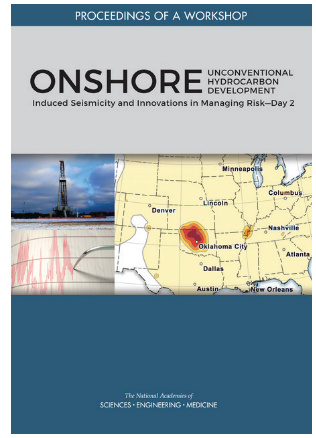
WORKSHOP PROCEEDINGS

January 2019

HIGHLIGHTS

Onshore Unconventional Hydrocarbon Development: Induced Seismicity and Innovations in Managing Risk



Earthquakes that develop as a result of human activity—known as "induced earthquakes or induced seismicity"—have been recognized for decades, but since 2010 a significant increase in the number of induced earthquakes felt in several regions of the United States has been documented. Many of these earthquakes have been attributed to deep subsurface injection of fluid associated with oil and gas development. At a December 2016 workshop, representatives of federal and state government, industry, non-governmental organizations, and academia gathered to discuss the current understanding of induced seismicity; the current and emerging options for monitoring and assessment technologies; and collaborative approaches to managing risk related to the potential for this kind of seismic activity.

Each year, billions of barrels of produced water are generated from oil and gas fields across the United States. Produced water, as described in this document, is a combination of water that existed naturally in underground rock formations for thousands to millions of years before being brought to the surface along with oil and gas resources, and 'flowback water', which returns to the surface after being injected as part of the hydraulic fracturing process.

Box 1. Underground Injection

Fluid injection related to oil and gas production falls into one of three main categories: disposal of produced water, which is water brought to the surface during oil and gas extraction; injection of fluids, including water and chemicals, for the purposes of hydraulic fracturing; and injection of water or other fluids for secondary recovery of oil or gas during production. Among these, most of the induced earthquakes that have been generated and felt by people in the United States have resulted from injection of produced water for permanent disposal in rock formations that lie below drinking water aquifers. A small proportion of the induced earthquakes have been correlated with fluid injection related to hydraulic fracturing. Fluid injection related to secondary recovery of hydrocarbons has not been identified as a significant contributor to these felt, induced earthquakes.

Produced water usually contains contaminants including salt, oil and grease, or other chemicals that derive naturally from the underground rock formation or were introduced as part of the drilling process. Therefore, the water must be managed by some combination of treatment, storage, release, recycling, or disposal, subject to regulatory requirements. Due primarily to economic and regulatory constraints, most produced water (approximately 91 percent across the nation's oil and gas fields) is managed by underground injection for permanent disposal into rock formations that lie below drinking water aquifers (Box 1).

The increase in oil and gas development since 2005 has correlated with a significant increase in the volumes of produced water that have been injected for disposal, and with the number of felt induced earthquakes in some regions of the country where oil and gas development is taking place (Figure 1; Box 2). These induced earthquakes, although generally small in magnitude, are being registered in parts of the country where earthquake activity has historically not been very high.

Because of the potential to induce earthquakes, there is growing interest among well operators, regulators, government and academic researchers, and non-governmental organizations in studying the circumstances that may lead to induced seismic events and in the measures that may be employed to mitigate and manage their occurrence. Exploring the geological and geomechanical conditions in the subsurface and the operating conditions at the well as fluid is injected; assessing current abilities to predict and model how volumes and rates of fluid injection

Box 2. How Does Injected Fluid Induce Earthquakes?

An earthquake can be described in terms of a block sliding on a plane attached to a spring. As the force on the spring builds, the stress also builds until the frictional strength (or resistance) along the plane is reached and the block jumps forward, releasing stress. In an analogous way, when the Earth's crust reaches its frictional strength along a fault (where two plates are moving relative to one another), the fault slips, causing an earthquake.

Most of the earthquakes attributed to oil and gas development are triggered by the underground injection of produced water for disposal. The injected water can have the effect of changing the pore pressure in the rock formation enough to exceed the frictional strength along a nearby geologic fault, allowing the fault to slip, thereby causing an earthquake. If the slip is large enough, the earthquake may be felt by people at the Earth's surface.

Faults are present everywhere in the Earth's crust, including the crystalline basement, the geological rock units that are composed of metamorphic or igneous rocks and that typically lie below sedimentary rocks bearing oil or gas. At any given time, only a small subset of faults either in the crystalline basement or in sedimentary rocks is in the proper orientation relative to the surrounding crustal stress field to have the potential to slip and generate an earthquake. Faults in the crystalline basement, workshop participants noted, are the faults of greatest concern because of their size and the potential for them, if they slip, to generate larger earthquakes. Workshop participants placed special emphasis on avoiding large-volume fluid injection into sedimentary units near the basement where basement faults might be intersected by the fluids.

In this way, the subsurface geology of a region is very important in terms of determining the potential for fluid injection to result in induced earthquakes. In some regions of the country where significant injection of produced water for disposal takes place, no induced earthquakes have been recorded, while other regions have seen a significant increase in the numbers of felt earthquakes. Evaluating the uncertainty of each key variable—including local crustal stresses, fault orientation, and frictional coefficients—can help researchers calculate the probability that a fault might slip with a given perturbation in fluid pressure—or identify those faults which are not likely to slip.

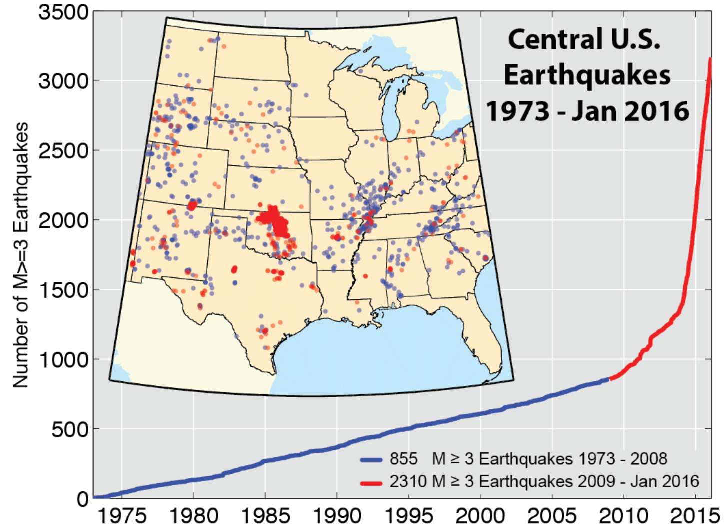


FIGURE 1

This chart shows the cumulative number of earthquakes of magnitudes greater than or equal to 3 in the United States since 1970. The insets show the locations of those earthquakes. A significant deviation in the number of earthquakes appears to have begun around 2005 and increased dramatically starting around 2010, concurrent with the expansion of oil and gas development in the United States. Source: Ellsworth, 2013.

relate to seismicity; developing tools to predict seismicity prior to injection; and gathering basic data on fault locations and properties will all be important to reduce the risk of earthquakes associated with fluid injection related to oil and gas development.

PROGRESS IN UNDERSTANDING THE CAUSES OF INDUCED SEISMICITY

In 2013, the National Academies of Sciences, Engineering, and Medicine released a consensus report that specifically addressed induced seismicity related to fluid injection for energy production. The information in the report was current through approximately the close of 2011, just as the numbers of induced earthquakes related to produced water disposal in the United States were increasing. Presentations and discussions at the 2016 workshop highlighted advances in understanding the causes of induced seismicity since the publication of that earlier consensus report.

For example, several presentations discussed work done in Oklahoma, where researchers are developing ways to assess the various parameters that could help estimate the probability that a fault could slip due to a given fluid pressure perturbation and cause an earthquake that could be felt at the surface.

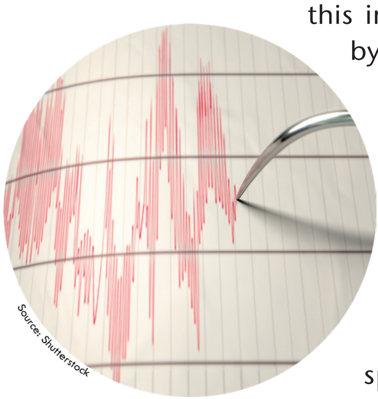
Most produced water in Oklahoma is injected for disposal into the Arbuckle formation, a sedimentary rock formation that is extremely permeable. Because the injected water can spread into the formation beyond the injection site, these fluids usually cause very little increase in pore fluid pressure in the rock unit. However, another important factor is the location of the injection zone. If injection takes place close to a fault in the crystalline basement underlying the Arbuckle, changes in fluid pressure could be transmitted deeply enough to intersect basement faults that could slip and potentially produce seismic events strong enough to be felt at the surface.

Other presentations focused on how geomechanical analysis of a given area allows researchers to identify faults that extend deeply enough to transmit changes in fluid pressure into the basement rock. Participants at the workshop discussed work carried out in Kansas to map faults at regional and field scales and to understand the nature of the stresses in the crust. This involves collecting and examining data including well logs, water injection volumes, and reservoir pressures. Surface elevation data can identify lineaments at the surface of the Earth, and gravity and magnetic data can be collected to identify corresponding features in the subsurface.

USING SCIENTIFIC KNOWLEDGE TO MITIGATE EARTHQUAKE RISK

Scientific understanding of induced seismicity has enabled regulators to develop more effective means of mitigating earthquake risk.

One example discussed at the workshop comes from western Canada, where significant faults extend along the Rocky Mountains and into the Yukon Territory and Alaska. Oil and gas reservoirs lie against these faults, and in some reservoirs, hydraulic fracturing has induced earthquake activity, as has deep well injection for disposal of produced water. In 2015, government authorities responded to this increased earthquake activity by implementing a 'stoplight' protocol for operators to assess and take action to mitigate the occurrence of felt seismic events during their hydraulic fracturing or other fluid injection operations. When seismic monitoring indicates earthquake activity passing a specified threshold, operators evaluate and make changes to their operating procedures to mitigate the hazard. These actions include slowing the injection rate or volume, pausing or ceasing the injection activity for a given time period, skipping particular stages of the hydraulic fracturing activity, or changing the type of fluid being used for the hydraulic fracture well completion. This approach allows regulators to test particular mitigation approaches that might help inform regulatory changes in the future.


Source: Shutterstock

Monitoring microearthquakes (earthquakes that are thousands of times too small to be felt at the Earth's surface) that are generated as fluid injection for hydraulic fracturing is taking place has also helped scientists better understand the impacts of hydraulic fracturing on surrounding rocks. By gathering data on microseismic activity, researchers can monitor the growth of new fracture networks in the subsurface that allow gas or oil to flow to the wellbore. This provides a better understanding of how the reservoir will produce oil or gas and maps pre-existing faults into which hydraulic fracturing may otherwise progress. Therefore, monitoring hydraulic fracturing projects with microseismic arrays can help identify fractures and faults to be avoided and allow oil and gas operators to adjust other aspects of their operational procedures to mitigate the potential of inducing felt seismic events.


Source: Shutterstock

One presenter noted that although reducing the rate and volume of water injection for disposal can lead to a decrease in the rate of earthquakes, the earthquake hazard does not entirely disappear. Examples cited were the magnitude 5.8 Pawnee and magnitude 5.0 Cushing earthquakes in Oklahoma, which occurred after a reduction in produced water injection in the state in 2015. In Oklahoma, earthquake risk persists because many billions of barrels of produced water were injected into the Arbuckle formation over a long period of time. As a result, the fluid pressure will likely take some time to re-equilibrate.

THE IMPORTANCE OF COMMUNICATION AMONG SCIENTISTS, REGULATORS, INDUSTRY, AND THE PUBLIC

A key theme at the workshop was the role of scientists in communicating information about induced seismicity to the public and of information exchange among state and federal government officials, regulators, researchers, and industry. Several presentations emphasized progress in building collaboration among industry, researchers, and regulators and the focus that is being paid by those groups, collectively, on the issue of induced seismicity. For example, one presenter highlighted the importance of combining established techniques with robust geologic and geophysical data sets for making predictions about which faults may reactivate. Collaboration on the part of industry and the regulatory community is necessary to provide access to some of these data sets, which can then be employed to inform better decisions.

Participants discussed the importance of ensuring that science continues to inform decision making in cases where scientific understanding and models are continuously evolving. In such cases, it is important that the scientific community makes clear that models being used are based on well-established principles, but also that the nature of the scientific process is one of constant analysis, correction, improvement, and moving forward, the participants said.

Despite recent progress in understanding the triggers of induced seismicity, gaps in knowledge still exist. Several workshop participants noted that researchers cannot easily resolve which specific well or wells caused which earthquake. At present, the data needed to address this issue—such as bottom hole pressures, a spatial array of deep pore-pressure monitors, and stress measurements—are not available. An experimental induced seismicity test site, participants noted, would allow characterization and modeling of subsurface geology, geophysics, and hydrology in four dimensions (including time). If such a site was shared among federal and state government, industry, and others, the research could be applicable to the needs of various stakeholders.

Participants also highlighted the need to consider the people who live in communities affected by induced seismic activity, or in areas where wastewater injection takes place. Workshop discussions emphasized the need to describe options for managing induced seismicity and alternatives to produced water injection, and to communicate the risk of induced seismicity to local communities, including the frequency and significance of these events, how they are caused, and ways to reduce their numbers.

PLANNING COMMITTEE FOR THE WORKSHOP ON ONSHORE UNCONVENTIONAL HYDROCARBON DEVELOPMENT: INDUCED SEISMICITY AND INNOVATIONS IN MANAGING RISK

Brian J. Anderson (Co-Chair), West Virginia University; **Julia Hobson Haggerty** (Co-Chair), Montana State University; **Melissa Batum**, Bureau of Ocean Energy Management, Department of the Interior; **Susan L. Brantley** (NAS), The Pennsylvania State University; **Jeffrey J. Daniels**, The Ohio State University; **Paul Doucette**, Baker Hughes, a GE Company; **David Glatt**, North Dakota Department of Health and Environmental Council of the States' Shale Gas Caucus; **Steven P. Hamburg**, Environmental Defense Fund; **Joe Lima**, Schlumberger Services, Inc.; **Jan Mares**, Resources for the Future; **Kris J. Nygaard**, ExxonMobil Upstream Research Co.; and **Amy Pickle**, Duke University; Staff of the National Academies of Sciences, Engineering, and Medicine: **Elizabeth A. Eide** (Senior Board Director), **Ed J. Dunne** (Program Officer; up to June 16, 2017), **Nicholas D. Rogers** (Financial and Research Associate), **Yasmin Romitti** (Research Associate), **Courtney R. DeVane** (Administrative Coordinator), **Eric J. Edkin** (Senior Program Assistant), and **Raymond Chappetta** (Senior Program Assistant)

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ABOUT THE ROUNDTABLE ON UNCONVENTIONAL HYDROCARBON DEVELOPMENT

Launched in 2015, the Roundtable provides a neutral forum where representatives from government, industry, academies, and nongovernmental and international organizations can critically examine the facts about the scientific, engineering, health and safety, regulatory, economic, and societal aspects of unconventional hydrocarbon development.

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For more information, contact the Board on Earth Sciences and Resources at 202-334-2744 or visit http://www.nationalacademies.org/besr. *Onshore Unconventional Hydrocarbon Development: Induced Seismicity and Innovations in Managing Risk – Day 2: Proceedings of a Workshop* can be purchased or downloaded from the National Academies Press, 500 Fifth Street, NW, Washington, DC 20001; (800) 624-6242; http://www.nap.edu.