Project Acronym and Title:

M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

REVIEW OF SEISMIC MONITORING NETWORK DESIGN, WAVEFORM PROCESSING PROCEDURES, AND BEST PRACTICES IN THE USA AND CANADA

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Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*. The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts.

The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation.

Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources

There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement.

The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary

This report summarizes the current efforts undertaken in the US and Canada to seismically monitor hydraulic fracturing operations in shale gas reservoirs. While induced seismic events raise public concerns the vast majority of hydraulic fracturing-induced earthquakes is of magnitudes too small to felt or even instrumentally detected at the surface. While best practice concepts to consistently monitor and eventually mitigate induced seismicity are needed, as of today only a small number of reservoir treatments is monitored and regulations are under preparation in individual states or region only.

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1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas source rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for European publics to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and exploitation. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

1.2 Study objectives for this report

The objectives of this report are to summarize the current best practice of microseismic monitoring related to hydraulic fracturing in shale gas reservoirs.

1.3 Aims of this report

This report aims at informing about the current best practice of microseismic monitoring in producing shale gas reservoirs.

2 RELEVANCE OF MICROSEISMIC MONITORING OF SHALE GAS HYDRAULIC FRACTURING OPERATIONS

General awareness of induced seismicity related to different types of reservoir treatments involving fluid injection has been on the rise for several decades. It has ever since been subject of both scientific studies and public acceptance issues. Because of their novelty in many naturally aseismic areas of the world, the small number of hydraulic fracturing-induced and potentially damaging local earthquakes has become a real public safety issue. The result has been a call for public seismic monitoring of shale gas exploration and production activities.

Public confusion exists in differentiating induced events from hydraulic fracturing versus both waste water disposal and fluids produced in conjunction with Oil and Gas (Rubinstein and Mahani, 2015). While similar monitoring procedures apply to all 3 activities, the discussion in this report is confined to shale gas stimulation and production induced earthquakes.

Monitoring of induced earthquakes has also taken on a significant role in guiding industrial shale gas development. On the whole, while monitoring a relatively small fraction of their frack jobs, the microearthquake data collected by industry has been used to estimate the economic potential of oil and gas production from such well completion techniques. While gathered with more sophisticated networks than used in public monitoring efforts, these efforts have fallen short of satisfactory results. Thus development of more advanced methods of detecting induced seismicity in shale gas exploitation has become a priority for both the public and industry sectors. A state of the art microseismic monitoring designed on a case by case incorporating local boundary conditions is needed but still far off.

The number of instances of hydraulic fracturing induced ‘felt’ seismicity related to unconventional shale gas production has significantly increased over the last few years. This has resulted in the necessity for developing Best Practice concepts for appropriate microseismic monitoring by industry protocols enforced through regulatory agencies. This is now a key pre-requisite to mitigate seismic hazard related to any reservoir treatment involving all fluid injections, including hydraulic fracturing in shale gas reservoirs.

In comparison to larger magnitude induced seismic events related to waste-water disposal (Ellsworth, 2013; Keranen et al., 2014), the magnitude and number of induced earthquakes directly associated with hydraulic fracturing of conventional and unconventional hydrocarbon reservoirs are usually smaller (typically on the order of magnitude -2) and fewer in number (Suckale, 2010; Warpinski et al., 2012). Most of the events induced during hydraulic fracturing operations cannot be felt or even instrumentally detected at the surface. Only approximately 70 felt fracturing-induced earthquakes are reported to have occurred in more than 3,000,000 wells that have been treated (Maxwell et al., 2015). Among these the most widely publicized were the M_l=2.3 event in Blackpool/UK (dePater and Baisch, 2011), the M_l=2.9 event in Oklahoma (Holland, 2011; 2013) and more recently events in Ohio – the largest event at the latter location being related to frack waste water injection as opposed to ongoing shale gas development there (Skoumal et al., 2015).

In Canada, however, the biggest hydraulic fracturing-induced seismic event is now believed to have a magnitude around 4.4. Several such M>4 events have occurred in the Montney (British Columbia Oil and Gas Commission Report, 2014) and in the Duvernay play in Alberta (AER, 2015). While no reported cases of damage or injury have occurred with any of these or a fore mentioned 70 felt earthquakes (Maxwell et al., 2015), the risk posed by them is quite real, and very relevant to the continued exploitation of shale gas resources.

3 SEISMIC NETWORK DESIGN AND WAVEFORM PROCESSING TECHNIQUES

Induced microearthquake detection and recording is a long- and well-established technique for monitoring reservoir treatments and imaging hydraulic fractures indirectly through locating reactivated natural fractures in its direct surrounding at depth (e.g. Warpinski, 2009; Bohnhoff et al., 2010). Prior to the past few years, public and industrial monitoring of induced events in shale gas plays was mostly accomplished by surface seismograph networks. Placing individual surface seismic stations at spacing of 10 to 100 km is usually sufficient for monitoring natural seismicity on a regional level and down to magnitudes as small as 2 or so. This, however, is by far not appropriate to detect small-magnitude events occurring during hydraulic fracturing treatments in shale gas (as well as in conventional oil and gas) reservoirs. As a step forward monitoring of reservoir treatments was then partly also performed by lowering down single three-component geophones as detectors for smaller-magnitude events not seen at the surface (e.g. during mini-frac operations in the frame of R&D projects (Sarda et al., 1988); placing single arrays of geophones in monitoring wells closest possible to the injection well to detect and locate small-scale seismic events at low magnitude-detection threshold (i.e. event magnitudes of $M<0$) using array techniques.

Surface seismic networks usually aim at providing good azimuthal coverage to precisely determine earthquake hypocenters. This is typically not possible in the reservoir context since single strings of borehole geophones can only be used to act as arrays (thereby functioning as a kind of antenna), providing means for applying technologies such as beam-forming to locate individual seismic events. Such installations take advantage of being closer to the activity, but also the dramatic reduction of surface noise just a few hundred meters underground. In either case, simply outlining the cloud of seismic events was generally seen by the industry/operators as sufficient for estimating frack created production.

In the context of underground natural gas storage, several campaigns were carried out, e.g. by IFPEN and Storengy in the 90’s on pilot sites to develop appropriate equipment suitable for long term monitoring applications such as gas migration mapping and reservoir geomechanical studies (see also Bohnhoff and Zoback, 2010; Bohnhoff et al., 2010). Especially on-tubing permanent downhole geophones associated with a smart downhole and surface instrumentation have been developed for both passive and active seismic (Deflandre *et al.*, 1995; Deflandre *et al*., 2004, Deflandre *et al.* 2009). In particular, downhole digitalization and digital transmission allow to improve the signal to noise ratio on the acquired seismic waveforms. Advanced acquisition software is used to avoid the recording of non-exploitable signals –in case of strong background noise due to fluid flow into the well. Note also that the installation of on-tubing permanent downhole geophones on a few well completions would allow to determine focal mechanism while contributing to reduce location uncertainties. So, this approach is complementary from the use of a single array of geophones in an observation well as sensors can be deployed at greater depth in exploitation wells (until the temperature remains below ~125°C) whereas devoted observation wells are generally shallower because of drilling costs.

However, transferring state-of-the-art network installations and waveform processing technology from both fundamental research and industrial sources is providing substantially more information on reservoir-related processes. In particular this includes the potential real-time monitoring of spatiotemporal changes in the seismicity cloud as the principal indicator for fracture growth and potential along-well leakage. In field data acquisition, basic research has established the significant value of recording seismic signal several hundred meters underground. While not universially used because of drilling costs, industry was quick to develop resource-estimation and production-monitoring systems of 100-or more channel, 100 m deep, buried arrays of ~ 4.5-to-15 Hz geophones. Typically spread over a few tens of square km, these arrays are able to provide faulting mechanisms for fault-plane characterization, anisotropy of the velocity field or variations in the local stress tensor orientation related to fluid injections (e.g. Wuestefeld et al., 2011; Kwiatek et al., 2013).

High-level seismic reflection signal processing of data from both surface and buried arrays has also been quickly adapted by industry. In the most recent developments, passive noise recorded by large channel (>2000 stations) systems listening for seismic emissions for many hours (>24 hrs) have been successfully applied to image active faults and fractures (Gaiser et al. 2011). Such methods have yet to be adapted to forecasting and monitoring of frack-induced seismicity.

4 REGULATORY REQUIREMENTS

While induced seismicity is on the agenda of the public, in the strictest sense the known instances of felt shale-gas-hydraulic fracturing earthquakes are so far actually isolated to several specific regions. They are mainly reported from Oklahoma (US) (Ellsworth, 2013), Blackpool (UK) (dePater and Baisch, 2011; Green et al., 2012), Horn River Basin and Montney reservoirs (British Columbia, Canada, Farahbod et al., 2015), the Duvernay play in Alberta, and the Utica play in Ohio (US), where much of the world's shale gas development has taken place. In other areas where significant induced earthquakes have occurred, the source can be traced back to either waste or produced water (i.e. water accompanying oil and gas production) injection (Ellsworth et al., 2015; Buchanan, 2015).

A common regulatory system enforcing operators to install adequate seismic monitoring networks and/or arrays is still far off. Specific monitoring of shale gas treatments is not mandatory in most places including most of the US and Canada. Probably less than 5% of hydraulic fracturing operations in nonconventional reservoirs are monitored by networks with detection thresholds low enough to confidently follow the small earthquakes lead up to felt and damaging events (W.L. Ellsworth, Stanford University, pers. comm.). While individual guidelines and/or regulations for specific sites, states or region exist (summarized in Walters et al., 2015a) they may not be transferable to all situations.

What monitoring efforts there are, these are done almost entirely under the control of the field operators. Their intention usually is to extract information on the local production potential rather than providing means for following, for example, some kind of "traffic-light system" for stopping short of felt and damaging events due to increasing earthquake numbers and sizes (Bommer et al., 2006).

This said there is currently a process of introducing regulatory best practice guidelines in several areas or states in the US and Canada. At present the state of Ohio has the most advanced monitoring requirements in conjunction with hydraulic fracturing enforced by the Ohio Department of Natural Recources (2015). New rules e.g. in California are currently underway and might be implemented in the near future. In Texas (2015), the state legislature has authorized the installation of a state wide network designed primarily determine whether or not felt events have locations associated with fracks or waste disposal sites. In Oklahoma, efforts have been done to monitor and characterize the recently observed seismicity while the Oklahoma Corporation Commission is working on new regulations for reporting and monitoring on waste water disposal wells (Mc. Namara *et al.* 2015).

In Canada, the regulations for seismic monitoring of hydraulic fracturing operations vary according to location. In areas where frack-induced seismicity is suspected, the most common regulation is that operators needs to ensure than monitoring will locate

M>2 events, which also must be reported to the regulator. The operations are generally stopped if there is an M>4 and/or events are being felt/nuisance. The details of this arrangement vary in location and situation (G. Atkinson, U of Western Ontario, pers. comm.).

While usually few hydraulic fracturing treatments are seismically monitored there are concepts on how to respond in case local microseismic monitoring is conducted. Further developing traffic-light system concepts that simply rely on magnitude thresholds, Walters et al. (2015b) suggest incorporating 'operational factors' that may influence the occurrence of triggered seismicity in a site-specific manner. These authors propose using risk-tolerance matrices that take into consideration the level of tolerance the affected groups (operators, regulators, stakeholders, and public) have for earthquakes triggered by fluid injections.

A potential avenue of advanced monitoring that would significantly improve the tracking of increasing event frequency and size would be the cooperative use of the buried multi-channel, ambient seismic noise and microearthquake monitoring system method mentioned in the previous section.

5 CONCLUSIONS

The here reported overview on current practice of microseismic monitoring in shale gas plays allows to conclude that comprehensive best practice concepts are currently still far off. While only a small number of shale gas treatments are seismically monitored, most of these are under the control of the field operator with specific economic objectives not necessarily matching with interests of the regulators or the public. A regulatory system towards an appropriate concept for microseismic monitoring is underway in some regions but not in sight as a general concept allowing for case-by-case design according to local needs fulfilling requirements defined by regulators.

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