Man-made Earthquakes – a review of the risk assessment and management process

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Industrial activities in the sub-surface (e.g. mining, hydrocarbon extraction, gas storage) have the potential to induce earthquakes or subsidence resulting in risks to infrastructure, people and the environment.

This paper focuses on the assessment and management of earthquake risks associated with industrial interaction with the sub-surface. It is not intended to be a technical review of the science that has established links between human activity and seismicity. The evidence proving that industrial processes can cause earthquakes is overwhelming and accepted by the scientific community as well as the bodies which they advise.

The paper starts with an overview of man-made (i.e. induced) earthquakes and the mechanisms by which they can occur. Case material is presented from two regions where the frequency and severity of induced earthquakes has increased in recent years, resulting in significant damage to infrastructure and changes to the general stability of the subsurface. This problem has affected hundreds of thousands of people and has required significant government effort in conjunction with the industrial operators responsible, to progress towards a resolution. Consideration will be given as to how such risks are currently identified during planning of new projects. The final part of the paper provides thoughts on how the assessment and management of seismic risk could be improved, acknowledging that such effects may be immediate or delayed, short or long term, localised or extensive, and / or the result of cumulative activities.

Keywords: anthropogenic seismicity, induced earthquakes, risk assessment, cumulative impact assessment

Introduction

Industrial activities in the sub-surface (e.g. mining, hydrocarbon extraction, gas storage, deep strata injection) have the potential to cause earthquakes or subsidence resulting in risks to infrastructure, people and the environment. Impacts associated with certain technologies have attracted considerable attention in the press, while others remain largely unheard of or the potential risks misunderstood. In the UK, exploratory drilling using the technique of hydraulic fracturing (“fracking”) resulted in minor earthquakes that were widely reported in the media during 2011. The risks have been further sensationalised following a recent increase in seismicity in Oklahoma [Austin, 2015], even though it is not scientifically linked to hydraulic fracturing [Oklahoma Geological Survey (OGS), 2015]. In contrast to hydraulic fracturing, seismic activity caused by other industrial activities seems not to have received the same amount of publicity.

The focus of this paper is on the assessment and management of earthquake (or “seismic”) risks associated with industrial interactions with the sub-surface. It is not intended to be a technical review of the science that has established links between human activity and seismicity. The evidence proving that industrial processes can cause earthquakes is overwhelming and accepted by the scientific community as well as the bodies which they advise.

The paper starts with an overview of man-made (or “induced”) earthquakes and the mechanisms by which they can occur. Case material is presented from two regions where the frequency and severity of induced seismicity has increased in recent years, resulting in significant damage to infrastructure and changes to the general stability of the subsurface. The man-made earthquakes in these regions have affected hundreds of thousands of people and significant government effort, in conjunction with the industrial operators responsible, has been required to progress towards a resolution. Consideration will be given as to how the potential to cause earthquakes is currently identified during the planning of new projects. The final part of the paper provides thoughts on how the assessment and management of seismic risks could be improved, acknowledging that such effects may be immediate or delayed, short or long term, localised or extensive, and / or the result of cumulative activities.

In this paper, the following terms are used interchangeably: man-made, induced and anthropogenic; earthquakes and seismicity. The scale is logarithmic. In this paper, the term is simplified to “**M**” and it is assumed that published data uses the common $\mathbf{M}_w$ scale. An earthquake of **M** 6.0 releases energy equivalent to 3.3 Hiroshima-size Atom bombs. Earthquakes of less than **M** 2.0 are unlikely to be noticeable by the general public.

Man-made seismicity

Anthropogenic interaction within the sub-surface has been recognised to induce earthquakes for over a century. Earthquakes felt in Johannesburg in 1894 were attributed to the local gold mining operations by 1908 [cited in McGarr, 2002]. In the same year, stations were established to monitor seismic events attributed to coal mining in Germany and Poland. Additional causes of anthropogenic seismicity were confirmed throughout the 20th century: extraction of crude oil for petroleum production in the early 1920s, reservoir construction in the late 1930s, high-pressure liquid injection at depth in the mid-1960s and natural gas extraction in the late 1960s. More recently, the harnessing of geothermal energy via fluid injection or extraction has been recognised as a source of increased seismic activity in regions that are already seismically active [Giardini, 2009]. Seismicity has been linked to industrial activity in the Americas, Asia, Australasia and Europe.

Factors that contribute to induced seismic events

Man-made earthquakes occur as a result of physical changes created within the sub-surface which alter the stability of the ground [McGarr, 2002; Rubinstein 2015]. Physical changes include variations in pore pressure; resource volume changes; temperature effects; and changes to applied forces, loads or stress characteristics. These changes can occur separately or simultaneously as a consequence of liquids, solids or gases being extracted from, injected into, or placed upon the ground. A further mechanism is where injected materials can 'lubricate' existing faults, thus reducing the stress required to cause fracture. The industrial activities that cause these changes may be undertaken at many kilometres below the Earth's surface, but have the potential to cause effects at the surface including subsidence or earthquakes. The likelihood for such effects to occur depends on a range of factors in what is a highly complex system.

The factors that contribute to earthquake risk can be split between:

- process characteristics, i.e. the nature of the industrial activity, rate of application, injection or extraction of material, duration of operations and chemical/physical properties of the applied/injected/extracted material, and
- the geological setting that the activity interacts with.

The science and understanding around earthquakes is highly complex; however, there are some generally accepted theories. For example, the zone of the earth's surface within which most earthquakes are initiated (i.e. the continental crust, which varies in thickness from 25 to 60 km under continents [BGS, 2016b]) is vulnerable to failure regardless of whether it is in a tectonically active zone. Small changes in pressure may be sufficient to trigger an earthquake and this has been confirmed by numerous studies. One implication is that in regions where the background seismicity is normally low, earthquakes triggered by industrial activities are more obvious and the consequences may be more significant as infrastructure is not designed to withstand the effects. At locations which are tectonically active, industrial activities may facilitate the onset of natural ground movement processes resulting in increased frequency of occurrence.

Other geological factors in the potential risk for man's activities to induce seismicity include the following:

- existing stress conditions of the geological unit where material is injected, extracted or loaded;
- existing stress conditions of adjacent geological units;
- the chemical and physical properties of the geological units affected; and
- the presence of existing fault systems.

In addition, the characteristics of near surface soils contribute to the potential vulnerability of infrastructure to damage during an earthquake.

The complexity of the process ultimately leads to the conclusion that the each location is unique. The hazard potential and final risk assessment should therefore be evaluated independently for each set of circumstances.

Examples of induced seismic events

Examples of causative mechanisms and high magnitude earthquakes linked to specific processes are illustrated in Figure 1 and described below:

- Reservoir construction where the weight of water held in the reservoir applies stresses to underlying geology which activates existing faults or fractures; an earthquake of **M** 6.4 occurred in Maharshtra, India in 1967 with seismic effects observed over the 34 years of reservoir use [Gupta, 1997]. Approximately 180 people were killed [IRIS, 2005];

- Removal of groundwater from quarries or deep mines to prevent flooding which depresses the water table and reduces sub-surface pore pressure as well as the effective overburden load [McGarr, 2002];

- Mining which changes pressure characteristics by removal of solid material; an earthquake of **M** 5.6 associated with coal mining occurred in 1989 in Newcastle, Australia [Klose, 2012] - this left 13 people dead, 160 injured and thousands of buildings damaged, resulting in economic losses equivalent to A$5 billion (3.4% of Australia's Gross Domestic Income). Other significant earthquakes from mining processes include an earthquake of **M** 5.4 associated with potash mining which occurred in 1989 in Volkerhausen, Germany and an earthquake of **M** 5.2 associated with gold mining in in 1977 in Klerksdorp, South Africa [cited in McGarr, 2002];

- Groundwater extraction which reduces pore pressure by removal of water; an earthquake of **M** 5.1 occurred Lorca, Spain 2011 [González, 2012];

- Oil or gas extraction which reduces the pore pressure within the natural reservoir; an earthquake of **M** 4.2 was associated with gas extraction from the Pau basin, near Lacq, France and occurred 10 years after gas extraction commenced [Grasso, 1990];

- Liquid injection (often waste water) at depth which raises the pore pressure on faults in the vicinity; an earthquake of **M** 5.6 occurred in Prague, Oklahoma in 2011 [Keranen, 2013];

- Hydraulic fracturing where small volumes of liquid are injected to increase pore pressure; two **M** 4.4 earthquakes occurred in central west Alberta and northeast British Columbia [BC Oil and Gas Commission, 2014];

- Enhanced oil recovery where injection of water, chemicals, steam or carbon dioxide increases pore pressure [Rubinstein, 2015]; an earthquake of **M** 4.6 occurred in 1978 near Snyder, Texas, where injection for secondary recovery has been ongoing since the 1950s and induced seismic activity has been observed since 1974 to present [Frohlich, 2012];

- Geothermal energy production involving injection or extraction; an earthquake of **M** 6.6 occurred at Cerro Prieto, Baja California, Mexico [Glowacka, 1996].

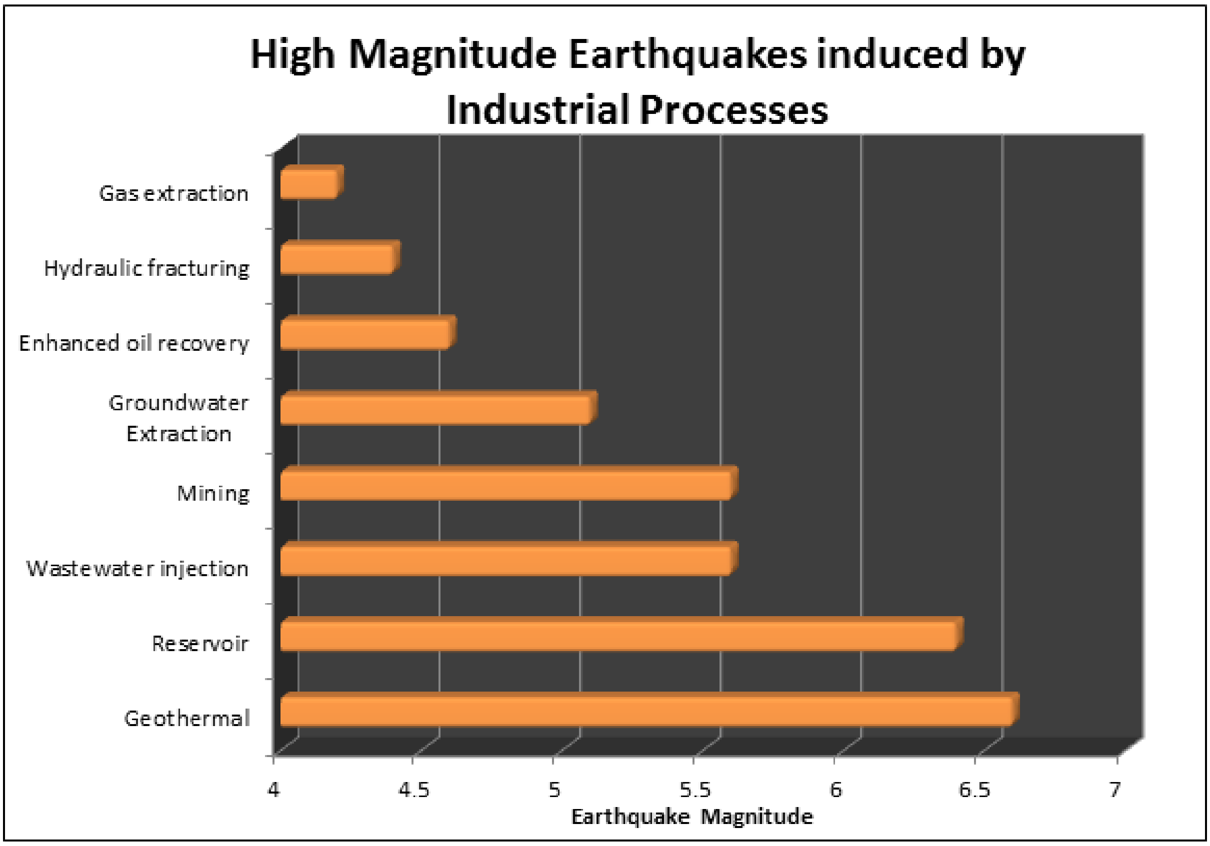

Figure 1 – High Magnitude Earthquakes associated with Specific Industrial Processes

Risk of seismic effects occurring

The potential for industrial processes to induce earthquakes is well-established, although the risk of such hazards being realised is relatively low. There are a large number of industrial activities with sub-surface effects that either have not been shown to induce earthquakes, or, have only induced very low magnitude earthquakes undetectable to the public and which have not damaged infrastructure [Rubinstein, 2015]. For example, of the 150,000 injection wells in the US from waste water disposal, enhanced oil-recovery and hydraulic fracturing operations, only a small proportion are associated with earthquakes of a magnitude noticeable to people.

Two Case Studies

Two case studies are presented for regions where industrial activity has caused earthquakes of increasing frequency and severity (relative to the pre-industrial background). Although the case studies presented below are not in densely populated regions, the combined total of affected people is over a million. Increasing public concern has put considerable pressure on politicians who have had to allocate significant resource to address the concerns. For the process operators involved, there has been disruption to production plans, imposition of financial liability and reputational damage while risk assessment and mitigation activities are under enhancement.

Case 1 - Earthquakes caused by conventional gas extraction - Groningen, the Netherlands

Significant natural gas reserves are located in the Netherlands, the largest in the province of Groningen, where gas has been extracted for over 50 years [Koster, 2015]. The Groningen gas field contained around 25% of the European natural gas reserves, with the “original gas in place” estimate being 2900 billion m^3. Approximately a quarter of the reserve remains [Muntendam-Bos, 2015]. The field is approximately 900 km^2 and located at 3 km depth, below an area occupied by about 580,000 people. The tectonic setting is stable and the region is therefore naturally low in seismic activity. Gas extraction operations are overseen by the Ministry of Economic Affairs.

The first recorded earthquake in Groningen occurred in 1986, nearly 30 years after the commencement of gas extraction [van Elk, 2014]. Further earthquakes were of low magnitude but noticeable to people and some caused damage to buildings. In the early 1990s, a multidisciplinary study concluded that the earthquakes were of non-tectonic origin and were induced by the reservoir depletion. An authority from the State Supervision of Mines for the Netherlands believes that the seismicity results from the reactivation of faults following the extraction of gas [Muntendam-Bos, 2015].

Since the early 1990s, more than 700 earthquakes have been recorded and there has been considerable damage to property [Koster, 2015]. The frequency and severity of earthquakes has steadily increased (Figure 2). In 2012, an earthquake of **M** 3.6 occurred which resulted in more widespread damage and raised fears of safety risks to the public. An analysis of the event, along with a review of induced-seismicity in other hydrocarbon fields, led to a revised estimation of the potential for a credible maximum earthquake of **M** 5 [Dost, 2013], although this has been challenged by experts from the State Supervision of Mines [Muntendam-Bos, 2015].

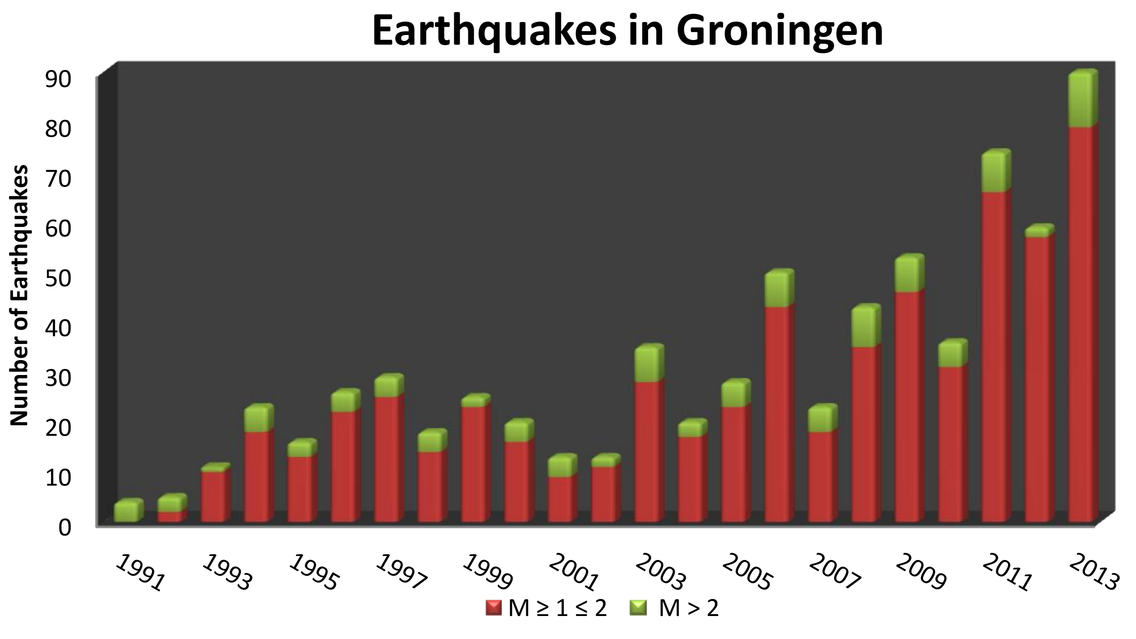

Figure 2 – Earthquakes in Groningen province (1991 – 2013)
Data source: Koster, 2015

The gas field operator initiated an extensive monitoring and risk analysis study in autumn 2012, which has evolved and continues to undergo refinement [van Elk, 2014]. The objectives of the work have been to improve the understanding of the hazards and risks to buildings and the public resulting from the gas extraction; to quantify and reduce the uncertainty associated with the assessment; and to identify effective risk reduction measures. The programme includes the following elements:

- Enhancement of the fully probabilistic hazard assessment model supported by geological experts which considers gas extraction, rock deformation, seismicity and ground motion;
- Development of a fully probabilistic risk assessment methodology supported by civil engineering experts which considers the potential for exposure to seismicity, the fragility of the buildings exposed and the potential for injury to people;
- Reduction in assessment uncertainty by progressive collection and inclusion of validated local data;
- Implementation of an improved monitoring network which includes:
    - GPS stations for continuous monitoring of vertical and horizontal subsidence;
    - additional passive seismic monitoring equipment to enable recording of earthquakes from multiple locations;
    - accelerometers in a range of public and private buildings representative of different types of construction in different soil conditions.
- Identification and evaluation of hazard and risk reduction measures, including:
    - modification of production practice;
    - pressure maintenance options, e.g. use of nitrogen;
    - strengthening of buildings.

Governance and quality assurance of the programme has been provided by the appointment of suitably qualified internal and independent external technical experts. Consultation with stakeholders includes the Ministry of Economic Affairs, the local authorities and the relevant technical organisations: State Supervision of Mines, the Royal Dutch Meteorological Institute (KNMI which has responsibility for seismic monitoring) and a specialist unit within the Netherlands Organisation for Applied Scientific Research (TNO-AGE).

The complexity of the seismic risk analysis is acknowledged by the State Supervision of Mines [Muntendam-Bos, 2015]. The limitations in existing seismic data for the Groningen field means that a probabilistic seismic hazard analysis cannot provide an accurate prediction of seismic activity nor determine the upper magnitude boundary. Moreover, the scientific uncertainties associated with the relationship between seismic activity and management of the gas extraction operation makes it difficult to evaluate the reduction in risk from potential mitigation measures. Nevertheless, there have been increases and decreases observed in seismicity associated with increases and decreases in gas extraction from the Groningen gas field. This suggests the potential to reduce seismic risk by controlling the gas extraction rates. Further research is required to confirm this.

Since 2003, seismic risk assessment has been required for production license applications in the Netherlands [Muntendam-Bos, 2015]. The assessment must consider the potential risk of subsidence and induced seismicity, describe risk prevention and mitigation measures, and propose an appropriate monitoring strategy. There is a guideline used for the assessment which consists of three levels requiring further analysis as appropriate to the level of risk identified. The Groningen gas field is the only field at present which is subject to the Level 3 requirement for a quantitative seismic risk assessment and management plan. A current limitation of the approach is that the Dutch government has no defined policy or thresholds for seismic risk.

The efficacy in the mitigation measures planned at Groningen remains to be established, however, there is little doubt that the enhancement in data collection and modelling will contribute to the scientific understanding of the seismic issues. In the meantime, the Dutch government has implemented new building standards for the region and allocated funds for the reinforcement of up to 10,000 buildings over the next five years [Government of the Netherlands, 2015].

Case 2 - Earthquakes caused by waste water injection – Oklahoma, USA

Seismic activity has also increased dramatically in central and north-central Oklahoma over the past few years, where the number of **M** ≥3 earthquakes exceeded 900 in 2015 (Figure 3). On 7th January, 2016, a pair of earthquakes, **M** 4.7 and 4.8, occurred within 30 seconds of each in northern Oklahoma. Investigations undertaken by the US Geological Survey (USGS) and Oklahoma Geological Survey (OGS) determined that the majority of recent earthquakes in this area, including a **M** 5.6 earthquake in 2011, are likely to be triggered by the disposal of produced water (formation brine) from oil and gas extraction [Ellsworth, 2014; OGS, 2015]. The waste water is injected into wells in large volumes and over extended time periods. The increase in earthquakes in Oklahoma corresponds to a doubling of the waste water disposal rate during the period 1999 to 2013 [Walsh, 2015]. Although the earthquakes are occurring in an area of existing faults, they differ from naturally occurring seismic events in both their nature and frequency [OGS, 2015].

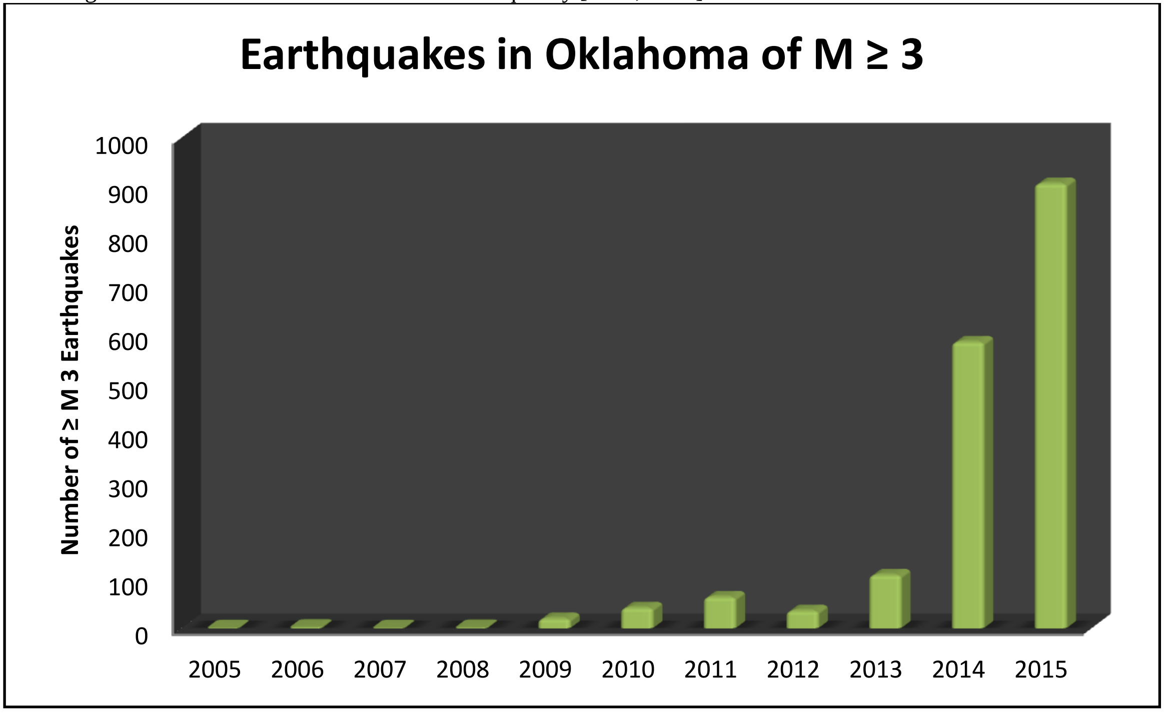

Figure 3 –Earthquakes of M ≥ 3 in Oklahoma (2005-2015)
Data sources: Office of The Secretary of Energy & Environment, 2015; OGS, 2015; Wines, 2016; Chow, 2015

By 2014, the situation was attracting considerable concern. The State Governor, in conjunction with the Oklahoma Secretary of Energy and Environment, took steps to bring the situation under control and manage communications to the public [Office of The Secretary of Energy & Environment, 2015]. A Coordinating Council on Seismic Activity was set up to determine what action was required to address the problem, identify gaps in resources and coordinate efforts among state agencies, researchers and the state’s oil and gas industry. An information website was set up to keep the public informed.

The Oklahoma Corporation Commission (the “Commission”) has regulatory oversight of the oil and gas industry, although no specific regulatory powers in regards to seismicity. It does however, publish rules and procedures for preventing and responding to seismicity associated with disposal well operation and is working with operators to encourage voluntary implementation of a raft of risk reduction measures. The Commission has published a number of action plans and advisories to address the escalating seismicity problem [Office of The Secretary of Energy & Environment, 2015, Oklahoma Corporation Commission, 2015]. These have already resulted in investigations and / or changes in operation of approximately 600 wells and include:

- Depth checks on existing wells, with cessation of disposal unless the bottom of the well is at least 30 m above the base of the geological formation being used;
- A seismicity review for all proposed disposal wells;
- Limited permitting of wells in high risk areas (maximum of six months with earlier shut down of well if there are seismicity concerns);
- Expansion of a “traffic light” approach which requires some operators to monitor seismic activity and modify their operations accordingly;
- Development of action plans for the areas experiencing the increased seismicity. These include:
    - progressive reduction in wastewater disposal volumes on a prescribed schedule,
    - installation of gauges and flow meters on wells where not already installed,
    - daily monitoring of pressure and disposal volumes, submitted to the Commission on a weekly basis for use on a website accessible to researchers,
    - phased return to injection following any significant power outage,
    - permanent closure of disposal wells in high risk areas.
- Reservoir pressure testing of wells in proximity to observed significant earthquakes.

Although there has been an intensification of risk reduction measures implemented over 2015, further actions are planned.

Monitoring of seismicity and mapping of the strata and faults which are involved is on-going by the OGS, which is also collaborating with the Commission and other partners to develop an appropriate regulatory framework [OGS, 2015].

Case study comments

Although the examples considered are from different industrial processes (gas extraction in Groningen and waste water injection in Oklahoma), there some common features:

- There have been no deaths or serious injuries reported from the earthquakes that have occurred to date.
- The scientific evidence regarding the potential for induced seismicity from the particular processes involved has been established since the 1960s.
- The specific local data required to underpin a robust risk assessment process is insufficient or lacking. Thus early actions have included enhancement of existing monitoring arrangements and collection of more data.
- There have been weaknesses in regulatory involvement and powers.
- Significant action to prevent and reduce risks has followed heightened awareness of increasing seismicity by the public.
- The authorities believe that earthquake frequency and severity can be reduced by a reduction in the intensity of operations or if necessary, a cessation of operations. This remains to be proven.
- Curtailment of industrial operations has occurred within relatively short time periods which may be disruptive to business plans.

The Current Risk Assessment Process

Environmental and safety risk assessments of industrial projects normally consider potential risks from earthquakes and subsidence which may be present in the vicinity. If the studies are for projects that include extraction or injection of substances into the sub-surface, they should also consider the potential for the new activity to induce hazards of the same type. In areas where multiple operators are involved in activities of this nature, collaboration may also be undertaken to consider potential cumulative impacts.

There are various regulations, standards and guidance applicable to such assessments which have been in use for many years (e.g. BS/IEC 61882:2002 Hazard and operability studies; US Government Code of Federal Regulations, 29 CFR (OSHA) 1910.119 Process Hazard Analysis). Many companies develop their own internal procedures.

The potential for a project to cause sub-surface impacts would normally be considered at the very earliest stages in project development, i.e. during site selection or conceptual hazard study, which might then be followed by a qualitative or semi-quantitative risk assessment. There are various routes by which risks to the sub-surface may be identified during hazard studies:

- Review of incidents which have occurred on similar projects or processes, including search of information from third parties such as regulatory bodies or Scientific Associations,
- Study prompt list phrases, e.g. "long term effects to ground",
- Other (normally rare event) considerations, e.g. subsidence, earthquake.

Where a potentially significant off-site risk is identified, this would trigger the need for a specialist risk assessment. It is obviously important to ensure that in addition to external ground risks affecting the development, the potential for the development to trigger hazards via the ground also requires consideration.

The key to successful completion of hazard identification is the involvement of an appropriate team with the relevant experience and qualifications. Experts in the potential process hazards and local geology/ground conditions would normally be included either in the core team or to provide specialist studies.

A question posed in this paper is whether the existing typical process can adequately consider anthropogenic seismicity risks, in particular the potential for delayed and cumulative effects, and what other routes are available for the identification and management of such effects.

Improvement of Our Risk Management Systems

The risk assessment process is expected to consider long term and cumulative impacts, but this remains a challenging area for a number of reasons. The scientific knowledge base required to adequately support such assessments requires further development. Guidance for risk assessment does not always specify that process-induced seismicity or subsidence needs to be considered as well as natural hazards of these types. Business planning cycles and plant lifetime projections may be shorter than the timescales over which effects might occur and in some cases, the project life may significantly extend beyond the original planned duration. Access may be limited to information on what other industrial operations in the vicinity have done historically, are currently doing or have planned. Regulatory oversight of development risk assessments may be insufficient, allowing poorly developed risk analyses to form the basis of on-going operations.

A further consideration is where the ultimate responsibility lies for management of the large scale, long term and cumulative impacts. It is unrealistic to expect that these issues can be fully addressed through the initial project hazard assessment process, nor should the responsibility lie only with industry, which provides services and revenues that are of value to people and government.

Effective improvements in the assessment and management of such risks will require a collaborative approach comprising:

1) On-going science and research programmes to address areas of uncertainty and provide the evidence required to underpin decision making;

2) International agreements and government policy, e.g. through the vehicles of Strategic Environmental Assessment, land use planning controls, taxation;

3) Standards development, e.g. regularly updated mapping of induced seismicity made available for use by operators and developers;

4) Regulatory framework, e.g. through the vehicles of environmental permitting, on-going process monitoring and reporting requirements, and addition of periodic risk review in regard to longer term issues;

5) Operator good practice, e.g. through the vehicles of responsible management and monitoring of current operations; improved hazard study and risk assessment for new development opportunities; corporate sustainability/business risk assessment programmes, adoption of improved lower impact technologies.

Each of these elements is discussed further below.

1) Science and research

There are a number of uncertainties associated with the knowledge we hold about anthropogenic seismicity and what could be done to prevent significant effects. Some questions posed by the case studies considered are as follows:

- Are the earthquakes in Groningen and Oklahoma due to the intensity of industrial operations, the result of cumulative / long term impacts or a combination of these factors?

- Will induced seismicity cease if the activities are reduced or stopped?

- Could cumulative effects result in a long term cycle of seismicity that cannot be controlled or mitigated?

- If answers emerge to these questions in Groningen and Oklahoma, how informative would they be in regards to assessment of risk elsewhere?

It is already evident that our understanding of the sub-surface, although improving, requires enhancement through on-going research. There is vast complexity existing in the sub-surface at both macro and micro-scale. The detail necessary to robustly assess and manage the risk of man-made seismic activity has yet to be fully understood. There may be parameters for which a generic or general assessment may be sufficient, while for other parameters, detailed site-specific sub-surface investigations may be required to inform the risk assessment. Furthermore, the work being undertaken at the Groningen gas field indicates that in addition to the need to assess the sub-surface features that contribute to seismic risk, it is also necessary to characterise near surface soils as these contribute to the potential vulnerability of infrastructure to damage during an earthquake.

To support characterisation studies, as well as the assessment of seismicity during operation, improvements in monitoring instrumentation and data management are always to be welcomed.

Further research is required on the potential to manage seismic risk associated with injection and extraction processes by control of pressure within the seismic zone. Research undertaken in the 1970s indicated that control of earthquakes was possible by varying of fluid pressure by alternate injection and recovery of water from wells penetrating the seismic zone [Raleigh, 1976]. This suggested that even in seismically active locations, additional seismicity triggered by industrial processes could be prevented or reduced by monitoring and management of sub-surface pressure. This premise is supported by evidence from Groningen and other gas fields [Muntendam-Box, 2015]. Nevertheless, it remains to be proven that this would be the case for all processes and locations.

Finally, investigations are needed on the causes for delay in the onset of observed seismicity, although it is acknowledged that these could vary according to the nature of the process, as well as susceptibility of the sub-surface. The potential parameters that might lead to irreversible triggering of seismicity arising from cumulative process effects could also be investigated.

2) International agreements and government policy

Little will be accomplished unless there is recognition at government and international level that improved controls are required, as funding is needed to cover the cost of policy development and implementation. Nevertheless, the foundations for improved management of delayed, long term, physically extensive and cumulative impacts already exist.

An obvious vehicle for improved impact managements is Strategic Environmental Assessment (SEA), whereby a scientific and evidence based assessment approach is used to underpin government policies, plans and programmes for sustainable land and resources use. To be fully effective in addressing the issues of concern raised in this paper, these would need to be undertaken at continental scale, with country, regional and local SEAs cascading down from the macro-scale assessment. The SEA provides the most effective means for identification and management of cumulative effects, which can be assessed across the relevant area.

The Protocol on SEA was negotiated by the European, Caucasus and Central Asian member states of the United Nations Economic Commission for Europe (UNECE) and came into force in 2010. It is now open to all UN Member States. Besides its potentially broader geographical application (global), the Protocol differs from the corresponding EU Directive in its non-mandatory application to policies and legislation - not just plans and programmes. It also places a strong emphasis on the consideration of health which is not included in the EU counterpart.

A further example of the same approach has been taken by the Organisation for Economic Cooperation and Development (OECD), which has a task team on SEA and has developed guidance on its application in development assistance. This aims to improve the effectiveness of aid through use of environmental evidence and considerations to underpin informed decision making and encourage a systematic and thorough examination of development options.

A robust SEA would consider the full range of past, current and potential sub-surface activities in the region of interest, along with the potential for delayed, long-term or cumulative adverse impacts to the built environment, people, or the natural environment. The potential interactions and cumulative impacts from past activities (such as mining) and current activities (such as conventional oil and gas extraction) need to be understood before a robust assessment can be undertaken of the risks associated with future activities (such as shale gas extraction, carbon dioxide sequestration, underground coal gasification or deep well injection).

Management of future impacts from new development can be implemented through the adoption of appropriate land use zoning supported by requirements for detailed risk assessment and mitigation plans prior to planning approval. In Canada for example, the use of “hydraulic fracturing buffer zones” has been suggested as a means for protection of sensitive infrastructure and sub-surface development [BC Oil and Gas Commission, 2014]. Management of future impacts from historic or current activities will require consideration at government level, where policy decisions can be taken to promote voluntary cooperation / improvement programmes, implement new legislation and allocate funds for further research or mitigation purposes. In all cases, it is imperative that the work is undertaken by suitably qualified specialists on behalf of government agencies.

In areas of low natural seismicity, there is also the need for governments to develop seismic risk analysis procedures and define relevant risk thresholds that can be used for project assessment. The tolerability of seismic risk is something that requires consultation between government, regulators, industry and the public. Views on the tolerable risk are likely to vary between countries. Such policies and guidance already exist in many countries which are situated in tectonically active areas. These could be drawn on for policy development in other areas. A good framework for determination of tolerable risk is provided by the UK Health and Safety Executive [2001], which could be used as a basis for development of appropriate risk thresholds that would be consistent with other risks associated with industrial processes.

3) Standards development

Periodic review of standards that are relied on to underpin risk assessment is important and enables their enhancement to incorporate the findings of evolving scientific understanding. It is currently the case in many countries that the standards used for seismic hazard assessment and specification of building design only provide information on natural seismicity [e.g., in the US - Petersen, 2014; and in Europe – Musson, 2007]. However, as can be seen from the evolving work in Groningen, changes to building standards are being implemented to ensure that new build is designed to withstand effects from induced seismicity.

It would be beneficial for government, regulators and industry to have mapping information on anthropogenic seismicity as this would provide an improved foundation for commencement of the risk assessment process as well as ensuring appropriate building design. As induced seismicity can occur and change within short-term timescales, such mapping information would need to be updated much more frequently than information on natural seismicity. In the US, a project is underway to develop a database and hazard model containing information on induced earthquakes for use in risk assessment [USGS, 2015]. The proposed model would provide details of seismicity experienced during the previous year with an annual update. A similar approach is taken in the UK for application of radon protection measures in areas where naturally occurring radioactivity from igneous rocks is generated.

4) Regulatory framework

The development of more robust regulatory controls, supported by detailed guidance, would be beneficial. Experience from the nuclear industry, where it is normal practice to consider impacts over geologic timescales, could be useful to inform evolving good practice in other industry sectors.

Specific regulatory requirements and restrictions in relation to the sub-surface could include:

- Identification of industrial processes with the potential to induce seismicity and requirement for seismicity risk assessment at process permitting; existing processes could be required to undertake such an assessment as an improvement condition at permit review;
- Requirement for site-specific geological characterisation using 3-D seismic imaging methods [Zoback 2012] at permitting or as an improvement activity;
- Development of site specific hazard models using local data with projected operational parameters, e.g., for Groningen, models are being developed to assess compaction, seismic hazard, ground motion, damage to infrastructure and overall risk [e.g. van Elk, 2014, Zoback, 2012];
- Permitting for specified operating lifetime, with a requirement for a risk assessment review where an extension to operating life is proposed.
- Prohibition of processes with a high risk of inducing seismicity in zones where there are active faults or brittle rocks unless an adequate mitigation plan can be demonstrated [e.g., prohibition of injection – Zoback, 2012]
- Additional requirements during the operational phase would also be appropriate. These could include:
    - Minimise sub-surface changes, e.g. pore pressure changes at depth or compaction. This can be achieved by one or more of:
        - selection of appropriate strata (e.g. high permeability strata with high volume pore space availability or strata that does not deform);
        - minimisation of solids removal or withdrawal rates of liquids or gas;
        - control of reservoir levels to prevent rapid changes in physical conditions;
        - minimisation of injected fluid or gas (by avoidance of generation, in-process recycling or other recovery processes).
- Additional requirements during the operational phase, based on the perceived level of risk, could include:
    - On-going monitoring and reporting of critical parameters, e.g. pore pressure, injection/withdrawal/removal volumes, loading rates [Oklahoma Corporation Commission, 2015];
    - Regulatory requirement for the processes that have potential to cause seismicity to collect and release pertinent data to support advancement of research [McGarr, 2002; Department for Energy & Climate Change - DECC, 2013; BC Oil and Gas Commission, 2014; Oklahoma Corporation Commission, 2015];
    - Imposition of additional sub-surface monitoring requirements in the potential region of impact, e.g. seismic monitoring arrays in areas where process activities might trigger an earthquake [Zoback 2012; BC Oil and Gas Commission, 2014];
    - Operating protocols agreed for the modification or termination of operations in the event that seismic effects are observed e.g., the “traffic light system” recommended by Zoback [2012];
    - Periodic review of delayed or cumulative hazard impacts, with mitigation and adjustment of operations to ensure the acceptability of on-going risks.

It is noted that a number of these regulatory controls have been adopted by the UK government in their regulation of hydraulic fracturing operations [DECC, 2013] and consideration should be given to extending the seismic risk assessment and management requirements to other industrial processes with a potential to cause earthquakes. Hydraulic fracturing operations will be required to obtain planning permission, an environmental permit, a coal authority permit and consent from DECC to drill. The Health & Safety Executive will also need to be notified in advance of commencement. For the DECC consent, operators have to propose monitoring arrangements and data reporting methods. The "traffic light system" will be used to control on-going operations and ensure that early action is taken in the event of any evidence of seismic effects.

Operators may wish to implement some of these practices on a voluntary basis as good practice management controls.

5) Operator risk assessment and reduction measures

The benefits of operators adopting a more robust approach to assessment of delayed, long term, physically extensive and cumulative impacts are many; yet most businesses only consider 5 to 10 years for operational planning and 25 years for capital investments. Nevertheless, the drivers for integrating longer term risk management into corporate strategy are well known and already adopted by many companies to protect economic performance, professional reputation and share value.

Developing a robust understanding of complex risks facing company performance is a challenge and risks can only be managed where they are recognised. Many companies have produced sustainability reports that consider risks due to resource limitations, including water and raw materials. As part of such assessments, it would be appropriate to consider the long term viability and risk profile of company geographic distribution, including land use and seismic risk issues. This would require a formal (rather than ad hoc) consideration of operations within a geographical area. There is a strong impetus for adoption of good practice in regard to understanding induced seismic risk, regardless of the formal regulatory controls in place at specific locations. The experience of Groningen and Oklahoma indicates that business activities can be severely disrupted in a relatively short time period when operational impacts escalate rapidly or are perceived to be posing a high risk by the public or government officials.

A further change that would be beneficial would be greater transparency and sharing of data collected for the assessment and management of risk, particularly provision of information on sub-surface parameters, operating conditions and observed effects. Currently such information is considered to be commercially confidential by many companies, which has limited progress in scientific assessment of the problem. Greater openness on a level playing field, for example through a regulatory reporting requirement, would facilitate scientific studies to inform our understanding of the potential risks.

Conclusions

There are extensive industrial activities undertaken around the world which involve interaction with the sub-surface and consequently pose a risk of inducing earthquakes. A robust assessment and management process is needed to address these risks. Around the world, current government policies, regulations and standards do not require this, nor is it easy for process operators to fully assess long-term and cumulative impacts. The science to underpin improvements across all these areas is evolving. Although the prediction of seismic impacts remains fraught with difficulty and the determination of tolerable risk thresholds is undefined in many countries, the tools for more effective assessment and management of seismic risk already exist and should be adopted wherever possible.

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