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Feasibility Of Permanent Seismic Monitoring Of A CO2 Storage Site Offshore Norway

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Summary

A CCS monitoring plan should demonstrate containment of CO2, ensure that CO2 distribution in the storage complex is monitored and understood to ensure long term conformance and assess the effectiveness of any corrective measures taken in case of a leakage out of the storage complex. Such a monitoring programme should be flexible and designed to address all aspects described above in a cost efficient and flexible manner. Here we discuss some aspects of monitoring the proposed Smeaheia site offshore Norway.

Introduction

The Norwegian state has announced plans to develop a full-scale CO_2 capture and storage (CCS) project to be operative by 2022. A feasibility study conducted in 2016 evaluated three potential storage sites and concluded that a location east of Troll oil and gas fields was best suited, given that identified risks are mitigated. The required storage capacity for the site was 37.5 Mt injected over 25 years. Equinor (formerly Statoil) and partners Total and Shell were assigned the task of concept study development, and investigating a potential increase of the capacity. During this work the location east of Troll was deemed to have too high risk for this higher capacity, and focus was shifted to open acreage south of Troll. This second location is presently being evaluated by the partners. Here we present recommendations for sub-surface and environmental monitoring solutions for the original location east of Troll, named Smeaheia, with special focus on the applicability of permanent seismic monitoring.

Smeaheia storage option

The Smeaheia area is located 30 km east of Troll Øst gas field, in a fault block uplifted approximately 300 m relative to Troll Øst gas field (Figure 1). Late Jurassic Sognefjord, Fensfjord and Krossfjord formations form the primary storage unit. These are also the producing reservoir zones in the Troll fields. Deeper units in Early Jurassic and Triassic sand are considered secondary storage units. The Smeaheia area is penetrated by two hydrocarbon exploration wells drilled (in 1996 and 2008, respectively) into two closures, Alpha and Beta. Both exploration wells were dry, and the Smeaheia area is not believed to have been charged by hydrocarbons. The initial pore pressure was found to be hydrostatic.

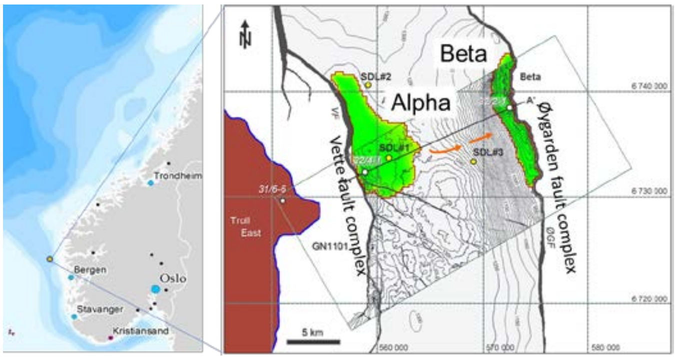

Figure 1 *The Smeaheia area of the Norwegian CCS Central Storage, with closures Alpha and Beta indicated.*

Seismic data acquired using onshore observations from NNSN (Norwegian National Seismic Network) show that the Horda platform lies in a moderately active seismic area. Both vertical and lateral location uncertainty is however high due to the distance between the onshore sensors and Smeaheia. Seismic activity has particularly been observed on the Øygarden fault south of Smeaheia, and 3D seismic acquisitions imaging the Øygarden fault also indicate that the fault has been active during Quaternary.

Developing a monitoring strategy

CO_2 storage and monitoring are governed under the Norwegian Petroleum law and aligned with the European CCS directive. The monitoring plan should:

- demonstrate containment of CO_2
- ensure that CO_2 distribution in the storage complex is monitored and understood to ensure long term conformance
- assess the effectiveness of any corrective measures taken in case of a leakage out of the storage complex

- detect significant adverse effects for the surrounding environment

Fulfilling the above criteria requires a monitoring programme covering both subsurface and the marine environment. The monitoring programme should cover the full lifetime of the injection project, from baseline monitoring prior to injection start, via monitoring throughout the injection period, and finally post-injection monitoring. This would in our case require a monitoring period of 25 years in addition to the post-injection period, which is still under negotiation.

Equinor has extensive experience with monitoring CO_2 injection at NCS (the Norwegian Continental Shelf) through the Sleipner and Snøhvit projects (Furre *et al.* 2017, Hansen *et al.* 2013). The advantage of subsurface methods (such as seismic or gravimetric) is the ability to monitor CO_2 remotely without adding additional penetrations into the storage complex. Seismic monitoring has proven a very versatile and efficient way of monitoring CO_2 distribution because injecting CO_2 in a saline aquifer provides excellent acoustic contrast. Experience from Sleipner has shown that saturation changes down to a couple of meters vertical thickness are detectable. Gravimetric monitoring has provided a useful supplement to the seismic monitoring (Alnes *et al.* 2011).

Conventional 3D/4D seismic streamers have been the preferred acquisition methodology for both Sleipner and Snøhvit. In the early phases of both projects acquisition frequency was relatively high (2-4 years between surveys), but as the sites and monitoring strategy have matured over time, the frequency has decreased. This frequency depends on several factors, such as injected mass of CO_2, reservoir properties and consequently expected time-lapse response, injection strategy, cost/benefit and health and safety issues.

For Smeaheia, conventional 3D/4D streamer seismic was considered the basic choice. Other acquisition methods have also been evaluated and could act as supplements to or replacement of one or more streamer surveys. Depending on the need to detect small changes a permanent installation might be preferable over repeated marine-streamer surveys (because source and receiver positions are difficult to repeat). A PRM (permanent seismic reservoir monitoring) system could then be an option.

Seabed surveillance using sonar and other acoustic techniques are routinely applied to detect disturbances in the sediments or potentially natural gas bubbles leaving the seabed. The ability to detect CO_2 seepage will depend on the CO_2 rate and behaviour in the sea water and sediment. A challenge with CO_2 bubbles is that they dissolve in water shortly after leaving the seabed and would be hard to detect. Several research projects are focusing on resolving this issue.

Both the environmental and subsurface monitoring programme needs to be closely integrated with a leakage risk assessment plan, to enable a tailored programme to focus on the highest leakage risks. In addition, the impact of CO_2 release on the ecosystem is an important element in deciding the frequency and extent of the monitoring program.

Permanent seismic reservoir monitoring (PRM)

Equinor has successful experiences with PRM operations. A full-field PRM system was installed at Snorre and Grane fields during 2013-2014 and is used to acquire seismic once or twice per year for monitoring production effects. Additionally, a smaller layout for monitoring waste injection in the overburden at Oseberg Field was installed in 2013.

The main advantages of PRM systems are that permanent receivers provide superior repeatability and additional shear wave information compared to towed-streamer receivers and that they offer the ability to detect natural or induced seismicity (passive seismic surveillance). Since the main costs of a PRM system are related to fabrication and installation of seismic cables, it is important to optimize cable layout covering the area of interest in a cost-efficient way.

As part of the evaluation of using PRM technology at Smeaheia, an illumination study was performed to check illumination in overburden and reservoir as a function of cable spacing, using reservoir simulations from the feasibility study to predict the plume development. Four cases were investigated: a small-scale array of 4 km^2 seabed array with sparse and dense receiver line intervals of 400 and 200 m, respectively and a large-scale 9.3 km^2 array with similar sparse and dense receiver line intervals. For all cases we evaluated illumination at Top Sognefjord level, and at a shallow target 200 m below seabed (seabed is approximately 340 m below sea surface). The shooting carpet was designed to provide a minimum of 3 km maximum offset for all azimuths.

Hit maps show that illumination at Top Sognefjord (Figure 2) is adequate for all arrays, but with time the CO_2 plume is expected to extend beyond the coverage of the small-scale PRM system. For the sparse PRM system, we modelled an acceptable minimum reflection angle of 13 degrees at Top Sognefjord mid-way between the receiver cables. On the other hand, for a reflector 200 m below seabed the illumination is very poor using this sparse array (Figure 3), with a minimum angle of 44 degrees mid-way between the receiver cables (Figure 3b).

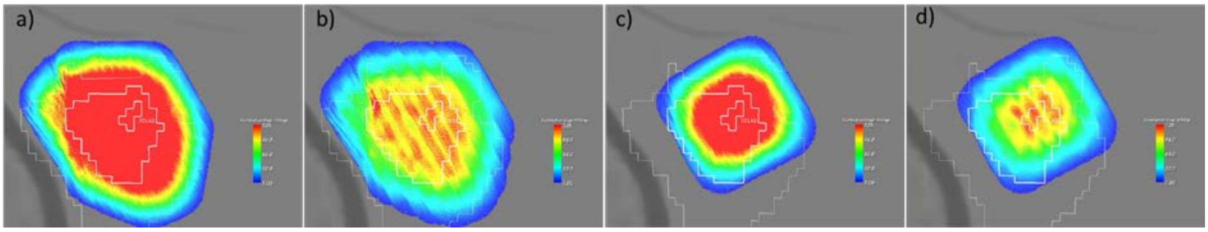

Figure 2 *Illumination hit maps at Top Sognefjord for a) large-scale dense, b) large-scale sparse, c) small-scale dense, d) small-scale sparse receiver spacing. The white outlines denote simulated* CO_2 *extent at Top Sognefjord after 5 (small), 10 (middle) and 25 (large) years injection.*

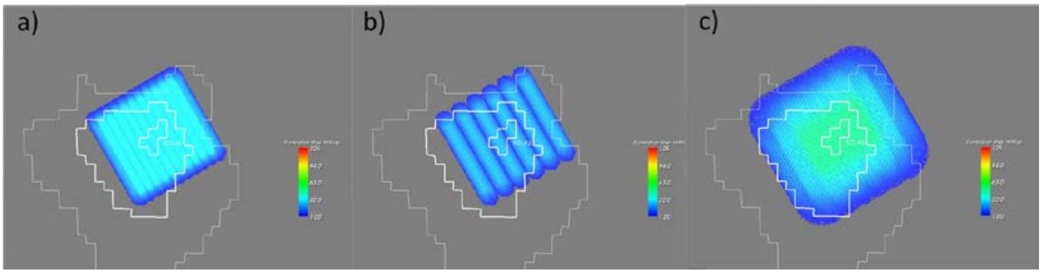

Figure 3 *Illumination hit maps 200 m below seabed for a) small-scale dense, b) small-scale sparse, c) mirror imaged small-scale sparse receiver spacing. The white outlines are as described in Figure 2.*

In conventional ocean bottom seismic acquisition, the down-going wavefield reflected from the sea surface is removed from the recorded data at the seabed. For reflection points mid-way between the receiver cables, the corresponding minimum offset is always larger than the cable spacing, which for sparse layouts and shallow reflection points results in poor imaging due to high reflection angles. This offset limitation can be overcome by utilising the down-going wavefield, which gives smaller reflection angles for a given reflection point. This technique is referred to as mirror imaging and the water depth at Smeaheia is well suited for this method.

Figure 3c shows the mirror imaged illumination hit map for the small-scale sparse arrays at depth 200 m below seabed. The dense array gives a minimum reflection angle of 15 degrees between the cables. It is worth noting that mirror imaging with the sparser array of 400 m cable spacing actually gives a better illumination with respect to reflection angles than conventional imaging with the denser array of 200 m cable spacing.

By doing a rough comparison of acquisition costs between a small-scale PRM system and conventional 3D/4D streamer seismic covering the same small area (Figure 4), the PRM system clearly has high installation costs upfront. The acquisition costs, however, would become lower than the towed streamer reference after approximately 10 repeated surveys. In the case of hydrocarbon monitoring, a cost/benefit analysis would be performed to optimize decision of timing and type of technology to use for monitoring. In the case of CO_2 injection, however, there are no production benefits from the monitoring, and repeated streamer seismic would be favourable on a purely cost basis. In addition, as there are significant uncertainties related to the CO_2 plume expansion area, a streamer survey layout would be more flexible to extend over time.

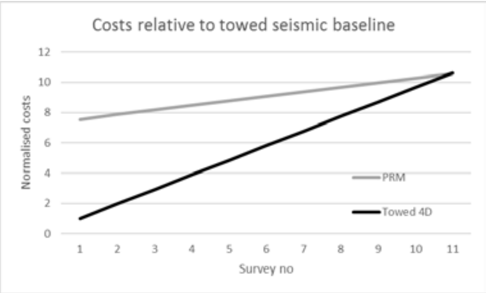

Figure 4 *Cost estimate of small-scale sparse PRM system compared to seismic towed streamer surveys. Costs are normalised to the cost of one towed seismic survey.*

Further evaluation of monitoring at Smehaiea and other similar offshore sites should include possible combinations of other technologies as well, such as 2D seismic lines (to get a quick assessment of plume direction), downhole fibre optic monitoring (DAS) of the near wellbore, and use of permanent sensors at the seabed for potential earthquake detection or passive seismic and gravimetric monitoring. Use of ocean-bottom nodes is an alternative approach to PRM which could be considered as a cost-effective option for future projects.

Conclusions

The overall challenge is to find a flexible, site specific monitoring programme, both with respect to timing, extent and technology. The first line of defence should be subsurface monitoring, using the best suited seismic technology, and possibly supplementing with gravimetric monitoring. For Smeaheia, repeated towed 3D streamer seismic appears to be the best solution, due to cost and flexibility. Further evaluations of emerging technologies should also be considered. The environmental monitoring programme should be tailored to the leakage risk assessment and linked to observations from the subsurface monitoring programme.

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