GEOPHYSICS

Coping with earthquakes induced by fluid injection

Hazard may be reduced by managing injection activities

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Large areas of the United States long considered geologically stable with little or no detected seismicity have recently become seismically active. The increase in earthquake activity began in the mid-continent starting in 2001 (*1*) and has continued to rise. In 2014, the rate of occurrence of earthquakes with magnitudes (M) of 3 and greater in Oklahoma exceeded that in California (see the figure). This elevated activity includes larger earthquakes, several with $M > 5$, that have caused significant damage (*2*, *3*).

POLICY

To a large extent, the increasing rate of earthquakes in the mid-continent is due to fluid-injection activities used in modern energy production (*1*, *4*, *5*). We explore potential avenues for mitigating effects of induced seismicity. Although the United States is our focus here, Canada, China, the UK, and others confront similar problems associated with oil and gas production, whereas quakes induced by geothermal activities affect Switzerland, Germany, and others.

These injection activities include (i) disposal of wastewater by injection into deep formations; (ii) injection of water or CO$_2$ into depleted reservoirs for enhanced oil recovery (EOR); (iii) hydraulic fracturing (fracking) to enable production of oil and gas from low-permeability reservoirs; (iv) injection of supercritical CO$_2$ into deep formations for permanent carbon capture and storage (CCS); and (v) injection into geothermal reservoirs to replenish water lost to steam production or to develop enhanced geothermal systems (EGS).

Although only a small fraction of disposal wells have been associated with induced earthquakes large enough to be felt, there are so many disposal wells that this contributes significantly to the total seismic hazard, at least in the mid-continent (*1*, *2*, *6*). EOR has been associated with earthquakes as large as M4.5, but felt earthquakes are rare (*7*). For the most part, fracking induces only micro-earthquakes (too small to be felt), although there have been a few felt earthquakes (*8*). CCS may pose future seismic hazards (*9*), but few projects are under way, and the largest earthquakes have been too small to be felt at the surface. Geothermal fields and EGS sites are few in number and, within the United States, limited to western states where earthquakes up to M4.6 have been associated with geothermal production (*10*).

Wastewater injection directly into the crystalline basement has induced earthquakes of particular notoriety [e.g., in the Denver region during the 1960s (*11*)]. EGS case histories (e.g., the Deep Heat Mining Project in Basel, Switzerland) show that injection of water into crystalline basement is likely to result in significant earthquake response (*10*, *12*).

> ***"Developing a hazard model for earthquakes induced by industrial activities is key to determining effective ways to mitigate their damaging effects."***

Most disposal wells inject not into basement but into sedimentary layers of high permeability and porosity, targeted because of their ability to accept fluid, with little or no earthquake response (*13*). For some cases, however, effects of fluid injection were not confined to the target formation but were communicated to greater depth along a preexisting fault, as evidenced by earthquake locations in the basement (*14*) and simulated by numerical modeling (*15*).

Large volumes of injected wastewater may be required for an earthquake response that includes events large enough to be felt, or even damaging (*5*). The magnitudes of the largest induced earthquakes in some sequences correlate with the volume of injected fluid. Nonetheless, there is debate as to whether injected volume is the key factor that limits maximum magnitude (*6*) or whether it is controlled by the size of a nearby fault and its relation to the contemporaneous stress state, as is the case for natural earthquakes. Although faults evidently play at least several possible roles that affect the likelihood of inducing felt earthquakes, most of these faults are only detected when they are imaged by well-located induced earthquakes (*3*, *14*).

SEISMIC HAZARD MODELS. The long-term (50-year) model for seismic hazard in the United States, which sets design provisions in building codes, intentionally excludes, as much as possible, contributions from induced earthquakes (*16*). Developing a corresponding model for earthquakes induced by industrial activities is key to determining effective ways to mitigate their damaging effects. But to do so requires taking account of some essential differences between induced and natural seismicity.

Natural seismicity is usually assumed to be independent of time in assessing its hazard. Seismicity induced by fluid injection, in contrast, varies with time, often because of changes in injection rate. When a project is terminated, the rate of induced earthquakes diminishes with time, often in an irregular way (*11*). The spatial distribution of injection also changes as oil and gas production declines in one region and increases in another. These realities rule out simply combining induced and natural earthquake sources to develop a model for setting seismic safety provisions for new construction, the traditional application of the hazard model. Instead, a separate 1-year hazard model for induced earthquakes is being developed and will be updated frequently (*17*).

Thus, it is important to be able to determine whether an earthquake sequence was induced or natural, so as to avoid inappropriate earthquake input to either hazard model. This is not always straightforward. Induced and natural earthquakes appear similar when observed on seismograms. If an injection activity and an earthquake sequence correlate in space and time, with no known previous earthquake activity in the area, the earthquakes were likely induced (*11*, *18*). Some sequences are more challenging. There may be a lengthy delay between the start of injection and the first detected earthquakes or an offset of many kilometers between the injection site and earthquakes (*5*). Adding to the difficulties are enigmatic

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swarms of natural tectonic earthquakes unrelated to fluid injection (*19*). Novel approaches for addressing these challenges are being tested; for instance, analysis of earthquake rate changes has revealed systematic differences between natural and induced earthquake sequences (*20*).

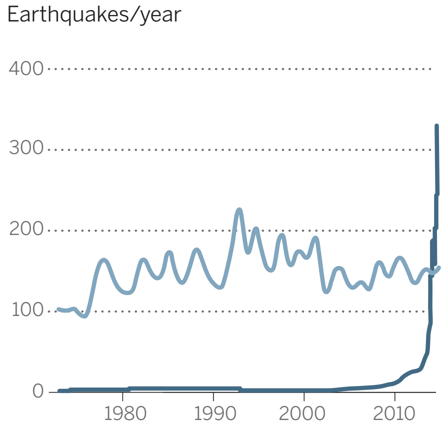
REDUCING HAZARD, MITIGATING RISK. The general public is the most important stakeholder because they may be exposed to potential injury and damage. Organizations with more specific roles and stakes in mitigating impacts of induced seismicity include (i) oil and gas producers, wastewater disposers, and geothermal energy providers; (ii) land-management, regulatory, and permitting agencies (federal, state, and local); (iii) emergency managers and responders; (iv) building owners, insurers, and mortgage holders; and (v) scientists in the research community investigating induced seismicity.

The U.S. Environmental Protection Agency has federal responsibility for regulating wastewater disposal wells, but in most cases permitting authority has been delegated to state agencies. These agencies, federal and state, work with constituents to add or modify regulations or practices regarding the possibility of induced seismicity from fluid injection. Research agencies such as the U.S. and state geological surveys have operational roles in monitoring seismicity and may also be responsible for assessing associated seismic hazard.

Actions may be directed toward reducing the hazard, which is not possible for natural earthquakes, or reducing the risk (hazard times consequences). For instance, risk can be reduced for new injection projects by siting them away from population centers or critical facilities for which the largest, but lowest-probability, earthquakes are of greatest concern.

The possibility of reducing the hazard of induced earthquakes has policy implications inasmuch as stakeholders are in a position to balance economic benefits of energy production activities against costs incurred owing to the increase in hazard. This cost-benefit analysis is rarely straightforward because benefits, mostly economic, are geographically diffuse, whereas hazardous effects are localized to the environs of the injection wells. Moreover, if an induced earthquake sequence results in damage, then blame can be assigned with legal implications for liability (*21*). The question of whether an earthquake sequence was induced or natural is of more than academic interest.

Seismic surge in Oklahoma



Annual rate of earthquake sequences with at least one $M \geq 3$ earthquake in California (light blue) and Oklahoma (dark blue) since 1973. (Based on USGS earthquake catalog data from http://.earthquake.usgs.gov.)

The importance of seismic monitoring cannot be overstated. The current detection threshold within most of the contiguous United States is *M*3. For adequate monitoring of the hazard from fluid-induced earthquakes, it would be advisable to augment the national network to detect and locate events with significantly lower magnitudes (e.g., as low as 2 or less) to identify seismic hazards in time to take corrective actions while the problems are still manageable. For instance, a seismic network capable of precise locations of small earthquakes could reveal the presence of a large, possibly dangerous, fault being reactivated due to fluid injection (*14*). Information of this sort might prove invaluable for avoiding a damaging earthquake.

Local seismic networks are the main components of "traffic light" systems (*12*, *22*), which have been useful for reducing the hazard of induced earthquakes. These systems set magnitude thresholds that, if exceeded, result in adjustments to injection operations so as to avoid inducing earthquakes of greater consequence. Such a network was deployed near Greeley, Colorado, in 2014 by seismologists from the University of Colorado, following a felt earthquake in the vicinity of a wastewater disposal well. Based on seismic data from his network, the Colorado Oil and Gas Conservation Commission required the operator to modify disposal rates and depths in response to an earthquake located near the well (*23*).

Traffic light systems, and other approaches to hazard reduction based on seismic network data, are most effective during early stages of an injection project. The possibility of controlling seismic hazard diminishes as the pore pressure effects migrate away from the injection interval and become less amenable to control from the wellhead (*11*).

For purposes of transparency and avoiding public distrust, it is important to put the results of these seismic network operations into the public domain in near real time. Even if a network is owned and operated by industry, regulators must ensure that seismic data are not withheld from the public. Similarly, making injection data, such as daily injection rates, wellhead pressures, depth of the injection interval, and properties of the target formation, publicly accessible can be invaluable for attaining a better understanding of fluid-induced earthquakes. Open sharing of data can benefit all stakeholders, including industry, by enabling the research needed to develop more effective techniques for reducing the seismic hazard. ■

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