Multidisciplinary Approach to Identify and Mitigate the Hazard from Induced Seismicity in Oklahoma

Austin Holland, Randy Keller, Amberlee Darold, Kyle Murray, Steve Holloway, Kevin Crain
Acknowledgements

- Industry contributors to RPSEA and fault database
- Oklahoma Independent Petroleum Association (OIPA)
- USGS – providing many different temporary seismic stations
- Oklahoma Secretary of Energy and Environment
- Oklahoma Corporation Commission
- OU Mewbourne College of Earth and Energy
Oklahoma’s Increase in Earthquakes

Earthquake rates per year

Magnitude 4 or Greater Earthquakes

- **Years 1882-2008**: 24 earthquakes
- **Year 2009-2013**: 3 earthquakes
- **Year 2014**: 0.1 earthquake

Magnitude 3 or Greater Earthquakes

- **Years 1980-2008**: 427 earthquakes
- **Year 2009**: 67 earthquakes
- **Year 2010**: 40 earthquakes
- **Year 2011**: 42 earthquakes
- **Year 2012**: 20 earthquakes
- **Year 2013**: 109 earthquakes
- **Year 2014**: 1.6 earthquakes

Updated Oct. 20, 2014
Earthquake Forecasting

- Probability of one or more earthquakes of magnitude (m) over the specified time
- Not a prediction, but a forecast

<table>
<thead>
<tr>
<th>Duration</th>
<th>3.0</th>
<th>4.0</th>
<th>4.5</th>
<th>5.0</th>
<th>5.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Year</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.9212</td>
<td>0.4621</td>
<td>0.1404</td>
<td>0.0362</td>
</tr>
<tr>
<td>1 Year</td>
<td>1.0000</td>
<td>0.9983</td>
<td>0.7908</td>
<td>0.3179</td>
<td>0.0893</td>
<td>0.0226</td>
</tr>
<tr>
<td>6 months</td>
<td>1.0000</td>
<td>0.9755</td>
<td>0.5849</td>
<td>0.1882</td>
<td>0.0482</td>
<td>0.0117</td>
</tr>
<tr>
<td>30 days</td>
<td>1.0000</td>
<td>0.6067</td>
<td>0.2036</td>
<td>0.0540</td>
<td>0.0135</td>
<td>0.0033</td>
</tr>
<tr>
<td>10 days</td>
<td>0.9984</td>
<td>0.2470</td>
<td>0.0579</td>
<td>0.0125</td>
<td>0.0026</td>
<td>0.0006</td>
</tr>
</tbody>
</table>
Oklahoma Recurrence Rates & Probabilities

Calculated with a 6 month moving window

Mc=1.9
Mc=2.3

Calculated with a 6 month moving window
Oklahoma Earthquakes 2009-2014

Area of greatest increase is about 15% of Oklahoma. Captures areas of significant waste-water disposal wells.
Cumulative Seismicity in Oklahoma

SWD well volumes (bbl/mon) in 2013

- up to 150,000
- 150,000 - 500,000
- greater than 500,000

Regional Faults
County

Prepared by:
Kyle E. Murray
OGS Hydrogeologist

Summary of UIC Well Volumes in 2013 by Geologic Zone of Completion

<table>
<thead>
<tr>
<th>Geologic Zone</th>
<th>Volume (MMbbl) of Saltwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permian</td>
<td>0-100</td>
</tr>
<tr>
<td>Virgilian</td>
<td>100-200</td>
</tr>
<tr>
<td>Missourian</td>
<td>200-300</td>
</tr>
<tr>
<td>Desmoinesian</td>
<td>300-400</td>
</tr>
<tr>
<td>Atokan-Morrowan</td>
<td>400-500</td>
</tr>
<tr>
<td>Mississippian</td>
<td>500-600</td>
</tr>
<tr>
<td>Woodford</td>
<td>600-700</td>
</tr>
<tr>
<td>Dev to Mid Ord</td>
<td>700-800</td>
</tr>
<tr>
<td>Arbuckle</td>
<td>800</td>
</tr>
<tr>
<td>Basement</td>
<td></td>
</tr>
<tr>
<td>Multiple-Undiff</td>
<td></td>
</tr>
<tr>
<td>Other or Unspec</td>
<td></td>
</tr>
</tbody>
</table>

Index Location Map for Oklahoma

SWD Vol ~ 1192 MMbbl (~3080 wells)
EORI Vol ~ 1080 MMbbl (~4993 wells)
Oklahoma Earthquakes 2009-2014

Area of greatest increase is about 15% of Oklahoma. Captures areas of significant waste-water disposal wells.
RPSEA - 4D Integrated Multi-scale Reservoir and Geological Modeling

• 4D geophysical monitoring
• Localized well-based pressure tests
• Goals
  – Improve model predictive capabilities
  – Maintain a suite of progressively updated models
  – Improved representation of the preferential flowpaths
  – Geomechanical properties and fault characteristics in the subsurface
OKRaH Seismic Network

Oklahoma Seismic Stations

Network
- ▲ OKRaH
- ▼ OTHER
3D geologic and geophysical model

- 100,000’s of Wells in central Oklahoma
- Geological and geophysical logs combined to build 3D models
- Incorporated into 3D seismic velocity models

Geospatially referenced surfaces Hunton (orange) and basement (brown).

Geologic units are assigned physical properties such as from well logs with spatially varying properties such as permeability, density, porosity, and velocity.
Gravity Observations Provide Constraints on Geologic Models
Industry Contributing to Enhanced Fault Database
Interagency Cooperation

OCC UIC Program
- New Permit & Existing Permits

Data
- Fault Maps
- Earthquake Information
- Injection and Operational Data

OGS
- Optimally Oriented Faults
- Fault Database Project
- Earthquake Monitoring and Reporting
- Additional Studies

Industry, DOE and State of OK Support
- Industry Fault Database Contributors & OIPA
- Improvements to Seismograph Network
- Reservoir & Geomechanical Modeling RPSEA
Current Mitigation Steps

• Oklahoma Corporation Commission is the regulator of UIC Class II wells, and have implemented different mitigation strategies
  – New rules regarding reporting of injection volumes and pressures in the “Arbuckle”
  – Permit modifications; i.e. “Traffic Light System”
  – Enhanced reporting requirements in OCC areas of interest, currently 10 km around ML 4+ earthquakes
    • Not required by rule for non-Arbuckle wells, but operators have complied for requests of greater reporting
  – New permits are checked against fault maps and background seismicity
Summary

• The rate of seismicity has increased dramatically and so has the seismic hazard
• Building large geological and geophysical data sets at varying scales and dimensions
• Continue to provide data products to stakeholders and identifying new data sources
• A greater understanding of physical processes in Oklahoma will help to inform future mitigation strategies
• Multi-agency cooperation has now been solidified in the governor’s Coordinating Council
Abstract

Oklahoma has experienced a very significant increase in seismicity rates over the last 5 years with the greatest increase occurring in 2014. The observed rate increase indicates that the seismic hazard for at least some parts of Oklahoma has increased significantly. Many seismologists consider the large number of salt-water disposal wells operating in Oklahoma as the largest contributing factor to this increase. However, unlike many cases of seismicity induced by injection, the greatest increase is occurring over a very large area, about 15% of the state. There are more than 3,000 disposal wells currently operating within Oklahoma along with injection volumes greater than 2010 rates. These factors add many significant challenges to identifying potential cases of induced seismicity and understanding the contributing factors well enough to mitigate such occurrences. In response to a clear need for a better geotechnical understanding of what is occurring in Oklahoma, a multi-year multidisciplinary study some of the most active areas has begun at the University of Oklahoma. This study includes additional seismic monitoring, better geological and geophysical characterization of the subsurface, hydrological and reservoir modeling, and geomechanical studies to better understand the rise in seismicity rates. The Oklahoma Corporation Commission has added new rules regarding reporting and monitoring of salt-water disposal wells, and continue to work with the Oklahoma Geological Survey and other researchers.