Potential for Induced Seismicity in Oklahoma and Recent Cases

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Outline

• Oklahoma’s significant increase in earthquake rates
  – General patterns
  – Seismicity which may be associated with the large amounts of produced water in the Mississippi Lime play
  – General comments

• Seismicity that may be associated with hydraulic fracturing and it’s possible contribution rate increases
  – Small but significant contribution to rate increase

• Overview of recent possible case of induced seismicity from a disposal well (If time permits)
Seismicity Rate Increases in Oklahoma

- Earthquake rates began accelerating in 2009
- And continued to accelerate in 2010
  - Roughly constant since 2010
- Earthscope and temporary networks coincident with rate increase
- Increase is real because
  - # M>=3
  - # Felt Earthquakes
Earthquakes 1882-2008

Earthquakes of Oklahoma 1882-2008

EXPLANATION
Magnitude:
0-3
3-4
4-5
5-6

Subsurface Fault
Surface Fault
Earthquakes 1882- Aug. 2013

Earthquakes of Oklahoma 1882-Present

EXPLANATION

Magnitude 1882-2008: Magnitude 2009-Present:

- 0-3  0-3
- 3-4  3-4
- 4-5  4-5
- 5-6  5-6

--- Subsurface Fault
--- Surface Fault
Earthquakes 1882- Aug. 2013

Earthquakes of Oklahoma 1882-Present

EXPLANATION

- Magnitude 1882-2008: 0-3
- Magnitude 2009-Present: 0-3
- Magnitude 2009-Present: 3-4
- Magnitude 2009-Present: 4-5
- Magnitude 2009-Present: 5-6
- Subsurface Fault
- Surface Fault

- 2009-Present Jones Swarm
- 2010-2011 Woodford Shale Play
- 2011-2012 M5.6 Prague & Hunton Dewatering
- 2012-Present Mississippi Lime Play
Seismicity Rates Mississippi Lime Play

- Large amounts of produced water
  - ~10% oil cut
- Best correlation to change in injection volumes and seismicity rates
- Increase in 2009
  - Southern extent
- Increase in 2012-Present
  - Heart of the play, northern Oklahoma
General Comments

• No dramatic increase in injected volumes in significant areas are associated with corresponding earthquakes
  – Except for the Mississippi Lime Play & perhaps the Woodford Shale Play
  – Injected volumes have been decreasing in the Hunton Dewatering Play

• Given the rate of known cases of induced seismicity it is unlikely that the entire earthquake rate increase in Oklahoma is due to fluid injection from oil and gas
  – More than 10,000 UIC Class II wells in Oklahoma
  – More than 80% of Oklahoma is within 15 km of a UIC Class II well (It would be hard not to have spatial correlations)

• Either there is a natural contribution to some of the rate increase, or there is a large-scale tipping point that has been reached

• Developing a set of best practices
  – [http://www.gwpc.org/sites/default/files/event-sessions/Holland_Austin.pdf](http://www.gwpc.org/sites/default/files/event-sessions/Holland_Austin.pdf)
Earthquakes triggered by hydraulic fracturing

- Several earthquakes felt by one local resident
- Largest earthquake M 2.9
- 11 earthquakes >= M 2.0

Identification is “easy” when you have more information; took ~6 months to get injection data.
Well Completions 2010- 6/ 2012

- ~5000 wells completed
- Compilation from the OCC
- ~50 wells bad spatial referencing
Earthquakes 2010-6/2012

- ~3100 earthquakes
- Large concentration in central Oklahoma
Identifying Triggered Seismicity in Space and Time

- Similar approach to de-clustering an earthquake catalog
  - Identify foreshocks and aftershocks
- Instead we are looking for earthquakes that aren’t dependent on a large earthquake, but on a well completion

Spatial Filter

Actually
0.08 degree
Spatial window

Well location

8 km

Temporal Filter

21 Days

Well Completion Date in OCC Data

Time
Windowed search for triggered seismicity

- 318 Earthquakes
- 96 different wells
- Average epicentral uncertainty \( \sim 7 \) km
- Average offset between earthquakes and completion – 11 days
- \( M_{\text{max}} \) 3.4 with 10 M3+
Identified Earthquakes

Is this really meaningful or could this be a coincidence?
Creating a synthetic catalog

- Earthquakes are assigned a time by generating Poisson distributed sequence with a rate parameter
  - Number of earthquakes per day
- Earthquakes are assigned a random location within Oklahoma
- Compared to the location of existing wells and completion dates

Each rate model had 1000 unique iterations
Statistical Significance

- 3 different earthquake rate models
- Simply by the number of wells identified
  - Results using the real data are inconclusive
  - Could simply be a coincidence with random earthquakes

<table>
<thead>
<tr>
<th>Model</th>
<th># EQs/Day</th>
<th>Total # EQs</th>
<th>Mean # Wells</th>
<th>Range # Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire Catalog</td>
<td>3.39</td>
<td>3097</td>
<td>485</td>
<td>590-390</td>
</tr>
<tr>
<td>Declustered Catalog</td>
<td>0.41</td>
<td>377</td>
<td>60</td>
<td>104-25</td>
</tr>
<tr>
<td>Central OK excluded</td>
<td>0.93</td>
<td>844</td>
<td>137</td>
<td>192-84</td>
</tr>
</tbody>
</table>

- Declustered catalog - removes aftershocks and foreshocks
- Central OK excluded - removes earthquakes that occurred in Oklahoma and Lincoln counties where there is a large swarm and a M5.7 earthquake and aftershocks
Earthquakes Triggered by Hydraulic Fracturing

• This is preliminary work which needs to be revisited

• If we consider seismicity rates prior to 2009 nearly all of the identified earthquakes are statistically significant
  – The number of earthquakes identified is greater than the number of earthquakes that would have been observed over the same time period prior to 2009
  – ~10% of earthquakes for the study time

• If we use the full earthquake current earthquake rates these identifications are not significant

• At most about 2% of completed wells from 2010-2012 triggered earthquakes

• Using the de-clustered current seismicity rates it is more likely that only about 1% completed wells triggered earthquakes

• Appear to continue to see occurrences of earthquakes triggered by hydraulic fracturing (some felt)
Damage summary from the magnitude 3.4, Sep. 23, 2013

Damage to Homes
• Collapsed Chimney (1)
• Shattered Window (1)
• Damaged brick façade (~5)
• Doors and frames crooked (~5)
• Cracked foundations
  – Difficult to distinguish from normal OK soil effects
• Cracked drywall and cosmetic damage (~15-20)
• Fallen objects and strong shaking (>20)

Photo courtesy of Rhonda Lumry
Felt Reports to Modified Mercalli Intensity

M3.4, 23 Sep 2013 13:56

Legend
- Report Locality
- Earthquake MMI:
  - III
  - IV
  - V
  - VI
  - VII

Created 4:00 PM (CST) 09/26/2013
Current Status

• The OCC has placed a yellow light on operations at the Love County Disposal Well #1 (LCD #1)
  – 1,000 bbls/day and 375 psi
  – This level is based off of the operators ability to run on one pump at 375 psi
  – Required to install a continuous pressure monitor
• Operator has stopped injecting, because at 1,000 bbls/day the operation is not economical
• There is another disposal well within 0.5 miles which is waiting to see what happens before going operational
  – Closer to the earthquakes than the LCD #1
  – Already drilled but not completed
Why allow injection at LCD #1

• Cannot definitively state that the earthquakes were directly caused by injection at LCD #1
  – The earthquakes are similar in characteristic to past swarms in the area and could simply be an odd coincidence
• Damage estimates from M3.4 are much less than the cost of a disposal well
• We are developing a system that would minimize risk and allow the operator to potentially continue operating and recover cost of the well
  – Cannot predict earthquakes and there is some risk in allowing injection to resume
• If the earthquakes can be shown to clearly be caused by injection at LCD #1, then proper damage claims could be assessed
Path Forward

• Establish a set of criteria to allow injection to resume at the yellow light with initial injection starting at the current level for some period of time
  – If all earthquake criteria are met for some period of time not yet identified (few to several days?)
  – Injection is allowed to increase to two pumps ~3,000 bbls/day and will be held at this level for some amount of time
  – If all is still fine injection would be allowed to increase to full scale, but under the yellow light condition
    • Earthquake monitoring continues and a red light could occur if any of the earthquake conditions are met.
Probability based monitoring

Past earthquakes even small can help determine the likelihood of exceeding some threshold “real-time” traffic light system.
Proposed earthquake criteria for Red Light on injection

- Still working out the details, but these are our general thoughts at present
- If any one of these criteria is met a red light on injection occurs
- If a magnitude 1.8 (M threshold), occurs this is the magnitude, which people are feeling earthquakes
  - If it is a foreshock to a larger earthquake generally a mainshock is ~ 1 magnitude unit greater (Still below the damage threshold)
Proposed earthquake criteria for Red Light on injection (continued)

- If the rate of earthquakes increases after injection begins such that we can say at the 99% confidence interval that the earthquake rate is distinct from the background rate currently being monitored.

- If we reach the point in the Gutenberg-Richter law where we have a 95% or greater chance of the next earthquake exceeding magnitude (M threshold).
Questions or Comments?

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Potential for Induced Seismicity in Oklahoma and Recent Cases

Induced seismicity from fluid injection has long been recognized. Over the past few years, Oklahoma has seen nearly 100 times more earthquakes than had occurred in the past. Some researchers suggest this is all due to oil and gas operations within the state. Disposal wells and hydraulic fracturing are important components of Oklahoma’s oil and gas production. Preliminary research shows that as much as 2% of completed wells may have triggered seismicity associated with hydraulic fracturing of wells. This research focused on 2 ½ years from the beginning of 2010. This work looked for earthquakes that occurred both spatially and temporally coincident with well completions within Oklahoma. Of the more than 5,000 completed wells, only about 100 wells may have earthquakes triggered by hydraulic fracturing with more than 300 earthquakes occurring close in space and time with these well completions. The largest of these earthquakes was a magnitude 3.4 with many of these being felt by local residents. Analysis of how many of these could be a simple coincidence suggests that at least about half of these are not likely to be a coincidence of the two random processes. Triggered seismicity from hydraulic fracturing appears to be continuing and a number of potential cases have been Identified this year. This level of activity cannot explain the dramatic increase in earthquakes occurring within Oklahoma, but represents more earthquakes than generally observed in Oklahoma in any given year.

Determining the potential from fluid injection associated with UIC Class II wells is much more challenging. There are more than 10,000 such wells operating within Oklahoma. More than 80% of the state lies within 15 km of an injection well. In addition most of the areas with the greatest increase in seismicity have had these injection wells for at least a decade and do not show a corresponding change in injection parameters with seismicity rate increases within the region. A recent potential case from a commercial disposal well occurred in far south-central Oklahoma. This case study provides a method to identify with verifiable uncertainty whether or not this sequence was caused by fluid injection or not. This demonstration is important in this case, because there was damage associated with the largest earthquake within the sequence. This level of confidence will be required as potential cases of induced seismicity go to court or are acted upon by regulatory agencies.