifer formation. The mean porosity is 15% and the intrinsic permeability is assumed to be spatially homogeneous at 200.10^{-15} m². Note that the presence of heterogeneities (e.g. low permeable zones) are expected to have an influence on the frequency content of the pressure pulse (in a filter fashion for instance) and a future line of research will, therefore, focus on this aspect.

Capillary pressure and relative permeability model (and their parameters) are described in details in Andre et al. [13]. Initial temperature and pressure conditions respectively reach 75°C and 18.0 MPa. Salinity in the Dogger reservoir reach very low to moderate values (from 5 g of NaCl per 1000 g of water in the Southern part of the basin to about 30 g of NaCl per 1000 g of water in the Eastern part of the basin, Andre et al. [13]). The model was homogeneously assigned a mean value of 15 g of NaCl per 1000 g of water.

Numerical simulations are performed using the multi-phase, multi-component transport simulator TOUGH2 with the ECO2N Equation of State (Pruess [7]), which takes into account the thermodynamic and thermophysical properties of water–NaCl–CO_2 mixtures. The problem is assumed to be isothermal.

3.2. Analysis of the cyclic injection

The cyclic injection is performed by imposing a time-dependent pressure evolution (following equation 1) at the grid cell representing the injection wellbore. The constant injection pressure P_0 is chosen as ~20.0 MPa (1 MPa=10^6 Pa) so that approximately 1 million tons of CO_2 per year are injected through a single injection well. Accounting for the two constraints described in section 2, the time-period T is chosen as 200 days, and the low magnitude of the harmonic signal δP_0 as 2.0% of P_0 (0.4 MPa). The harmonic temporal evolution of the imposed injection pressure is depicted in Fig. 1A.

The small variation of injection pressure implies a variation in the injected amount of CO_2 (relatively to the one that would be injected with no variation in P_{inj}) corresponding to a maximum of about 40,000 t (see Fig. 1B), which is in good agreement with the capacity of existing storage unit (see section 2.2).

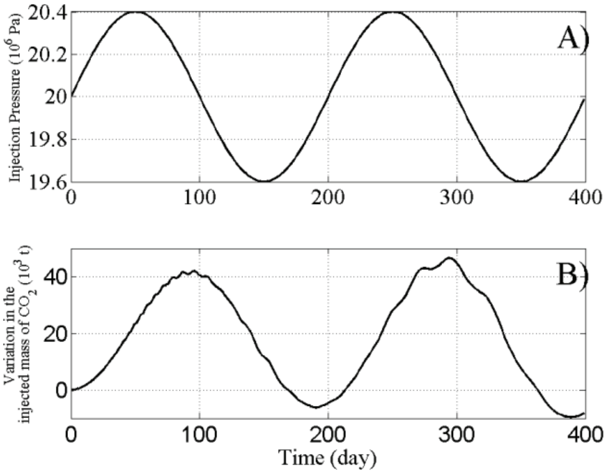

Fig. 1. (A) Harmonic temporal evolution of the imposed injection pressure with P_0=20 MPa (1 MPa=10^6 Pa), T=200 days and δP_0= 0.4 MPa (2% of P_0); (B) Temporal variation of the injected mass of CO_2 due to cyclic injection, relatively to the one that would be injected with no variation in P_{inj} (small oscillations are due to rounding errors in the post-treatment procedure)

Fig. 2 depicts the temporal evolution of the over- pressure (difference between the actual and the initial pore pressure) observed at different distances from the injection zone (2, 10, 20 and 40 km) over a time period of 1,000 days of injection (~2.75 years). This shows that the pressure pulse can travel very far. For instance the over- pressure reaches 0.15 MPa at a distance of 20 km after 1000 days of injection. Such an order of magnitude can be judged moderately significant regarding the risk of brine uplift through potential high- permeable conduits (Birkholzer et al. [11]). Yet, we show that the harmonic pattern is only distinguishable through a mere visual inspection for both cases at 2 and 10 km. Over 10 km, the pattern appears to be hardly distinguishable. Logically, increasing δP_0 implies detecting the harmonic pattern at farther distances, but this also means increasing the amount of temporally stored CO_2. In the next section, we show how to extract the harmonic signal using signal processing methods.

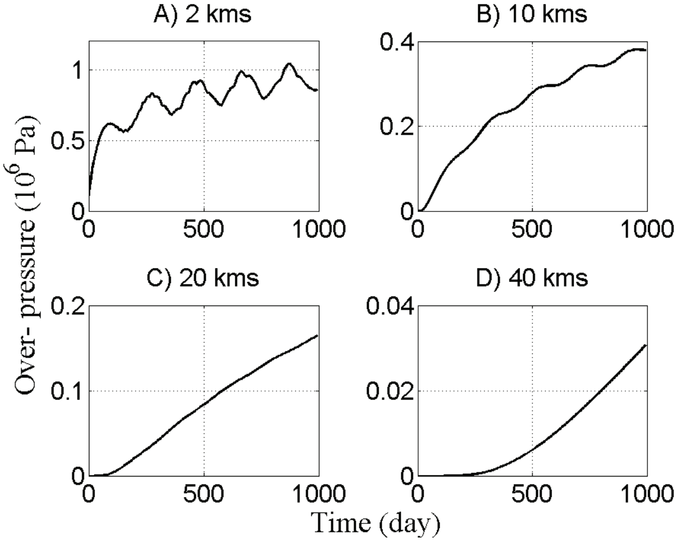

Fig. 2. Temporal evolution of the over- pressure (A) at 2 km away from the injection zone; (B) at 10 km; (C) at 20 km and (D) at 40 km. Note the differences in the choice of over- pressure scales used for each signal.

4. Tracing back the pressure-impact zone

Downhole pressure transducers - coupled with electronic data-loggers - are commonly used during ground water investigations to measure and record water levels in wells for long periods at relatively short intervals. Tracing back the pressure-impact zone implies detecting the harmonic pattern associated with the cyclic injection. The issue of extracting seasonal (periodic) fluctuations from these measures has long been studied in the field of hydrology and hydrogeology (see e.g., Toll and Rasmussen [8] and references therein) resulting in the development of several post- processing techniques, which basically rely on spectral analysis of time series.

A popular approach is the Fast Fourier Transform, denoted FFT, analysis (see mathematical description provided for instance by Edge and Liu [14]). This analysis relies on the representation of the data via Fourier series: instead of representing the signal amplitude as a function of time, an alternate is to represent the signal by how much information is contained at different frequencies, i.e. the coefficients of the Fourier series. The output of such an algorithm is the power spectrum of the signal representing the frequencies versus the square of the absolute value of the FFT coefficients (i.e. power of the signal).

One major difficulty associated with the considered signals is the presence of a trend, i.e. the average over time is not a constant, but a function of time, which can be non-linear (as illustrated by Fig. 2). A typical pre-processing step in spectral analysis is to de-trend the time series. This can be achieved by fitting a polynomial regression model (least-squares-fit) to the data and then remove it from the original data. More advanced techniques exist; please refer to Hamilton [15] for a review.

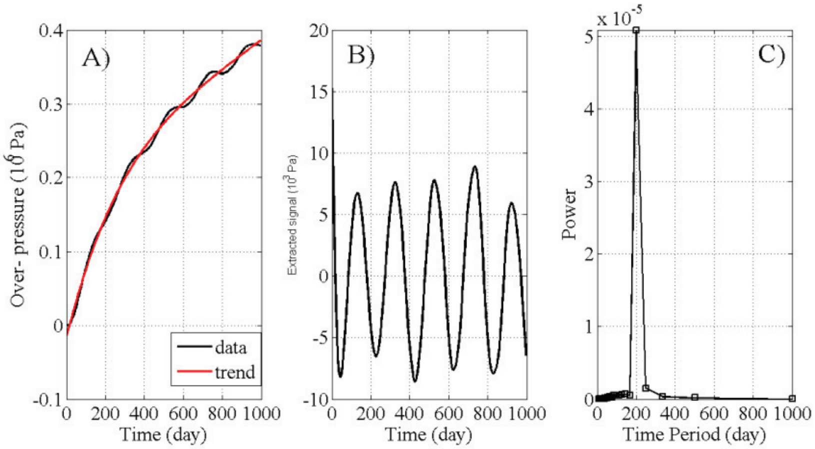

Fig. 3. (A) Pressure signal (black curve) at 10 km from the injection zone and the associated trend fitted by a polynomial model of the order 5 (red curve); (B) Pressure signal extracted from the original signal by removing the trend; (C) Power spectrum (expressed in time period versus power) computed through FFT analysis of the extracted signal.

Fig. 3 illustrates the procedure for data where the harmonic pattern can be detected through visual inspection. Fig. 3A the original pressure signal observed at 10 km and the associated trend fitted by a polynomial regression model of order 5. Fig. 3B shows the output (extracted signal) of the de-trending procedure. Applying the FFT analysis, the power spectrum (Fig. 3C, note that it is directly presented in terms of time period versus power) clearly shows a peak at the time period of 200 days. Fig. 4 illustrates the procedure for the pressure signal at 20 km with no visual detection of harmonic pattern.

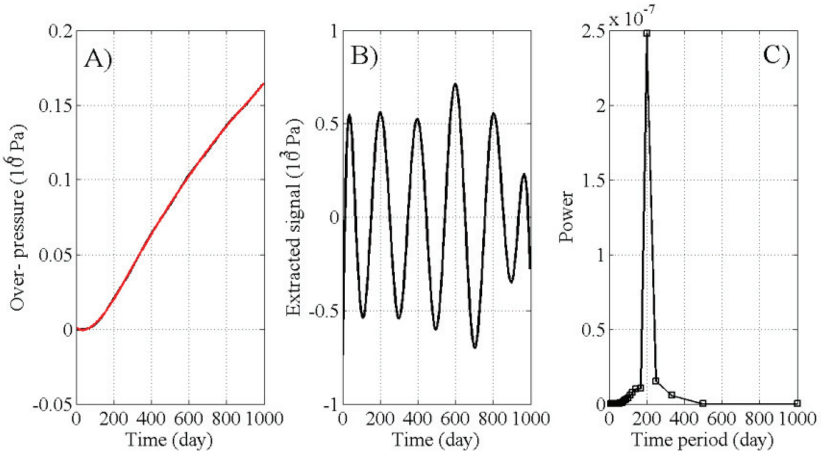

Fig. 4. (A) Pressure signal (black curve) at 20 km from the injection zone and the associated trend fitted by a polynomial model of the order 7 (red curve); (B) Pressure signal extracted from the original signal by removing the trend; (C) Power spectrum (expressed in time period versus power) computed through FFT analysis of the extracted signal.

Yet, the afore-described analysis is conducted on synthetic data and structures of real data are expected to be far more complex and associated with different sources of noise. On the one hand, as mentioned in section 2, fluctuations caused by gravitational Earth tides and barometric pressure fluctuations, which can be on the order of 100 – 1,000 Pa (see e.g., Chang and Firoozabadi [9]), should be filtered, hence potentially introducing processing errors. On the other hand, the proposed monitoring should be conducted over long time periods (years), and pressure transducers are known to “drift” on long term, which can interfere with the detection of the harmonic pattern. Based on the approach of Chabora and Benson [16], a cutoff of 1,000 Pa was used to categorize the detection potential as “unlikely” so that the harmonic pattern should be detected at 19 km away from the injection zone.

Such a distance can then be considered as the maximum spatial extent, according to the harmonic amplitude used in this study, at which it is possible to ascertain that the pressure perturbation (here of the order of $1.5\ 10^5$ Pa after 1,000 days of injection) is due to the CO_2 storage operations. This distance should be put in perspective from a conflict of use point of view: this method can be useful to manage conflict of use from underground activities like hydrocarbon exploitation, deep geothermal activities, but at such a distance, activities related to the exploitation of drinking water may not exist. A future direction of improvement of the proposed technique is to quantify, in such a context of multiple uses of the underground, the proportion of the overpressure due to the CO_2 storage only (relatively to the over-pressure due to other activities).

5. Concluding remarks and further work

Industrial-scale CO_2 injection into deep aquifers might induce far-field pressure perturbations on the basin scale, potentially impacting other underground uses present within the same aquifer formation. We propose an approach to assign to the injection a signature of hydraulic nature through an injection strategy in a cyclic manner over time. If detected, it would be possible to “clearly” identify the CO_2 storage site causing the observed hydrodynamic impact.

Based on synthetic pressure signals numerically generated using a typical injection scenario in the Paris basin case, the present study defines the basis and discusses the difficulties (especially regarding the existing sources of noise) for such the detection of the hydraulic signature.

Further works should confront the proposed methodology to complex real pressure signals. Complexity can arise from noise, but also from the phasing of the CO_2 capture and transport process. In the present preliminary study, we have assumed that the CO_2 is injected at a constant pressure (to which a cyclic signal is added). This assumption may not be valid for industrial real injection operations. See for instance the complex pressure time series at the Ketzin site ([17]: Fig. 2). Hence, as a future line of research, we can envisage taking advantage of this process-related complexity to define the hydraulic signature specific to the CO_2 storage site.

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