Experiences with a permanently installed seismic monitoring array at the CO2 storage site at Ketzin (Germany).

- A status overview -

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Abstract

Since July 2008, CO2 is injected into a saline aquifer near the town of Ketzin in Germany. For monitoring the CO2 migration close to the injection well, TNO installed a fixed 2D seismic array of 120 meters length in 2009, with 3-component geophones at the surface, 4-component receivers at 50 meters depth and a central vertical array of 4-component receivers. This specific test acquisition set-up was and is being used both for the recording of high-quality active time-lapse seismic data as well as for continuous passive seismic data recording. The latter gave rise to the identification of a large number of surface noise related events and some very weak events possibly originating from the deeper subsurface.

The active seismic data acquisition consisted of a conventional repeat survey after 2 years using an accelerated weight drop source, as well as a test with a prototype semi-permanent source located at the site during a period of 3 weeks in which CO2 injection was stopped. In both cases subtle changes at the reservoir level have been observed, though the limitations of the experimental lay-out make it difficult to come up with firm conclusions in terms of CO2 induced pressure and saturation changes. Further analysis of the data is ongoing work.

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1. Introduction

CO₂ has been injected since June 30th 2008 in well Ktzi 201 into a saline aquifer near the town of Ketzin, west of Berlin in Germany [1]. Currently about 61 kTonnes CO₂ are injected. Two additional observation wells, Ktzi 200 and Ktzi 202, were drilled prior to injection to a depth of 750 m to 800 m at a distance of 50 m to 100 m from each other (Figure 1). At the far monitoring well Ktzi 202 breakthrough of CO₂ has been observed in March 2009. TNO designed and implemented a seismic monitoring system in 2009 consisting of vertical and horizontal geophones and hydrophones at different locations along a line and at different depths [2]. This system has been used to continuously record passive seismic data. A summary of the results will be given in section 2.

Besides passive seismic listening this monitoring system was used to record data for an active survey carried out on October 29th 2009, results are shown in [2,3]. The imaged 2D line obtained with this survey is virtually crossing the monitoring well Ktzi 202. A repeat survey with the same seismic source was acquired in October 2011, two years later. Results are shown in section 3.

Starting in May 2012, a third observation well Ktzi-203 penetrating the reservoir, is being drilled. Because of the drilling operations, injection of CO₂ has been stopped temporarily on May 18th 2012. A period of a month around this date has been used to test a prototype semi-permanent seismic source [4] in order to create a “true” 4D seismic monitoring system. Preliminary results are shown in section 4.

Finally section 5 describes the first attempts to apply seismic ambient noise interferometry on the vast dataset of Ketzin. In this section the results of a synthetic feasibility study will be shortly presented.

Fig. 1. Air photo (courtesy GFZ) of the site with the locations of the injection well (Ktzi 201), the two monitoring wells (Ktzi 200 and Ktzi 202) and the newly drilled well (Ktzi 203) indicated. The location of the permanent source is indicated with a light blue dot, the location of the 120 m long TNO array is (approximately) indicated with a dark blue line, the numbering of the 10 m spaced boreholes from 1 to 13 is from right to left. The visible part of the shot line used for the 2D seismic data acquisition is indicated with a red line (Note, that this shot line continues on the right hand side out of the picture).
1.1. Geology

The Ketzin storage site is located at the southern flank of a gently dipping anticline, which formed above a salt pillow situated at a depth of 1500–2000 m. The target formation for CO$_2$ injection is the Stuttgart Formation of Triassic age, located at a depth of about 650 m. The Stuttgart Formation, is on average 80 m thick and lithologically heterogeneous: sandy channel-(string)-facies rocks of good reservoir properties alternate with muddy, flood-plain facies rocks of poor reservoir quality ([5], [6]).

The thickness of the sandstone interval may attain several tens of meters where sub-channels are stacked. The top seal of the Stuttgart Formation is the Triassic Weser Formation. The Weser Formation, deposited in a clay/mud/sulfate playa environment, consists mostly of mudstone, clayey siltstone, and anhydrite as observed on well logs and on 30 m core obtained in the CO$_2$ Ktzi 200 and CO$_2$ Ktzi 201 wells [7]. The top of the Weser Formation is a 10 to 20 meter thick anhydrite layer generally referred to as the K2 reflector, situated about 70 meters above the reservoir. This reflector is very clear on 2D and 3D surface seismic data [8]. The overburden of the storage formation contains several aquifers and aquitards.

1.2. Layout of the permanent seismic monitoring system

TNO designed and implemented a permanently installed seismic monitoring system based on [9]. This system is used for both passive and active seismic observations. It consists of receivers placed at 13 locations (TNO-01 –TNO-13). On each location a 3 component geophone and a hydrophone were placed at 50 m depth. At 8 locations, geophones were also located at the surface. Additionally, geophones and hydrophones were placed at 10 m depth intervals at location TNO-07. The location of shots and receivers is shown in Figure 1, common-depth-points (CDP) are located in between. The distance between the boreholes is about 10 m. The layout of the receivers in depth is shown in Figure 2.

The geophones and hydrophone were mounted in one receiver casing and connected to a cable with depth marks. The sensors at depth were placed in shallow boreholes, that only penetrated the quaternary sediments. In fact, their bottom is located hardly above the Quaternary - Paleogene transition, which varies from 50 to 60 m below surface as observed in the three wells drilled at the storage site. The receivers were lowered in the drilling mud in the borehole down to the desired 50 m depth. Subsequently a grouting was added to the drilling mud with the intention to stiffen it and improve the coupling.

![Fig. 2. Layout of the individual geophones and hydrophones in the 13 boreholes (TNO-01 to TNO-13 from right to left). The hydrophone trace numbers are indicated in red.](image-url)
2. Passive seismic monitoring

Since September 2009 passive seismic data have been recorded continuously with a sample rate of 2 msec using the permanent array. This has resulted in a huge dataset of Tbytes of data up to now. A procedure has been developed to automatically detect and locate very low magnitude seismic events [10]. The procedure consists of three main steps: (step 1) A quality control step, (step 2) a noise suppression & event picking step and (step 3) an event localization step. The approach is completely data-driven. A result of a noise-suppressed gather (step 2) for all receivers is shown in Figure 3, where both a P-wave and an S-wave arrival can be observed. Note, how the S-wave event disappears (as expected) on the hydrophone data.

A full description of the first results is given in [11], including a calibration test with a known surface source, where two months of data have been investigated in detail. Over 20,000 seismic events were detected automatically during this period, of which the 200 strongest ones were analyzed in more detail. Localization of these 200 events learned, that more than 99% originate from a single location at the surface, most likely related to industrial activity. Much weaker events originating from the subsurface have been observed as well.

Additional hodogram analysis has been carried out for these events. This is illustrated for one of the events in Figure 4. Note the clear P-wave response in blue. The shear wave polarizations are less clear. Using a laterally invariant velocity model derived from well log data, the most likely localization of the event is in the depth interval of 600-1000 m and at a distance of 500-1000 m east of the array. There seems no connection to the CO2 injection, that takes place at only a few meters from the array (Figure 1).
3. Active time-lapse seismic data acquisition

Two active seismic surveys have been conducted, one in October 2009 and one in October 2011. For these active surveys the sampling frequency has been temporarily increased from 500 to 2000 Hz. Both active datasets were acquired after CO₂ injection started, therefore making it more challenging to relate observed changes to potential CO₂ migration or pressure changes. Nevertheless, some changes can be observed. No attempt has been made so far to further quantify the observed changes. These changes are close to the limits of detectability and repeatability.

Fig. 4. Example of a hodogram corresponding to a weak, deeper event with the P-wave polarization in blue and the S-wave polarization in red. The event is originating most likely from a depth between 600 – 100 meters at a distance of 500 – 1000 meters. The uncertainty in localization is largely due to the 2D-geometry of the array and, to a lesser extent, to the uncertainty on the velocity model.

Fig. 5. Zoomed in part of the seismic data from 400 msec to 600 msec with the baseline (left) acquired in 2009 and the repeat (right) in 2011. Note however, that in both cases CO₂ was already injected in the reservoir. Subtle changes can be observed at the reservoir level (circled in red) just below the strong K2 reflector at 470 msec. The CDP spacing on the horizontal axis is 5 m.
4. 4D seismic data acquisition using a permanent source

As described in the previous section, results of the time-lapse seismic data acquisitions of the 2D lines in October 2009 and October 2011 only indicate very small changes at the reservoir level, barely above the noise level of the repeatability. A new experiment was set up to investigate, whether the use of permanent sources can enhance the repeatability and resolution even more. The new experiment was centered around a period, where injection stopped, such that besides saturation effects, one could expect to see a maximum effect of pressure relaxation in the vicinity of the injection well. The increased repeatability and resolution due to the permanent source and receiver system in combination with the potentially larger effect of pressure relaxation should then lead to a more pronounced time-lapse response.

From May 4 to May 29, 2012, a “permanent” source has been temporary installed at Ketzin. Strictly speaking the definition of a permanent source in this context is a source emitting a seismic signal continuously. Though technically this is possible with the source selected [4, 12, 13], in this experiment the source has been operational only for about one hour per day. This had to do essentially with safety procedures (a person had to be present when the prototype source was in operation). The source was installed at a fixed position (Figure 1) and during each hour typically 60 shots (or sweeps actually) were emitted. During this measuring period, injection of CO2 was stopped (May 18, 2012) due to the drilling of the new well Ktzi-203.

The source itself is a highly innovative prototype source under development at the Technical University of Delft. It is a vibrator system driven by linear motors. This principle leads to a 6.5 kN ground force for a frequency bandwidth of 2 to 200 Hz, with high repeatability. More information can be found in [4], [12] and [13]. A photo of the source being installed at Ketzin is shown in Figure 6.

![Photo of the installation of the permanent seismic source at Ketzin.](image)

Results of the experiment so far do show a high repeatability of the shots, higher than acquired with the more traditional source of the repeat survey in October 2011. Of course the spatial coverage is much less, since only one shot position is available. Preliminary identified problems encountered are, that
unexpected arrivals (most likely a mix of shear waves and converted waves) seem to mask the imaging at the reservoir level. Processing of the shots is still ongoing, but these reflections make the interpretation in terms of pressure response more difficult and non-conclusive so far. A solution to this problem is to change the location of the source. This is not as straightforward as it sounds due to the available space and infrastructure and to the time-consuming installation of the source. Some initial tests however have been performed at the end of the measurement campaign in May 2012. Overall this first period of measurements served as a test to gain experience with the operations of the source and its optimal location, a second test is envisaged as soon as injection resumes towards the beginning of 2013.

5. Monitoring with ambient seismic noise interferometry

A recent seismic technology development exploiting passive seismic reflection data is the application of ambient noise seismic interferometry [14, 15, 16]: noise registrations continuously measured over a long period of time are correlated with each other to produce P-wave reflection data as if these were generated by active seismic sources at the surface. These data can be interpreted in terms of contrasts in elastic subsurface layer properties. We decided to test the feasibility of using this technique in a time-lapse application for the monitoring of CO$_2$-migration paths in the subsurface at the Ketzin site. Particularly the vast amount of data covering more than two years of continuously recorded data made us optimistic about the success of applying this method. Initial synthetic results are promising: Figures 7a-c show the differences between the responses for two scenarios representing a base case without CO$_2$ saturation and a ‘monitor’ case with a CO$_2$ saturation that causes a 20% P-wave velocity decline in the reservoir interval.

The responses of these two scenarios are obtained by cross-correlating synthetic continuous noise recordings from TNO’s horizontal array of vertical geophones at the surface with noise sources distributed in various horizontal distance intervals (Fig. 7a-c). The reference response of Figure 7d has been calculated using an active source in the center of the horizontal array at the surface. We can see that amplitude differences between the passive noise reflection responses of the two scenarios are relatively insensitive for the noise source location distribution and that the differences occur in the two-way-time interval predicted by the active source modeling.
6. Discussion and conclusions

At the Ketzin CO\textsubscript{2} storage demonstration project site in Germany, both passive and active seismic data were recorded with a dedicated permanent array installed both at the surface and in the shallow subsurface (50 m depth). These data were used to detect micro-seismicity and obtain high-resolution reflection information at various stages of CO\textsubscript{2}-injection.

Concerning the passive seismic data analysis, the array is suitable for the detection of events, particularly the buried hydrophones. The vertical array helps to distinguish between up- and downgoing waves. The geometry of the array is not optimal for estimating the source location. This was known upfront, but no alternatives were possible due to financial and infrastructural restrictions. Hodogram analysis supports the localization analysis, but most hodograms are quite noisy due to the low amplitudes of detected events. No events directly linked to the CO\textsubscript{2} injection have been detected.

The encouraging results produced from noise source modeling have provided support for the idea to use ambient noise interferometry for monitoring the migration of injected CO\textsubscript{2} using the continuously recorded data. Real data processing with this new technique is currently ongoing.

Concerning the active seismic data analysis, it is clear that differences between baseline and monitoring data are very subtle and changes observed are barely above the threshold of repeatability noise. Again, this has partially to do with the 2D geometry of the array, but also with the lack of a true baseline acquired prior to CO\textsubscript{2} injection. The differences between a situation prior to injection and after injection are expected to be largest.

In order to increase the repeatability of the active seismic monitoring, a first experiment with a permanent seismic source has been carried out. This first test was centered around a period, where injection stopped. One could expect to see an effect of pressure relaxation in the vicinity of the injection well, where the system is monitoring. Experiences with this first experiment are meant to tune a second experiment, that is envisaged beginning 2013, when injection resumes. For this second experiment a more suitable location will be selected with less influence of both shear and converted waves disturbing the signal at reservoir level. What can be learned from the first experiment though is, that the repeatability of both fixed receivers and a fixed source is high.

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