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Some induced seismicity considerations in geo-energy resource development

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HIGHLIGHTS

- Fluid injection and extraction associated with energy resource development technologies and waste disposal can induce seismic events, usually of low magnitude, but in a few cases magnitudes greater than 5 have been measured.
- Currently hydraulic fracturing operations are not thought to be a significant cause of measurable seismic events; however, large volume wastewater injection wells can be.
- The characteristics of ground motions resulting from induced earthquakes differ from those associated with tectonic seismic events.
- Protocols for mitigation of the risks associated with induced seismicity have been developed for enhanced geothermal systems, but are needed for enhanced hydrocarbon recovery technologies, wastewater injection wells, and carbon capture and storage.

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ABSTRACT

It is now well established that past and current geo-energy resource recovery operations associated with geothermal systems, oil and natural gas recovery operations, and long-term underground storage of waste fluids can induce earthquakes, some having magnitudes as great as 5–6. Injection into or removal of fluids from existing faults and highly stressed rocks associated with energy resource recovery and waste fluid disposal can generate the stress changes needed for fault rupture and slip along the fault plane. Important aspects of the present state of knowledge of induced seismicity, including causal mechanisms, characteristics of different energy technologies, hydraulic fracturing and waste disposal injection wells, carbon capture and storage, and assessing and managing the hazards and risks from induced seismicity are summarized in this paper. Induced earthquakes occur at shallower depths than natural tectonic earthquakes, and for a given magnitude event, shaking intensity is more severe in the epicentral region of an induced earthquake but dissipates more rapidly with distance than for a natural earthquake. In general, the greater the imbalance between the extraction and injection volumes at a site, the larger the magnitude of an observed induced earthquake. The likelihood of shaking of a given intensity at a given location can change with time for anthropogenic events in response to variations in source locations and fluid injection and withdrawal rates and volumes. Methods to account for these variations in seismic hazard and risk assessment are under development.

1. Introduction

Since the 1920s anthropogenic activities have been documented as responsible for inducing or triggering[3] a very few of the nearly 15,000 earthquakes of magnitude (**M**) 4.0 or greater and more than 1.4 million events with **M** greater than 2.0 that occur worldwide each year. Until the last few years most of the induced events could be attributed to such activities as reservoir impoundment, controlled explosions related to mining or construction, or

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3 Most of the earth's crust is highly stressed, and an earthquake can be "triggered" in response to a small shear stress change in relation to the pre-existing stress on a fault. This is analogous to pulling the trigger of a loaded gun; whereas, a fully "induced" earthquake would involve a stress change of considerably greater magnitude on an initially more stable fault; which would be analogous to loading the gun and then pulling the trigger. Consistent with most current practice, the term "induced" is used herein for both cases.

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underground nuclear tests. More recently seismic events have increasingly been related to new energy technology developments and operations, and these events have become the subject of increased attention owing to the potential associated hazards and risks posed to the environment and existing and new infrastructure.

The results of a recent comprehensive study of the induced seismicity potential related to energy technologies by the National Research Council of the US National Academies (NRC) are presented in Ref. 1. The energy technologies addressed in this study include: (1) geothermal energy development, (2) oil and gas development, (3) hydraulic fracturing for shale gas recovery, and (4) carbon capture and storage (CCS) for long-term removal of CO_2 from the atmosphere.

In this paper, we draw heavily on the NRC report and summarize the main characteristics of these technologies as they relate to potential seismicity. We examine in more detail four issues with significant geotechnical components that have received extensive additional study and clarification or emerged during the last few years as important problems needing further study and resolution. These are: (1) hydraulic fracturing, (2) injection wells for waste fluid disposal, (3) carbon capture and storage (CCS) and whether it can be done safely and economically, and (4) induced seismicity hazards and risks related to ground motion characteristics and their potential impacts on hydrocarbon resource recovery, ground stability and infrastructure. Other environmental and societal impacts of energy technology and geo-energy resource development; e.g., water and air pollution, are outside the scope of this paper, but are discussed in some detail by Zoback and Arent[2] among others.

2. Mechanisms for inducing seismicity

The mechanisms for fault rupture and sliding are well known. Extensive field measurements and other evidence indicate that the earth's crust, even within stable tectonic plates, is stressed to near the critical limit for fault slip.[3] Thus, even small changes in the rock stress and/or pore fluid pressure, generated as shown schematically in Fig. 1,[4] can cause a critically oriented fault to slip in accordance with the Coulomb strength criterion. The relevant stresses and stress changes are shown in Fig. 2. Four ways by which fluid injection can influence pore pressures and rock stresses are listed by Rubinstein and Mahani[5]:

1. Injection pressure raises pore pressure within a fault.
2. Injection of fluids fills and compresses fluids within pore spaces causing deformation.
3. Injection of fluid colder than the rock causes thermo-elastic deformation.
4. Injected fluid adds mass to the injected formation.

Fluid extraction leads to pore pressure reduction accompanied by subsidence and changes in rock stress. The net fluid balance; i.e., the difference between the total amounts of fluid introduced or withdrawn from the subsurface has been shown to provide a good correlation with the occurrence and magnitude of induced events.

For natural earthquakes, each unit increase in magnitude corresponds to an increase of about 8 times in fault rupture area and about 4-1/2 times in rupture displacement.[6] For a **M** 4.0 event the rupture surface area is about 1.4 km^2 and the fault displacement is about 1 cm. Fig. 3[7] shows relationships among earthquake magnitude, earthquake moment, fault rupture length, stress drop across the fault and the magnitude of slip. As some induced events have reached magnitudes greater than 5, the associated fault slip may be several centimeters.

The frequency of occurrence of earthquakes of different magnitude is known to follow a power law proposed by Gutenberg and Richter[8]:

$$\mathrm{Log}_{10}\mathbf{N} = \mathbf{a} - \boldsymbol{b}\mathbf{M}$$

where **N** is the cumulative number of earthquakes with magnitudes equal to or larger than **M**, and **a** is the logarithm of the number of events of $\mathbf{M} = 0$ or larger (i.e., $\mathbf{N} = 10^{\mathbf{a}}$ for $\mathbf{M} \geq 0$). The variable ***b*** is the negative of the slope of the best fit line between the annual number of earthquakes $\geq\mathbf{M}$ and **M**. It defines the relationship between the relative number of events of different magnitudes.[8] The greater the ***b***-value, the greater the proportion of small earthquakes to large ones. The global average of ***b*** for natural tectonic earthquakes is approximately 1.0. It has been suggested that because the ***b***-values at some sites for events that are considered to be anthropogenic are >1.0 there are some differences in the seismic source mechanisms of induced versus natural tectonic earthquakes.[9]

3. Energy technologies

Induced seismicity concerns have centered on several aspects of current energy development technologies. The NRC report on induced seismicity[1] focused on geothermal energy, hydrocarbon (oil and gas) withdrawal by different means, and carbon capture and storage (CCS). These technologies are discussed briefly in this section.

3.1. Geothermal energy

Three types of geothermal energy have been developed: (1) "vapor dominated" systems, in which steam is pre-existing in the rock fractures and pores (maximum felt event in the US as of 2013 was **M** 4.6), (2) "liquid dominated" systems, where hot water is in the rock ($M_{max} = 4.1$), and (3) "enhanced geothermal systems" (EGS), where water is injected into a hot, dry rock ($M_{max} = 2.6$) and heated for use as the energy source. More details and schematics of the power cycles for these systems are given in Ref. 1 and the references cited therein. Induced seismicity associated with geothermal systems has been recognized for many years and has been more extensively studied and managed than for the other geo-energy technologies. Geothermal systems differ from the other energy sources in the much higher temperature of the reservoir and fluids involved.

Induced seismicity in geothermal systems appears related to both net fluid balance considerations and the temperature changes produced in the subsurface, and different forms of geothermal resource development appear to have differing potential for producing felt seismic events. High-pressure hydraulic fracturing in some EGS projects has caused seismic events that can be felt. The temperature changes associated with geothermal development have also induced felt seismicity, with The Geysers geothermal field in California being one example.

A Protocol for Enhanced Geothermal Systems[10] has been developed that provides a reasonable initial model and guidance for managing induced seismicity that could serve as a template for other energy technologies as well.

3.2. Oil and gas

As of 2013 conventional hydrocarbon withdrawal, involving removal of large volumes of fluids over decades, usually with fluid injection, had resulted in felt seismic events at 20 sites from approximately 6000 projects in the US, with $M_{max} = 6.5$ associated with basin subsidence. A notable exception was the occurrence of events near the Gazli Gas Field in Uzbekistan, where three large earthquakes of magnitude about 7 were recorded in the mid-1970s and 1980s.[1] This region had been largely aseismic previously, and gas extraction was suggested as a possible cause. Secondary oil and gas recovery, usually using water flooding, has induced at least one felt event at 18 sites among about 108,000 wells in the US, with