Experience of induced seismicity in other geological settings and jurisdictions.

Contents

1. Summary

This paper presents a short overview of the experience of injection induced seismicity in other jurisdictions and is drawn from conversations with N American regulators, operators and service companies and from recent relevant publications. It is not intended to be comprehensive but highlights some current thinking on topics with relevance to UK operations, specifically a description of other geological settings; the experience of seismicity caused by other applications of water injection including geothermal; the maximum magnitude of induced events in other geological settings; the various Traffic Light Systems that have been adopted and the potential improvements and the operational mitigations that have been tried and their success.

Two general conclusions are drawn. The first is that the tendency for injection to induce seismicity appears to be very location/geology specific with, probably, less dependency on the mere presence of faulting or on the engineering parameters of the injection operations themselves. The second is that, while the basic understanding of the physical processes that can cause seismicity are reasonably well understood, the application of those processes to a specific operation or geology, the data on which is often sparse, is still in the early stage of development. In the light of this, it is not surprising that few, if any, generally applicable rules have been established that can be reliably applied to eliminate or mitigate induced seismicity. This underlines the need take every opportunity to improve the understanding of the geological setting prior to operations, conduct operations with caution, rapidly identify unexpected seismic responses and be prepared to react quickly, if necessary suspending operations to accommodate new information.

When relating seismicity to **geological setting**, in certain areas of Canada and the US there is some correlation between significant seismicity and the proximity, and even direct involvement, of deeper basement faulting. Fracking in areas not in such close proximity results in very much lower frequency and magnitude of events even if shallower faulting is present. Similarly, in China, the presence of unexpected very localised intense seismicity has been shown to arise from a large, previously unidentified, fault below the fracturing horizon although a correlation with basement rock was not established. Canadian experience is also that there is a strong correlation between induced earthquakes and fracturing in areas of high in-situ pore pressure (such pore pressure is also a feature of the Bowland shale at Preston New Road). Given that the great majority of well fracturing operations in Canada, US and China do not give rise to significant induced seismicity and that is likely that these wells do encounter faults, it maybe that the presence of faulting of itself is a necessary but not a sufficient condition for seismicity. Further work on the correlation of seismicity and, particularly, event magnitude with deeper faulting and/or overpressure may show these are indicators that could be more generally applicable predictors.

Various approaches have been taken to **mitigating seismicity** either from the start of operations or at resumption following induced events. Much attention has been given to reducing injection rate and/or volume. While there are several hypothesises linking injected volume to the maximum magnitude of induced events, the empirical evidence for this is inconclusive. Opinions on the benefit of immediate flowback of injected fluids are sharply divided over whether an immediate flowback reduces limits the number and maximum magnitude of induced events or increases them. It may be that, in certain geological settings both volume and flowback mitigations will work and in others they won't. Similarly, the effectiveness of skipping stages to avoid induced seismicity is inconclusive, again the effectiveness of such a strategy could be very dependent on the particular geological setting.

Many jurisdictions require some form of **Traffic Light System** which monitors for unusual seismic events and requires action, including mitigation or suspension of operation, should a certain magnitude threshold be exceeded. It has been observed that while these systems are beneficial, they may not be effective at preventing either large events or aftershocks. It should be noted however that for the largest (>4 M) events identified in this paper either no TLS was in place, the TLS was not followed or the thresholds were so large as to be ineffective. As the understanding of induced seismicity has improved a number of suggestions have been made for improvements to TLSs such as monitoring the real-time development of the magnitude or location of events, or incorporating the mathematical simulation of induced seismicity. It should be noted that the UK's TLS adopts the most precautionary thresholds of any jurisdiction and already incorporates real time monitoring of magnitude and location and, to a degree, induced seismicity simulation.

2. The influence of geological setting

The Preese Hall Shale Gas Fracturing Expert Report (2012) recommended that, to better understand the hazard of induced seismicity, there should be a characterisation of any possible active faults in the region using all available geological and geophysical data. Experience in N America has indicated that, in addition to the prevalence of faulting, there are geological characteristics which, at least for the studied setting, signal a predisposition to induced seismicity.

In Alberta, (**ref Alberta, Canadian Consortium**) it has been found that proximity to the Swan Hills reef formation is a proxy for the presence of basement controlled faults. Such faults have been observed as being associated with an increase in seismogenic potential for hydraulic fracturing operations. In this setting, Devonian sedimentary rocks unconformably overlie an eroded Cambrian section in the southeast part of the Swan Hills region; in the northwest part of the region, Devonian rocks lap onto the Precambrian granite of the Peace River arch. A correlation between seismogenic potential and geographical proximity to Swan Hills has shown a significantly higher potential for wells within 10-20 km of the reef edge (as denoted by the Swan Hills formation) than for wells further away. In the same setting, concentrations of lithium and Strontium have also been linked to the involvement of basement faulting and consequent elevated seismographic potential.

In the lower stratigraphic portion of the Montney formation in British Columbia (**ref British Colombia paper**), induced seismicity has been observed to be greater than in the shallower horizons. It is postulated that hydraulic fracturing in these deeper horizons is more likely to re-activate deeper existing faults. Higher levels of induced seismicity in the Montney has also been observed in the structurally deformed Rocky Mountain foothills belt and close to the pre-existing structures of the Fort St John Graben complex. This is a regional-scale, west-trending, fault system situated on the Peace River Arch on the north flank of the Fort St. John Graben. Historically, seismicity was generated by conventional injection and production in the 1980s and, at that time, appeared to display seasonality which was not linked to variations in extraction or injection rates and was unexplained. It is thought that the unique tectonic history of the complex has given it a high seismogenic potential from both water injection and hydraulic fracturing.

It has been observed that two areas of the Montney and Duvernay in Western Canada (**ref Eaton)** where induced earthquakes are strongly clustered are also characterised by a high in- situ pore pressure gradient - in excess of 15 Kpa/m. Induced seismicity is virtually absent in the Montney and Duvernay formations elsewhere and there is a statistically a negligible probability that this correlation is chance. Interestingly, a pre-drill geomechanical model was developed for the PNR-1 Bowland shale well (**ref Clarke**) included a comprehensive pore pressure interpretation showing a significant over-pressure (0.69 psi/ft, 15.61 Kpa/m). The model was backed up by the observed splintery cuttings and gas shows in offset wells and it was concluded that this abnormal pore pressure combined with the tectonic strike slip stress regime (with large horizontal stress anisotropy) and intrinsic anisotropic shale properties were the primary causative factors for a number of drilling incidents.

3. Hydraulic fracturing compared to water disposal seismicity

Experience in N America has indicated that seismicity induced by large scale produced water disposal and that initiated by hydraulic fracturing may have different physical causes and, consequently different mitigations. Atkinson (**ref Atkinson)** has noted that in the central US, most induced seismicity is linked to deep disposal of produced water and that in Western Canada most recent cases are highly correlated with hydraulic fracturing.

The contrasts between the two processes are quite marked (**ref British Colombia**). For disposal, high cumulative volumes can be injected typically well over 100,000 m^3 whereas for fracturing injected volumes vary from 600 to 5,000 m^3 per stage. Disposal volumes are only very rarely flowed back from the target formation and are injected through a set of perforations in a vertical well into fair to good quality reservoir rock where, within a short distance from the well, flow can be achieved without creating high pressure gradients. In contrast, for hydraulic fracturing typically 50 per cent of injected fluid volume is flowed back when a well is put into production, the injection point changes as new hydraulic fracture stages are completed along a horizontal wellbore and injection is purposefully into poor quality rock intended to fracture the rock.

It is observed that, probably as a consequence of the combination of these characteristics, disposal can induce events far distant or deeper than the injection well, often delayed by months or even years from the initiation of injection. Hydraulic fracturing typically induces events within much shorter times and much closer to the injection point where the fracture or well intersect faults although in some cases deeper events, up to 800 m below the injection point or up to 500 m horizontally from the injection point, have been observed.

Operationally, disposal injection rates can be controlled to mitigate seismicity by maintaining the injection pressure below the formation fracture pressure whereas for fracturing the pressures are designed to achieve breakdown pressure which is usually well above the fault re-activation pressure, given this requirement, rate does not appear to control seismicity. In consequence, the mitigation of induced seismicity related to wastewater disposal may be accomplished by limiting injection rates and pressures. The effectiveness of mitigation methods for induced seismicity related to HF is more difficult to assess given the many operational parameters involved.

For disposal wells, a key observation in mitigating risk (**ref Walters**) is whether there is the potential for triggered earthquakes to occur on relatively large, critically stressed, pre-existing basement faults. Over the life of an injection project, it is thought that pore pressure perturbations have the potential to migrate toward critically stressed, permeable faults in the crystalline basement. It has also been observed that in Oklahoma / Kansas, earthquakes characteristically occur at about 4km below the top of the basement and do not reach sedimentary cover, are no closer than 10 km to significant wastewater disposal activity and exhibit a lag of several years to injection activity. Almost none of the observed sequences are associated with any of the mapped faults. Activity on some faults is dominated by slow processes such as fluid diffusion and on others by fast processes such as stress transfer from one rupture to the next. It is noteworthy that that none of the individual faults activate with the largest event. Instead, magnitudes tend to increase as more events are produced.

4. The magnitude of induced seismicity

Induced seismicity caused by fluid injection has been observed in oilfield enhanced recovery, water disposal and hydraulic fracturing operations and in enhanced geothermal system (EGS) energy operations. Numerous studies have analysed the physical and geological causes of the seismicity and the magnitude and frequency of the events.

Rubinstein's review paper of 2015 noted that the largest earthquake known to be induced by enhanced oil recovery was then a M 4.6 event close to Snyder in Texas. For disposal, the injection of chemical waste at the Rocky Mountain Arsenal in the 1960s caused events up to M 4.9. More recently, in 2011 and prior to the introduction of effective mitigation, events induced by produced and flowback water injection have been recorded as high as M 5.3 and M 5.6 in Colorado and Oklahoma respectively.

There are now many international examples of significant felt seismic events induced by hydraulic fracturing. Figure 1 details the largest recorded seismic events by region, putting the events in Lancashire in context. While this illustrates that the Lancashire experience is not unique, it should be noted that other regions have seen far greater hydraulic fracturing activity with induced seismicity seen only rarely. In Lancashire, significant induced seismicity has been seen in all fracked wells.

Region	Country	Max. event	Year	Comment
Sichuan	China	5.2 M_W	2018	Changning
British Columbia	Canada	4.6 M_W	2015	Fort St. John
Alberta	Canada	4.1 M_W	2016	Fox Creek
Ohio	USA	3.7 M_L	2017	
Oklahoma	USA	3.2 M_L	2014	
Lancashire	United Kingdom	2.9 M_L	2019	Preston New Road 2
West Virginia	USA	2.7 M_L	2013	
Lancashire	United Kingdom	2.3 M_L	2011	Preese Hall 1
Pennsylvania	USA	1.9 M_L	2016	

Figure 1 - Examples of notable seismic events considered to be likely to have been induced by hydraulic fracturing operations*(modified from The Human-Induced Earthquake Database (HiQuake), (www.inducedearthquakes.org). Last accessed 25/09/2019.* The magnitudes used in the text are from this table rather than the originating papers to avoid confusion.

The largest hydraulic fracturing induced earthquakes to date in N America are the 4.1 and 4.6 Mw events western Alberta and northeast British Columbia, for these it was noted that the total injected volumes were high for hydraulic fracturing – of the order of 100,000 m^3. **Meng** has reported on a sequence of more than 15,000 earthquakes with magnitudes ranging up to 5.2 Mw recorded in 2018 that were induced by fracturing operations in the Sichuan Basin in China, an area where there are few natural earthquakes. These were mostly from a single well pad with the hypocentres of the largest events originated in a dolomite formation beneath the shale reservoir but above the basement rock. Over the previous three years, some 76 M> 3.0 Mw events had been recorded which were attributed to fracturing operations within an area of just ~20 km diameter. Despite this obvious tendency to seismicity, there is no mention in Meng's paper of any TLS or other mitigation techniques being attempted.

Geothermal EGS technology purposefully fractures otherwise impermeable rock to create new fractures and force pre-existing fractures to open (ref Ellsworth). Several EGS projects have encountered problems of induced seismicity, the maximum being the M 5.5 event in 2017 near Pohang, South Korea which injured 135 residents and displacing more than 1700 people. Ellsworth notes that even during drilling the on-site geologists recognised that the well intersected a fault and that the loss of drilling fluids induced microseismicity of the fault but that the importance of this previously unknown fault was not appreciated at the time and so did not lead to changes being made to the operational plan. Later, the fracture stimulation itself gave rise to a M 3.2 event in April 2017 but, despite this and the abrupt resurgence of tectonic seismicity during each stimulation phase, operations continued until September 2017. The ~ M 5.5 event occurred in November several months after injection ceased. In this case, a TLS system was in operation but appears to have focused on keeping induced seismicity below a threshold magnitude of 2.5 (having been raised from 2.0 during the operation), nor did attempts at mitigation include the accurate location and tracking of event hypocentres or the evolution of the seismicity sequence that had become apparent even at the drilling stage. This narrow focus meant that the evolving risk was neither recognized nor communicated. Commenting on the same events, Meier observed that Pohang city lies within a seismically active region of South East Korea and that operations adopted high pressure and were "motivated to (desperately) establish a circulation between both wells".

It is thus clear that induced seismicity can give rise to significant events in the range of 4-6 M indicating that, at least in the case of shale gas and EGS activities, more energy can be released than has been introduced by the injected fluids. While possible relationships can be postulated between the maximum induced magnitude and one or more of depth of event, injected volume and the natural seismicity and faulting of the area, even if confirmed these may well be very closely related to the site-specific geology and so cannot be taken as generally applicable. For example, in Canada and China earthquake susceptibility and maximum magnitude do appear to have some correlation to location and/or depth of the event. However, the mechanisms leading to this correlation is not understood and is of little help in prediction elsewhere until there is experience at a particular location.

There is however some evidence that TLS and other mitigation techniques can be effective in limiting maximum event magnitude. Events induced by waste water injection in the US appear to have been reduced by changes in injection rate/pressures. In both China and South Korea, there were many indications of the likelihood of large events and opportunities for mitigation which were missed, either as a result of the lack of, or laxity in applying, observations and controls. Similarly, the TLS thresholds in Canada have typically been set quite high even at the "amber" level with "red" thresholds close to the maximum size of event subsequently observed. In addition, mitigation protocols do not appear to take into account the real-time development of the frequency or location of potential precursors to larger events although this data has sometimes been available for post operational analysis. The mitigations currently adopted in the UK have both a (very) low threshold for mitigation and incorporate the real-time monitoring of events, magnitudes and locations as fracturing progresses.

5. The numerical modelling of induced seismicity

There is a common view that the seismogenic potential of any hydraulic fracture is the result of the interaction of many, often ill-defined, geological characteristics. **Schultz**, Maxwell and **Walters** all indicate that understanding of these characteristics, while still far from complete, has reached a level where geomechanical models could be useful tools to predict induced seismicity. Proper assessment of induced seismicity requires accurate flow simulation and associated geomechanical and fracture mechanics to investigate how the injection might lead to seismic sources. Where, as will often be the case, the required stress and discrete fracture network characteristics are not well defined, sensitivity testing within a model could be used to understand the conditions that might lead to seismicity.

In due course, the absence of abnormal seismicity in the great majority of fractured wells could help further calibrate geomechanical models.

Application of a relatively simple conceptual model involving the migration of pressure perturbations from injection horizons in Oklahoma to active basement faults has confirmed how long-duration fluid injection has the potential to trigger slip on relatively large faults (**ref Walters**).

6. Mitigation methods

Various approaches to modifying fracturing operations to reduce or prevent induced seismicity have been considered and applied in N America. Reports are anecdotal and there is little peer reviewed material.

Reduction of injected rate and volume on seismic potential and magnitude

There appears to be a broad consensus that the volume injected is closely correlated to the seismic potential (number of induced earthquakes). There is also a degree of agreement that the volume of injection also influences the expected maximum magnitude of the induced seismicity. There is very little evidence that the rate of injection has a strong correlation to the seismic potential for hydraulic fracturing in contrast to water disposal operations where there is stronger evidence that rate does influence induced seismicity.

Maxwell is of the view that empirical evidence is inconclusive for the impact of rate or volumes on seismic potential. Despite injection pressure being correlated directly to rate and so changing pressure impacts injection energy and hence seismic energy, the effectiveness of reducing seismic potential by slowing pumping remains unclear. Although injection rate does not appear to make a difference, “average rate per day “does - likely due to pressure leak off. Maxwell is also of the view that there is an uncertain outcome of changing the injection rate (or even shutting in) once seismicity is encountered - once the release of stored energy is triggered on a fault the process will continue until some new equilibrium is reached. Once a fault is encountered, more volume goes preferentially into that fault - and will simulate a greater area of that fault.

For the Canadian Kaybob Duvernay formations, **Schultz** considers that seismic productivity scales linearly with injection volume but that injection pressure and rate have an insignificant association with seismicity (in possible contrast to disposal wells in the US where injection rate has been suggested as a driving factor). For Canada, geological factors also play a prominent role in seismic productivity and the combined volume and geological factors account for ~96% of the variability in the induced earthquake rate near Fox Creek. In contrast, pad, well and stage pressure show no compelling relationship to seismicity for fracturing. In British Columbia, no clear correlation is apparent between pump rate or volume and the magnitude of induced seismicity.

More generally, **Van der Elst** considers that there is a direct correlation between seismic potential and injected volume (but not absolute maximum magnitude), **Hallo**, **McGarr** and **Shappiro** each extend this to a relationship between volume and absolute maximum magnitude but via different mechanisms.

Flowback

Opinions divide over the effectiveness of immediate flowback on induced seismicity. Some see it as positively beneficial, others as potentially ineffective but harmless while others view it as increasing the risk of induced seismicity. This divergence of view and experience may reflect the influence of the particular local geological setting rather than point to a ubiquitous beneficial or harmful effect. In any event it is difficult to see that the flowback of relatively insignificant volumes could have a beneficial effect and are, in truth, close to a shut-in condition.

In 2014, the British Columbia Oil and Gas Commission believed flowback appeared to be effective in reducing seismicity in Montney and indeed identify flowback of fracture fluids as probably the best mitigation technique. Similarly, **McClure**'s study of seismicity during injection into fractured, very low permeability rock suggested that post-injection events could be caused by backflow into larger fractures that host the largest seismic events from "dead-end" fractures that differentially pressurize during injection. In these circumstances, flowback of fluid to the surface immediately after injection could mitigate this effect and reduce post-injection seismicity. Schultz (pers com) views flowback, in general, as a good approach for Albertan operations.

In contrast, **Maxwell** is of the view that wells should never be flowed back since pressure in a fault may become disconnected, flowback will close fractures and the pressure difference may then lead to further seismicity through relative pressure difference (i.e. fractures are not always in pressure communication). (Pers com). **Atkinson** sees that flowback (and/or traffic light protocols) while beneficial may not have immediate effect in preventing the occurrence of further induced events. **Karimi's** data set from Western Canada shows at least one case where the seismicity continued to be recorded for months after completion. This suggested that the causal mechanism was fluid diffusion across the fault via an existing hydrological connection - an activation mechanism characterized by low fluid-recovery rates with large leak off, thereby pressurizing and "lubricating" the fault. This process was seen as more likely to occur where the fault is closer to the well laterals (i.e., tens or hundreds of meters). Karimi noted that, for this case, standard mitigation techniques, such as flowback (or reduction in pumping rates and volumes) would have very little effect.

Stage Skipping and buffer zones

There is less reported N American experience of the effect of skipping stages to avoid further induced seismicity following an event. As with flowback it may be that the differences of view reflect to specific geology rather than an overarching physical causation.

In Montney, where events can be triggered from outside the reactivation zone- perhaps 200-300 m away (or deeper) due to pressure being transmitted through fracture networks, two operators reported skipping stages near fault reactivation zones in an effort to reduce the magnitude and frequency of events. The **British Columbian Commission** viewed this effort as inconclusive and in contrast considered that, in the vicinity of Horn River, fault reactivation zones are well defined and it appeared that injection had to be very close to a zone for reactivation to occur indicating that the skipping of stages would have benefit. More generally, Alberta considered it may be prudent to place a "buffer zone" around sensitive infrastructure.

One Operator reported that it was not economic to skip stages while another stated that if they found a well was highly seismogenic they simply move to another well.

7. Traffic Light Systems – use and improvements

Traffic Light Systems (TLS) or Protocols (TLP) are widely implemented in Canada and, for geothermal operations, across many continents. There is general support for their use and for improvements to allow them to incorporate live data and mitigation opportunities.

Both Alberta and British Columbia require their operators to follow a TLP with a threshold requiring operators to notify regulators and take steps to mitigate further seismicity. **Alberta** for example consider changes in operations, avoidance of susceptible areas and/or setbacks from critical infrastructure as mitigations. The "red" threshold is currently set at 4.0 M but recently for at least one more highly populated area in British Columbia a threshold of M 1.5 has been introduced requiring notification within 24 hrs and the development of a protocol for mitigation.

More generally, **Atkinson** has noted that TLPs, while beneficial, may not have immediate effect in preventing the occurrence of further induced events and note that of the six red light events >4m that were observed, several of these either had no preceding yellow light events or occurred after injection operations had ceased.

Several avenues have been proposed for improving TLP performance, **Alberta** term these Adaptive Traffic Light Protocols. **Ingonin** has observed that for the Toc2me, Fox Creek operations, variabilities in the b value over space and time provide insight into the changes of behaviour during fracturing operations with the b value being strongly influenced by the orientation and depth expression of the fault activation – indicators of changes in seismicity which could incorporated in a TLP. **Maxwell** has noted that geomechanical models could be used as part of a TLS both to proactively identify potential problems and, as a decision tool, to modify injection to mitigate seismic hazards or to test various operational changes to identify a scenario that reduces seismic hazard.

Walters has indicated that a risk-management TLPs could be increasingly effective when updated as new data become available. He proposes the incorporation of subtle, but potentially diagnostic, geological and geophysical characteristics that may indicate a potentially larger event to come by focusing on specific observations that suggest the presence of a fault large enough to host a significant triggered earthquake. This could, for example, enable operators to transition between the green and amber zones or, for both disposal and hydraulic fracturing, move into the red zone of the traffic light. For disposal, a relatively simple conceptual model involving the migration of pressure perturbations from injection horizons in Oklahoma to active basement faults has been constructed that shows how long-duration fluid injection has the potential to trigger slip on relatively large faults.

Current TLPs do not directly link thresholds to the maximum magnitude of an induced event. **Eaton**, working with Igonin, notes that there are at least three approaches to estimating the strength of the largest earthquake to the injection operation that could be applied in real time but that this remains an unsolved problem. They emphasise the importance of considering all three models when assessing the potential hazard.

For geothermal operations, **Meier** has noted that only rarely are TLS probabilistic, for example the injection being stopped if the probability of exceeding of a certain magnitude event is high. Adding such criteria confers the TLS with forecasting capabilities, thus becoming an Advanced Traffic Light System, or ATLS. Such a system has been developed by the Swiss Seismological Service and has been calibrated using the data from the Basel project where the injection is stopped if: (a) an equivalent radius R = 300 m is reached or (b) the maximum calculated magnitude exceeds a threshold value M = 2 or (c) the exceeding probability of a magnitude 2.6 is larger or equal than 5%. Such a combination of criteria is deterministic (the injection is stopped if “something happens”, i.e., M = 2) and probabilistic (the probability that “something will happen”) exceeds a threshold value.

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