C010

Design of Passive Seismic Monitoring for Underground Gas Storage in the Vienna Basin, Austria

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SUMMARY

We present a case study for designing a passive seismic monitoring network in a large underground gas storage site. The study included measurements of background seismic noise at selected locations across the site and background seismic noise along a string of receivers cemented in a shallow monitoring borehole. We measured the noise levels over a period of three months and studied the background seismic noise reduction in the shallow monitoring borehole. Specifically this study reveals a significant decrease with depth of the temporal variations in background seismic noise levels at the shallow monitoring borehole relative to the surface. We compare location accuracy from the downhole and surface monitoring arrays, and combinations of these to determine the optimal monitoring array. We also evaluate the detection threshold for microseismic events in the proposed shallow borehole monitoring array based on measured noise levels and empirical observations of microseismic events in similar reservoirs.

Introduction

Passive seismic monitoring has become a tool of choice for hydraulic fracture optimization. Recently, permanent arrays are gaining popularity as they provide consistent monitoring over long period of time in support of reservoir management activities (Duncan and Eisner, 2010). Microseismic monitoring of underground gas storage (UGS) sites around the world has been used for several decades (e.g., Deflandre et al., 1995; Maisons et. al., 2006) providing information on optimal placement of the stored natural gas and monitoring of activated faults. Optimal passive seismic monitoring is dependent on array coverage spanning the UGS reservoir in a consistent and continuous manner for the life of the UGS facility. In this study we investigate the optimal design of a monitoring array for the deepest level of a proposed underground gas storage in a fractured reservoir near Vienna, Austria (De Kok et al., 2006). In particular, we investigate optimal sensor string placement in wells decommissioned after the final stage of pre-UGS production. We combine our passive seismic results with background noise measurements and estimated the threshold of detectability for microseismic events for the proposed monitoring array.

Uncertainty of locations

The proposed new UGS is located in the Vienna Basin northeast of Vienna. It will be an extension of an existing UGS positioned in the Neogene section of the Vienna basin. The new proposed storage site utilizes a depleted reservoir which consists of dolomites, exhibits high permeability, and has sufficient storage capacity to make it a good site for UGS operations. Figure 1 shows a map of the top of the reservoir of the proposed UGS site with existing deep and shallow (less than 1000 m) wells. Shallow wells are continually being abandoned. Note the expected extent of the gas storage exceeds 2x6 km. The gas storage interval intersects several faults that act as fluid flow barriers. The purpose of the microseismic monitoring is to monitor the integrity of those seals, particularly associated with the largest faults; No. 13, 14 and 18. Figure 1 also shows a large number (more than 80) of wells that are currently used for reservoir extraction that, if abandoned, can be used for monitoring of any UGS induced seismicity. However, only seventeen wells penetrate to 3 km depth where the new UGS interval is proposed and only 1 or 2 of these wells can be abandoned and used for monitoring. Six shallow wells shown in Figure 1 will be abandoned in 2011 and can be used for initial monitoring, however none of these wells is deeper than 1500 m.

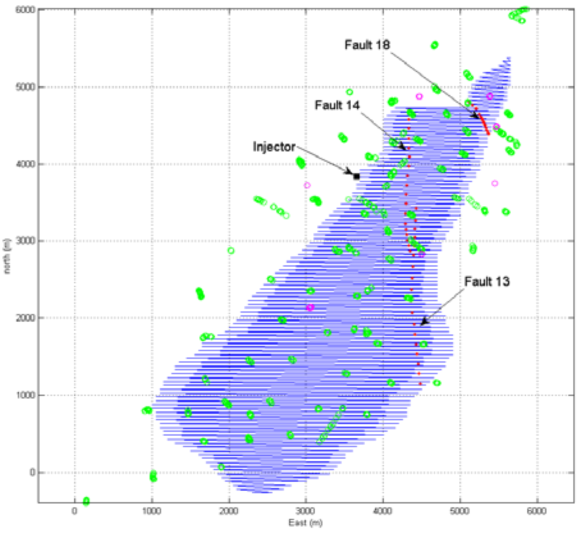

Figure 1. Map view of the expected extend of the UGS site (blue lines) with existing and potentially abandoned wells (green circles, including their 3D trajectories) and 2011 abandoned wells (violet circles). Locations of the largest faults No. 13, 14 and 18 are represented red dotted lines. Wellhead of the nearly vertical injector borehole is shown as a black square.

We considered three possible designs of the monitoring array:

- Downhole monitoring from one or two boreholes with vertical arrays of geophones spanning the UGS interval.
- Shallow borehole monitoring array with approximately 12 geophones deployed in shallow sections of the abandoned wells and additional 21 purpose drilled shallow boreholes, each containing an array of (vertical) geophones.

- A combination of the downhole and shallow borehole monitoring arrays listed above.

The shallow borehole array design is guided by a requirement to install receivers at lateral offsets approximately equal to the depth of the reservoir. Figure 1 shows the extent of wells across the southwest sector of the reservoir but insufficient coverage in southeast, northwest and northeast; these sectors are accommodated with the proposed 21 purpose drilled shallow boreholes.

Event Location	Shallow borehole array	Combined	Dual downhole
Fault 13	6, 9, 15	9, 5, 14	1, 4, 22
Fault 14	5, 5, 12	12, 6, 1	1, 1, 1
Fault 18	6, 6, 9	7, 4, 21	1, 1, 24
Injector	6, 6, 12	7, 5, 9	1, 1, 12

Table 1. One standard deviations (in meters) for locations of hypothetical microseismic events in the UGS. The three numbers in each line and column represent 1-σ standard deviations in east, north and vertical direction for an microseismic event detected on a given monitoring array. Shallow borehole array is composed of twelve 350 m deep arrays of geophones combined with twenty-one 100 m deep geophone arrays. Combined array assumes monitoring from a single monitoring borehole and shallow borehole array. Dual downhole represents monitoring array from two boreholes in the vicinity of Fault 14.

We used the methodology of Eisner et.al. (2010) to calculate uncertainties of hypothetical microseismic events from the proposed monitoring arrays. We assumed 2 ms (Gaussian) uncertainty in arrival times and 10^o uncertainty in backazimuth (see Eisner et.al., 2010 for more discussion on backazimuth uncertainty) on borehole array estimates even for events up to 2 km away and 4 ms uncertainty on the shallow borehole array receivers. Table 1 shows one sigma uncertainties for location errors of microseismic events in the vicinity of the three largest faults (faults No. 13, 14, and 18 in Figure 1) and the injector. As the anticipated storage volume is rather large (see Figure 1) the faults where microseismic activity should be monitored are several kilometers apart thus it is impossible to design a dual borehole array such that both boreholes are within 500 m of all faults. Despite this we assume that P and S-waves are detected on all downhole geophones for each hypothetical microseismic event. Table 1 presents the case where both boreholes are within 500 m of Fault 14, while the 'combined' array includes the shallow borehole array combined with a single 'downhole' borehole close to Fault 14. It is surprising that adding a single monitoring borehole decreases horizontal uncertainty for the Combined array; however, adding a single monitoring borehole far from microseismic events can decrease overall location accuracy. While having two monitoring boreholes significantly decreases horizontal uncertainty, it actually increases vertical uncertainty especially for events located far away from the boreholes. This is due to poorly constrained vertical positioning of hypocenters as was shown by analysis of Frechet derivatives for dual borehole monitoring (Grechka, 2010).

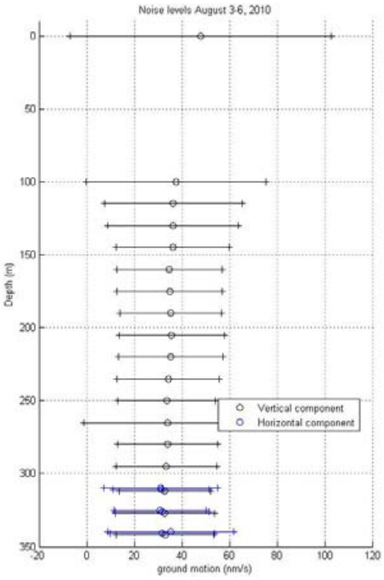

Figure 2. Noise levels measured along a vertical profile. Open circles represent an average RMS value from 1 second intervals. The horizontal bars represent standard deviations of these RMS values.

Data

This survey design case study also benefited from noise measurements carried out at the sites of wells scheduled for abandonment in 2011 (see Figure 1), and in a vertical array of geophones in an abandoned borehole. Prior to this study, it was not clear if an abandoned borehole can be used for a near surface shallow borehole array owing to concerns over casing cement bond integrity. In this case, the quality of the bonding seems to be very good (these boreholes were drilled and cemented by OMV service department) as receiver-to-receiver signals show a high degree of consistency and the downhole amplitudes are consistent with amplitudes observed at the surface, free surface correction (see Eisner et.al., 2011 for more details). In Figure 2 we present average RMS values of background noise levels observed during 4 days in August, 2010. The observed noise levels and their scatter (represented by standard deviations in Fig. 2) are characteristic for the period of 3 months. Note, that the average noise level drops from approximately 50 nm/s to less than 40 nm/s at 100 m depth and to approximately 30 nm/s at depths greater than 300 m. We also observed similar noise levels on both vertical and horizontal components in the deepest geophones. The true particle velocities observed on surface geophones were benchmarked with a highly sensitive Guralp® seismometer. One important aspect of the background noise levels shown in Figure 2 is a reduction of the noise scatter with depth. This is perhaps a more important factor for use of the shallow borehole monitoring array than the reduction of the average background noise itself as the shallow boreholes provide a more consistent detection threshold throughout the monitoring. Figure 3 shows ratios for the 10th and 90th percentiles of noise levels between the vertical component of a geophone at 340 m depth and the vertical component of a surface geophone. We show the ratios of low and high percentile noise since instantaneous values of particle velocity vary greatly from time to time along the shallow borehole profile, but the 1 minute averages are remarkably stable (none of ratios is less than 2). Note that the noise level ratios (as well as noise levels) show larger ratios (more reduction with depth) during daytime periods. Furthermore, the high value ratios (i.e. high reduction in noise) are almost exclusively associated with the 90th percentile. Both observations are consistent with downhole geophones being more decoupled from surface cultural noise and the majority of the surface noise being of cultural origin – note that the noise reduction is on average lower during the weekends of 7-8, 14-15 and 22-23 of August, 2010.

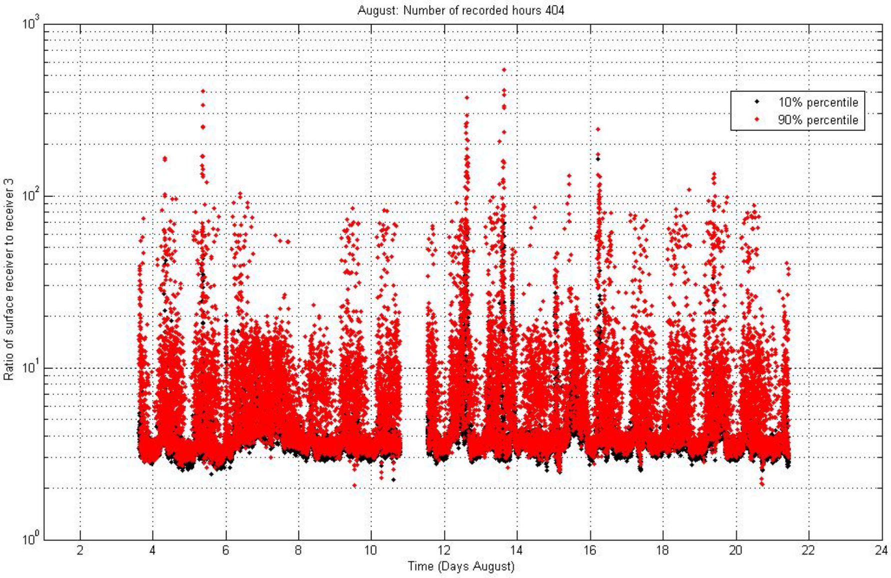

Figure 3. Ratios of average noise levels for a borehole phone at 340 m depth versus a surface phone for 10th and 90th percentiles of RMS noise level.. The black dots represent ratios of 10-percetile (quiet periods in the noise) and red dots represent 90-percetiles. The percentiles are evaluated from 1 minute periods of 60 1 second RMS measurements.

Detection threshold

Assuming that the measured noise levels in the shallow borehole are representative of the entire shallow borehole array we can calculate an approximate detection threshold for microseismic events from such an array. Both abandoned and purpose drilled shallow borehole sites would be equipped with 3 levels of vertical geophones experiencing 30 nm/s and 40 nm/s average noise levels for the 12 deep sites (in abandoned boreholes) and 21 shallower sites (purpose drilled 100 m deep boreholes), respectively. Assuming uncorrelated noise at each geophone (this condition implies a minimum geophone spacing in shallow boreholes), such an array should enhance signal to noise ratio (SNR) with amplitude A (in nm/s) by stacking as the square root of the number of geophones:

$$SNR = \sqrt{12}\frac{A}{30} + \sqrt{21}\frac{A}{40} = A\,0.23$$

Requiring *SNR* to be at least 3, we can see that the proposed shallow borehole array will be able to detect signals with amplitude $A>13$ nm/s. Based on our empirical measurements from reservoirs at similar depths we can assume that a microseismic event with (moment) magnitude -0.5 (i.e. moment of $10^{8.3}$ Nm) has peak particle velocity amplitude of 400 nm/s, thus the detection threshold of the shallow borehole monitoring array is approximately moment magnitude -0.5 + log(13/400) ≈ -2.0 or a moment of $10^{6.1}$ Nm. This result means we should be able to detect events with a moment greater than $10^{6.1}$ Nm (i.e. moment magnitude -2) by stacking P-waves and the resulting stack should have signal-to-noise ratio larger than 3.

Conclusions

We have shown that the shallow UGS borehole array provides the most consistent uncertainty in location estimates for simulated microseismic events across the entire site. Microseismic monitoring with downhole arrays would require more than 2 dedicated boreholes. The noise measurements in vertical profile reveal significant background noise level reduction with depth allowing for design of a sparse shallow borehole based monitoring array consisting of abandoned and purpose drilled boreholes. Noise levels observed in shallow boreholes allow estimates of microseismic events detection with seismic moment greater than $10^{6.1}$ Nm (i.e. moment magnitude -2).

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