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Resilience to potential CO2 injection induced seismicity, estimated from historic ground motion exposure.

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Summary

North Sea subsurface structures provide prolific opportunities to reduce Europe's carbon footprint through permanently storing emitted CO2. In this paper we present a methodology to estimate resilience of manmade facilities and environment to potential induced seismicity during injection operations, based on historically observed regionally seismicity. This enables a robust design of a well informed risk management system that provides confidence to stakeholders while properly recognizing and establishing the right level of resilience to seismic events.

The method is demonstrated by applying the assessment for offshore structures on the Norwegian shelf to address resilience to potential seismicity around the NorthernLights prospect. It appears that is likely an event with Moment Magnitude equal to 3.7 can be managed adequately. The method can be extension to other areas in the North Sea, such as the Dutch and UK sectors, and can also address for instance resilience of onshore domestic areas to offshore induced events.

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Introduction

North Sea subsurface structures are prolific opportunities to abate Europe's industrial carbon footprint through permanent subsurface CO_2 storage. Successful development of offshore CCS-sites is a necessity to meet emissions reductions commitments from the Paris Agreement.

Northern Lights JV is developing the world's first open-source CO_2 transport and storage infrastructure on the Norwegian Continental Shelf. The first phase of the development has a storage capacity of 1.5 million tonnes CO2 per annum, with an ambition to expand the storage capacity for phase 2 to a total of at least 5 Mtpa. Storage sites are also being developed in the Dutch, UK, and Danish concession areas of the North Sea. The Aramis project, targeting subsurface store sites in the Dutch offshore K- and L-blocks, will potentially unlock a storage capacity of 400 Mt.

A concern when operating a subsurface CO_2 storage site is associated seismicity, both induced and triggered. Well-known examples of associated seismicity, such as the Groningen gas-production, and Castor gas storage cases, demonstrate the necessity for proper seismic hazard and risk (the combination of likelihood and impact) assessment.

To address the risk of induced and triggered seismicity related to these storage sites, use of direct and relevant analogues is a credible way to predict the impact of potential seismicity related to offshore CO_2 storage operations.

In this abstract we evaluate the impact of historic North Sea seismicity on facilities and environment. We look at activity since the 1960s/1970s when significant offshore activities were started, based on the catalogue of seismic events produced by the ACT-SHARP project (Kettlety et al., 2024; Skurtveit et.al., 2022).

From this catalogue the historic exposure to earthquake ground motion of offshore structures will be computed using the ground motion prediction equation (GMPE) of Akkar et.al. (2014) for pan-European seismicity.

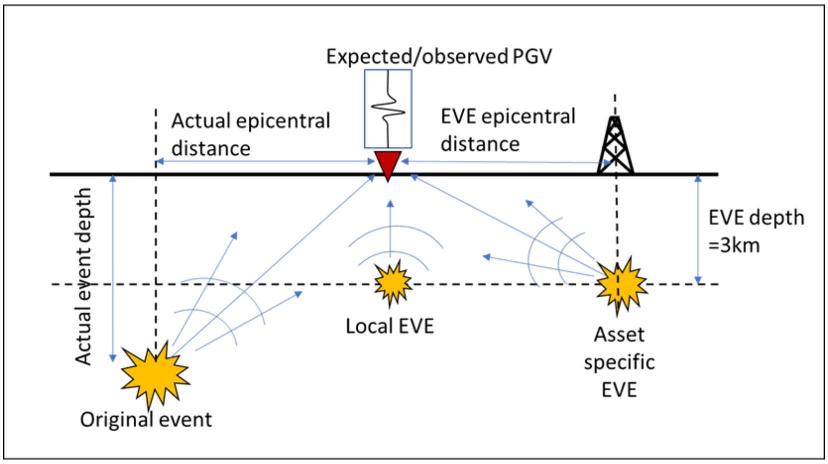

Figure 1: *Schematic explanation of the definition of an equivalent virtual event (EVE). In this example the EVE depth is chosen to be equal to 3km, but this can be varied.*

Having knowledge of the historic exposure to ground motion we can then back-calculate, using the same GMPE, the range of earthquake magnitudes which would give rise to similar levels of ground-motion for an equivalent virtual event (EVE) with its epicentre at a storage facility site. This is schematically explained in Figure 1.

Comparing the modelling results with available historically reported damages and site-investigation results then provides the level of resilience to induced seismicity. This can then be used as input to the design of risk assessment frameworks to manage the impact of induced seismicity.

Method and Theory

As addressed by the SHARE project (Giardini, Woessner and Danciu, 2014), the European continent sees various levels of seismic hazard and risks. However, the resulting continental hazard and risk maps do not properly address offshore hazard and risks, where CO_2 storage sites are being developed.

To compliment the knowledge base of seismic hazard and risk in Europe, a catalogue with integrated earthquake locations and magnitudes, focal mechanisms for the North Sea was compiled within the SHARP project (Kettlety et al., 2024). Figure 2 displays an excerpt from this catalogue, showing historic seismic activity around the Norwegian shelf. All Norwegian shelf fields and activities are indicated as well, with the Northern Lights project area annotated explicitly.

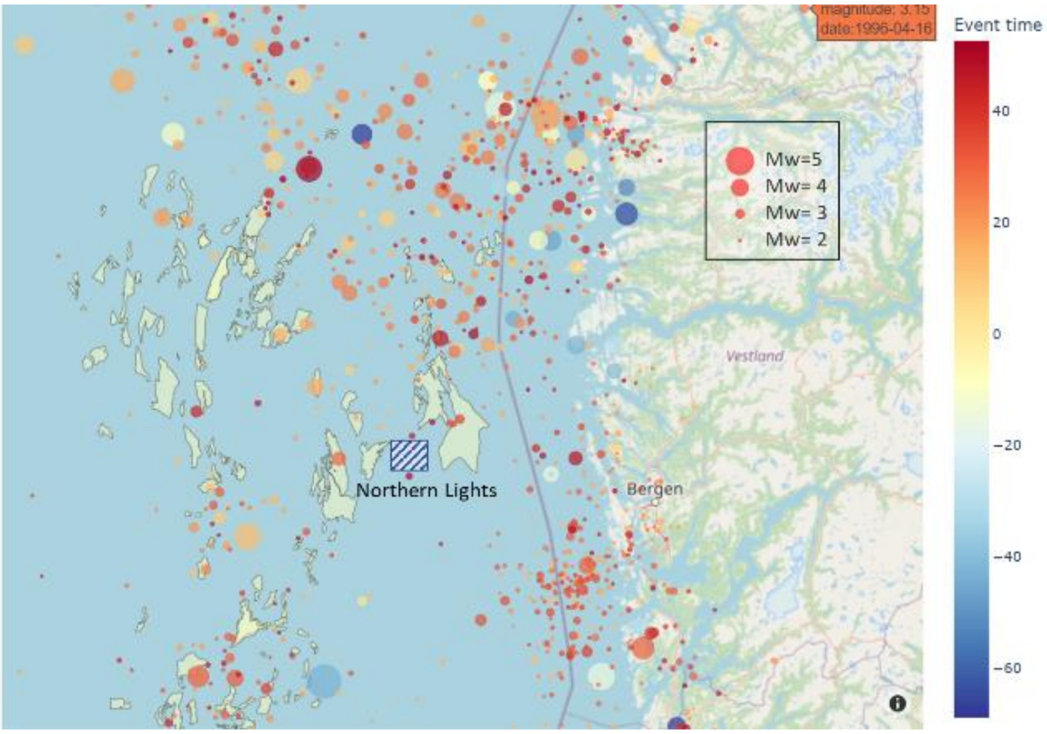

Figure 2: *Historic seismic events that have occurred on the Norwegian shelf. Their magnitudes are indicated by the size of the circle, the colour indicates the occurrence time relative to 1970. Also shown in light green are the offshore oil and gas fields.*

In a first modelling step, we have used the GMPE of Akkar et.al.(2014a), to compute the ground motion exposure in terms of Peak Ground Velocity, PGV, given this catalogue,

$$\ln(PGA_{ref}) = a_1 + a_2(M_W - c_1) + a_3(8.5 - M_W)^2 + [a_4 + a_5(M_W - c_1)]\ln\left(\sqrt{R^2 + D^2 + a_6^2}\right) + a_8 + a_9$$

$$\ln(S_{pgv}) = b_1 \ln\left(\frac{V_{s30}}{V_{ref}}\right) + b_2 \ln\left(\frac{PGA_{ref} + C\left[\frac{V_{s30}}{V_{ref}}\right]^n}{(PGA_{ref} + C)\left[\frac{V_{s30}}{V_{ref}}\right]^n}\right)$$

$$\ln(\mathrm{PGV}) = a_1 + a_2(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln\left(\sqrt{R^2 + D^2 + a_6^2}\right) + a_8 + a_9 + S_{pgv} + \varepsilon\sigma$$

in which M_W is the estimated moment magnitude, R the epicentral distance, and D the depth of the considered event. C, V_{ref}, n, σ, a_i and b_i and c_i are constants calibrated to observations, with their values, according to Akkar et.al.(2014b), listed in table 1. V_{s30} is the shear velocity at 30m depth, which in principle has a site-specific value but was taken equal to 200 m/s in this study. The term $\varepsilon\sigma$ gives the uncertainty with respect to the median ground motion value, given a standard deviation of σ and the standard normal variable ε.

Table 1: *Calibrated parameters of the Akkar et.al.(2014b) GMPE*

	a_1	a_2	a_3	a_4	a_5	a_6	a_8	a_9
PGA_{ref}	3.26	2.9e-3	-0.048	-1.479	0.252	7.5	-0.109	9.3e-2
PGV	6.72	2.9e-3	-0.114	-1.176	0.252	7.5	-0.061	6.3e-2

V_{S30}	V_{ref}	b_1	b_2	c_1	C	n	σ
Site specific	750	-0.72057	-0.19688	6.75	2.5	3.2	0.71

Being aware of epistemic errors and uncertainties that are introduced when different classes of seismic events and large variations of hypocentral locations are present, the Akkar GMPE was compared to the GMPE designed specifically by Bommer et al. (2019) to characterise induced seismicity at the Groningen gasfield. It appears that the Akkar model agrees reasonably well with the Bommer model for short epicentral distance, shallow, and relatively small magnitude events. The overlap between the models by Akkar and Bommer gives confidence in the robustness of the Akkar model when various event types are mixed, as the Akkar model calibration was dominated by deeper, larger magnitude, basin events.

In a second step, the estimated ground motion is used to estimate the required magnitude of a so called equivalent virtual event (EVE). This is artificially positioned at an epicentral location of a storage facility of interest, at a depth equal to the reservoir, as explained by Figure 1.

The resulting event magnitudes of these EVEs can then be directly used to find the resilience of facilities and environment to seismicity, within commonly accepted risk management frameworks, through designing thresholds for acceptable seismic magnitudes.

Examples

Figure 3 displays the median expected magnitude EVEs at reservoir depth of 3 km, with their epicentre located at the operational locations shown on the vertical axis, for each year since 1970 (horizontal axis), given the probable Peak Ground Velocity at the site in the specific year. This result is the basis for addressing resilience to induced seismicity.

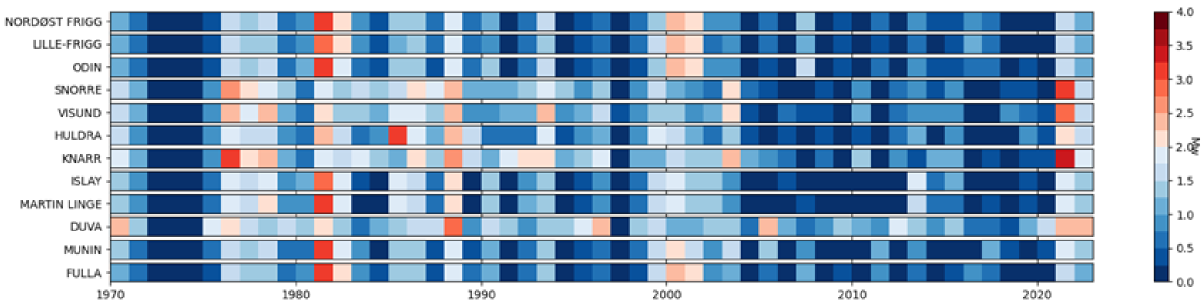

Figure 3: *The yearly estimated variation in magnitude of local Equivalent Virtual Events, given the exposure to observed ground motion in that specific year, at 12 offshore facilities on the Norwegian shelf.*

For instance, the seismic event that occurred in 2022 resulted in a computed magnitude of 3.7 for an EVE at Knarr (Figure 3). This event was described by Zarifi et.al.(2022), concluding no damage was caused. Since, production has continued as usual.

Conclusions

We have presented a methodology to support the assessment of induced seismicity risks that potentially might occur around CO_2 storage sites, and the impact that it might have on facilities and environment. A well-informed assessment supported by historic observations is key to a robustly designed risk management system that provides confidence to stakeholders while properly recognising and establishing the right level of resilience to seismic events. Assessment of resilience is a mitigation measure for seismic risks in the development cycle for offshore subsurface CO_2 storage sites, motivated by the needs of European climate policy.

The described example focussed on resilience of offshore structures on the Norwegian shelf, providing evidence that impact resulting from induced events with moment magnitudes of at least up to 3.7 can likely be managed adequately for such facilities. The method can be easily extended to other areas in the North Sea as well as be extended to other types of assessments; for instance, to address the resilience of onshore domestic areas to offshore induced events.

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