Project acronym and title:

SECURe – Subsurface Evaluation of Carbon capture and storage and Unconventional risks

REPORT FOCUSING ON BEST PRACTICE METHODS TO ESTABLISH BASELINE LEVELS POST OPERATIONAL ACTIVITY

Authors and affiliation:
Niels E. Poulsen [1], Tine Larsen[1]

[1]Geological Survey of Denmark and Greenland (GEUS),
Øster Voldgade 10, DK-1350, Copenhagen, Denmark

Email of lead author:
NEP@GEUS.DK

D3.2

Revision:1

Disclaimer

This report is part of a project that has received funding by the *European Union's Horizon 2020 research and innovation programme* under grant agreement number 764531.

The content of this report reflects only the authors' view. The *Innovation and Networks Executive Agency (INEA)* is not responsible for any use that may be made of the information it contains.

Project funded by the European Commission within the Horizon 2020 Programme	
Dissemination Level	
PU	*Public*
~~CO~~	*~~Confidential, only for members of the consortium (incl. the Commission Services)~~*
~~CL~~	*~~Classified, as referred to in Commission decision 2001/844/EC~~*

Deliverable number:	**D3.2**
Deliverable name:	**Report focusing on best practice methods to establish baseline levels post operational activity**
Work package:	**WP 3. Environmental base line and monitoring strategies**
Lead WP/deliverable beneficiary:	BRGM/GEUS

Status of deliverable		
	By	**Date**
Submitted (Author(s))	**Poulsen, N., Larsen, T.**	**11th Sept. 2019**
Verified (WP leader)	W Kloppmann	12/9/19
Approved (EB member)	E Hough	13/9/19
Approved (Coordinator)	E Hough	13/9/19

Author(s)		
Name	**Organisation**	**E-mail**
Tine Larsen	GEUS	tbl@geus.dk
Niels E. Poulsen	GEUS	nep@geus.dk

Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURe comprise recommendations for best practice for unconventional hydrocarbon production and geological CO2 storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate best practice. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURe partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

Executive report summary

Establishing a post-operational monitoring baseline for detection of induced/triggered (anthropogenic) seismicity is not straight forward. Ideally, a baseline of natural seismicity is established in the undisturbed subsurface and before any operational deployment. If not the case, an alternative approach should be pursued to compensate for lack of pre-operational data.

The present report suggests the approach, to establish a micro-seismicity post-operational baseline by measuring in similar geology under a similar tectonic regime and compare the undisturbed site with the site in operation. The method might however, only be applicable in areas with a relative high level of natural seismicity in order to minimize uncertainties in noise levels.

The approach is tested in the SECURe project, where ongoing micro-seismic data acquisition is deployed around an operating natural gas storage facility in Denmark. The acquired data can be compared with an existing pre-operational micro-seismic baseline obtain at a drilling test site for shale gas. The drilling site is approximately 200 km from the gas storage facility, but the geology is similar. Data acquisition will be continued throughout the SECURe project.

Contents

Public introduction ii

Executive report summary ii

Contents iii

1 Introduction 4

2 Baseline monitoring 5

2.2 Establishing a baseline post-operational 8

2.3 Conclusions 8

3 References 9

1 Introduction

Exploitation of the subsurface for a wide range of purposes such as hydrocarbon production, CO_2 and natural gas storage, waste water disposal, geothermal energy production, shale gas fracking etc. can lead to an increased level of seismicity around the operation facility. As increased seismicity can lead to potentially damaging effects and to strong public concern, it is compulsory to improve methods to distinguish between natural seismicity and induced/triggered seismicity.

Knowledge of induced and triggered earthquakes is important for guiding risk assessment processes and setting up mitigation measures, such as a traffic light system (e.g. Koppelman et al., 2012, de Pater & Baisch, 2011, Cherry et al., 2014). A fundamental part of this process is to establish the baseline level of natural seismicity in the area.

Risk assessment is considered a key element in a CO_2 storage project, as exemplified by the prominent position of risk assessment in the various regulatory documents including the EU storage directive and the ISO/TC265 (2018). The most important tool for successful risk management is monitoring, i.e. "a continuous or repeated observation of a situation to detect changes that may occur over time". The essential role of monitoring according to the EU directive Guidance Document 2 can be summarised as: a) to confirm containment of CO_2, b) to alert in case of increased leakage risk, c) to identify leakage and/or significant irregularities, and d) to verify the CO_2 plume behaviour. Moreover, monitoring should ensure the effectiveness of any corrective measures applied. As a result, monitoring issues are given top priority in the EU and other international legal documents and guidelines. For meaningful analysis and support of any deployed monitoring or surveillance program well established baselines are mandatory.

The main objective of this report on best practice is to identify and review monitoring methods to establish baseline levels for natural seismicity post operational period. The report D3.1 (Larsen et al., 2019) discusses how establishing a baseline for natural seismicity after the start of subsurface operations is by all no simple task, and best practice methods needs to be identified and evaluated based on the ongoing research in the SECURe project.

The results from Deliverable D3.1 and this report will depict the state of the art of post-operational baseline assessment and the current best practices in the field of natural seismicity as input to SECURe deliverable D3.5 (Report on state of the art and new developments for defining the seismic baseline for gas storage and exploitation). It will furthermore outline the planned field activities and data acquisition program till the end of the project. In the SECURe project (Subtask 3.1.4.) a microseismic monitoring network has been established around an active natural gas storage facility in the Gassum Formation near the city Stenlille, Denmark. The monitoring campaign is ongoing throughout the project and gained experiences from this activity will also feed in to deliverable D3.5 that is due at M30 of the SECURe project. The Gassum Formation is a sandstone of Upper Triassic – Lower Jurassic age and is considered the most prominent formation for CO_2 storage onshore Denmark.

2 Baseline monitoring

In general, monitoring is the systematic collection, analysis and use of information on projects, techniques or processes following three basic objectives i) learning from acquired experience in order to improve future actions, ii) documenting and accounting for resources used and results obtained and iii) supporting well-founded decisions on the activity.

Monitoring of CO_2 storage sites shall provide data on state and processes of the storage complex and the surrounding environment for the durable, safe, efficient and environmentally friendly management of storage operations. It shall provide all the information needed for to planning, performing and supervising actions in all stages of storage, during normal operations, incidents and after site closure. Monitoring is a periodically recurring task that allows comparisons of performance (progress against plan) and succeeds decision-making, particularly with regard to corrective measures if the state of a process is not as foreseen.

The monitoring requirements by the EU CCS Directive (2009/31/EC) and by ISO_TC265 (ISO 27914, 2018) the respective Guidance Documents and those of the EU ETS Monitoring and Reporting Guidelines are described in this chapter. Risk is generally defined as an "effect of uncertainty on objectives" (ISO 31000:2009), with potentially unwanted consequences.

In addition, other high-level regulations in place are presented, including the OSPAR and London protocol for protection of marine environment and the Clean Development Mechanisms of the United Nations Framework Convention on Climate Change. On a national level, many different directives, regulations and laws concerning CO_2 storage site monitoring are in place, implemented or developing in different parts of the world, in particular, in the US, Canada, Australia and member states of the European Union. Only in EU, there is one common EU CCS Directive applicable to all 27 Member States and countries of the European economic area. In the US, Australia and Canada the monitoring requirements are defined at state and provincial level.

For any new CO_2 storage site a comprehensive, integrative, dynamic monitoring strategy is needed that addresses identified site-specific risks. A flexible multi-level approach needs to comprise the elements detection, verification, characterization and long-term monitoring invoking local knowledge regarding topography, geology, etc. In addition, it is essential for site performance assessment to relate monitoring data to the geological model and reservoir simulation studies. Baseline monitoring should reveal natural (e.g. seasonal) variations for relevant parameters and unravel controlling factors of these variations. The EU CCS Directive (2009/31/EC) does not specify methods or monitoring technologies that should be used but requires that the choice is based on best practice available at the time of design.

Developing an optimal design of a site monitoring programme depends principally on the objectives of the monitoring; the main objectives are:

- Direct imaging (and if possible, quantification) of CO_2 in the storage reservoir (including the verification and calibration of predictive models).
- Detection of migration of CO_2 from the primary reservoir.
- Detection of migration of CO_2 through the overburden to shallower depths.
- Detection and/or measurement of CO_2 at the surface, i.e. in the atmosphere or water-column.

The measurement of microseismicity using downhole and/or surface sensors depends on the CO_2 injection inducing microseismic events. Thus, if a cause and effect link can be established between the appearance of microseismicity and the increase in pore pressure in the reservoir due to the flow of CO_2, then, theoretically, a real-time picture can be developed of the movement of CO_2 at certain specific points. It is also possible to characterize zones of weakness in the reservoir (or its caprock), where pre-existing fractures or joints move in brittle shear and therefore constitute preferential flow paths.

A feasibility study for microseismic monitoring was carried out at Sleipner (Fabriol 2001). From a practical point of view, microseismicity appears mainly in low permeability reservoir rocks and when injection pressures are relatively high (several tens of MPa). Given the porosity values around 8 Darcy (8000 mD) at Sleipner, microseismicity is unlikely to appear in the Utsira Sand except perhaps in the intra-reservoir mudstones or in the overlying mudstone caprock (Fabriol 2001). This latter case could be the most interesting to monitor as it could reveal the presence of any leakage into the caprock.

Ideally, a baseline of natural seismicity is established while the subsurface is still undisturbed. A local network of seismographs is placed in the area of interest, measuring over a period of a few years or more before operations commence (e.g., Wilson et al., 2015, Schoenball et al., 2015). When production is up and running, statistical methods are applied to the seismicity timeline.

In their simplest form, statistical methods compare the pre-operational seismicity at the location of interest to the post-operational seismicity at the same location. If the level of seismicity has increased, the "excess" earthquakes are most likely a result of the operational activities (e.g., Ellsworth, 2013, Grigoli et al, 2017).

However, there are several reasons why a baseline may not have been established pre-operationally: The operations may have started years before anyone realized a baseline would be useful, or alternatively there is not enough time to measure a baseline before operations commence. In those cases, it is necessary to establish the baseline in the post-operational phase. When doing so, it would be very useful to be able to distinguish between natural earthquakes and those caused by anthropogenic activities. Discriminating between natural earthquakes and induced/triggered earthquakes is not trivial (e.g., overview in Grigoli et al., 2017). Calculating a precise hypocenter and focal mechanism for each earthquake is very useful, however, this is often not possible for small events. High noise in part caused by production activities, insufficient seismograph coverage, and poor velocity models are common obstacles for a comprehensive physics-based analysis. A statistical analysis on populations of earthquakes at the Coso Geothermal Field in California, USA shows that the induced earthquakes to a high degree share the same characteristics as the natural earthquakes in the area (Schoenball., et al 2015), however the analysis also shows a way forward when the number of earthquakes is large. This is described below.

Microseismic monitoring has been employed for about 40 years to measure down-hole processes. Microseismic events can be monitored with geophysical instrumentation such as accelerometers, hydrophones or geophone arrays. For example, microseismic surveys are regularly used to monitor hydrofracturing in commercial oil fields, as well as to track flow fronts and pressure waves during water injection (e.g. water flooding in hydrocarbon fields or water disposal operations). These technologies are rooted in earthquake seismology and thus, the basic theoretical underpinnings are clearly known. Microseismic monitoring provides an image of fractures by detecting microseismicity (micro-earthquakes) triggered by shear slippage.

The location of the microseismic events is obtained, e.g. using a down-hole receiver array that is positioned at specified depth, preferably in a second (monitoring) well near the injection well (Streit and Siggins, 2004). This way, very small seismic events, commonly between M-4 and 0, can be measured. In cases where suitable offset monitoring wellbores are not available, microseismic mapping can be performed in the injection well. However, the seismic waves attenuate in the rock environment, and it is therefore often difficult to detect events that are more than 800 m away. Furthermore, some fluid-rock systems may not produce any acoustic signal.

2.1.1 The Coso Geothermal Field example

Tests and descriptions on how to establish a post-operational baseline are virtually absent in literature on induced and triggered seismicity. There are, however, indications of a useful method in Schoenball et al., (2015). The paper contains an analysis of the seismicity at the Coso Geothermal Field in California, USA, a site with a high level of natural seismicity with tectonic and magmatic sources, as well as strong indications of the presence of induced/triggered seismicity.

In the Schoenball et al. (2015) study the Coso Geothermal field is divided into two areas: a large study area covering the entire geothermal field, and a smaller subarea at the center of the field with active geothermal power production. A pre-operational baseline was established in the field during 1975-1977 and the seismicity in the center region did at the time not stand out compared to the rest of the field. However, after production has started, a significantly higher level of seismicity is observed in the actively developed part of the field compared to the undisturbed region, indicating that the natural seismicity is supplemented by induced/triggered seismicity. The geology and tectonic setting are very similar in the two areas.

To further investigate the nature of seismicity in the Coso Geothermal field, Schoenball et al. (2015) carried out detailed analysis of the earthquake population in the field, both combined and separate analysis for the undisturbed region and the production part. Most parameters were similar, however, in the active field a significantly higher portion of earthquake pairs was found, when using a nearest neighbor algorithm based on a space-time-magnitude distance measure. The earthquake pairs were widely distributed in time but had hypocenters in almost exact same location. This would be very unusual for natural earthquakes, but would make physical sense for induced earthquakes, where injection and production occur at the same fixed positions. Indeed, a significantly higher concentration of these earthquake pairs was found in the production area than outside.

Lessons learned from Schoenball et al. (2015) from the Coso Geothermal field are that in an area with a high level of microseismicity, the presence of many earthquake pairs may indicate a high level of induced/triggered earthquakes. The statistical analysis on populations of earthquakes at the Coso Geothermal Field in California, USA shows that the induced earthquakes to a high degree share the same characteristics as the natural earthquakes in the area (Schoenball., et al 2015), however the analysis also shows a way forward, when the number of earthquakes is large. Based on the experience from Coso, we conclude that it is possible to establish a microseismic baseline post-operationally by measuring it in similar geology under a similar tectonic regime and compare the undisturbed site with the production site. The specific analysis methods may vary. The method is however, only useable in areas with high level of seismicity, and it needs to be tested if this specific analysis applies to other geological settings and production methods.

2.1.2 Stenlille natural gas storage facility

As described in SECURe report D3.1, a microseismic monitoring network was successfully deployed around the Stenlille Gas storage facility, Denmark. Data acquisition is still in progress, including 6 added experimental stations at distances from 10 – 100 km and will continue until August 2020. Data analysis is in progress, and will continue throughout the SECURe project.

A similar monitoring network was deployed near Dybvad, Denmark, approximately 200 km from Stenlille, in 2014-2015. A pre-operational microseismic baseline was established by GEUS in 2014-2015. Almost two years prior to a test drilling by Total for shale gas near Dybvad, Denmark, GEUS established a microseismic monitoring network surrounding the site. The network consisted of 6 seismographs transmitting continuous data to the data center 24/7. During the period of measurements, no earthquakes were detected in the area. The test drilling was abandoned by Total, but the baseline established on the Gassum formation can be applied elsewhere on sites with similar geology and under a similar tectonic regime.

The geology and tectonic setting are comparable for the two sites, and the natural seismicity is therefore expected to be similar as well. The measured natural background noise level is slightly lower near Stenlille. However, injection and production at the main pump dominate the recorded data at high frequencies at periods of high activity out to distances of approximately 3 km. Preliminary data analysis has not yet found any earthquakes near Stenlille. The natural seismicity is very low, and the relatively soft geology makes it challenging to detect small induced/triggered earthquakes. Based on the experience from the Dybvad network we do expect to be able to detect earthquakes down to a magnitude of 1.0, smaller ones only during times of low or no pumping activity. The data analysis is ongoing. This method to establish best practice will combine microseismic monitoring around an active site with experimental instruments in a range of distances from the well/storage facility, between 10 and 100 km. These instruments were installed during summer 2019.

Based on the experience from Coso, we conclude that it is possible to establish a microseismic baseline post-operational by measuring in similar geology under a similar tectonic regime and compare the undisturbed site with the production site. The specific analysis methods may vary.

The Stenlille network has not been running long enough to detect any microseismic events near the gas storage facility, and we don’t know if there are any, so there are presently no recorded events for a detailed analysis. However, the concept of monitoring with a similar network in a similar geology and a similar tectonic setting will be tested.

Our analysis reveals challenges of monitoring close to the active production due to substantial subsurface noise in the same frequency range where we expect the microseismicity to appear. These disturbances are significantly muted at a distance of 3 km in this particular geological setting. It will be necessary to check the disturbance radius in the geology in question.

In some cases, a production area sees a significant increase in the number of earthquakes with magnitudes large enough to be detected by regional seismograph networks. In those cases, the earthquakes recorded by the regional network can constitute a baseline (e.g. Ellsworth, 2013).

So far, we have learnt that the natural background noise level is slightly lower than the noise level at the monitoring network near the Dybvad site, Denmark. However, during periods of injection and production, high frequency noise dominates at distances less than 3 km from main pumping activity. To date, we have not seen any microseismicity at the Stenlille site (Larsen et al., 2019).

2.2 ESTABLISHING A POST-OPERATIONAL BASELINE

It is possible to establish a microseismic baseline post-operationally by measuring in similar geology under a similar tectonic regime and compare the undisturbed site with the production site. The specific analysis methods may vary. However, we use the concept of monitoring using a similar network in a similar geology and a similar tectonic setting.

A comprehensive monitoring concept shall meet the challenges of monitoring close to the active production site due to substantial subsurface noise in the frequency range, where the microseismicity could potentially appear. These disturbances are significantly muted at a distance of 3 km in the geological settings. It will therefore be necessary to check the disturbance radius in the geology in question.

In some cases, a production area sees a significant increase in the number of earthquakes with magnitudes large enough to be detected by regional seismograph networks. In those cases, the earthquakes recorded by the regional network can constitute a baseline (e.g. Ellsworth, 2013).

The establishment of a baseline post-operational can therefor either be based on measuring around the storage site out to a distance from the storage site where the is no more storage noise recorded and a "baseline" can be stablished, or to identify a similar nearby geological setting, where the "baseline" data can be collected.

2.3 CONCLUSIONS

Our preliminary recommendations for establishing a microseismic post-operational baseline:

An undisturbed baseline can be measured in similar geology under a similar tectonic regime and compared to the seismicity measured at the active operation site. The establishment of a post-operational baseline can therefor either be based on

- measuring around the storage site out to a distance from the storage site, where there is no more storage noise recorded and a "baseline" can be stablished, or
- identifying a similar nearby geological setting, where the "baseline" data can be collected.

3 References

Cherry, J., Ben-Eli, M., Bharadwaj, L., Chalaturnyk, R., Dusseault, M B., Goldstein, B., et al. 2014. Environmental Impacts of Shale Gas Extraction in Canada. The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction.

de Pater, C J J., Baisch, S. 2011. Geomechanical Study of Bowland Shale Seismicity. Synth. Rep. 71.

DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

Ellsworth, W L. 2013. Injection-induced earthquakes, *Science*, *341*(6142), 1225942.

Fabriol. H. 2001. Saline Aquifer CO2 Storage (SACS) Feasibility study of microseismic monitoring (Task 5.8). Research carried out in the framework of the EU project no. ENK6-CT-1999-00014 "SACS2". BRGM/RP-51293-FR. 64 pp

Grigoli, F., S. Cesca, E. Priolo, A. P. Rinaldi, J. F. Clinton, T. A. Stabile, B. Dost, M. G. Fernandez, S. Wiemer, and T. Dahm. 2017. Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective, *Rev. Geophys.*, *55*, 310–340, doi:10.1002/2016RG000542.

ISO 31000:2009. RISK MANAGEMENT -- PRINCIPLES AND GUIDELINES https://www.iso.org/standard/43170.html

ISO/TC265, 2018. ISO 27914. Carbon dioxide capture, transportation and geological storage — Geological storage. 74 pp. https://infostore.saiglobal.com/en-gb/Standards/ISO-27914-2017-608309_SAIG_ISO_ISO_1394669/

Koppelman, B., Walker, A. and Woods, E. 2012. Shale gas extraction in the UK: a review of hydraulic fracturing. London: RS-RAENG.

Larsen, T., Dahl-Jensen, T., Poulsen, N E. and Voss P. 2019. Report on addressing methods to establish baseline levels post operational activity. SECURe project (H2020). Report D3.1. 15 pp.

Schoenball, M., Davatzes, N C. and Glen, J M G. 2015. Differentiating induced and natural seismicity using space-time-magnitude statistics applied to the Coso Geothermal field, Geophys. Res. Lett., 42, 6221–6228, doi:10.1002/2015GL064772.

Streit, J E., and Siggins, A F. 2004. Predicting and Monitoring Geomechanical Effects of CO2 Injection. Greenhouse Gas Control Technologies, Vol. I, January 2004.DOI: 10.1016/B978-008044704-9/50065-3

Wilson, M P, Davies, R J., Foulger,G R., Julian, B R., Styles, P., Gluyas, J G. and Almond, S. 2015. Anthropogenic earthquakes in the UK: A national baseline prior to shale exploitation, Marine and Petroleum Geology, 68, 1-17