Project acronym and title:

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

REPORT ON STATE OF THE ART MICROSEISMICITY TECHNIQUES IN EUROPE AND NORTH AMERICA

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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 CO_2 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

As part of the H2020 SECURe project, WP2 deals with assessment of the potential risks. One of the most important is the risk of seismicity induced by subsurface use. Induced seismicity can indeed arise from a variety of situations, usually in relation with extraction or injection of fluids, but always strongly influenced by local geological factors. For these subsurface uses, one of the challenges is monitoring the (micro)seismicity, before assessing the actual risk.

The objective of this report is to make a brief state-of-the-art review regarding monitoring of induced seismicity and microseismicity. Microseismicity is potentially induced by many subsurface activities, including CO_2 storage and unconventional gas production. Low magnitude (< 2 or even negative) microseismicity that does not compromise integrity is expected, whereas induced seismicity should be avoided and is monitored for safety reasons. Different sensors (geophones and broadband seismometers) and layout strategies are possible (borehole stations or surface arrays) for monitoring microseismicity. Processing the signal allows for the estimation of magnitude and location of events. Automated processing can allow fast decision-making but human expertise is still necessary. Several examples of monitoring layouts are given from CO_2 storage projects, unconventional gas production, as well as other fields, showing the diversity of options, including operator and public networks. On-going developments focus on reducing the signal-to-noise ratio, the densification of networks and clustering methods, or new detection algorithms. Monitoring is increasingly integrated into real-time mitigation strategies of induced seismicity, with advanced ‘traffic light’ risk management systems.

This preliminary work serves as introduction for many induced seismicity tasks in the SECURe project, with a mix of modelling and field work, including risk assessment of induced seismicity, recommendations for baseline and monitoring strategies, tests of innovative sensors, and risk mitigation strategies. In addition to technological improvements, we recommend a more systematic approach to the availability of data to regulators and researchers, as well as a standardisation of magnitude and ground motion computations that are often used as regulatory thresholds.

Contents

1 Introduction

In the context of Work Package (WP) 2 - dedicated to risk assessment of CO_2 storage and unconventional gas production risks - of the H2020 project SECURe[1], this report aims at providing a review of the state-of-the-art concerning the monitoring of induced (micro)seismicity from subsurface exploitations. This review is a preliminary work regarding induced (micro)seismicity within the SECURe project. Several tasks are dedicated to induced seismicity in the project and address many aspects of risk management: risk assessment, risk monitoring and risk mitigation.

It is important to clarify the vocabulary in order to explain the terms of “induced seismicity” and “microseismicity”. This is the purpose of Chapter 2 which will also detail the purpose of monitoring. The third and fourth chapter will respectively tackle the subject of setting of sensors and processing of data. The fifth chapter summarizes several projects from various fields, highlighting how monitoring induced seismicity is performed in practice. The sixth chapter considers some on-going developments with the potential of improving the state-of-the-art, before conclusions and recommendations.

2 Induced seismicity and microseismicity: definitions and monitoring objectives

2.1 DEFINITIONS

2.1.1 Induced seismicity

The majority of the earthquakes that occur around the Earth are qualified as tectonic (or natural) seismic events. With the recent development of some anthropogenic industrial activities, many sources of potential new seismic activity appear. Among them, we note by frequency mining activities (exploitation and post mining adjustments), hydrocarbon industrial activities (hydraulic fracturing, secondary recovery, oil and gas extraction, and gas storage including Carbon Capture and Storage -CCS), filling or extraction of reservoirs and dams, geothermal activities and finally waste water injection operations. More rarely, other “human seismic sources” can generate significant seismic motion, including nuclear tests. This seismicity is generally qualified as *induced seismicity* because it is induced by human activity. Some induced faults or cracks in bedrock can be newly created.

Other authors evoke the concept of *Triggered Seismicity* particularly for the context of dam and reservoir seismicity (ICOLD, 2009). In this case, the seismic potential originates in one or more pre-existing faults close to the human activity, which may be in a state of stress already close to rupture. The potential triggering of an earthquake follows the modification of the local properties of the ground (stress, diffusion of water pressures in the substratum, decreasing the effective stresses and the shear resistance). To sum up, the triggered earthquake is initiated by anthropogenic perturbation of mechanical local properties. The more the tectonic context of the industrial site is associated with potential pre-existing faults, the more the anthropogenic disturbance will be potentially influential. In other words, in certain scenarios, the human activity accelerates the triggering of an earthquake.

One challenge is to discriminate the induced and the natural seismicity. Some statistical studies based on the inter-event time and inter-event distance (space-time-magnitude analysis) help to distinguish induced seismicity from natural seismicity. The precise location of the event is also decisive in the distinction. Another approach is to study precisely the waveforms recorded (shape, duration, seismic source or moment tensor inversion). For example, the collapse of a mine roof (rockburst) in a room and pillar exploitation can easily be distinguished from a seismic shear rupture. Today, these studies often take place several weeks, months even years after the occurrence of the event with sometimes divergent opinions (Moyer et al., 2017; Eyewitness News, 2014; Sandton Chronicle, 2014).

[1] http://securegeoenergy.eu/

2.1.2 Microseismicity

Some industrial activities can generate microseismic events that are not felt by the local population. This activity is described as microseismicity. The domain of microseismicity concerns seismic events with magnitude typically less than 2 ML. For example, in South African mines, micro events as small as -4.4 ML were recorded (Kwiatek et al., 2011).

If the induced seismic events have mainly low magnitudes less than 3 ML, they are often very shallow, at a few kilometers or even a few hundreds of meters depth. In these cases, a significant seismic activity can be felt by resident population. Unfortunately, one of the common features of induced seismicity is its repeatability or frequency during the whole duration of the industrial process that generated it. In addition, the cessation of seismic activity does not always stop with the cessation of industrial activities and can last longer in general, sometimes with consequences several years after the end of the process. This induced seismicity can also appear several kilometers away from the industrial plant, many years after the beginning of the industrial operations (e.g., Groningen gas field, Van Thienen-Visser and Breunese, 2015, see also the Special Issue[2]).

2.2 MONITORING PURPOSES

Designing a robust monitoring plan will involve many decisions from the operator, such as the number of sensors involved, their location, the duration of monitoring, and frequency of interest. These choices should be guided by the following questions:

- Has the level of background seismicity change since the industrial activity?
- When, how big and low long will the next induced seismic event or crisis be?
- How does seismicity evolve spatially and temporally?
- When can we expect events felt by populations? Can these events be damaging to structures (inside or outside the plant)?
- In case of strong motion, can we assess the level reached on a specific installation or area?

2.2.1 Risk of induced seismicity

Risk can be defined in several ways. Traditionally it is defined as a combination of the probability and scope of the consequences. The ISO31000 norm introduces a new definition as “the effect of uncertainty on an organization’s ability to meet its objectives”. However, in the natural risk / disaster community, in general risk is considered as a combination of a hazard (induced seismicity) and of exposed stakes (constructions, lifelines, strategic nodes, population) (e.g. Bommer et al. 2015). As described in Section 2.2, the induced seismic hazard assessment is a great challenge since it depends on natural conditions supposed to be approximately stable in time and anthropogenic modifications (injection, extraction) that can change significantly with time. In the specific case of the induced seismicity, the repeatability can constitute an additional risk assimilated to a nuisance.

Unfortunately, the first studies of the seismic hazard and risk on a region typically start with the occurrence of the first felt events by the population, particularly in the area where no regular seismic activity exists.

Fortunately, most industrial projects do not produce seismic activity. Sometimes, the seismic activity is limited to felt events with no structural damage. Rarely, following damage on houses or strong motion, some projects have been forced to stop (e.g., a geothermal project in Basel in 2009, Mediterranean Spanish offshore gas storage Castor in 2014) (Cesca et al., 2014; Deichmann and Giardini, 2009). In these rare cases, the potential seismic hazard and risk gave rise to fears of even stronger events. Moreover, the public pressure did not allow to take the risk to continue the industrial activities.

These observations show the need of a good knowledge of the natural seismic state and of the external anthropogenic factors that can modify the balance of this initial state. All these parameters and factors drive the induced seismic hazard and by consequence the induced seismic risk in an urban area. Today, the best tool to monitor this initial state and its evolution in time and space is a seismic network.

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[2] https://www.cambridge.org/core/journals/netherlands-journal-of-geosciences/issue/induced-seismicity-in-the-groningen-gas-field-the-netherlands/5AD5EE9E8EF77A8DE50D6D60963AFFBB

2.2.2 Monitoring microseismicity for performance

In some cases, microseismicity monitoring is also used for following the performance aspect (i.e. checking that the operations are evolving as expected). This is particularly true for hydraulic fracturing or stimulation operations: the main purpose of monitoring is primarily to check how the fractures evolve (i.e expected microseismicity, SHFRP, 2019). Moreover, a good monitoring and understanding of microseismicity, and main generation mechanisms, is very important in order to get a better capacity of limiting larger induced seismicity (Bonhoff et al. 2018).

3 Techniques and methods for monitoring seismicity

Eaton (2018) describes the main sensor types: geophones, seismometers, accelerometers, and distributed acoustic sensing (DAS). Geophones are motion-sensitive transducers that use a damped mass-spring system to convert ground motion into an electrical signal that is proportional to the ground velocity. Geophones are traditionally used in large quantities for active seismic surveys in exploration applications (Yenier et al. 2018). A seismometer is a capacitive force-balance device. This type of device uses a mass-spring system, but rather than measuring the elongation of the spring a compensating force is applied to maintain the mass in a central position. Broadband seismometers are high performing instruments rooted in earthquake seismology. Accelerometers respond to instantaneous acceleration of the ground, using piezoelectric ceramic transducers with a mass that provides a pressure in order to generate a voltage. *DAS* is an emerging technology in which an optical fibre provides both the medium for signal transmission as well as the sensor (See Chapter 6 for a discussion on the use of DAS for microseismicity monitoring). In addition to the difference in technology, the usage is also different mainly due to the different frequency range of each sensor. Traditional earthquake monitoring typically use broadband seismographs that can detect moderate to large earthquakes (M>1.5), with their better precision at lower frequencies. For microseismicity however, the higher corner-frequency for small magnitude events (M<1.5) enables accurate estimates of source parameters from geophones at a fraction of the cost of broadband seismometers (SHFRP, 2019). However, Yenier et al. (2018) note that the use of geophones for induced seismicity monitoring may come at a risk of underestimating magnitudes and ground motion amplitudes.

Due to the specificity of microseismicity, the seismic stations used for recording it need to be well designed.

The magnitude of the induced seismic events is generally below 2 ML. Moreover, the seismic sources are shallow (some hundreds of meters to a few kilometres depth) and a microseismic network is in principle “just above” or very close geographically to the seismic sources. These characteristics indicate that the precision of the acquisition time need to be the best possible (less than 1 ms) and that the frequency band of the sensor (sensitivity) should be greater than 10-100 Hz. Consequently, the sampling of the data should be at least equal to 1 000 Hz, in order to obtain the required precision for picking the different phase arrivals. Even with a protection vault for the station, we recommend also to favour waterproof devices (IP67 or greater[3]) for outside conditions, particularly in an industrial environment.

If these high frequency characteristics are indispensable to guarantee the detection and the hypocentral location of very local microseismic events, it can be also very helpful to have sensors with longer period characteristics in order to record greater regional or local earthquakes that can influence the seismic activity on the industrial site. It can also help source mechanism study (Aochi and Burnol, 2018).

A compromise is use of accelerometer sensors which have the required sensitivity in terms of frequency, that allow the recording of strong motion without saturation, and also regional earthquakes. This type of sensor is also able to record acceleration that can be directly compared to the standard response spectra provided by the national regulations in the building code. Another benefit is its robustness and relative stability with external conditions (temperature, pressure).

If some events have been felt, a strategy to implement the seismic stations consists in putting them all around the area of perception up to a few hundred of meters or kilometers depending on the expected depth of the

[3] See https://en.wikipedia.org/wiki/IP_Code for more details

seismic event. If there is not an existing network, it is necessary to deploy urgently a temporary network after a felt event (generally in the 24 hours following the felt event) because the seismic activity can decrease very quickly.

A network should be composed of at least 5 to 6 seismic stations for a small temporary seismic array, but for detailed earthquake surveys, or if the area is large, it should be better to extend it to 10 to 20 stations. The density of seismic stations will give the reliability and the resolution of the results provided by the network, particularly the threshold of detection and the precision of the hypocentre determination.

The use of borehole sensors can also help to better detect and locate the events, particularly if interference is locally generated by industrial or human activities (so-called 'noisy' surface conditions). Unfortunately, this anthropogenic noise is often in the same frequency span than those of the microseismicity that constitutes supplementary difficulties to find a good installation site. The disadvantage of borehole sensors is that they are more costly to install and sometimes a little more complicated to orient sensors. This technique is also inappropriate in case of emergency installation.

Finally, modern systems of communication (4G, internet) allow the merging of seismic waveforms from different stations or even networks (creating a 'virtual network'). This allows the management of a real-time system giving automatically the detection, location and magnitude of seismic events and in the most advanced system to be connected to a Classical or Traditional Traffic Light System (TLS) or even Adaptative (ATLS) Traffic Light System (Wiemer et al., 2014; Grigoli et al., 2017). Such automatic processing is particularly useful during emergency situations (e.g., cases of seismic crisis).

See also Bohnhoff et al. (2018) for a discussion about the main design decisions related to the setup of a induced seismicity monitoring network.

4 Processing and use of the data

The main goal of microseismicity monitoring is to follow the spatio-temporal evolution of the events. For that, the best finalised tool is the production of an earthquake catalogue.

The first stage directly related to the microseismic monitoring consists in:

- Detecting the events emerging from natural and anthropogenic noise;
- Picking the seismic wave arrivals;
- Locating the event (with associated uncertainties);
- Quantifying them (magnitude assessing);

The second stage is to compare the set of detected events with the parameters related to injection/extraction phases for fluid or gas (time periods, duration, rate of flow, pressure, volume, modification of the geomechanical, chemical and/or thermal environment) that can impact the seismicity.

Once the knowledge of the site (velocity model, station correction, potential site effects for amplification or de-amplification) and the potential seismic events that can occur in the future are correctly established, it is very helpful to retrieve the data (in real time or near real time) and to process them automatically. While this automatic processing (detection, location and magnitude assessing) cannot yet fully replace the direct assessment of a trained human specialist, it can help the analyst in the case of a seismic crisis generating a huge amount of microseismic events with potential migration towards risk areas. This automatic process will give the very first information that can be delivered to the operator, the administration, local authorities and populations. Automated alerts are already in place for natural seismicity in seismological observatories and are often used by industrial site operators in order to monitor with greater ease the stimulation operations.

One of the benefits of such microseismic monitoring is the reliability and quality of the produced information in regard with that provided by national or regional agencies (location, level of stress that affect structures or people). This can bring to the site operators several advantages:

- A better understanding of the site behaviour, which allows the operator to improve site management, enhancing performance and reducing risks

- Modern communication tools for professionals and general public (Seedlink feeds, websites) can be used by most monitoring systems, increasing the transparency and therefore the trust between the operator and its environment (policy makers, neighbours) – as trust has become an important consideration for public acceptance

Finally, coupling automatically these seismic characteristics with external forcing parameters described above in the 2nd stage can drive to a Traffic Light System (TLS). This assumes that the mechanisms of the interaction relationships between microseismicity and external 'stresses' are well known and shared with the different communities.

5 Examples of induced seismicity and microseismicity monitoring

In this Chapter, we review some real-life examples, following the format of the report: what purposes? What sensors? What layout? How is the data processed and used?

The main purpose of this section is to outline the setup for microseismicity monitoring. However, some case studies are notable because of induced (potentially felt) seismicity. It should be clear to the reader that, as explained in Chapter 2, microseismicity is expected in many subsurface operations, and is monitored for performance purposes, whereas induced seismicity is in general an undesired feature and is monitored for safety and public acceptance reasons. A thorough database of anthropogenic seismicity was compiled by Foulger et al. (2018).

5.1 CO_2 STORAGE

Verdon & Stork (2016) summarize the seismic monitoring at pilot CCS projects including Weyburn, Sleipner, Snøhvit, In Salah, Aquistore, Cranfield, Decatur, Aneth and Lacq-Rousse.

Aquistore (Canada): Extensive seismic monitoring experiments have been deployed (Stork et al., 2018).

- An array of 50 geophones (10 Hz one-component, at about 20 m deep) was operational before injection, aligned NS and EW lines over 2.5 km long. This was enhanced or replaced by additional 25 geophones (3 components at about 6 m depth), and a 65-geophone array is fully available, deployed in January 2015. Sampling rate is 500 Hz.
- Three broadband seismometers (0.1-50 Hz) within about 1 km of the injection well with two others added (December 2016). Sampling rate is 100 Hz and data are transmitted to the Canadian National Seismograph Network.
- During the first 8 months of injection (May to December 2015), an array of five geophones (15 Hz, 3 components) was deployed in the observation well between 2950 m and 3010 m depth.

To date no injection-related induced seismicity has been observed. Using synthetic data added to noise models, the estimated minimum detectable event local magnitude is −0.8 ML for the broadband stations and between −1.6 and −0.6 ML for the near-surface geophones. Thus far, small volumes of CO_2 have been injected at Aquistore (~140 kt) and injection has generally occurred below the host rock fracture pressure. As a result, predicted pore pressure changes are small and periods without injection have allowed relaxation of the pressure plume. (Stork et al., 2018).

Lacq-Rousse (France): A microseismic monitoring system was installed (Payre et al., 2014).

- 1 surface seismometer (conventional for natural seismicity)
- 7 shallow-buried arrays (SBA - about 200 m depth) at a radius of 2 km around the injection well (1 is at the center and 6 are in the surroundings). Each SBA consists of a vertical array of four 10-Hz triaxial geophones, called master network.
- 1 deep vertical array of 3 accelerometers (4180, 4280, 4380 m depth), called the 'research network'.

The network was designed for recording events of a magnitude as low as –1. During the injection of 51 kt during 2011-2014, about 2500 events were detected, and over 600 events of magnitude between –2.3 ML and –0.5 ML were located in the reservoir (Payre et al., 2014).

Quest-Alberta (Canada): For a plan of injecting up to 1 Mt/year of CO_2 starting in August 2015, Alberta Sequestration Lease Area (SLA) is defined about 40 km from the injection sites (Rock et al., 2017). Regionally, a public seismic monitoring network has an ability of detecting a magnitude 3 ML event at least. More than 50 potential technologies for monitoring have been considered and, for example, surface microseismic monitoring was excluded due to insufficient sensitivity (https://www.energy.alberta.ca). The downhole microseismic monitoring is designed for detecting M= -2 ML at an 800 m distance, and M= -1 ML from 3000 m from the geophone array. To date, no seismic events were recorded in the monitoring range (SCL 2015).

- Dowhnhole microseismic monitoring (eight level downhole geophone array, 3 components) installed several months prior to the injection.

5.2 SHALE GAS

Induced seismicity associated with hydraulic fracturing in unconventional reservoirs (tight sands, coal beds or shale formations) has been reported from many operations across the world (e.g. Lopez-Comino et al., 2018). In Europe, the first recorded instance of induced seismicity associated with shale gas operations occurred at a shale gas exploration site near Blackpool, Lancashire in the north-west of England (a number of earthquakes up to ML 2.3 were recorded in 2011) (Clarke et al., 2014). Previous H2020 projects including M4ShaleGas and Fracrisk, have many resources dedicated to the monitoring of shale gas operations[4].

Preese Hall, Blackpool (UK): Hydraulic fracturing in the UK was suspended following induced seismicity to a maximum magnitude of 2.3 at the Preese Hall site in 2011, Following these events, a traffic-light-system was established, designed to mitigate the occurrence of felt seismicity and using an upper limit of 0.5ML at which operations would be subject to review (Green et al., 2012). The largest, first earthquake was reported by BGS (British Geological Survey) and regional networks could detect a magnitude down to 0 in this region (Clarke et al., 2014). Proactively up to 6 local seismometer stations are installed, being capable to detect events to ML-2.

Preston New Road (UK)[5]: Hydraulic fracturing operations started at Preston New Road, near Blackpool, on 15 October 2018. BGS and Liverpool University have deployed a dense network of temporary seismic sensors around Blackpool. This allows detection of smaller magnitudes than with the national seismic network. The largest event detected to date had a magnitude of 1.5 ML.

Oklahoma (USA): Activation of seismicity in Oklahoma is well known due to the massive waste water injection (inducing a Mw5.8 in 2016, Foulger et al., 2018) and some cluster (South-Central Oklahoma in 2011, ML from 0.6 to 2.9) was likely triggered by hydraulic fracturing (Holland, 2013). Many stations (more than 100 seismometers) have been installed and detecting seismicity has improved according to the catalogue of Oklahoma Geological Survey[6].

British Columbia (CA): SHFRP (2019) describe the history of development of shale gas production in the state of British Columbia (BC) in Canada. Contrary to Oklahoma, induced seismicity experienced in BC has more often been linked to hydraulic fracturing. The local regulations require the shut-down of operations for M≥4 ML events and events with felt ground motions within a 3km radius of the well pad. BC is currently the only jurisdiction where the collection of near-field accelerograms is required. The largest recorded event was a ML 4.6 on August 17th, 2015, induced by hydraulic fracturing.

Regarding instrumentation, 11 broadband seismograph stations are deployed in the vicinity of the operations, in addition to a 9-station dense array from McGill University. This allows a minimum detectable magnitude of M0.6-1.6 and a resolution of ±2 km for hypocentre location in the main area. The operator-deployed arrays routinely detect events with magnitudes as small as 0.5 with epicentre location uncertainty of ± 100 m and hypocentre location uncertainty of ± 250 m. However the data are not routinely available to the regulators or researchers.

5.3 OTHER CASES

Here we describe experiences from other subsurface technologies such as Enhanced Geothermal System (EGS e.g. Soultz) or conventional gas production/storage (e.g. Groningen).

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[4] http://www.m4shalegas.eu/reportsp1.html ; http://www.fracrisk.eu/
[5] http://earthquakes.bgs.ac.uk/research/PrestonNewRoadFAQ.html
[6] http://www.ou.edu/ogs

Soultz-sous-Forêt (France): An EGS experiment started in 1986 and is operational nowadays (https://geothermie.es.fr/). The stimulation tests have been repeated since 1993. In 2003, a magnitude of 2.9 ML was felt largely in the area during the hydraulic stimulation of GPK3 (e.g. Charléty et al., 2007; Dorbath et al., 2009; Calò et al., 2014). The monitoring network consists of:

- Borehole network of 6 wells (1500 m or deeper) consisting of 4-component accelerometers and 3-component geophones.
- Surface network of 9 stations (1 or 3 components).

Vendenheim (France): Another EGS project in Alsace began in 2016 and is currently under construction. The area is monitored by 4 borehole 3 components geophones and a vault broadband seismometer, the latter being directly connected to the regional observatory. This matches with the requirement by the regional authority[7]. Temporary arrays using geophones or broadband seismometers are also deployed during the critical phases of the drilling.

Groningen (Netherlands): The induced seismicity due to the gas extraction is known since 1986 (M=2.8) and several earthquakes of magnitude larger than 3 (M3.4 in 1997, M3.5 in 2001, M3.4 in 2006, M3.6 in 2012) were detected. Study and Data Acquisition Plan Induced Seismicity Groningen was launched in 2012[8].The seismic monitoring network comprises:

- 10 GPS stations.
- 69 geophone wells and accelerometers.
- 2 vertical geophone arrays.
- Real-time compaction monitoring fibre optic cable.
- More than 300 accelerometers in the foundations of buildings.

6 On-going developments

In this part, we review some on-going developments that may progress monitoring technologies beyond the current state-of-the-art.

Microseismicity monitoring drew great benefits from the real time monitoring of natural seismic events undertaken by observatories. Several algorithms (Seiscomp locator nucleation) and communication protocols (Seedlink feeds) were adapted for site operations. However, microseismicity monitoring has its own specific set of challenges; these challenges are currently considered in ongoing R&D projects.

6.1 IMPROVING THE NETWORK DETECTION CAPACITIES

While natural seismicity monitoring focuses on larger damaging earthquakes, microseismicity monitoring strives to get the faintest signals in order to draw the most complete picture of the site mechanical behaviour. As such, there is a real challenge to improve the ways to get a signal out of the noise by all means possible.

A) Improving signal to noise ratio through a densification of the networks and clustering methods

The first step to obtaining a better signal is to cluster several sensors together and use array processing methods developed in volcanology monitoring settings. To make that possible, new cost-effective and efficient geophone systems are currently tested for passive seismic monitoring; massive data gathering methods are implemented in order to take advantage of huge geophone deployments (eg. Rittershoffen experiment - Maurer et al. 2015).

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[7] http://www.grand-est.developpement-durable.gouv.fr/ (In French)

[8] Study and Data Acquisition Plan Induced Seismicity Groningen, Update Post-Winnigsplan 2016, available on https://www.nam.nl/algemeen/mediatheek-en-downloads/winningsplan-2016/_jcr_content/par/textimage_996696702.stream/1461000509432/e4eae9c707995c86544bf28c51dd9382016d619b25bb326ebb501a40adc06501/study-and-data-acquisition-plan-for-induced-seismicity-for-winningsplan-2016-part1.pdf

New processing of the ambient noise can also be used in addition to microseismic events in order to retrieve more information from the subsurface. This is particularly useful during shale gas hydro-fracturing operations where operators are more interested in imaging the micro-fractures and the development of permeable pathways (Ross et al. 2017, Sicking et al. 2017; Bohnhoff et al. 2018).

Another path to improve the density of sensors is the recent use of Distributed Acoustic Sensors (DAS – Eaton, 2018): fiber optic cables are deployed and used as high density geophone arrays. DAS systems were at first deployed in the well cement for use as downhole sensors (at Rousse-Lacq), but recent developments (Reyjkanes experiment within the FP7 IMAGE project[9]) show that a surface deployment for seismic monitoring can lead to new possibilities.

B) Development of new detection algorithms

Operational detection algorithms usually use Short Term Average over Long Term Average ratios (STA/LTA, Earle and Shearer 1994; Eaton, 2018) to detect arrivals on single stations; these detections are then processed at the network level to transform them into event locations.

New detection algorithms can take advantage of dense networks to use synchronous detections in order to reduce the noise levels, and therefore resolve less powerful events. Another strategy is to use the increasingly abundant event database available coupled with machine learning algorithms to set smart automated pattern recognition mechanisms that can reduce the influence of noise on event detection.

6.2 INTEGRATING SEISMIC MONITORING INTO SMART DECISION PROCESS

Operational seismic monitoring systems are currently using simple rules: if an event magnitude is greater than a given threshold, the operations are put on pause in order to assess the impact on production and environment of ground motions associated with the subsurface activities (including hydraulic fracturing, CO_2 storage or EGS; Eaton, 2018). These monitoring strategies are likely to evolve as exploration activities continue to be the subject of intense public scrutiny in the UK and elsewhere (Kendall et al., 2019).

Ongoing R&D projects such as the SECURe project, are trying to merge the knowledge gained by observed small seismic events into production and reservoir behaviour models, with the following goals:

- Get a better understanding of the reservoir behaviour, its capacities and its limits, in order to better plan ahead the future production
- Produce early warnings that can be taken into account by the site operator to adapt the production in advance instead of stopping it when significant events occur.

7 Conclusions, future works within SECURe and recommendations

This report provides an overview of the main requirements for induced seismicity monitoring. After clarifying some terms (induced seismicity vs microseismcity), the state-of-the-art in terms of sensors, deployment and processing has been outlined. Examples from CO_2 storage, unconventional gas production, as well as other subsurface technologies are provided. Current research priorities are highlighted.

This report serves as an introduction to the induced seismicity related activities in several WPs of SECURe. In WP2, focussing on risk assessment, activities are dedicated to the risk of seismicity potentially leading to a fracture in the caprock. The result from the task will provide recommendations for monitoring strategies. Within WP2, task 2.4 will combine physical and statistical models on a real-data set in order to gain a better understanding of the risk in relation to operational parameters. This modelling approach will be complemented by observations made on a Danish gas storage facility and will try to correlate induced (micro)seismicity with pressure changes.

[9] http://www.image-fp7.eu/reference-documents/Pages/default.aspx

In WP3, dedicated to baseline and monitoring strategies, activities will provide recommendations for optimising baseline and monitoring of microseismicity. These include work based on modelling and previous data, and field experiments.

WP4, dedicated to monitoring sensors, activities will provide recommendations for optimising monitoring, this time more in relation to the hardware components. Again, these activities are based on modelling and previous data and field experiments.

In WP5, dedicated to risk mitigation, activities address the development of operational strategies combining the competing objectives of performance and safety. The strategies will be informed by predictive models based on microseismic data.

This report highlights the difference between microseismicity and induced seismicity. Induced seismicity data is largely available (Foulger et al. 2018), but microseismic data is often held as commercial-in-confidence/proprietary and remains the property of industrial operators. A wider dissemination towards regulators and researchers would improve the collective understanding of the underlying mechanisms. Of particular interest is the correlation between the observed microseismicity and the potential for induced (felt) seismicity and associated ground motion.

A second recommendation is to work on standardization of data processing (SHFRP, 2019). This is particularly critical as many regulations express a threshold in magnitude. Hence a uniform method of computing magnitudes (preferentially moment magnitudes) would help the enforcement of such regulations.

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