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ENSURE - Public report

D2.1b Recommendations for cost-effective, validation-optimized microseismic monitoring networks

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Contents

List of abbreviations

CO_2 Carbon dioxide.

1C one-component.

3C three-component.

CCS Carbon Capture and Storage.

DAS Distributed Acoustic Sensing.

SNR Signal-to-Noise Ratio.

WP Work Package.

Executive summary

The overarching ENSURE project goal was to advance microseismic monitoring of CCS both technologically and socially.

In this report we present monitoring recommendations which we derive mainly from technological advancements achieved within the project. These recommendations are developed from analysing and comparing microseismic data from different monitoring technologies but also from summarizing conclusions of expert discussion groups.

Every monitoring network needs to provide robust observations in a cost-effective manner. As the purpose of monitoring differs between projects and subsurface geology is inherently site specific, the network design will likewise be site-specific. Hence, it is impossible to construct one general robust and fit-for purpose monitoring network. While we focus our conclusions on our results obtained from the Quest CCS site, Alberta, Canada, many of our recommendations are also more generally applicable.

The most vital aspects of all instrumentation are their ability to detect the event with sufficiently low threshold, broad bandwidth, and wide aperture, such that the event can be properly characterised, classified, and inverted for source location.

With advanced processing methods, the detection threshold can be further lowered, such that the number of detected events can be significantly increased. Using the statistics from the additional low-magnitude events allows to extract probabilistic information about future hazards, which increases the value of information. However, this only holds if the initial monitoring effort is adequate.

1 The ENSURE project

Microseismic monitoring is a geophysical surveillance technology to verify the integrity of any large-scale CO_2 storage site. The interpretation of microseismic events in terms of origin time, location, and size provides direct insights into CO_2 migration, pressure and stress changes that may potentially lead to caprock failure. Verification of seal integrity is a major challenge for CCS as it requires the recognition of tiny precursor movements as indicators of injection-related reservoir and caprock dynamics before potential seal failure. Optimally designing cost-efficient monitoring systems for this purpose have been identified as a critical knowledge gap. At the same time, public acceptance of CCS technology hinges on the ability of the general public to differentiate between harmless microseismic deformations (perceived risks) and earthquakes with damaging potential (actual risks). An improvement of microseismic monitoring systems will enhance operational safety. Simultaneously, a larger number of small-magnitude events will be detected, which might be perceived as an increased threat. Hence, there is a need for a more effective communication strategy to establish trust and transparency between CO_2 storage operators and the public.

The ENSURE project addresses both of the above objectives. The project is summarised in Figure 1. The overarching project goal is to advance microseismic monitoring of CCS both technologically and socially. We aim for microseismic monitoring to become an accepted tool for seal integrity verification in large-scale CO_2 sequestration operations. Furthermore we assess public perceptions, preferences, and alternative means of communication of CCS technology. To this end, we imply the necessity to address climate change through the reduction of CO_2 in the atmosphere with underground CO_2 storage as one possible element.

The three underlying project objectives were:

- build knowledge on CCS, induced seismicity and long-term seal stability assessment,
- address both actual and perceived risks for seismicity and CO_2 leakage,
- develop strategies for effective communication of complex information around CCS.

These objectives help to enable stakeholders to educate and advance public trust in CCS technology. Thus, research towards these aims and objectives was based on two pillars: technology and social science. Technological advancements were sought to derive recommendations to design the most fit-for-purpose, robust and cost-effective network for specific storage sites. We achieved this by:

- analysing data from a variety of microseismic sensor technologies, including fiberoptic DAS cables, from different CCS sites (deliverable D1.2, D2.2);
- developing and applying advanced data processing methodology (deliverable D1.2, D2.2);
- comparing results to modelling (deliverable D2.1a);
- understanding the controlling factors of seismodynamic behaviour of CO_2 storage reservoirs and identified the most relevant seismological parameters for long-term seal stability assessment by advanced interpretation of microseismic event clouds and comparison of seismicity from different sites (deliverables D2.2, D2.3).

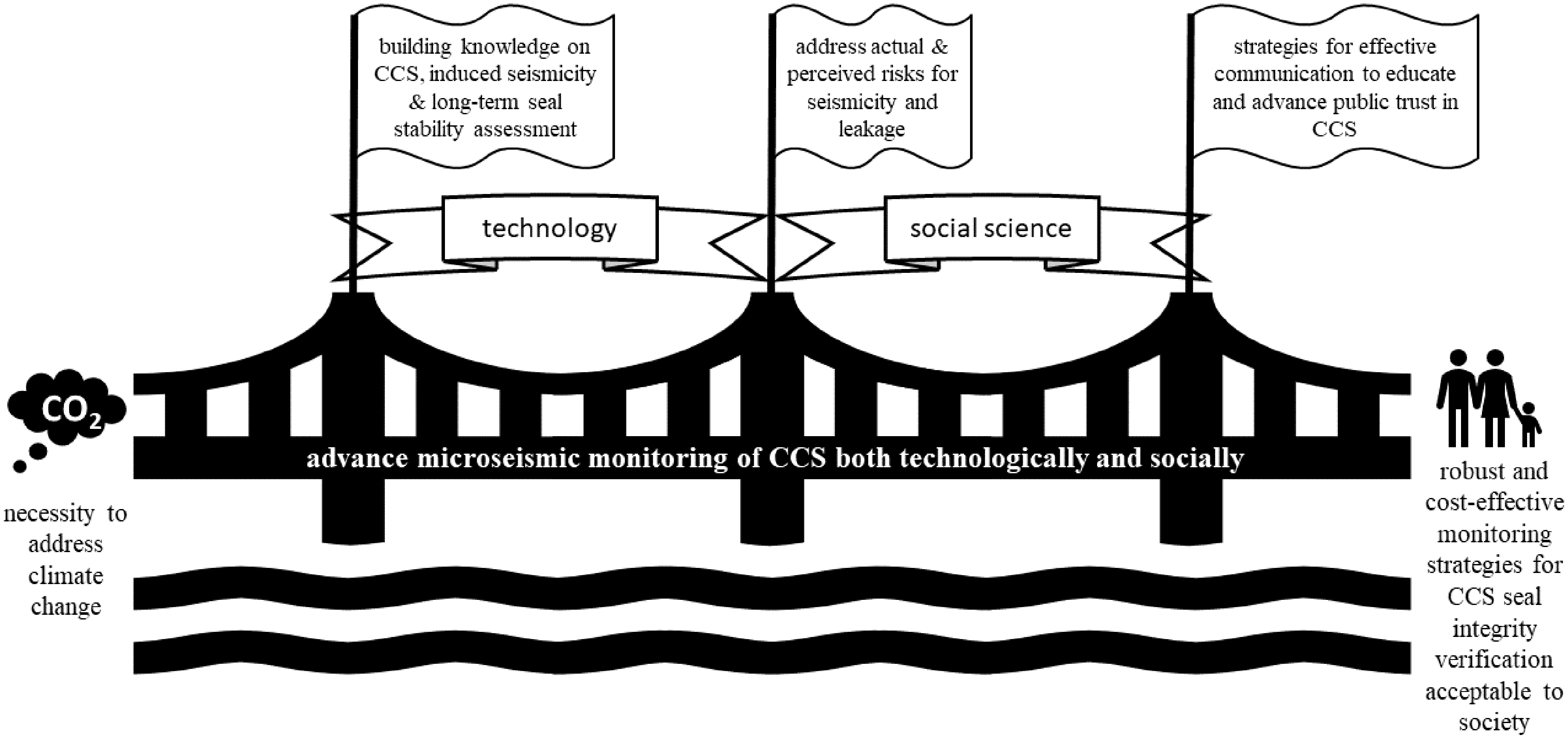

FIGURE 1: The ENSURE project: goals and means (see text for details)

Recommendations are summarised in the current report.

The second aim of advancing CCS socially was addressed by state-of-the-art empirical socio-economic surveys using scenarios and parameters provided by the seismological analysis (deliverables D3.1, D3.2). This leads to recommendations on effective communication strategies for advancing public trust in CCS technology (deliverable D3.3). The social science survey revealed the importance of public consultation, engagement and transparent information throughout the life cycle of CCS with oversight and monitoring potentially performed by independent institutions or authorities. Further, it demonstrated that awareness, support, perceived risks and expectations of CCS ventures depend on nationality, belief, age, gender and knowledge base.

2 Monitoring recommendations

The main aim for every monitoring network is to provide robust observations in a cost-effective manner. Especially for monitoring of CCS, data quality and long-term consistency of datasets are important due to the fact how agreements are built: the liability of the operator increases with time, while the subsurface risk decreases in the very long-term. Ideally, this also means consistent data acquisition and analysis parameters should be in place in order to avoid reprocessing of previous data. The main requirements for a robust, cost-efficient monitoring network are:

- consistent data collection with inbuilt redundancy,
- minimum maintenance and minimum downtime,
- real-time processing with remote access and real-time system performance controls,
- automatic triggering in case of events.

We refer to deliverable D2.1a for a more detailed discussion on a robust monitoring network.

As the purpose of monitoring differs between projects and subsurface geology is inherently site specific, the network design will likewise be site-specific. Hence, it is impossible to construct a **general** robust and fit-for-purpose monitoring network. In this report, we draw conclusions mainly with respect to microseismic monitoring solutions installed at the Quest site, which offers the possibility for comparison between a large variety of monitoring technologies.

In order to provide more general monitoring recommendations, as far as they are inferable from the studies performed in ENSURE, we collect here recommendations from data analysis as presented in deliverable D1.2, recommendations deduced from modelling, as presented in deliverable D2.1a and complement these by results from a discussion among project partners held on the ENSURE consortium meeting in June 2024.

2.1 Recommendations from data analysis and network design modelling

The data provided by the consortium's members introduced diversity in terms of instrumentation, deployment methods, and environmental conditions. The different types of deployments that we discuss here comprise: borehole installations (geophone strings, distributed acoustic sensing, i.e., DAS) and surface sensors in various configurations (single sensors in a sparse network, densely spaced nodal networks, multiple nodal arrays, and surface-deployed DAS). In addition, we address various combinations of these networks and supplement the data-based experience with modelling insights.

The most vital aspects of all instrumentation are their ability to i) detect the event, ii) to characterise the type of event, and iii) to jointly invert the events for source location and classification.

Aspects to achieve the best possible seismic event detection:

- Generally, **borehole installations** provide the lowest noise floor for sensor deployment, as long as sensors are placed in either dedicated observation wells, or decoupled from injection noise by being deployed or even cemented behind casing. Therefore, borehole geophone installations are often employed to trigger data recording on additional systems. Long strings of three-component borehole geophones are the best installation to achieve detection of the very small magnitude seismicity. They likely require a dedicated observation well and are hence an expensive and often complicated deployment option. Some solutions exist to install geophones within injection wells (e.g., Decatur, Illinois, USA). Installation of DAS within injection wells is an alternative and provides the second best potential for event detection, even though DAS only measures monodirectional strain-rate. Tests at Quest showed that DAS is about 40 times less sensitive compared to geophones when comparing signal-to-noise ratios (SNR). In addition, DAS data processing is more complex and time-consuming than the analysis of geophone data. Employing advanced signal processing techniques allowed for detecting about 50% of events on DAS data that were detected with the borehole geophones. The longer and the deeper the borehole installations reach, the better the detection of even small amplitude signals, because more sophisticated noise identification and subsequent noise removal strategies can be employed.

- **Surface installations** - especially individual sensors - are less suited to detect smaller magnitude events, because the noise level at the surface is higher, and near-surface layers usually attenuate signals more strongly. However, individual surface sensors deployed as a network may still contribute to the detection of larger magnitude events. In combination with existing borehole installations, the surface sensors primarily contribute to the detection of larger magnitude events. Other benefits of individual surface sensors are the low instrument and deployment costs and simple data processing.

- The quality of signal detection from surface sensors can be significantly improved if **groups of sensors** are deployed. One way to achieve this is through large nodal arrays, where both signal stacking and noise cancellation methods are applied to improve the SNR. Alternatively, local patches of surface sensors deployed in array configurations can be used to improve the SNR, since noise can be effectively attenuated and coherent signal stacking provides improved detection results. Tests at Quest showed that advanced data pre-processing in combination with array processing allowed to detect about 80% of events that were detected with borehole geophones. Likewise, surface stretches of DAS can be incorporated in data processing with limitations regarding SNR and coupling, though potentially being more cost-effective in case of existing cable-infrastructure.

- Trade-offs between sensor type (e.g., broad-band seismometers, geophones, accelerometers), their quality, maintenance and costs play a significant role for the choice of network components.

- An optimised cost-effective design of a network aimed at event detection depends on the magnitude threshold of events that need to be detected to guarantee no false negatives (i.e, to avoid overlooking events with the potential to damage the caprock), and may require single or multiple borehole installations, potentially combined with surface nodal arrays or surface DAS to detect larger magnitude events at farther distances from the injection location, or to cover a larger, e.g., Giga-scale storage complex.

To characterise the type of detected signal, a sufficient SNR is required. In addition, the ability to spatially scan the full wavefield is of great advantage. This can be achieved either with long and densely spaced receiver lines, both at the surface or within boreholes, as well as with DAS cable deployments. Apparent velocities can be estimated and secondary arrivals as well as waveform conversions may provide information on different wave phases. This can provide important additional constraints for lower event location uncertainties and characterisation of the source, as well as on subsurface properties.

To successfully locate the source, a good representation of the seismic velocity model, correct identification of seismic phases as well as a favourable receiver network geometry are required. To this end, we see again the need for a combination of borehole instrumentation and surface networks. Worth noting are the following observations that may strongly influence the ability to locate seismicity with reasonable certainty:

- Observations limited to a single DAS in a vertical well can be used to detect seismicity, but not to locate. Multiple wells, 3C geophones or surface sensors need to be included for successful event locations.
- Information obtained from combined DAS and geophone borehole installations allows to improve both DAS detectability and geophone phase identification.
- A long vertical aperture is required to improve focal depth estimation. In this respect, downhole DAS can provides valuable input.
- Large nodal networks and DAS data comprise very large data volumes, requiring specialised and advanced real-time processing strategies. Edge-computation and data selection may be required in certain cases with respect to limited data storage capabilities.

Modelling results confirmed the above mentioned findings. In addition, modelling was conducted to verify that observed differences in seismicity are caused by differences in subsurface processes and are not artificially produced by the acquisition footprint. Such acquisition footprints, acting as spatial filters, should be designed to be as homogeneous as possible. Further, the limitations of using only individual networks were analysed. These turned out to have difficulties in detecting small magnitude events or to even being able to locate an event due to the inability of characterising individual seismic phases. Any combination of networks reduces location uncertainties compared to individual networks.

2.2 Recommendations from round of experts

During the ENSURE consortium meeting in June 2024, we discussed monitoring recommendations with all project partners, differentiating between onshore and offshore monitoring as well as borehole stations, surface stations, downhole DAS, and surface DAS installations. In addition to the recommendations from previous deliverables summarised above, we include here additional outcomes of the discussion.

The installation of borehole geophones is regarded as a well-established and trusted technique. Although, in case of just one well being available, borehole geophones need to be combined with other systems offering a better azimuthal location certainty. Three-component instruments allow for backazimuth computation and better phase detection. For more advanced data analyses such as magnitude estimation, source mechanism inversion or stress drop computation, surface stations or arrays with sufficiently low SNR and known instrument response are required to provide the necessary azimuthal coverage. However, surface installations require land access. The low installation costs of DAS are attractive, however, despite its quickly raising TRL, DAS data are still not exhaustively exploited and more research is needed. In addition, for surface DAS installations, more research is needed on potential useful geometries and the lower SNR of DAS data in combination with additional issues such as coupling and anthropogenic or wind noise is seen sceptically.

In many cases the monitoring network will be integrated in some kind of a traffic-light system. In order to obtain unbiased magnitude estimates and to be able to provide peak ground acceleration (PGA) and peak ground velocity (PGV) values to regulators and authorities, a wide sensor bandwidth is required, i.e., sufficiently low eigenfrequency need to be included in the monitoring network. For example, 15 Hz geophones are not sufficient to properly estimate magnitudes for larger events (M > 1) since they can be biased towards lower values.

Additional comments were provided towards the differences between offshore and onshore monitoring projects. The main distinction is the huge extra cost load of offshore monitoring. The main additional cost factors are linked to limitations of real-time monitoring requiring cabled connections and power as well as higher network deployment or maintenance costs. Except for DAS, offshore borehole installations are almost unattainable due to their costs. Offshore seafloor permanent reservoir monitoring (PRM) installations are also very costly, but were proven to be able to detect and locate seismicity in offshore settings like Ekofisk, Oseberg, and Grane in the North Sea. Effective noise reduction methods are of particular importance in offshore installations to tackle the often extreme noise conditions imposed by platform noise, vessel traffic, storms and seismic shooting campaigns. The installation of sensor cables restricts the network geometry, however, the deployment of individual sensors precludes the real-time data availability and poses a challenge with regard to powering the sensors. Trawl hazards as well as problematic sensor coupling in soft, muddy seafloor requires trenching, making the installation more expensive. Maintenance operations are likewise more costly and difficult than for onshore installations. Depending on the location of the project, monitoring through nearby onshore stations or arrays may provide a solution. A comparative study would be welcome on the preferability of installing a higher number of cheaper sensors versus a lower number of expensive OBS units.

The application of offshore DAS cables for seismicity detection and location has been demonstrated at the Northern Lights storage site in the North Sea and shows promising results. However, further experience and comparison with existing methods is required including research into noise cancellation, processing, and event location using such data.

In offshore scenarios, the impact of offshore wind farms is increasingly discussed. The presence of wind turbines in the vicinity of storage sites including seismic monitoring certainly poses a danger of introducing a significant amount of noise on the seismic data. However, seismic noise data originating from offshore wind parks has not been studied to our knowledge and the impact on seismic monitoring with respect to distance and size of wind parks are currently not yet understood.

In general, dual-purpose monitoring is highly recommended, such as reuse of existing telecommunication cables for DAS applications or integration of other sites monitoring data from e.g., oilfield monitoring PRM installations in the vicinity of a storage site.

Whether for onshore or offshore installations, advanced processing methods can further reduce event detection thresholds and location uncertainty, but their effectiveness depends on meeting specific noise conditions and sensor network requirements. These enhanced techniques can significantly increase the value of information, extracting much more from existing hardware with minimal additional costs. However, the following principle holds true: if the initial monitoring effort is inadequate, no level of data processing will achieve the desired observation accuracy.

Table 1 and 2 summarise again some of the advantage and disadvantages of various monitoring systems.

TABLE 1: Comparison of advantages and disadvantages of various onshore monitoring systems

Properties	Borehole geophones	Surface stations	In-well DAS (vertical)	Surface DAS (horizontal)
specific characteristics	useful for triggering records on other systems	easy coverage of areas of arbitrary size	dense channel spacing allows for easier phase identification	dense channel spacing allows for easier phase identification
sensitivity	most sensitive	sensor-dependent, increased by array processing techniques	low sensitivity, increased by signal processing techniques	low sensitivity, application of signal processing techniques dependent on geometry
self-noise	low	sensor-dependent, especially at higher frequencies	high self-noise	high self-noise
ambient noise	very good SNR	requires quiet environments	relatively insensitive	anthropogenic/wind noise
azimuthal resolution	degrades rapidly with increasing event-borehole distance	robust epicentral location within the network aperature	monodirectional (needs to be combined with other systems)	monodirectional (needs to be installed in suitable geometry)
depth resolution	quality of event depth estimate depending on aperture, depth position relative to the event and event-borehole distance	quality of event depth estimate depending on number and distribution of sensors recording event	similar to borehole geophones but often larger available aperture	quality of event depth estimates depending on geometry
measurement quantity	velocity	velocity	strain rate	strain rate
costs onshore	costly	cheap	relatively cheap	relatively cheap
amount of data	low	high if many sensors	huge	huge
processing demands	minimal	significant if many sensors	significant	significant
application of advanced analyses	none that require azimuthal coverage	yes, if SNR is sufficient	none that require azimuthal coverage	none that require 3-component
deployment	simple, if pre-existing wells	challenging	simple, if pre-existing wells; potential issue with well abandonment if installation behind casing as recommended	challenging if trenching required to increase coupling
maintenance	costly in case of issue	medium	low	low
network geometry	limited to line	high flexibility	limited to line	flexibility
land access	only at well-head	large ground footprint	only at well-head	large ground footprint
maturity	trusted, well-established technique	depending on configuration	more research required to optimally exploit	more research required

TABLE 2: Specific challenges in offshore monitoring

Challenge	Borehole geophones	Surface stations	In-well DAS (vertical)	Surface DAS (horizontal)
high ambient noise, seismic shooting	best SNR	arrays of sensors required for application of noise-cancelling processing techniques	relatively insensitive	major concern: surface noise level combined with lower sensitivity
costs offshore	very costly	costly	costly	low-cost if existing telecommunication cables can be used
connection	at well-head	with cable: limited geometry, without cable: real-time unfeasible	problematic connection to surface if well-heads only on seabed	with cable: limited geometry
trawl hazard	none	yes	none	yes
coupling	good	problematic coupling in soft, muddy seafloor requires trenching	good	problematic coupling in soft, muddy seafloor requires trenching