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A coupled geomechanics and fluid flow model for induced seismicity prediction in oil and gas operations and geothermal applications

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ABSTRACT

The combined horizontal drilling and hydraulic fracturing has revitalized economically viable production from tight oil and gas shale reservoirs. This joint technology application enabled extensive unconventional resource exploration and development activities first in the United States followed by around the globe for unlocking the vast hydrocarbon resources. While the contributions from these accomplishments also created an enhancement in the local economies and technological advancements, these activities also have raised significant concern on potential surface and groundwater contamination and air pollution issues and more recently induced seismicity for geohazard risk. In this research study, we provide a summary of induced seismic activities related to oil, gas and geothermal operations in the U.S. The role of the stress alteration and behavior of physicochemical interactions taking place between the fracturing fluids used and the shale matrix under stress have been presented using a coupled geomechanics, fluid flow and physicochemical model. Examples of fluid injection in shale reservoir hydraulic fracturing and waste disposal operations have been provided toward better understanding of the predictive methodologies for induced seismicity and preventive effort for sustainable and safe unconventional operations. The impact of the presence of a fault at various distances away from the injection site nearby the disposal and injection operations on occurrence of the induced seismicity was studied. It was shown that microseismic monitoring along with the coupled geomechanics, fluid flow models and statistical analysis of the microseismic data can provide a good lead for prediction of potential fault reactivation and induced seismicity generation in association with oil and gas production, EOR and EGS fluid injection and waste disposal operations.

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1. Introduction

Large gas shale and tight oil reserves with significant unconventional development activities have been geographically located in the areas with minor seismicity in the United States and considered to have small potential for possible earthquakes. However, recent sizable earthquakes (2–5.3 Richter scale magnitudes) in the states with low seismic activities such as Texas, Oklahoma, Colorado, Pennsylvania and Ohio have raised further concerns and associated interest in the role of fluid disposal operations as well as the hydraulic fracturing related fluid injection and oil and gas production related withdrawals on induced seismicity (Tutuncu et al., 2012; Tutuncu, 2012; Rutqvist et al., 2013; McGarr, 2014).

United States Geological Survey (USGS) reported significant increase in the number of earthquakes with Richter scale $M > 3$ from an average of 29 per year between 1970 and 2000 to over 100 per year in the period of 2010–2015 as shown in Fig. 1 (Folger and Tiemann, 2015; Ellsworth, 2013; USGS, 2015). Most of these events have been associated with waste disposal or water injection applications for enhanced oil recovery operations. Magnitude of these small earthquakes typically increases as the total injected fluid volumes increase. Injection pressures as well as the injection rates have been subject to investigation for determining the key influencing factors to these tremors. The increasing number of seismic stations in recent years for monitoring the seismicity with better coverage even in the remote corners of the US with higher resolution as well as advance technologies utilized in the geophone assemblies for recording, data acquisition, signal processing and communication networks used have increased small magnitude earthquake detection capability in many US states evidently contributing to the number of increased recorded earthquakes.

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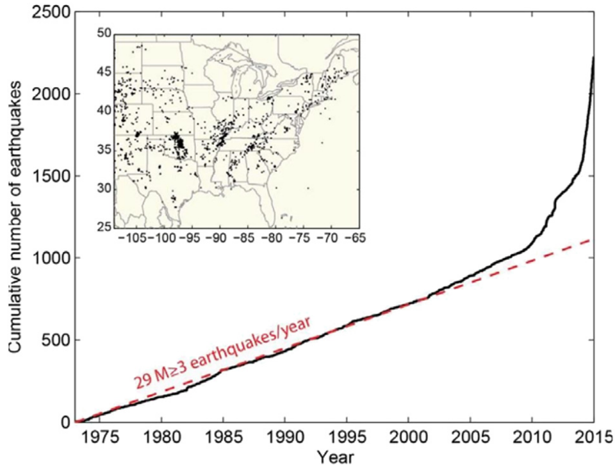

Fig. 1. Cumulative number of Magnitude (M) 3.0 or greater earthquakes in the central and Eastern United States between 1970 and 2014 (after USGS, 2015). The dashed line indicates 29 earthquakes per year between 1970 and 2000 with average rate being the same. There is a sharp increase in the rate of earthquakes since 2009.

The microseismic monitoring from the hydraulic fracturing operations in shale gas and tight oil reservoirs indicate event magnitude ranges typically from -4.0 to −1 ($-4.0 < M < -1.0$) depending on the injected fluid volumes, injection pressure, injection rate, formation and fluid properties, and geology of the area including the density and distribution of the natural fractures, the difference between the in situ horizontal principal stress magnitudes and local tectonics. In most cases, the amount of energy released in seismic waves is estimated from the earthquake magnitude through the semi-logarithmic magnitude-moment relations in Eq. (Barnhart et al., 2014) and Eq. (Colorado Geological Survey, 2014) developed by Gutenberg and Richter (1954) and Kanamori (1977), respectively and presented in Fig. 2.

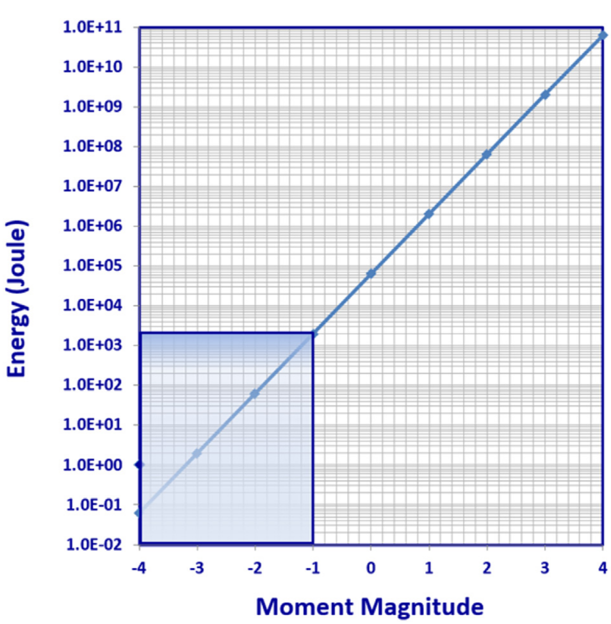

Fig. 2. Energy released versus Moment Magnitude in an earthquake. The shaded box corresponds to microseismic event caused by hydraulic fracturing while triangle symbol marks 0.5 kg dynamite explosion for M = 0.5 for comparison [using Eq. (1) (Gutenberg and Richter, 1954) and Eq. (2) (Kanamori, 1977) and converting the Energy unit from erg into Joule)].

$$\log_{10} E = 1.5M + 11.8 \tag{1}$$

$$E = \frac{M_o}{2*10^4} \tag{2}$$

where E is the seismic energy released in erg, M is the earthquake magnitude and Mo is seismic moment in dyne-cm. The energy was converted to Joule for Fig. 2.

In a recent report published by the National Research Council (2012), induced seismicity from the wastewater injection operations has been reported to occur in less than 1% of the injection wells. Induced seismicity with Richter scale M > 1 from hydraulic fracturing operations is also quite rare. On contrary, there is more recorded evidence of induced seismicity activities with higher energy release on Enhanced Geothermal Systems (EGS) applications as presented in Fig. 3.

Due to public perception in addition to ever increasing trends on triggered events near waste disposal and other fluid injection operations, induced seismicity has gained significant research attention in recent years from the oil and gas industry, regulatory agencies, EGS, carbon capture and storage process groups. The environmentally friendly, safe and economically viable operations particularly from gas shale and tight oil formations, CO_2 injection and long term storage, waste disposal and geothermal applications are strongly dependent on better understanding of the key factors controlling the induced seismicity in addition to predictive models and monitoring methodologies for site selection and operational parameters.

Prior to the release of the National Research Council Induced Seismicity study in 2012, over 100 injection induced seismicity events with the largest magnitude of 3.9 were reported in Youngstown, Ohio in 2011 (Kim, 2013). The earthquakes epicenters were traced to the Precambrian crystalline basement rock below the sedimentary formations. These events have been attributed to the fluid pressure alterations in association with deep waste disposal operations (Sumy et al., 2014; Rubinstein et al., 2014). More recently in March 2014, state investigation of five small tremors in the Youngstown area at the Appalachian foothills indicated that the injection of sand and water accompanying the fracturing operations in the Utica Shale may have increased shear stress on a small, unknown fault nearby the drilling (Kim, 2013). The state has placed a moratorium on drilling activity at the site near the epicenter of where the small quakes occurred, while allowing five existing wells in the same area to continue

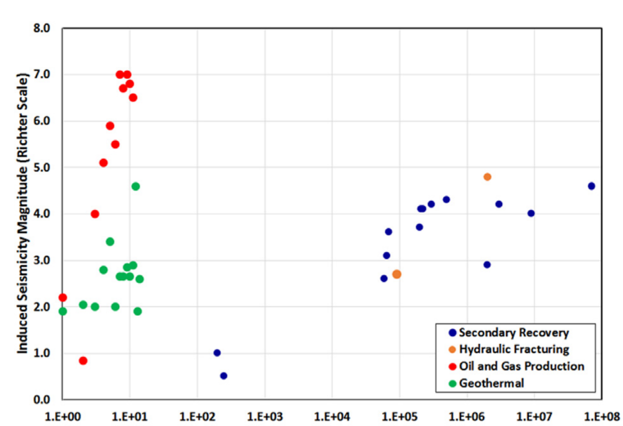

Fig. 3. Relationship between the injected fluid volume and induced seismicity magnitude reported in the literature for secondary recovery, hydraulic fracturing, oil and gas production and geothermal EGS operations (National Research Council, 2012).

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