The Past and Future Seismic Hazard in Oklahoma

Jake Walter, Ph.D. – State Seismologist
Paul Ogwari, Ph.D. – Geophysicist
Fernando Ferrer – Lead Analyst/Metadata
Andrew Thiel – Analyst/Outreach/Field
Isaac Woelfel – Field Technician

jwalter@ou.edu
• Risk analysis suggests similar earthquake in Dallas metro area … ~$5 billion damage

• November 2011 – Magnitude 5.7 near Prague, OK
• September 2016 – Magnitude 5.8 near Pawnee, OK
• November 2016 – Magnitude 5.0 near Cushing, OK
A) Hydraulic Fracturing of a Production Well

Following hydraulic fracturing, production begins (extraction)

B) Oil Production

C) Oil Production and Wastewater Disposal

Arbuckle Group in Oklahoma

Rubinstein and Mahani, 2015
Forecasts for the future

Langenbruch and Zoback, 2016

Dempsey and Riffault, 2019
Fence off induced seismicity areas

Long-term hazard models won’t include induced seismicity because decision made that it is a short-term hazard

Conflicting views of the hazard?
Download our scientific products: ogs.ou.edu

Stream our raw data in real-time

Walter et al., 2019
As of May 29, OGS is the authoritative regional network in the state, so USGS earthquakes are reported by OGS.

M 1.8 - 21km SSE of Tonkawa, Oklahoma
2019-05-29 14:23:06 (UTC)  |  36.504°N 97.218°W  |  5.7 km depth

Origin
Contributed by OK last updated 2019-05-29 15:01:56 (UTC)
The data below are the most preferred data available
The data below have been reviewed by a scientist

Details | Phases | Magnitudes
---|---|---
Magnitude uncertainty | 1.8 ml | ± 0.2
Location | 36.504°N 97.218°W
Depth uncertainty | 5.7 km | ± 0.5
Chance of potentially minor-damage ground shaking from an earthquake

Petersen et al., 2018
You might want to know the probability of having an earthquake, so just like a dice game one would want to know how many sides to the die (maximum magnitude) and outcomes of previous rolls (seismicity rate/magnitudes).

**Diagram:**

- **Cumulative Earthquake Number**
  - **b-value, Western Oklahoma**
  - **Green Line:** 1.46±0.08 (2014)
  - **Red Line:** 1.22±0.05 (2015)
  - **Yellow Line:** 1.19±0.06 (2016)

**Diagram Flow:**

1. **Earthquake catalog**
2. **Decluster**
3. **Earthquake rate**
4. **Ground-motion model**
5. **Hazard model**

**Source:** Goebel et al., 2017
Probabilistic seismic hazard modeling (PSHA) uses past seismicity rates and rates of background events, but what is a good statistical representation of earthquakes over geologic time or even recorded time?
• What is declustering?
  
  Want only seismicity which obeys a stationary Poisson process
  
  Must define spatiotemporal criteria relative to mainshock to define “dependent” events
  
  Example:

\[
\begin{align*}
t &= \begin{cases} 
  10^{0.032M + 2.738}, & \text{if } M \geq 6.5 \\
  10^{0.5409M - 0.547}, & \text{else}
\end{cases} \quad \text{[days]}
\end{align*}
\]

\[
d = 10^{0.1238M + 0.983} \quad \text{[km]}
\]
Are Oklahoma aftershocks the same as other aftershocks?

Zach Rosson
MS Student
<table>
<thead>
<tr>
<th>Zones of induced seismicity</th>
<th>Weight based on scientific consensus—considered induced</th>
<th>1-year count M2.7+ through fall 2015</th>
<th>2-year count M2.7+ through fall 2015</th>
<th>Start year–end year (if applicable)</th>
<th>Largest earthquake (M, date)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oklahoma-Kansas</td>
<td>1.0—yes</td>
<td>dec. 149</td>
<td>full 3,528</td>
<td>2006–present</td>
<td>5.6, Nov. 2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>292</td>
<td>5,991</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Zones that have had M2.7 and greater earthquake activity in years 2014–2015

Based on results from the 2014 National Seismic Hazard Model

Based on results from this study

Chance of potentially moderate-damage ground shaking in 2018

(Peterson et al., 2018)
Spatial aftershock decay – Analysis/results

- Stack all mainshocks and the distances to their aftershocks
- Compute nearest-neighbor linear density (Silverman, 1986; Felzer and Brodsky, 2006) between adjacent, stacked aftershocks
- Fit inverse power law to aftershock decay

Rosson et al. (GRL), 2019
Proposed declustering

\[ r = 10^{0.2217M - 0.0227 \pm 2\delta} \]

(where $2\delta = 2.5585$ km)
September 2016
Pawnee M5.8

50 km away

November 2016
Cushing M5.0
All slightly different rates, all very much above the background rate.

Thus, the chance for a large earthquake in Oklahoma is still statistically higher than pre-unconventional times.
You might want to know the probability of having an earthquake, so just like a dice game one would want to know how many sides to the die (maximum magnitude) and outcomes of previous rolls (seismicity rate/magnitudes).

CuMulative Earthquake Number

\begin{align*}
\text{b-value, Western Oklahoma} & \\
\text{1.46±0.08 (2014)} & \\
\text{1.22±0.05 (2015)} & \\
\text{1.19±0.06 (2016)} & \\
\end{align*}

\begin{align*}
\text{Magnitude} & \\
\text{2.0} & \\
\text{2.5} & \\
\text{3.0} & \\
\text{3.5} & \\
\text{4.0} & \\
\text{4.5} & \\
\text{5.0} & \\
\text{5.5} & \\
\text{6.0} & \\
\end{align*}

Earthquake catalog

\rightarrow

Decluster

\rightarrow

Earthquake rate

\rightarrow

Ground-motion model

\rightarrow

Hazard model

Statistical seismology informs us of the hazard based on what we know about past earthquakes.
Complexity of faults and smaller features not captured
Stress development in heterogenetic lithosphere: Insights into earthquake processes in the New Madrid Seismic Zone (Zhan et al., 2016)
Seismicity and pore pressure models

Langenbruch and Zoback, 2016

Norbeck and Rubinstein, 2018

Dempsey and Riffault, 2019
OKLAHOMA EARTHQUAKES

OCC: SHUTTING DOWN WELLS, REDUCING VOLUME

THE LATEST
Cushing earthquake

Fairview earthquake
Consider geologic time
AREAL VIEW OF THE MEERS FAULT
THE MOST PROMINENT HOLOCENE FAULT SCARP EAST OF THE ROCKY MOUNTAINS!
LARGE (~7 MAGNITUDE OCCURRED EVENTS, ~1300, ~2600, AND MAYBE ~5000 YEARS AGO)

Photo by D.B. Slemmons, Univ. of Nevada, Reno, in Madole, 1988.
Seismic hazard “before” induced earthquakes
Midcontinent seismicity since January 1, 2019 (earthquakes > M2.5)

Earthquakes occur everywhere in the world, in unexpected places and those places lead to the most damage.

Midcontinent may be more active than the East Coast, but everywhere east of California is lumped into "Central and Eastern US" in federal hazards program.
Perhaps the midcontinent is more seismically active than assumed?
M4.0 Snyder-Cogdell Field, induced earthquakes since the 1970s, CO2 waterflood operation

M3.2 Venus, TX site of the 2015 M4.0 Venus earthquake (Scales et al., 2018), wastewater disposal
Great Central US Shakeout happened – Did you miss out?

October 17 10:17 AM

Your organization can participate: www.shakeout.org
Arbuckle Group in Oklahoma

Rubinstein and Mahani, 2015
SCOOP/STACK enters the picture…
FracNotice available since Oct 2016
Oklahoma Corporation Commission Protocol for earthquakes associated with well completions (issued Dec 20, 2016, since updated, with more updates likely)

SUMMARY OF WELL COMPLETION SEISMICITY GUIDANCE

Terms: Oil and Gas Conservation Division (OGCD)
        Oklahoma Geological Survey (OGS)

Action following anomalous seismic activity within 1.25 miles of hydraulic fracturing operations:

• If magnitude, as determined by the OGS, is greater than or equal to 2.5M:
  o OGCD contacts designated representative for the operator with active completion operations within a 2 km radius of located seismic events.
  o Implementation of the operator’s internal mitigation practices commences.
  o Operation continues.

• If magnitude is greater than or equal to 3.0M:
  o Operator initiates a pause of operations for no less than 6 hours.
  o Technical conference/call held between the OGCD staff and operator about operator mitigation practices.
  o Upon agreement between operator and OGCD regarding mitigation practices and reduced seismic activity, operator permitted to resume with revised completion procedure.

• If magnitude is greater than or equal to 3.5M:
  o Operator suspends operations
  o In-person technical conference held with OGCD staff and operator to examine whether operation can resume with changes.
Hydraulic fracturing – injection occurs over days, mitigation on hours

Wastewater injection - injection for several years, mitigation for several years?

Rapid mitigation appears to successfully reduce aftershock productivity
Unconventionals in Oklahoma

Horizontal drilling (~95% of new wells are horizontals - coupled with legislative change to allow 2 mi long laterals vs 1 mi long laterals previously)

Completion-triggered seismicity during hydraulic fracturing

Geology includes rocks with substantial produced water

Wastewater disposal-induced earthquakes

Arbuckle Group in Oklahoma

Rubinstein and Mahani, 2015
Unconventionals in Oklahoma

Horizontal drilling (~95% of new wells are horizontals - coupled with legislative change to allow 2 mi long laterals vs 1 mi long laterals previously)

Completion-triggered seismicity during hydraulic fracturing

<5% of completed wells and largest events only M3.6

Geology includes rocks with substantial produced water

Wastewater disposal-induced earthquakes

Large earthquakes are rare, but have incurred ~$10 million damage total (claims paid in Oklahoma), likely an underestimate of actual damage

($74 million in gross production taxes collected in September 2019)
Conclusions – takeaway points:

- Longer term hazard remains elusive to estimate but likely elevated chance of a moderately damaging (or several?) earthquakes in the next decade

- Short term challenges related to hydraulic-fracture triggered seismicity – hazard and risk associated with these actions?

- **Science we can use:** State agencies support scientists working toward understanding mechanics of induced seismicity

- **How can we better serve our stakeholders?:** Local and regional scientists so incredibly important to our communities and often only access some citizens have to science. Follow-up questions: jwalter@ou.edu

Acknowledgements

The State of Oklahoma through the Secretary of Earth and Energy, DOE RPSEA funding for network upgrades in early mid-2010s, collaboration funding provided by DOE for Regional Induced Seismicity Collaboration (RISC), Current DOE NETL research funding
QUESTIONS?