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Terminology for fluid-injection induced seismicity in oil and gas operations

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A glossary of terms, applicable to fluid-injection induced seismicity in oil and gas operations, is compiled from various sources. Creation, adoption and widespread use of standard definitions for induced seismicity and related terms will promote consistency and uniformity and will help to avoid confusion that may arise if different definitions are used in different jurisdictions. A modified scheme is introduced here for magnitude-based classification of seismic activity, with the intent of reconciling the term microseismic, as commonly used within the oil and gas industry, with existing earthquake classifications.

Introduction

Induced seismicity refers to earthquakes or other seismic events that are attributed to human activities (e.g., BCOGC, 2012; CAPP, 2013). Induced seismicity has been extensively studied for a number of different types of human activities, such as impoundment of water reservoirs (Talwani and Acree, 1984; Gupta, 1992), mining (McGarr et al., 2002; Li et al, 2007) and geothermal applications (Majer et al., 2007). There are also documented cases of earthquakes that have been triggered by poroelastic stress changes associated with withdrawal of hydrocarbons (Segall, 1989; Baranova et al., 1999).

Several different types of fluid injection processes are considered here. Hydraulic fracturing is a process of injecting fracturing fluids into a rock formation at a force exceeding the fracture pressure of the rock, thus inducing a network of fractures through which oil or natural gas can flow to the wellbore (CCA, 2014). Enhanced oil and gas recovery may include injection of CO2 or salt water (brine) into a partially depleted reservoir (e.g. Horner et al., 1994). Wastewater injection includes the disposal into an underground formation of produced water associated with the production of oil, bitumen, gas or coaled methane, as well as fluids from solution mining operations, water containing polymers or other chemicals for enhanced recovery and waste fluids from circulation during well cementing.

It has long been understood that injection of fluids into the subsurface can activate slip on a fault (Healy et al., 1968); however, seismicity induced by fluid injection in association with oil gas operations has come into sharper focus in recent years (Ellsworth, 2013; Keranen et al., 2013). With this sharpened focus has come an urgent need to ensure that terminology is carefully defined (Cypser and Davis, 1998).

Although induced seismicity is defined here to imply that an event is anthropogenic, it is worth noting that an alternative school of thought distinguishes between the terms induced versus triggered seismicity as a means to differentiate between the amount of stress required to cause a seismic event (McGarr et al., 2002). In this view, given here for the sake of completeness, the term induced seismicity refers to earthquake activity that is caused by stress changes that are comparable to the ambient stress field, whereas the term triggered seismicity implies earthquake activity that arises from stress changes that are only a fraction of the ambient stress change.

Legal Context

The definition of "induced seismicity" can have significant implications when courts evaluate negligence claims of plaintiffs that allege oil and gas wastewater injection and/or hydraulic fracturing (HF) operations created vibrations that caused property damage. To prove negligence, a plaintiff must establish that the defendant caused foreseeable damage and that the operator's conduct falls below the standard of care expected. An industry operator will not be liable in negligence for damage caused solely by a natural seismic event. The definition of "induced seismicity" incorporated into legislation or regulations can be applied by the courts when evaluating whether an industry operator has met the standard of care expected in the legal system and when deciding whether the operator is liable for failing to meet the expected standard of conduct.

In addition to courts assessing liability, the definition of induced seismicity and related terminology should be an important consideration for regulators monitoring the potential seismic risks from HF operations and/or wastewater injection. In North America some regulators are in the process of evaluating the risks from HF and wastewater injection activities and identifying risk mitigative practices that can be incorporated into the permitting/approvals process and monitoring programs. The following questions based on work completed by Nicholson and Wesson (1990) and Davis and Frohlich (1993), recently discussed by the U.S. Environmental Protection Agency (EPA) in November 2014, provide a starting point to for the courts to evaluate negligence, causation and "induced seismicity" and for policy maker and regulators interested in risk mitigation practices:

1. Are the earthquakes the first reported ones in the area?
2. Is there a clear correlation between injection and seismicity?
3. Are the changes in fluid pressure at well bottoms enough to facilitate seismicity?
4. Are the changes in fluid pressure at hypocenter locations enough to facilitate seismicity?
5. Do some earthquakes occur at or near injection depths?
6. If not, are there subsurface structures that can channel flow to the earthquake sites?
7. Are earthquake epicenters located within 3 to 5 km of injection wells?

Ambiguity will prompt additional "induced seismicity" lawsuits. Carefully considered definitions of "induced seismicity" incorporated by regulators into industry best practices will reduce the number of lawsuits and minimize the resources incurred by industry, government and landowners to resolve disputes.

Seismicity size categories: what does "micro" mean?

Bohnoff et al. (2010) proposed a classification scheme for earthquake size categories based on magnitude, or equivalently, seismic moment. Their scheme is modified in Table 1, which also provides a summary of approximate scales for rupture length, displacement and dominant frequency. This classification adapts prefixes micro, nano, pico, femto, atto, zepto, etc. from the SI system, for application to low-magnitude seismic events. For larger events, standard terminology from earthquake seismology is adopted. Since moment magnitude is proportional to two thirds of the logarithm (base 10) of the seismic moment, the prefixes micro, nano, etc. go by 10^2 rather than the SI standard increment of 10^3. Noting that the term "microearthquake" traditionally refers to earthquakes with M < 3, Bohnhoff et al. (2010) suggested a compromise such that it applies to the magnitude range from 0 to 2 instead, to adapt this term to their proposed SI naming conventions.

Here, we propose the use of the prefix milli to cover the moment magnitude range from 0 to 2. Our proposal is largely motivated by the fact that, within the engineering and applied geophysics literature as well as in industry, the term "microseismic" is very established in reference to events that are generally below magnitude 0. Accordingly, in our revised scheme, magnitude ranges associated with the prefixes "micro", "nano", "pico" and "femto" are each reduced by 2 magnitude units from the scheme proposed by Bohnhoff et al. (2010). In addition to making the scheme more consistent with established usage in the oil and gas industry, the "milliseismic" range from 0 – 2 is emerging as a potentially significant observational gap for monitoring of hydraulic fracturing. Baig and Urbancic (2014) show that this apparent gap may simply be an artifact of instrumentation (geophones) that arguably saturate above magnitude zero.

This new scheme also suggests a broader phenomenological subdivision:

- "Earthquakes" for M > 2 (where the lower magnitude limit corresponds roughly with the minimum threshold for felt natural events)
- "Seismic events" for M < 2 (magnitudes for which it is unlikely that natural events would be felt at the surface)

Table 1. Classes of seismic activity (modified from Bohnhoff et al., 2010). Length and displacement scales are approximate and are based on an assumed stress drop of 3 MPa.

MAGNITUDE RANGE	CLASS	LENGTH SCALE	DISPLACEMENT SCALE	FREQUENCY SCALE	SEISMIC MOMENT[3]
8-10	Great earthquake	100-1,000 km	4-40 m	0.001-0.1 Hz	1 kAk – 1 MAk
6-8	Large earthquake	10-100 km	0.4-4 m	0.01-1 Hz	1 Ak – 1 kAk
4-6	Moderate earthquake	1-10 km	4-40 cm	0.1-10 Hz	1 mAk – 1Ak
2-4	Small earthquake	0.1-1 km	4-40 mm	1-100 Hz	1 μAk – 1 mAk
0-2	milliseism[1] or Microearthquake	10-100 m	0.4-4 mm	10-1,000 Hz	1 nAk – 1 μAk
-2 to 0	microseism[2]	1-10 m	40-400 μm	0.1-10 kHz	1 pAk – 1 nAk
-4 to -2	nanoseism	0.1-1 m	4-40 μm	1-100 kHz	1 fAk – 1 pAk
-6 to -4	picoseism	1-10 cm	0.4-4 μm	10-1,000 kHz	1 aAk – 1 fAk
-8 to -6	femtoseism	1-10 mm	0.04-0.4 μm	1-100 MHz	1 zAk – aAk

[1] Proposed new term, approximately equivalent to the legacy term microearthquake that has been variously applied in the seismological literature in reference to earthquakes with magnitude less than 2, 2.5 or 3 (Bohnhoff et al., 2010).

[2] Prefixes micro, nano, pico and femto have each been decremented by one level, compared to Bohnhoff et al. (2010), in order to accommodate the new proposed term milliseism. The term microseism should not be confused with microtremor (see below).

[3] One Aki (Ak), named for Keiiti Aki, is defined as 1018 Nm. This unit is recommended by the International Association of Seismology and Physics of the Earth's Interior as the standard unit of earthquake size.

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Glossary of Terms

Aftershock: Aftershocks are earthquakes that follow the largest shock of an earthquake sequence. They are smaller than the mainshock and located within 1-2 rupture lengths distance from the mainshock. Aftershocks can continue over a period of weeks, months, or years. In general, the larger the mainshock, the larger and more numerous the aftershocks, and the longer they will continue (USGS, 2015).

Anomalous seismicity: Seismicity above a moment magnitude range of approximately -3 to 0 that is normally expected when performing hydraulic fracture completions (CAPP, 2013).

b-value: The slope of the magnitude-frequency distribution for the Gutenberg-Richter relation, which describes the relative size distribution of earthquakes. Most earthquake fault systems have a b-value close to unity, implying that for each unit increase in magnitude there are ten times fewer earthquakes (El Isa and Eaton, 2014).

Class II injection well: Defined by the U.S. Environmental Protection Agency (EPA) as wells that inject fluids associated with oil and natural gas production. Most of the injected fluid is salt water (brine), which is brought to the surface in the process of producing oil and gas. Well types include disposal wells, enhanced recovery wells and hydrocarbon storage wells (EPA, 2015).

Disposal well: A type of class II injection well used to inject brines or other fluids associated with the production of hydrocarbons. In the U.S., disposal wells represent about 20% of 151,000 class II injection wells (EPA, 2015).

Earthquake: A term used to describe both sudden slip on a fault, as well as the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth (USGS, 2015). The threshold magnitude for felt effects is approximately 2.

Earthquake sequence: A series of earthquakes in a given area with a well-defined mainshock-aftershock, or foreshock-mainshock-aftershock events.

Earthquake swarm: A series of earthquakes in a given area that lacks a well-defined mainshock-aftershock pattern.

Enhanced recovery well: A well used to inject brine, water, steam, polymer, or carbon dioxide into oil-bearing formations to recover residual hydrocarbons (EPA, 2015). In the U.S. approximately 80% of 151,000 Class II wells are enhanced recovery wells.

Epicenter: The point on the surface vertically above an earthquake's focus (USGS, 2015).

Fault: A discontinuity in the subsurface that has accommodated displacement between rock masses on either side of the discontinuity. Sometimes the term geologic fault is used to describe a surface where displacement occurred in the geologic past.

Faulting mechanism: Description of the rupture processes of an earthquake, including the style of faulting (i.e., normal, reverse or strike-slip) and the rupture fault plane on which it occurs (Majer et al., 2012).

Focal depth: Depth below the surface of an earthquake's focus.

Focal mechanism: A graphical representation of the faulting mechanism of an earthquake. Typically, this is represented as a lower-hemisphere projection of P-wave first motion polarity, also known as a beachball diagram.

Focus: The point in the subsurface where earthquake rupture initiates.

Foreshock: A relatively smaller earthquake that precedes the largest earthquake in a sequence, which is termed the mainshock. Not all mainshocks have foreshocks (USGS, 2015).

Ground motion prediction model: A relationship that predicts the amplitude of a specified ground-motion parameter (e.g. PGA, PGV) as a function of magnitude, distance, focal depth and site conditions (Majer et al., 2012).

Gutenberg-Richter relation: An empirical power-law formula that describes the magnitude-frequency relationship for a region. It has the form $\log 10\ N = a - bM$, where N is the number of earthquakes whose magnitude is greater than or equal to M, and a and b are constants.

Hazard: The probability that a given event will produce damage or harm. Hazard (H) is related to Risk (R) and Vulnerability (V) by the risk equation: $R = H*V$.

Hydraulic fracturing: Injecting fracturing fluids into a rock formation at a force exceeding the fracture pressure of the rock, thus inducing a network of fractures through which oil or natural gas can flow to the wellbore (CCA, 2014).

Hydrocarbon storage wells: Wells used to inject liquid hydrocarbons in underground formations such as salt caverns where they are stored. In the U.S. there are over 100 liquid hydrocarbon storage wells in operation (EPA, 2015).

Hypocenter: The estimated location of an earthquake's focus.

Induced Seismicity: Seismic events that can be attributed to human activities (BCOGC, 2012; CAPP 2013). Examples of activities that can cause induced seismicity include geothermal development, mining, reservoir impoundment and subsurface fluid injection and withdrawal.

Instrument response: The response of an instrument such as a geophone or seismometer to a unit input ground motion. The instrument response needs to be corrected in order to estimate magnitude.

Intensity: The effects of earthquake ground motion on the natural or built environment. In North America, intensity is usually quantified using the Modified Mercalli Scale. Intensity is specified in Roman numerals and ranges from I (not felt except by a very few under especially favourable conditions) to XII (total damage) (NRCan, 2015).

Magnitude: A quantitative measure of the size of an earthquake based on seismograph recordings. Several scales have been defined, but the most commonly used are (1) local magnitude (M_L), also referred to as "Richter magnitude," (2) surface-wave magnitude (M_s), (3) body-wave magnitude (m_b), and (4) moment magnitude (M_w) (USGS, 2015).

Mainshock: The largest earthquake in a sequence, sometimes preceded by one or more foreshocks, and almost always followed by many aftershocks (USGS, 2015).

Microseismicity: Defined here as seismicity of magnitude less than 0.

Microtremor (aka Microseism): A more or less continuous motion in the Earth that is unrelated to an earthquake and that has a period of 1.0 to 9.0 seconds. It is caused by a variety of natural and artificial agents (modified from NRCan, 2015).

Moment tensor: A mathematical representation of the movement on a fault during an earthquake, comprising of nine generalized couples, or nine sets of two vectors. The tensor depends of the source strength and fault orientation (USGS, 2015).

Operationally induced seismicity: Defined here as weak (nano-, micro- and milli-) seismicity that occurs in close proximity (up to 100's m) from tensile fractures that are created during hydraulic fracture completions. The distribution of operationally induced events is often used as a proxy for the extent (height, length) of a hydraulic fracture. Unlike earthquake fault systems, the b-value for operationally induced events is usually much greater than unity (Eaton et al., 2014).

Peak ground acceleration (PGA): Maximum instantaneous amplitude of the absolute value of the acceleration of the ground (Majer et al., 2012)

Peak ground velocity (PGV): Maximum instantaneous amplitude of the absolute value of the velocity of the ground (Majer et al., 2012)

Probabilistic seismic hazard analysis (PSHA): Estimation of the probability of ground motions that are expected to occur or be exceeded within a specified time interval (Majer et al., 2012).

Probability of exceedance: Probability, or more accurately the frequency, at which the value of a specified parameter (e.g. PGA, PGV) is equalled or exceeded (Majer et al., 2012).

Unconventional resource: Oil and gas resources whose porosity, permeability, fluid trapping mechanism or other characteristics differ from conventional hydrocarbon reservoirs (CCA, 2014)

Rupture area: The surface area of a fault that is affected by sudden slip during a seismic event.

Seismic moment: A measure of the size of an earthquake based on the product of the rupture area, the average amount of slip, and the force that was required to overcome fault friction. Seismic moment can also be calculated from the amplitude spectra of seismic waves. (USGS, 2015).

Seismicity: Earthquakes or other seismic activity within a given area.

Tectonic stresses: Stresses in the Earth due to geologic processes such as movement of the tectonic plates (Majer et al., 2012)

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Triggered seismic event: A seismic event that is the result of failure along a pre-existing zone of weakness, e.g. a fault that is already critically stressed and is pushed to failure by a stress perturbation from natural or manmade activities (Majer et al., 2012). In earthquake seismology, natural triggering has been recognized due to both static stress changes (i.e. long-term changes to the stress field caused by an earthquake) and dynamic stress changes (e.g., transient stress changes from a propagating seismic wave).

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