A FRAMEWORK TO QUANTIFY INDUCED SEISMICITY DUE TO WASTEWATER INJECTION IN OKLAHOMA

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ABSTRACT

A bi-product of hydraulic fracturing is massive quantities of waste fluids, which are routinely injected underground. In regions such as Oklahoma, the injection rates are high enough to alter the poro-elastic stress-field significantly, leading to a sharp increase in seismicity rates. Even though most of the events in Oklahoma are of small size, magnitudes up to 5.8 have been observed. In an attempt to quantify the extent of the problem, we develop a framework for seismic hazard assessment in regions with potentially induced seismicity. The result is a statistical model capable of distinguishing natural/tectonic seismicity from injection-induced seismicity with a certain degree of confidence. It can also be used to forecast seismicity rates, given a scenario for future injection rates. The induced seismicity is assumed to follow a modified version of the Gutenberg-Richter law, incorporating the Seismogenic Index principles.

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\textbf{ABSTRACT}

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\textbf{Introduction}

Hydraulic fracturing enables energy-production from previously unproductive geologic formations. However, a bi-product of this new technique is massive quantities of waste fluids (e.g., saltwater), which are routinely injected underground, often very close to the basement rock. The shear stress levels in the tectonics of our case study region Oklahoma are near the strength limit of the crust \cite{1}. Under these conditions, small perturbations, e.g. pore pressure changes due to high injection rates, can alter the poro-elastic stress-field \cite{2}, affect the fault stability and trigger ruptures \cite{3}.

In an attempt to quantify the extent of the induced seismicity problem, the U.S. Geological Survey (USGS) has developed one-year seismic hazard forecasts \cite{4}, which simply use the (increased) observed seismicity from the last two years to forecast the activity rates of the next

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year. The only input is the declustered earthquake catalog, with no information about injection rates, volumes, etc. This model implicitly assumes that the injection rates do not vary significantly between consecutive years, which in general is not the case due to regulatory actions and fluctuations in the price of oil.

Recently, researchers have proposed models that predict the time dependent seismicity using both seismicity and injection data. Langenbruch & Zoback’s [5] approach uses a non-declustered earthquake catalog, as well as disposal data, proposing an empirical model that can capture the correlation between the injection rates and the triggered seismicity, for a given (large) area and time period. The main limitation of this model is that it forecasts only induced seismicity and does not cover the potential of naturally occurring events. Furthermore, it cannot capture injection scenarios where a rapid decrease in the disposal rate is followed by an equally rapid increase. McClure et al’s [6] method also seeks association between seismicity and waste-water injection, trying to fit a statistical model that describes best the correlation between observed seismicity and injection rates within previously defined grid blocks. This more complex model can only capture the scenario of steady or increasing injection rates and does not incorporate a magnitude size distribution.

Drawing inspiration from the last two studies [5, 6] we develop a framework that is generic enough to be more widely applicable.

**Proposed framework**

The goal of this work is to develop a statistical model that distinguishes natural/tectonic seismicity from injection-induced seismicity with a certain degree of confidence, and can be subsequently used to provide a forecast of the seismicity rates, in terms of space, time and magnitude distribution. To do so, we modify the framework of McClure et al [6], incorporating an extended version of the earthquake recurrence model of Langenbruch & Zoback [5]. In the proposed framework, the regional Gutenberg-Richter parameters for the natural/tectonic seismicity (i.e., the average monthly background rate $a_{BG}$ and b-value $b_{BG}$ [7]) are computed using the complete part of the earthquake catalog until the year 2009, which is the change point in seismicity rates in Oklahoma defined by Baker & Gupta [8]. Then, the study area is discretized into small blocks (e.g. $0.2^\circ\times0.2^\circ$) and the relationship between injection rates and seismicity within each block is investigated. To account for the spatial distribution of waste-water among neighboring blocks, one could smooth the monthly injected volumes using a Gaussian kernel over a specified radius larger than the block size (e.g. $0.25^\circ$ degrees).

Using the principles above, the number of events in block k during month i ($N_{k,i}$) above the magnitude of completeness (mc) [9] is separated into the tectonic and induced components:

\[
N_{\text{tectonic}}_{k,i}(M \geq mc) = 10^{A_{k} \cdot 10^{-b_{BG} \cdot mc}} \\
N_{\text{induced}}_{k,i}(M \geq mc) = 10^{\log(V_{k}) + \Sigma_{k} \cdot 10^{-b_{BG} \cdot mc}} = V_{k} \cdot 10^{\Sigma_{k} \cdot 10^{-b_{BG} \cdot mc}} \\
N_{\text{observed}}_{k,i}(M \geq mc) = (10^{A_{k}} + V_{k} \cdot 10^{\Sigma_{k}}) \cdot 10^{-b_{BG} \cdot mc}
\]

where $A_{k}$ is $a_{BG}$ normalized to the size of each block, $V_{k}$ is the total injected volume ($m^{3}$) inserted in block k during month (i – lag), and $\Sigma_{k}$ is the seismogenic index [10] of block k. $V_{k}$ is only considered during months in which the injection rate is above a triggering threshold $v_{min,k}$ ($m^{3}/month$), and $\Sigma_{k}$ quantifies the number of earthquakes induced by injection for a unit volume of fluid in block k [5] and is influenced by the volume concentration of preexisting faults and the state of stress. The free parameters that are derived from the observed seismicity and injection
data for each block \( k \) are the seismogenic index \((\Sigma_k)\), the triggering volume threshold \((v_{\text{min},k})\), and time lag in months \((\text{lag}_k)\). If the injection rate falls below \( v_{\text{min},k} \) Eq. 3 can be modified employing the Omori-Utsu law, as described in [11, 5].

Assuming the \( b \)-value derived from the natural/tectonic \((b_{\text{BG}})\) is applicable to the induced seismicity and with the free parameters known, Eq. 3 can be extended to represent the magnitude recurrence as:

\[
N_{\text{forecasted},k,i}(M \geq m) = (10^{A_k} + V_k \cdot 10^{\Sigma_k}) \cdot 10^{-b_{\text{BG}} m}
\]  

(4)

In principle, equation (4) follows the approach of Langenbruch & Zoback [5], complemented by the term \( A^k \) to account for the observed seismicity that is not associated to human activity. Figure 1 illustrates this point, with the magnitude recurrence of the tectonic events following a traditional Gutenberg-Richter relationship and this relationship being modified for induced seismicity based on the injection rates \((V_k)\). Thus, this model can be used to forecast seismicity given a certain scenario for the injection rates, which is the input parameter \( V_k \). One could also use the bounded Gutenberg-Richter relation, to account for maximum magnitude. We should note that one of the limitations of the proposed methodology is the assumption that the \( b \)-value is constant through time and not affected by changes in the poro-elastic stress field [2].

Figure 1. Magnitude recurrence for tectonic seismicity and tectonic + induced seismicity

An important issue raised by McClure et al [6] is the assessment of the statistical confidence of the observed seismicity as being induced. Given that the mean rate can change over time (Eq. 3), we can assume that the seismicity rate follows the homogenous Poisson distribution at any given month \( i \). As a result, correlating the fitted Eq. 3 to the earthquake time-history provides the maximum likelihood \( L_1 \) that the observed seismicity above the background rate is induced by waste-water injection. Accordingly, Eq. 1 can be used to define the maximum likelihood \( L_0 \) (null model) that none of the observed seismicity is induced by waste-water injection. Following the resampling method of McClure et al [6] and the likelihood ratio test statistic \( D=2\ln(L_1/L_0) \), we can derive p-values to assess overall statistical significance. The latter are calculated for each block as \((n+1)/m\), where \( n \) is the number of resamples with \( D \) greater than the value of \( D \) from the actual data, and \( m \) is the total number of resamples [6]. The corresponding p-values can be used in a
Monte-Carlo approach to provide stochastically simulated seismic hazard estimates in terms of frequency, location (grid-based) and size of future seismic events.

**Related issues**

Any model that investigates the correlation between seismicity and waste-water injection requires accurate and complete information on past earthquakes and waste-water disposal activities.

To compile a high quality parametric earthquake catalog for Oklahoma one should (i) merge the available event-lists from various sources (e.g. Advanced National Seismic System (ANSS) Composite Catalog, International Seismological Center (ISC) bulletin, [12]) into a single unified dataset free of duplicated entries, and (ii) develop empirical models (conversion equations) to harmonize all magnitude estimates into moment magnitude ($M_w$). Another important issue is the spatio-temporal variations in the magnitude of completeness, due to the increasing number of stations that were deployed in recent years. Schorlemmer & Woessner’s method [9] could be used to address this issue, since it uses a grid-based approach, which is perfectly compatible to our framework.

We should note that there is currently no consensus on how one should decluster earthquake sequences induced by fluid injection, since the triggering mechanism itself introduces a spatial and temporal correlation in the data. The analysis described within our framework can be performed twice, once with the full catalog and once with a declustered catalog, e.g. using the method of Schaefer et al [13], to check the sensitivity of the results to this factor.

Regarding the disposal data, due to confusion among operators on whether they should insert monthly or average daily injection rates in the forms, the injection data provided by the Oklahoma Corporation Commission (OCC) prior to 2011 contain errors. Our preliminary analysis shows that reported rates for years 2009 and 2010 could be underestimated by as much as 20%.

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