Second-Generation Toolset for Calculation of Induced Seismicity Risk Profiles

28 March 2017

Office of Fossil Energy

NRAP-TRS-III-005-2017
Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference therein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed therein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report (LLNL-TR-634717) has been reviewed by Susan Carroll for Lawrence Livermore National Laboratory (LLNL) and approved for public release.

Cover Illustration: Risk of nuisance from ground shaking at three sites at different distances from two seismogenic faults.


An electronic version of this report can be found at:
http://www.netl.doe.gov/research/on-site-research/publications/featured-technical-reports
https://edx.netl.doe.gov/nrap
Second-Generation Toolset for Calculation of Induced Seismicity Risk Profiles

William Foxall¹, Jean Savy¹,³, Scott Johnson¹, Lawrence Hutchings², Whitney Trainor-Guitton¹, Mingjie Chen¹

¹Atmospheric, Earth and Energy Division, Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94551
²Earth Sciences Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720
³Savy Risk Consulting, 733 Arimo Avenue, Oakland, CA 94610

NRAP-TRS-III-005-2017

Level III Technical Report Series

28 March 2017
This page intentionally left blank.
# Table of Contents

ABSTRACT ................................................................................................................................. 1

1. INTRODUCTION ................................................................................................................... 2

2. METHOD ................................................................................................................................ 5
   2.1 SIMULATION OF SEISMICITY CATALOGS ............................................................. 5
   2.2 HAZARD AND NUISANCE RISK CALCULATIONS ............................................. 6

3. RESULTS ................................................................................................................................ 9
   3.1 SIMULATION SCENARIO ..................................................................................... 9
   3.2 PORE PRESSURE MODEL .................................................................................. 10
   3.3 SEISMICITY SIMULATIONS ............................................................................. 10
   3.4 GROUND MOTION CALCULATION ................................................................ 12
   3.5 HAZARD AND RISK RESULTS ......................................................................... 13

4. DISCUSSION ........................................................................................................................ 18

5. REFERENCES ...................................................................................................................... 20
List of Figures

Figure 1: Schematic diagram of the PSRA computational framework for the second-generation toolset .......................................................... 3

Figure 2: Nuisance fragility curves showing the probability that an individual would find a given ground acceleration unacceptable. .......................................................... 7

Figure 3: Schematic illustration of the procedure for estimating risk of nuisance by combining a fragility function \( a \) with a hazard curve \( b \) .......................................................... 8

Figure 4: Synthetic seismic risk calculation scenario showing faults, surface recording sites, and the horizontal section of the injection .......................................................... 9

Figure 5: Pore pressure distribution within the horizontal reservoir at 1,800 m depth and on three faults 50 years after the start of injection .......................................................... 10

Figure 6: Example of seismicity simulated on Fault 1 over the first 500 years after burn-in ........................................................................ 11

Figure 7: Mean seismic hazard calculated at Sites 1 (a), 2 (b) and 3 (c) from seismicity on Faults 1 and 2 and for time periods 0–200 years and 200–250 years .......................................... 14

Figure 8: Comparison of mean seismic hazard for three sites calculated for the 200–250 year time period .......................................................... 15

Figure 9: Mean and Uncertainty bounds for two-fault scenario seismic hazard curves calculated at Sites 1 (a), 2 (b) and 3 (c) for the time period 200–250 years .................................. 16

Figure 10: Nuisance risk at Sites 1, 2, and 3 calculated for the two-fault scenario during the pre-injection and injection periods .......................................................... 17

List of Tables

Table 1: Earthquake source simulation parameter values .......................................................... 13
Table 2: Crustal velocity model used to generate Green’s functions .......................................... 13
## Acronyms, Abbreviations, and Symbols

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>β</td>
<td>Aleatory uncertainty on ground motion acceleration anchor value</td>
</tr>
<tr>
<td>Φ</td>
<td>Cumulative Gaussian function</td>
</tr>
<tr>
<td>µ₀</td>
<td>Base coefficient of friction</td>
</tr>
<tr>
<td>λ</td>
<td>Lamé’s first parameter</td>
</tr>
<tr>
<td>µ</td>
<td>Shear modulus</td>
</tr>
<tr>
<td>σ</td>
<td>Fault normal stress</td>
</tr>
<tr>
<td>τ</td>
<td>Fault shear stress</td>
</tr>
<tr>
<td>3-D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>A</td>
<td>Rate-and-state friction direct effect parameter (e.g. Marone, 1998)</td>
</tr>
<tr>
<td>A'</td>
<td>Anchor value, i.e., acceleration level at which there is a 50% probability that an individual would find a specified level of ground motion unacceptable</td>
</tr>
<tr>
<td>B</td>
<td>Rate-and-state evolution parameter</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>dσ/dz</td>
<td>Normal stress gradient with depth</td>
</tr>
<tr>
<td>Dc</td>
<td>Rate-and-state slip-weakening distance</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>EGS</td>
<td>Enhanced geothermal system</td>
</tr>
<tr>
<td>fA</td>
<td>RSQSim reduction factor for A</td>
</tr>
<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
</tr>
<tr>
<td>FKRPROG</td>
<td>Frequency-wavenumber Algorithm Program (computer program)</td>
</tr>
<tr>
<td>g(X)</td>
<td>Nuisance fragility function</td>
</tr>
<tr>
<td>GCS</td>
<td>Geological carbon storage</td>
</tr>
<tr>
<td>H(x)</td>
<td>Hazard function</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>LLNL</td>
<td>Lawrence Livermore National Laboratory</td>
</tr>
<tr>
<td>M</td>
<td>Earthquake magnitude</td>
</tr>
<tr>
<td>Mw</td>
<td>Earthquake moment magnitude</td>
</tr>
<tr>
<td>NRAP</td>
<td>National Risk Assessment Partnership</td>
</tr>
</tbody>
</table>
## Acronyms, Abbreviations, Symbols (cont.)

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUFT</td>
<td>Nonisothermal Unsaturated-Saturated Flow and Transport Model (computer program)</td>
</tr>
<tr>
<td>P[x]</td>
<td>Probability of x</td>
</tr>
<tr>
<td>PSHA</td>
<td>Probabilistic seismic hazard analysis</td>
</tr>
<tr>
<td>PSRA</td>
<td>Probabilistic seismic risk assessment</td>
</tr>
<tr>
<td>Qp</td>
<td>Seismic P-wave intrinsic attenuation factor</td>
</tr>
<tr>
<td>Qs</td>
<td>Seismic S-wave intrinsic attenuation factor</td>
</tr>
<tr>
<td>RSQSim</td>
<td>Rate and State Earthquake Simulator (computer program)</td>
</tr>
<tr>
<td>R(z)</td>
<td>Risk of nuisance</td>
</tr>
<tr>
<td>s</td>
<td>Stress overshoot factor</td>
</tr>
<tr>
<td>SIMRISK</td>
<td>Hazard and risk calculation computation module (computer program)</td>
</tr>
<tr>
<td>SYNHAZ</td>
<td>Synthetic ground motion simulator module (computer program)</td>
</tr>
<tr>
<td>U</td>
<td>Seismic event</td>
</tr>
<tr>
<td>V</td>
<td>Long-term fault slip rate</td>
</tr>
<tr>
<td>V_eq</td>
<td>Coseismic fault slip velocity</td>
</tr>
<tr>
<td>X</td>
<td>Ground motion acceleration</td>
</tr>
<tr>
<td>z, Z</td>
<td>Nuisance level (%)</td>
</tr>
</tbody>
</table>
Acknowledgments

This work was completed as part of the National Risk Assessment Partnership (NRAP) project. Support for this project came from the U.S. Department of Energy’s (DOE) Office of Fossil Energy’s Crosscutting Research program. The authors wish to acknowledge Traci Rodosta (Carbon Storage Technology Manager), Kanwal Mahajan (Carbon Storage Division Director), M. Kylee Rice (Carbon Storage Division Project Manager), Mark Ackiewicz (Division of CCS Research Program Manager), Darin Damiani (Carbon Storage Program Manager), Robert Romanosky (NETL Crosscutting Research, Office of Strategic Planning), and Regis Conrad (DOE Office of Fossil Energy) for programmatic guidance, direction, and support.

The authors also wish to acknowledge Prof. Jim Dieterich and Dr. Keith Richards-Dinger at the University of California, Riverside for making the RSQSim earthquake simulation program available to us and for their continued interest and support.
This page intentionally left blank.
ABSTRACT

This report describes development and demonstration of the second-generation toolset for the National Risk Assessment Partnership (NRAP). The toolset provides a probabilistic analysis of hazards and risks from earthquakes that could potentially be induced by increased subsurface pore pressures on faults resulting from carbon dioxide (CO₂) injection for geological carbon sequestration (GCS). Hazard and risk calculations utilize earthquake catalogs produced by physics-based simulations that incorporate injection-induced pressure changes generated by subsurface fluid flow modeling. The second-generation toolset has the capability of calculating the seismic hazard at an arbitrary number of ground surface sites from events occurring on multiple source faults. Hazard uncertainty bounds are determined using multiple realizations of simulated earthquake catalogs that sample the epistemic and aleatory uncertainty distributions on the input parameters. “Nuisance fragility functions” for seismic ground motion developed as part of the second-generation work are combined with the hazard curves to estimate the risk of nuisance from ground shaking. Hazard and risk estimates for different time periods before, during, and after CO₂ injection can be compared to assess the impact of the GCS operation and to inform operational decision making. The results described in this report demonstrate the functionality of the toolset based on its application to a hypothetical scenario involving two faults. Further development, including modifications to the current computer code implementation and code parallelization, will be needed to bring the toolset up to full functionality in dealing with large numbers of faults.
1. **INTRODUCTION**

Injecting carbon dioxide (CO₂) into the shallow layers of the Earth’s crust for geological carbon sequestration (GCS) has, in common with the injection of other fluids, the potential for inducing seismic events under certain circumstances. The vast majority of events induced by fluid injection in general are far too small to be perceptible. However, in certain cases—usually involving injection of large volumes of fluid at rapid rates—induced earthquakes have been felt at the ground surface, and in extremely rare cases have caused structural damage. As for other potential risks, one of the aims of a CO₂ injection operation is to avoid the occurrence of felt events by basing site selection, engineering design and short- and long-term operational strategies on rigorous risk analysis. Therefore, the National Risk Assessment Partnership (NRAP) is developing a toolset for assessment of risks associated with induced seismicity that could potentially occur as a result of CO₂ injection.

The general nature of the risk assessment problem for induced seismicity is described in a previous NRAP technical report (Foxall et al., 2013). That report also describes the first-generation development of NRAP’s probabilistic seismic hazard analysis (PSHA) method, which is a component of the probabilistic seismic risk assessment (PSRA) toolset. NRAP has adopted the well-established conventional approach to PSRA for damage from naturally-occurring tectonic earthquakes, but modified it to deal with the time- and space-dependent characteristics of induced seismicity and to extend the risk assessment to include nuisance caused by small events that may be felt in nearby communities. In general, elevated rates of seismicity are expected on faults that experience increased fluid pressures resulting from injection, potentially leading to an increase in seismic hazard and risk during and after injection over the levels attributable to naturally-occurring earthquakes. NRAP’s PSRA method is being developed for risk assessment beginning at the planning and design stages of a GCS project, when no record of induced seismicity exists. Therefore, development of the toolset is presently focused on physics-based fluid flow and seismicity simulation to generate catalogs of both naturally-occurring and induced earthquakes from which occurrence frequency-magnitude statistics can be estimated. The toolset also employs a physics-based analytical method to calculate ground shaking from the simulated earthquakes.

The first-generation effort was devoted primarily to constructing the computational framework for the PSHA component of the toolset by integrating the three program modules shown in Figure 1. The functionality of the PSHA method was then demonstrated by applying it to a hypothetical CO₂ injection scenario that incorporated a single fault. For that demonstration, the hazard was calculated for a single time period and was limited to one epistemic realization of the fault, tectonic loading, and crustal parameters.

As explained in the first-generation report, epistemic uncertainties stem from a lack of knowledge of the true parameter values, whereas aleatory uncertainties express the natural stochastic variability of a physical property, such as the heterogeneous distribution of strength on a fault. Multiple realizations are required to sample the full distributions of both epistemic and aleatory uncertainties in the input parameters and to propagate them through the calculation to determine the uncertainty bounds on the hazard.
The objective of the second-generation development described in this report was to expand the capabilities of the toolset to include:

- Multiple faults
- Multiple epistemic realizations of fault frictional parameters and tectonic shear loading rates
- Multiple aleatory realizations of fault properties and ground motion uncertainty distributions
- Calculation of hazard over several time periods of varying length and at sites at different distances from the injection well
- Calculation of the risk of nuisance from the hazard curves using “nuisance fragility” functions developed as part of the project

The hypothetical GCS injection scenario used in the first-generation demonstration and described in Foxall et al. (2013) was extended for the second-generation toolset to include two faults having different strikes and dips. The regional tectonic shear loading rate could be varied, and the long-term slip rate resolved on each fault was consistent with its strike, dip, and rake (slip vector). As in first-generation, the time-dependent fluid pressure distributions on the faults were generated by a reservoir flow model driven by injection at a single well. The magnitudes of
the pressures developed along the faults during the second-generation simulations are similar to those in the first-generation scenario, but they increase to the peak pressure and then fall off at much slower rates. This produces a longer duration of elevated pressure on the faults, which results in higher rates of induced seismicity and hence larger statistical samples from which to derive hazard estimates.

Development of the nuisance fragility curves was based on deterministic criteria used in the mining and construction industries to quantify levels of acceptability of ground motions and vibrations caused by blasting, operation of heavy machinery, heavy vehicular traffic, etc. These criteria have recently been adopted by the U.S. Department of Energy (DOE) as the basis for recommended best practices to mitigate nuisance from ground motions associated with seismicity induced by enhanced geothermal operations.
2. **METHOD**

The overall implementation of the second-generation PSRA toolset (shown schematically in Figure 1) remains similar to the first-generation PSHA toolset, except that the risk as well as the hazard calculation has now been implemented in the SIMRISK module. The functioning of the hazard component is essentially the same as described in Foxall et al. (2013), but with the addition of the multiple faults, multiple sites, multiple realizations, and multiple time period capabilities. Further details on the implementation of earthquake simulations in the toolset are discussed below, with an outline of the risk calculation methodology.

2.1 **SIMULATION OF SEISMICITY CATALOGS**

As described in Foxall et al. (2013), the role of the earthquake simulation program RSQSim (Richard-Dinger and Dieterich, 2012; Dieterich, 1995) in the toolset is to generate a seismicity catalog for each epistemic/aleatory realization passed by the risk calculation module, SIMRISK. This is done by simulating earthquake sequences on the faults in the earthquake source model. The physics of the rate-and-state friction law that lies at the heart of RSQSim and its implementation in the program are described in an NRAP technical report by Trainor-Guitton et al. (2016).

The fault geometries and long-term fault slip rates used in RSQSim simulations are sampled as epistemic parameters. Rate-and-state frictional parameters can be treated as either epistemic or aleatory (see Table 1). Appropriate ranges of key rate-and-state parameters were investigated by Trainor-Guitton et al. (2016). The pore pressure history on each fault element, input from an injection-driven flow calculation (described below), modifies the time-varying effective (confining) stress on the element, thus lowering its frictional strength until it fails in an earthquake. In essence, such induced events can be viewed as earthquakes that would have occurred eventually under the steady-state tectonic loading. The role of the evolving pore pressure field is to accelerate the weakening of fault elements and hence increase their failure rates. Note, however, that the evolving pressure distribution coupled with the complex series of interactions on the fault resulting from coseismic stress transfers leads to significant changes in the frequency-magnitude statistics of the seismicity (see Trainor-Guitton et al., 2016), not merely an increase in the overall rate of activity at all magnitudes. Furthermore, the frequency-magnitude behavior under the influence of an evolving pressure field will change both in time and space.

In order to generate realistic earthquake frequency-magnitude statistics, heterogeneous distributions of constitutive properties on the fault planes are required (e.g. Ben-Zion, 2008). Such property distributions are randomly prescribed as aleatory initial conditions at the beginning of each simulation. The initial seismicity characteristics are strongly influenced by the prescribed distribution, but the complexity and randomness of the stress field on the fault resulting from seismic events evolves rapidly so that the initial conditions are rapidly forgotten. To ensure that this is the case, the events that occur within a specified initial burn-in period are discarded. The burn-in period is determined by initial standalone runs of RSQSim, and can be regarded as to the time it takes a fault to evolve to a mature state. Therefore, the implicit assumption is that the faults in the model are mature as opposed to being newly formed.
2.2 HAZARD AND NUISANCE RISK CALCULATIONS

After a catalog of earthquakes has been simulated by RSQSim, the seismic hazard corresponding to each catalog is calculated. Hazard curves generated in each set of epistemic realizations are processed to determine their statistical characteristics, and the results are weighted according to the weights assigned to the individual realizations. At this point in the project, all the epistemic parameters are randomly selected from uniform probability distributions, which results in equal weights for all of the realizations. In order to capture the effects of time-dependent changes in fluid pore pressure resulting from injection, the seismicity catalogs are sorted into several time periods and a separate hazard curve is estimated for each period. Having calculated the hazard curves, the corresponding nuisance risk curves are calculated as described below.

The effects of ground motion produced by medium to large earthquakes (Mw > 4.5) on structures are usually modeled with a fragility function that expresses the probability of structural damage as a function of ground motion intensity. Extensive literature on this topic is available, but it deals only with the physical effects of earthquakes on structures, as exemplified by the U.S. Federal Emergency Management Agency (FEMA) catastrophe loss estimation project HAZUS (FEMA, 2013). In the case of seismicity induced by fluid injection and other anthropomorphic activities, however, the risk that residents of nearby communities will find felt ground motions unacceptable must also be taken into consideration. Clearly, the annoyance and apprehension engendered by such ground motions and the occurrence of minor cosmetic damage will have a large influence on public perception and hence acceptance of the operation itself. This was exemplified by the abandonment of an enhanced geothermal project in Basel, Switzerland, in 2006 because an M3.4 earthquake induced by injection was strongly felt throughout the city (Baisch, 2009). Therefore, it is important to define bounds on the acceptability of felt ground motions, and to quantify these criteria in the form of a probabilistic risk assessment.

The effects of felt, but non-damaging, ground motions has been extensively studied in the context of vibrations generated by mining and construction, which has led to the development of national (American National Standards Institute) and international (International Standards Organization) standards in the form of deterministic acceptability criteria (Dowding, 1996). These criteria formed the basis for the development by DOE of a protocol and recommended best practices for assessing and mitigating risks associated with ground motions induced by enhanced geothermal systems (EGS) (Majer et al., 2012, 2016). The DOE guidelines can also generally be applied to potential GCS-induced seismicity. One major recommendation of the EGS protocol is that the hazard and risk should be estimated probabilistically. Therefore, “nuisance fragility” functions that can be used to estimate risk from the hazard curves are developed below, employing the same approach as used for damage fragility.

Nuisance risk is defined as the probability that an individual will not find the seismic environment acceptable. The general approach followed by FEMA is used to model the response of individuals to ground motion using the deterministic acceptability criteria considered in Majer et al. (2012a,b) to anchor human response fragility functions.

Given a peak ground acceleration $X$, the fragility function $g(X)$ gives the probability that level $X$ is unacceptable, which is termed event $\{U\}$. Alternatively, $g(X)$ can be interpreted as the proportion of individuals in a community who would find the ground motion $X$ to be unacceptable. This is modeled by a typical fragility curve (Figure 2):
Second-Generation Toolset for Calculation of Induced Seismicity Risk Profiles

\[
g(X) = P[U|X] = \Phi \left( \frac{\ln(\frac{X}{A^*})}{\beta} \right)
\]  

(1)

where \( A^* \) is the acceleration level at which there is a 50% probability that an individual would find the level \( X \) unacceptable (the anchor value), \( \beta \) is a measure of the aleatory uncertainty on this probability, and \( \Phi \) is the cumulative Gaussian function.

Figure 2 shows two sets of fragility curves that express the epistemic uncertainty in the anchor values. One curve is anchored at a log-median value of \( A^* = 1 \) cm/s/s and the other at \( A^* = 10 \) cm/s/s. The figure also shows variability in the \( \beta \) parameter that reflects its epistemic uncertainty. These epistemic uncertainties are not accounted for at the present time in SIMRISK, but they will be easy to implement in future development.

![Nuisance Fragility Curves](image)

Note: Each curve shows fragility for a specified combination of the anchor value of log-median acceleration, \( A^* \), and the epistemic uncertainty value, \( \beta \).

**Figure 2: Nuisance fragility curves showing the probability that an individual would find a given ground acceleration unacceptable.**

Let \( z \) be a level of nuisance; since \( z \) is the probability of event \( \{U\} \), it takes on values in the range 0 to 1. Let \( R(z) \) be the risk, defined as the annual probability of exceeding level \( z \). In that case, the probability of exceeding \( z \) is equal to the probability of exceeding the ground motion value \( X \) that produces \( z \), or the hazard \( H(X) \). Then:

\[
R(z) = P[Z \geq z] = P[g(X) \geq z] = P[g^{-1}(z) \geq X] = H(g^{-1}(z))
\]

(2)

where $g^{-1}$ is the inverse of the fragility function.

Equation 2 is used to combine the hazard curve for each time period with the fragility curve to estimate the risk of nuisance, $R(z)$, as shown schematically in Figure 3. The steps in constructing the risk curve are:

1. Step through the range (0–1) of nuisance levels, $z_i$
2. For each nuisance level $z_i = g(X_i)$ find the corresponding ground acceleration $X_i$ from the appropriate fragility curve (Figure 3a)
3. Find the hazard, $H(X_i)$, for that acceleration from the hazard curve (Figure 3b)
4. For that hazard, calculate the risk using Equation 2, $R_i = R(z_i) = H(g^{-1}(z_i))$
5. Plot $R_i$ versus $z_i$ (Figure 3c)

![Figure 3: Schematic illustration of the procedure for estimating risk of nuisance by combining a fragility function (a) with a hazard curve (b).]

Nuisance results presented in this report used $A' = 10$ cm/s/s and $\beta = 0.80$ (Majer et al., 2016). Future developments in this project will investigate other ground motion parameters, such as velocity, or spectral representations to determine which is most appropriate for modeling of human response.
3. RESULTS

3.1 SIMULATION SCENARIO

The simulation scenario used for second-generation synthetic hazard and risk analyses extends the first-generation scenario described in Foxall et al. (2013) by adding an additional fault. Figure 4 shows the locations of the two faults used as sources of induced earthquakes in relation to the horizontal injection well and two of the sites at which ground motions are calculated; a third site is located off the map approximately 5 km due west of the map center. The map shows the traces of the upper edges of Fault 1 and Fault 2 at a depth of 885 m. Fault 1 extends vertically to a depth of 2,400 m. Fault 2 dips 60° NW to a depth of 2,300 m; the projection of the plane of Fault 2 on to the horizontal surface is shown dashed in Figure 4. (Note that Fault 2 is a segment of the larger dipping fault shown in Figure 5 and in light green on Figure 4.) The long-term regional tectonic loading is applied in a NW-SE direction so that right-lateral strike-slip displacement occurs on Fault 1 and reverse dip-slip on Fault 2. The long-term slip rates on the faults are specified as epistemic parameters and are varied over the range 1 to 2 mm/yr.

As discussed in Foxall et al. (2013), the scenario is representative of realistic field conditions in that it is based on a geological model derived from petrophysical and other properties measured at an actual GCS site. However, the scenario faults, fault properties, and tectonic loading are hypothetical. The sole purpose of the scenario is to test and demonstrate the second-generation hazard and risk toolset, rather than represent an actual field situation. The range of long-term fault slip rates is representative of regions having moderate seismicity. This tectonic characterization was chosen to generate sufficient seismicity to yield valid statistical samples from which to calculate hazard and associated uncertainties over time periods ranging from tens to hundreds of years.

![Figure 4: Synthetic seismic risk calculation scenario showing faults, surface recording sites, and the horizontal section of the injection.](image)

Note: A third site (S3) is located off the map approximately 5 km due west of the map center.
3.2 **PORE PRESSURE MODEL**

A NUFT flow model simulated the injection of super-critical CO$_2$ along the length of the horizontal well section into a 20 m-thick reservoir at a depth of 1,800 m. The flow simulation was carried out starting from initial hydrostatic pressures for a total time period of 200 years. The injection took place over the first 50 years at a rate of 0.6 million metric tons per year. Pressures were sampled throughout the three-dimensional (3-D) model domain every 10 years. Figure 5 shows a 3-D view of the pore pressure distribution after 50 years, when the pressure peaks in the reservoir. The pressure histories (offset in time by 200 years) at the points of intersection of the reservoir with Faults 1 and 2 closest to the well are shown on Figure 6. The pressure histories on the fault planes are extracted and written to a file by inserting the faults into the time-dependent 3-D pressure distribution and interpolating on to a defined set of fault grid cells. These pressure histories are used in the earthquake simulations by first interpolating from the pressure grid on each fault to the fault elements used for the simulations. This enables the size of the simulation elements to be varied as an epistemic parameter if required. The effective stress on each element at the time of occurrence of each event is determined by linear interpolation of its pressure history. As shown on Figure 6a, the pressure trends 200 years after the start of injection are extrapolated so as to fall back to hydrostatic (approximately 18 MPa at the reservoir depth) at 425 years. The entire pressure history can be offset in time to enable it to be applied at any stage of an earthquake simulation.

![Figure 5: Pore pressure distribution within the horizontal reservoir at 1,800 m depth and on three faults 50 years after the start of injection.](image)

**Note:** The two faults used in the present scenario are the smallest vertical fault (Fault 1) and the segment of the 60° dipping fault shown as Fault 2 in Figure 4. The reservoir layer is omitted in the right panel for clarity. Pressures are in Pa.

3.3 **SEISMICITY SIMULATIONS**

The hazard and nuisance risk curves and their associated uncertainty bounds are calculated from a sequence of earthquake simulations. Each hazard/risk calculation uses one realization of the epistemic parameters within which there are a specified number of samples of the aleatory parameters; i.e. the total number of catalog simulations per run is the number of epistemic
realizations multiplied by the number of aleatory samples. Second-generation hazard and risk calculations typically employed 20–30 epistemic realizations and 2 aleatory samples per realization. The epistemic and aleatory parameter ranges are given in Table 1 together with the values of fixed parameters. Each of the parameter ranges was treated as a continuous distribution. Each simulation was run for 700 years after an initial burn-in period of 500 years. The burn-in time was determined based on standalone runs of RSQSim used to assess the time taken to stabilize the earthquake frequency-magnitude distribution under constant hydrostatic pore pressure. The fault pore pressure time histories generated from the NUFT simulation are applied 200 years after the end of the burn-in period.

Notes:

a. Earthquakes are shown in blue with reference to axis to left. Pressures are shown as lines on Faults 1 (red) and 2 (green) with axes to right; values are at reservoir depth (1,800 m) at the point closest to the injection well. Hydrostatic pressure at this depth is approximately 18 MPa.

b. Figure 6b is an expanded view of the seismicity induced by injection shown in Figure 6a.

c. Injection (NUFT results) is started at 200 years after burn-in.

Figure 6: Example of seismicity simulated on Fault 1 over the first 500 years after burn-in.
Figure 6a shows the 500 years (post burn-in) of the seismicity time history generated by a standalone simulation using parameters within the ranges given in Table 1. The corresponding pressure history at the fault/reservoir intersection point closest to the injection well is also shown. It can be seen that the induced seismicity response begins within the first year of the pressure pulse reaching the fault at pressures only a few MPa above hydrostatic. There is then a rapid increase in the rate of seismicity above the pre-injection minimum magnitude (~Mw2), and the later onset of a prolonged burst of smaller events between Mw0 and Mw2. Larger events approaching the maximum magnitude (~Mw4) (corresponding to the area of the fault), about 1 magnitude unit above the seismicity during the pre-injection period, occur within the first 2 years. Figure 6b shows a 100-year period centered on the burst of induced seismicity. Events below Mw2 begin to occur about 15 years after the start of injection and continue until about 10 years after the peak in the pressure curve at 250 years. The enhanced rate of occurrence of larger magnitude events continues until peak pressure is reached and then abruptly falls to the pre-event level. Ten years after peak pressure the fault becomes entirely quiescent for about 20 years before activity gradually increases back to pre-injection levels.

3.4 GROUND MOTION CALCULATION

Ground motion calculations in SYNHAZ utilize a library of analytic source-site Green’s functions computed in advance using the program FKRPROG (Saikia, 1994) for the crustal structure detailed in Table 2. Because seismic wave propagation through this one-dimensional structure is radially symmetric, the Green’s functions were computed from an array of point sources located at depths between 1 and 8 km and bedrock surface sites at distances between 0.1 and 10 km from the injection well. While full finite-fault ground motion calculations are required for events larger than a threshold magnitude (selected at Mw2.5 in the present study), smaller events for which finite fault rupture propagation effects are negligible can be treated as point sources. This significantly reduces overall computation time, since a point source essentially requires only scaling of the Green’s function by seismic moment whereas a finite source requires full convolution of the earthquake source-time function with the Green’s function. In the present work, typical probability density functions derived for empirical ground motion relationships were applied as aleatory uncertainties on the computed ground motions.
### Table 1: Earthquake source simulation parameter values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base coefficient of friction, $\mu_0$</td>
<td>0.6 to 0.9</td>
<td>Assumed aleatory distribution</td>
</tr>
<tr>
<td>Lamè's first parameter, $\lambda$</td>
<td>18,034 MPa</td>
<td>Derived from well logs</td>
</tr>
<tr>
<td>Shear modulus, $\mu$</td>
<td>9,290 MPa</td>
<td>Derived from well logs</td>
</tr>
<tr>
<td>Fault initial normal stress at ground surface, $\sigma$</td>
<td>-0.7 MPa</td>
<td>Derived from well data</td>
</tr>
<tr>
<td>Normal stress gradient with depth, $d\sigma/dz$</td>
<td>0.02 MPa.m$^{-1}$</td>
<td>Derived from well data</td>
</tr>
<tr>
<td>Fault initial shear stress, $\tau$</td>
<td>4.0 MPa</td>
<td>Derived from well data</td>
</tr>
<tr>
<td>Long-term fault slip rate, $V$</td>
<td>1 to 2 mm y$^{-1}$</td>
<td>Assumed epistemic distribution</td>
</tr>
<tr>
<td>Rate-and-state friction direct effect parameter, $A$</td>
<td>0.0045 to 0.0075</td>
<td>Assumed aleatory distribution</td>
</tr>
<tr>
<td>Rate and state evolution parameter, $B$</td>
<td>0.015</td>
<td>Assumed value</td>
</tr>
<tr>
<td>Rate-and-state slip-weakening distance, $D_c$</td>
<td>15 to 35 x $10^6$m</td>
<td>Assumed aleatory distribution</td>
</tr>
<tr>
<td>Coseismic fault slip velocity, $V_{eq}$</td>
<td>1 m s$^{-1}$</td>
<td>Assumed value</td>
</tr>
<tr>
<td>Reduction factor for $A$, $f_A$</td>
<td>0.1 to 0.3</td>
<td>Assumed epistemic distribution</td>
</tr>
<tr>
<td>Stress overshoot factor, $s$</td>
<td>0.2 to 0.4</td>
<td>Assumed epistemic distribution</td>
</tr>
</tbody>
</table>

### Table 2: Crustal velocity model used to generate Green’s functions

<table>
<thead>
<tr>
<th>Depth to Top of Layer (km)</th>
<th>Crustal P-Wave Velocity (km s$^{-1}$)</th>
<th>Crustal S-Wave Velocity (km s$^{-1}$)</th>
<th>$Q_p$</th>
<th>$Q_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>2.50</td>
<td>1.50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>0.89</td>
<td>3.65</td>
<td>1.85</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>1.75</td>
<td>4.20</td>
<td>2.20</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2.00</td>
<td>3.70</td>
<td>1.90</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2.80</td>
<td>4.50</td>
<td>2.50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>3.50</td>
<td>6.12</td>
<td>3.50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3.60</td>
<td>6.12</td>
<td>3.50</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>7.00</td>
<td>6.22</td>
<td>3.50</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

### 3.5 HAZARD AND RISK RESULTS

Figure 7 shows mean hazard curves at Sites 1, 2 and 3 calculated from 30 epistemic simulations of earthquakes on Faults 1 and 2. The figure for each site compares the mean hazard for two time periods; the first (0–200 years) covers the 200 years prior to injection, and so corresponds to the background seismicity on the faults. The second (200–250 years) covers the first 50 years of injection, during which the pressure in the reservoir rises from hydrostatic to its peak.
Figure 7: Mean seismic hazard calculated at Sites 1 (a), 2 (b) and 3 (c) from seismicity on Faults 1 and 2 and for time periods 0–200 years and 200–250 years.

The mean hazard curve at Site 1 (Figure 7a), the site closest to the two faults, for the 200 to 250 year period lies somewhat above the background curve for ground acceleration levels between 5 and 90 cm/s/s, and substantially above it at higher accelerations. The differences in hazard between the two periods are generally consistent with the example seismicity history shown in Figure 6. The increased hazard above 90 cm/s/s during injection corresponds to the occurrence of larger induced events (magnitude greater than ~3.2) that are capable of generating the higher accelerations. In contrast, the steep fall-off in the background curve indicates the almost total absence (i.e. very low occurrence rate) of such events before injection begins.

The relatively small difference between the hazard curves for the 5 to 90 cm/s/s acceleration range at first sight seem surprising given the substantial increase in the overall rate of seismicity associated with injection indicated by Figure 6. The reason for this is not yet fully understood. A
likely explanation is that much of the increased activity over the 50-year injection period is at both lower and higher magnitudes than the ~M_w 2.5 to 3.0 events that probably dominate the ground motions and hence the hazard within this acceleration range at this close-in site. If the example shown in Figure 6 is taken as generally representative, then the rate of occurrence of M_w 2.5 to 3.0 events during the 50 years of injection is only modestly higher than in the preceding 200 years. Confirmation of this by evaluation of the relative contributions that different magnitude ranges make to the hazard at different distances would require a full deaggregation analysis (e.g. McGuire, 1995).

The 0 to 200- and 200 to 250 year mean hazard curves for Sites 2 and 3 (Figures 7b and 7c) diverge gradually between 2 and 10 cm/s/s and then more rapidly at higher accelerations. This behavior reflects the fact that at these more distant sites ground motions below 10 cm/s/s are produced only by the larger events (probably in the ~M_w 2.8–3.2 range) that occur more frequently during injection.

Figure 8 compares the mean hazard curves for Sites 1, 2, and 3 during injection (200 to 250 years), showing that the hazard decreases at all acceleration levels with increasing distance as expected.

![Figure 8: Comparison of mean seismic hazard for three sites calculated for the 200–250 year time period.](image-url)
Figures 9a to 9c show the mean hazard curves with their uncertainty bounds at the three sites for the 200 to 250 year time period. The uncertainty estimates are based on 30 epistemic realizations. For this number of realizations, the lower and upper uncertainty bounds correspond approximately to the 5th and 95th percentile values, respectively. The corresponding curves calculated using 25 epistemic realizations are closely similar.

Note: Results shown for the time period 200–250 years, estimated from 30 epistemic simulations.

Figure 9: Mean and Uncertainty bounds for two-fault scenario seismic hazard curves calculated at Sites 1 (a), 2 (b) and 3 (c) for the time period 200–250 years.
Figure 10 compares the risk of nuisance from ground motion during the pre-injection and injection periods at all three sites. Consistent with the hazard results, the overall differences in risk between the two periods increase with increasing distance from the source faults. However, the difference in the risk at Site 1 is approximately the same for all levels of unacceptability above about 30%. At Site 2 the difference between the curves remains approximately constant between about 30% and 75% unacceptability. This is because the nuisance is governed predominantly by ground motions close to the 10 cm/s/s acceleration criterion selected to anchor the fragility curve, so that higher levels of ground motion do not increase the risk appreciably. In contrast, significant differences in the risk curves at all levels of unacceptability are seen at Site 3, the largest differences occurring over the 35–80% unacceptability range. These differences correspond to ground motions at this distant site close to 10 cm/s/s generated by larger induced events that occur relatively frequently during injection, as discussed above. The slight divergence of the Site 2 risk curves for the two periods beginning at about 75% unacceptability is attributed to the same cause.

Figure 10: Nuisance risk at Sites 1, 2, and 3 calculated for the two-fault scenario during the pre-injection and injection periods.
4. DISCUSSION

The results discussed in this report demonstrate the capabilities of the NRAP simulation-based PSRA toolset at its present, second-generation, stage of development. The second-generation development extended the capabilities of the first-generation toolset to enable estimation of both hazard and the risk of nuisance from naturally-occurring and induced seismicity at multiple surface sites and over different time periods before, during, and after CO₂ injection. Uncertainty bounds on the hazard results are derived from multiple epistemic and aleatory realizations of seismicity simulation parameters and generic uncertainty distributions on ground motion estimates. Hazard results are carried forward to estimate nuisance risk by combining the hazard curves with nuisance fragility functions developed as part of the second-generation work. To the authors’ knowledge, the fragility functions described in this report are the first to have been developed for the purpose of quantifying nuisance from seismic ground motion.

Although the essential functionality of the toolset has been demonstrated, the ability to carry out multiple realizations of seismicity catalogs generated from multiple source faults is limited at present. The toolset can generate a relatively large number of catalogs from one or two faults but currently has difficulty handling multiple realizations for scenarios consisting of more than about 1,000 fault elements. The cause of this limitation is identified primarily as a programming issue. Specifically, there is an unresolved memory allocation problem across the three component programs that causes slow execution or errors within RSQSim during multiple fault/multiple realization runs that involve large numbers of elements. This stems primarily from the need to interface the C program RSQSim with the two other programs written in Fortran.

Unacceptably long simulation times may also occur in cases where RSQSim is presented with certain epistemic combinations of rate-and-state parameters that are unphysical or difficult to reconcile. While Trainor-Guitton et al. (2016) explored the sensitivity of simulated seismicity to individual rate-and-state parameters, there remains a need to investigate the validity of combinations of parameters within given ranges as well as possible correlations among the parameters. Another possible source of slow processing times is the way in which pore pressures are currently interpolated on to the fault planes during each epistemic realization.

The expectation is that the programming issue can be solved in a reasonable amount of time by further work. However, there are two alternative approaches that can be considered at the present stage of development. The simplest and most robust approach is to decouple RSQSim from the Fortran codes. This can be achieved by building a library of seismicity catalogs by performing in advance a large number of RSQSim simulations. These can be run automatically in batch mode, on a Linux cluster for example, to cover systematically the full range of epistemic and aleatory parameter distributions at appropriate discretization intervals. The catalog library can then be randomly sampled by SIMRISK as the earthquake frequency-magnitude input to the hazard and risk calculations. SIMRISK already has the capability to use an external catalog as input. The second alternative is to integrate the three codes within a Python wrapper.

The simulation-based approach demonstrated in this report is being developed for induced seismicity hazard and risk analyses conducted during the site selection, design, and permitting phases of a project, before injection commences. During the planning stage, many simulation-based assessments can be carried out to explore ranges of different injection strategies and to assess their attendant risks. An additional advantage of this approach is that it can be used to characterize the pre-injection background earthquake frequency-magnitude behavior in regions
of low seismicity where the existing earthquake record is sparse. Because of the low hazard from naturally-occurring events, seismic monitoring networks in such regions are typically sparse or non-existent so that the magnitude threshold for event detection is as high as $M_w$ 3.5 over substantial parts of the U.S., and $M_w$ 4.5 or higher in many other parts of the world.

Simulation-based seismic hazard and risk analysis techniques can also be applied during and after injection. The induced seismicity database built by seismic monitoring during the injection and post-shut-in phases characterizes the actual, evolving response of the geological system to injection, and so will provide the primary input to forward projections of hazard and risk as the GCS project progresses. The role of simulation in the analyses for these project phases would be to determine physics-based models of time- and space-dependent earthquake occurrence on a site-specific basis. These models can then be used to develop appropriate functional forms for empirical relationships to which the recorded data can be fit in order to continuously update hazard and risk forecasts, and thus inform injection and reservoir management strategies. This is seen as an important role for simulation because, unlike the assumption usually made in conventional PSHA, induced seismicity is non-stationary both in time and space.

The synthetic demonstration analyses described above suggest that seismicity falls off dramatically almost immediately after injection ceases and pressure begins to decline. This is generally consistent with observations at most injection operations, and suggests that reduction in flow rate and pressure and, ultimately, stopping injection and depressurizing the well should form the basis for mitigation procedures. Ideally, triggering of these procedures would be based on rigorous short-term hazard and risk forecasts, but could also be initiated, for example, simply when the earthquake occurrence frequency over a given magnitude range reaches a specified level. In the latter case, the greatest challenge is defining for a particular geological system what the appropriate thresholds are when there is no past record of the more extreme events. Physics-based flow and seismicity simulation utilizing the most complete characterization of the system parameters offers a promising approach to providing that capability.

Application of the toolset in practice will require comprehensive site characterization, including determination of in situ stresses, geomechanical properties and seismic velocities, and characterization of the subsurface hydrological and local fault systems. Larger faults, on the scale of ~1 km, can be detected and characterized using surface mapping, borehole data, and geophysical techniques. The frequency-size distribution of smaller faults and fractures capable of generating felt events can be characterized using geostatistical techniques constrained by the mapping, borehole and geophysical data. It is expected that site characterization at this level of detail will be required for industrial GCS projects in general. Moving forward, an important part of the third-generation development effort will be to demonstrate the overall viability of the PSRA approach by calibrating and validating RSQSim simulations against an induced seismicity data set recoded at an actual site.
5. REFERENCES


NRAP is an initiative within DOE’s Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO₂). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

**Technical Leadership Team**

*Diana Bacon*
Lead, Groundwater Protection Working Group
Pacific Northwest National Laboratory
Richmond, WA

*Jens Birkholzer*
LBNL Lab Lead
Lawrence Berkeley National Laboratory
Berkeley, CA

*Grant Bromhal*
Technical Director, NRAP
Research and Innovation Center
National Energy Technology Laboratory
Morgantown, WV

*Chris Brown*
PNNL Lab Lead
Pacific Northwest National Laboratory
Richmond, WA

*Susan Carroll*
LLNL Lab Lead
Lawrence Livermore National Laboratory
Livermore, CA

*Abdullah Cihan*
Lead, Reservoir Performance Working Group
Lawrence Berkeley National Laboratory
Berkeley, CA

*Tom Daley*
Lead, Strategic Monitoring Working Group
Lawrence Berkeley National Laboratory
Berkeley, CA

*Robert Dilmore*
NETL Lab Lead
Research and Innovation Center
National Energy Technology Laboratory
Pittsburgh, PA

*Nik Huerta*
Lead, Migration Pathways Working Group
Research and Innovation Center
National Energy Technology Laboratory
Albany, OR

*Rajesh Pawar*
LANL Lab Lead
Lead, Systems/Risk Modeling Working Group
Los Alamos National Laboratory
Los Alamos, NM

*Tom Richard*
Deputy Technical Director, NRAP
The Pennsylvania State University
State College, PA

*Josh White*
Lead, Induced Seismicity Working Group
Lawrence Livermore National Laboratory
Livermore, CA
NRAP Executive Committee

Cynthia Powell
Executive Director
Research and Innovation Center
National Energy Technology Laboratory

Donald DePaolo
Associate Laboratory Director
Energy and Environmental Sciences
Lawrence Berkeley National Laboratory

Roger Aines
Chief Energy Technologist
Lawrence Livermore National Laboratory

Melissa Fox
Program Manager
Applied Energy Programs
Los Alamos National Laboratory

George Guthrie
Chair, NRAP Executive Committee
Earth and Environmental Sciences
Los Alamos National Laboratory

Alain Bonneville
Laboratory Fellow
Pacific Northwest National Laboratory

Grant Bromhal
Technical Director, NRAP
Research and Innovation Center
National Energy Technology Laboratory

NRAP Technical Report Series