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Full Length Article

Carbon capture and storage, geomechanics and induced seismic activity

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A B S T R A C T

Injection of large volumes of carbon dioxide (CO_2) for the purposes of greenhouse-gas emissions reduction has the potential to induce earthquakes. Operators of proposed projects must therefore take steps to reduce the risks posed by this induced seismicity. In this paper, we examine the causes of injection-induced seismicity (IIS), and how it should be monitored and modelled, and thereby mitigated. Many IIS case studies are found where fluids are injected into layers that are in close proximity to crystalline basement rocks. We investigate this issue further by comparing injection and seismicity in two areas where oilfield wastewater is injected in significant volumes: Oklahoma, where fluids are injected into a basal layer, and Saskatchewan, where fluids are injected into a much shallower layer. We suggest that the different induced seismicity responses in these two areas are at least in part due to these different injection depths. We go on to outline two different approaches for modelling IIS: a statistics based approach and a physical, numerical modelling based approach. Both modelling types have advantages and disadvantages, but share a need to be calibrated with good quality seismic monitoring data if they are to be used with any degree of reliability. We therefore encourage the use of seismic monitoring networks at all future carbon capture and storage (CCS) sites.

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1. Introduction

Carbon dioxide (CO_2), produced from the burning of fossil fuels in thermal power stations and other large industrial facilities, can be captured and removed from a plant's exhaust gases. The captured CO_2 can then be transported to a sedimentary basin, and injected into a suitable geologic formation, where it is permanently trapped. This carbon capture and storage (CCS) technology has the potential to substantially reduce the greenhouse-gas emissions from fossil fuel usage.

By allowing continued fossil fuel use while mitigating emissions, CCS is vital in reducing the costs of decarbonisation. The International Energy Agency (Levina et al., 2013) has estimated that, if CCS is not used in the electricity generation sector, the capital investment needed to meet the same emissions constraints is increased by 40%. Moreover, CCS is often the only technology capable of mitigating emissions from other CO_2-intensive sources such as the cement, steel and refining industries.

Broadly speaking, research on CCS is divided between "capture" and "storage". The capture side focuses on how CO_2 is captured from the exhaust stream of a power plant (or cement factory, oil refinery, etc.): from a financial perspective, this is the costliest part of the CCS process (e.g. Nauclér et al., 2008). The storage side focuses on how CO_2 can be injected and stored in sedimentary formations. It is in understanding how the CO_2 will interact with the subsurface, and in ensuring that the injected CO_2 cannot return to the surface, that the most significant uncertainties associated with CCS are found.

Most early research on CO_2 storage was primarily concerned with the possibility that the buoyant CO_2 would move through the caprock, and eventually leak at the surface. While the fact that subsurface injection could trigger seismicity has been known for decades (e.g. Raleigh et al., 1976), the risks of CCS-induced seismicity were generally downplayed in early CCS papers (e.g. Damen et al., 2006). This was probably because induced seismicity in wider oilfield operations was relatively uncommon.

However, in recent years, a substantial increase in injected wastewater volumes in the mid-continental USA has been linked

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to a dramatic increase in the number of recorded earthquakes (e.g. Ellsworth, 2013), and similar observations have been made in some Canadian basins (e.g. BC Oil and Gas Commission, 2014), and during wastewater disposal in Chinese gas fields (Lei et al., 2008, 2013). Seismic activity also appears to have been triggered by natural gas injection for storage purposes (e.g. Cesca et al., 2014). Given that the proposed injection volumes for commercial-scale CCS sites significantly exceeds the volumes injected at many of these case examples (e.g. Verdon, 2014), the risk of injection-induced seismicity (IIS) at CCS sites is being re-appraised (e.g. Zoback and Gorelick, 2012, 2015; Verdon et al., 2013; Verdon, 2014).

At present, there are still very few active commercial-scale ($\sim$1 Mt/year or more of CO_2 injected) CCS projects. Given that the geomechanical effects of subsurface injection are generally assumed to be scale-dependent (e.g. Verdon et al., 2013), the lack of commercial-scale projects means that there are as yet few opportunities to study the geomechanical impacts of large-scale CO_2 injection directly. Instead, the nascent CCS industry should look to learn from other similar industries. Most notably, there are many similarities between CCS and wastewater disposal (e.g. Verdon, 2014), and we believe that the CCS industry should examine past cases of wastewater disposal-induced seismicity in order to learn lessons that can be applied to future CCS projects.

In this paper, we begin by reviewing case examples where wastewater disposal has triggered seismicity, with the particular aim of establishing the mechanisms for induced seismicity, and the factors that might make an area prone to (or not prone to) induced seismicity. Of particular interest is the link between injection and basement rocks. We go to consider how seismicity can be modelled: we outline two different modelling approaches, one statistical and one numerical, that can be used to estimate the likely largest event size that might be triggered by an injection project. We have applied these models to the induced seismicity recorded at the In Salah CCS project, Algeria. Finally, we make recommendations for the monitoring of induced seismicity at future CCS sites.

2. Case examples of injection-induced seismicity

2.1. Mechanisms for injection-induced seismicity

The first well-recorded example of seismic activity induced by injection occurred at the Rocky Mountain Arsenal, Denver (Healy et al., 1968). The link between injection and seismicity was conclusively demonstrated in the Rangely oilfield, Colorado (Raleigh et al., 1976), where variations in injection rates and pressures produced variations in seismicity.

It is generally accepted that injection-induced seismicity occurs on pre-existing faults. A fault can slide if the shear stress on the fault, τ, exceeds the Mohr−Coulomb failure envelope:

$$\tau > \mu(\sigma_\mathrm{n} - P) + \tau_\mathrm{O} \tag{1}$$

where μ is the coefficient of friction, σ_n is the normal stress acting on the fault, P is the pore pressure within the fault, and τ_O is the cohesive strength of the fault surface. Subsurface injection can thereby lead to seismicity if it leads to either shear stress increases, normal stress decreases, or pore pressure increases, on a fault. This can happen in a number of ways:

- When fluids are injected, pore pressures will inevitably increase to accommodate the additional volumes in the subsurface. This pore pressure increase is the most direct way that injection can lead to seismicity.
- Injection may also cause an expansion of the reservoir, which will alter the stress field in the rocks surrounding the reservoir, potentially leading to fault slip outside the reservoir.
- Once faults begin to slip, the displacement along a fault will create further stress changes capable of triggering events (e.g. King et al., 1994).

Several of these mechanisms may act together during a sequence of induced events. For example, Sumy et al. (2014) studied the seismicity triggered by wastewater disposal near to Prague, Oklahoma, finding that the initial events were likely to have been caused by pore pressure increases in the reservoir, but those subsequent events were triggered by static stress transfer generated by slip along the re-activated fault. It is often challenging to determine precisely the causative mechanism for a series of triggered events (e.g. Cesca et al., 2014).

2.2. Induced seismicity in sediments and basement rocks

Verdon (2014) examined a selection of IIS case studies (all induced by wastewater disposal), and found that seismicity tends to occur at depths below the injection interval, and indeed in many cases, most of the events are observed in the crystalline basement that underlies the sedimentary basin (Fig. 1). Vilarrasa and Carrera (2015) suggested that this is because deviatoric stresses tend to be higher in basement rocks compared to the overlying sediments. Vilarrasa and Carrera (2015) went on to conclude that IIS during CO_2 injection was therefore unlikely.

The relationship between injection into near-basement rocks and IIS merits further consideration. In many IIS case examples, fluids are injected into sedimentary layers that are in close proximity to the crystalline basement. For example, in Oklahoma, where a significant increase in IIS has been observed, much of the injection is into the basal Arbuckle Formation, which directly overlies the pre-Cambrian basement. Similarly, injection into the basal Mt Simon Formation in Ohio and Illinois has led to cases of IIS (e.g. Nicholson et al., 1988; Seeber et al., 2004), including at the Decatur CO_2 injection pilot project (Kaven et al., 2015).

Verdon et al. (2016) compared induced seismicity in two areas that have seen extensive hydrocarbon-extraction-related activity over many decades: Oklahoma, and southeast Saskatchewan. In

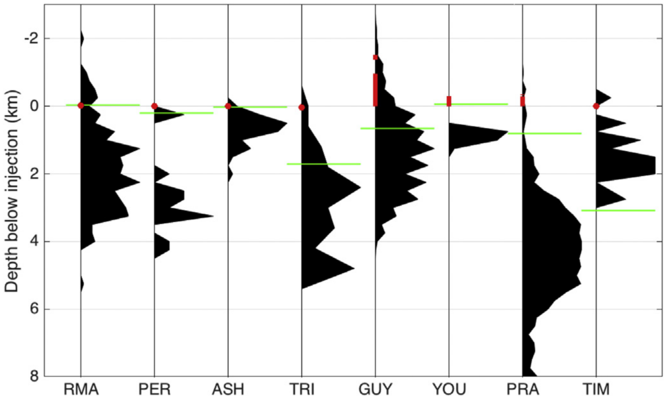

Fig. 1. Histograms showing event depths at various IIS case studies relative to the deepest injection depth. Modified from Verdon (2014). The red lines mark the injection intervals at each site, and the green lines mark the approximate position of the crystalline basement. The case studies considered are: RMA = Rocky Mountain Arsenal (Healy et al., 1968); PER = Perry, Ohio (Nicholson et al., 1988); ASH = Ashtabula, Ohio (Seeber et al., 2004); TRI = Trinidad, Colorado (Meremonte et al., 2002); GUY = Guy, Arkansas (Horton, 2012); YOU = Youngstown, Ohio (Kim, 2013); PRA = Prague, Oklahoma (Keranen et al., 2013); and TIM = Timpson, Texas (Frohlich et al., 2014).

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