# Managing Potential Injection-Induced Seismicity through Monitoring and Mitigation*

**Thomas E. Tomastik[1], J. Daniel Arthur[1], and Steve Tipton[1]**

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[1]ALL Consulting LLC, Galena, Ohio (ttomastik@all-llc.com)

## Abstract

With the continued public and regulatory concerns regarding the potential for induced seismicity associated with Class II disposal wells, the development of a monitoring and mitigation plan is becoming a critical consideration for Class II disposal operations. Even though the practical risk of injection-induced seismicity is minimal, it is perceived as a real risk by the public and the media and therefore cannot be ignored. A plan, which includes both monitoring and mitigation elements, would be built upon hazard identification, risk assessment, and data evaluation that will provide for a technology-based process for assessing and addressing actual and perceived risks.

Hazard identification and risk assessment involves evaluation and determination of site-specific subsurface geology, hydrologic conditions, injection reservoir analysis, injection history, and assessment of historical seismicity in the area. Additional risk considerations would include assessment of the population density, structures, infrastructure, human health, safety, and the environment.

In many parts of the United States, existing regional seismic networks are limited in their ability to accurately locate hypocenters or even detect microseismic events. For optimal constraints on the location of any seismic event, seismic monitoring would need to include deployment of a multi-sensor passive seismic local network along with a strong motion accelerometer to record peak ground acceleration. Installation of four seismometers evenly distributed around the disposal well and a fifth unit installed at a distance equal to the depth of the well would provide for: (1) Increased accuracy of both the hypocenter and epicenter locations, (2) Real-time monitoring, and (3) Automated e-mail alerts of any seismic events.

Mitigation should be proactive in its approach and based on local conditions such as existing infrastructure, population density, and risk level, with considerations to public sensitivity and tolerance. Key mitigation strategies, which would likely involve a phased approach such as a traffic light system, would include operational changes such as injection rate and/or pressure reductions that allows for regulatory agencies and stakeholders to work together to develop real world solutions to induced seismicity.

# Managing Injection-Induced Seismicity Through Monitoring and Mitigation

**Prepared by Thomas E. Tomastik, J. Daniel Arthur, P.E., SPEC and Steven Tipton, P.E., ALL Consulting**

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# Injection-Induced Seismicity

- There continues to be public and regulatory concerns regarding injection-induced seismicity.
- Even though the practical risk of injection- induced seismicity is minimal, it is perceived as a real risk by the public and the media and therefore, cannot be ignored.


Source: TulsaToday.com, 2014

# Mechanisms of Injection-Induced Seismicity

- Fluid injection-induced seismicity has been attributed to the increase in pore pressure and corresponding decrease in effective stress on a favorably-oriented fault.
- Once fluid injection commences, the structural and petrophysical properties of the injection reservoir controls the injection rate, pathways of injectate flow, and the movement of the pressure front through the reservoir.
- For a pre-existing favorable-oriented fault in proximity of injection operations to be frictionally reactivated, the following conditions must be met:
  - The pressure front must reach the favorable-oriented fault; and
  - The pressure change at the fault must exceed the critical stress on the fault.

Source: Wong et al, 2015

# Monitoring and Mitigation of Seismicity

- Development of a monitoring and mitigation plan is becoming a critical consideration for Class II disposal operations.
- This is a proactive approach that can effectively manage and mitigate injection-induced seismicity.

Source: ALL Consulting, 2018

# The Plan

- A plan, which includes both monitoring and mitigation elements, should be built upon hazard identification, risk assessment, and data evaluation that provides for a technology-based process for accessing and addressing actual and perceived risks.

**SENECA RESOURCES CLASS II INJECTION WELL**

**SEISMIC MONITORING AND MITIGATION PLAN**

**Prepared by**

**ALL Consulting, LLC**

**1718 S. Cheyenne Ave.**

**Tulsa, OK 74120**

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Source: ALL Consulting, 2016



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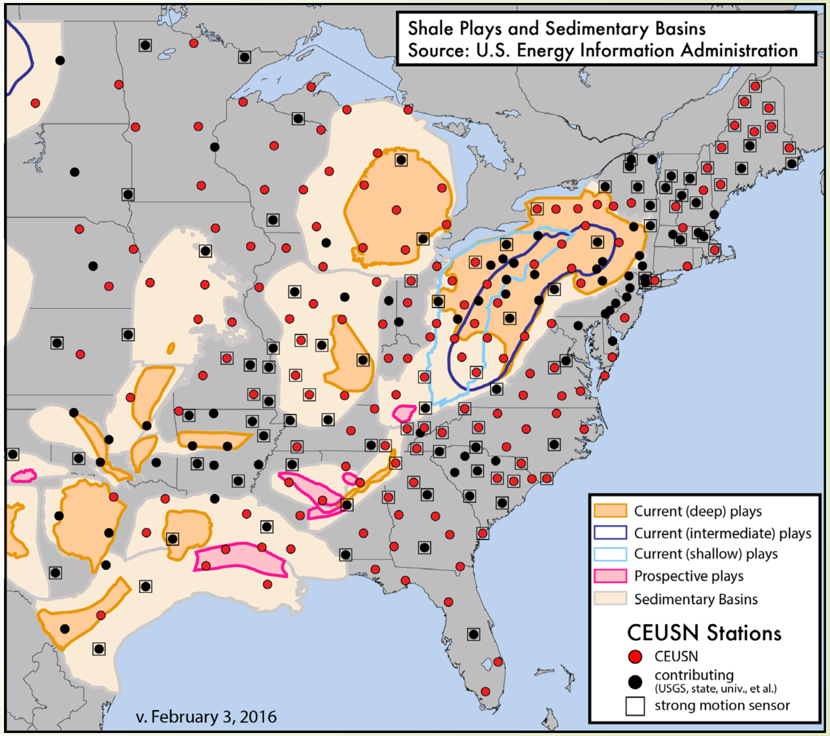
# Hazard Identification and Risk Assessment

- **Involves evaluation and determination of:**
  - Site specific subsurface geology and geophysical data;
  - Identification of pre-existing, favorably-oriented faults in the vicinity of injection operations;
  - Hydrologic conditions;
  - Existing seismic networks and their effectiveness;
  - Injection reservoir analysis;
  - Injection history; and
  - Assessment of historical seismicity in the area.

- **Additional risk considerations:**
  - Assessment of population density;
  - Structures;
  - Infrastructure; and
  - Human health, safety, and the environment.

# Seismic Monitoring Networks

- In many parts of the U.S., existing regional seismic network are limited in their ability to accurately locate hypocenter and epicenters, or even detect microseismic events.




Source: EIA, 2016

# Seismic Monitoring

- Locating a seismic event is a sophisticated form of triangulation.
- There are two requirements needed for the calculation of the travel time:
  - Accurate arrival times of the P-and S-waves; and
  - An accurate local velocity model.
- In areas of oil and natural gas exploration and development, actual velocity data can be obtained from sonic logs and can be useful in creating a more accurate velocity model.
- Determination of accurate focal mechanisms is also very dependent upon seismic event depth and the velocity model.

Source: Wong et al, 2015

# Example of Sonic Log

BAKER HUGHES

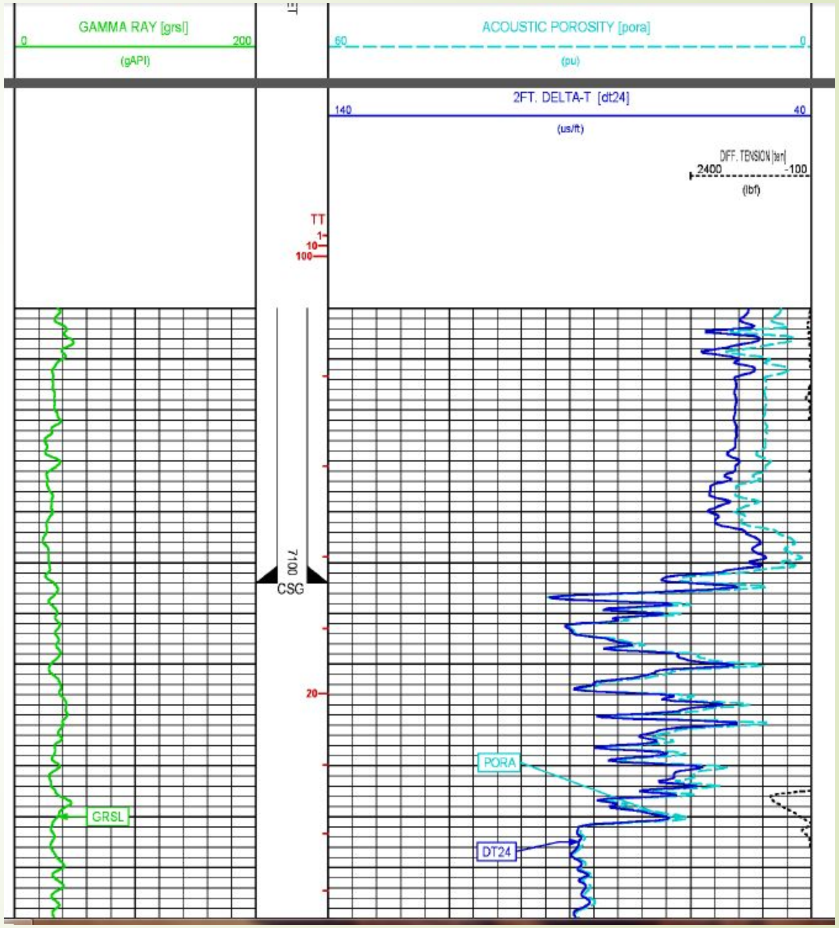
**DIGITAL ACOUSTILOG GAMMA RAY LOG**

| | | |
|---|---|---|
| FILE NO: | COMPANY | GLENN O HAWBAKER COMPANY |
| | WELL | HAWBAKER #1 |
| API NO: 34-031-2-7247-0000 | FIELD | BAKERSFIELD |
| | COUNTY | COSHOCTON STATE OH |

| | | |
|---|---|---|
| Ver. 4.06<br>5"/100' SCALE | LOCATION:<br>TOWNSHIP: OXFORD<br>LAT 40.28045 LONG -81.63819 | OTHER SERVICES<br>BOREHOLE PROFILE<br>D. SURVEY<br>TRIPLE COMBO |

| | | | | |
|---|---|---|---|---|
| PERMANENT DATUM | GL | ELEVATION | 831 FT | ELEVATIONS: |
| LOG MEASURED FROM | KB | 13 FT | ABOVE P.D. | KB 844 FT |
| DRILL. MEAS. FROM | KB | | | DF 844 FT |
| | | | | GL 831 FT |

| | | | | | |
|---|---|---|---|---|---|
| DATE | | 08-FEB-2017 | | | |
| RUN | TRIP | 1 | 1 | | |
| SERVICE ORDER | | US111087J | | | |
| DEPTH DRILLER | | 7472 FT | | | |
| DEPTH LOGGER | | 7461 FT | | | |
| BOTTOM LOGGED INTERVAL | | 7394 FT | | | |
| TOP LOGGED INTERVAL | | 6750 FT | | | |
| CASING DRILLER | | 7.0 IN | @ 7121 FT | @ | |
| CASING LOGGER | | 7104 FT | | | |
| BIT SIZE | | 6.125 IN | | | |
| TYPE OF FLUID IN HOLE | | BRINE | | | |
| DENSITY | VISCOSITY | 9.4 LB/G | - | | |
| PH | FLUID LOSS | - | - | | |
| SOURCE OF SAMPLE | | TOOL MEASURED | | | |
| RM AT MEAS. TEMP. | | 0.049 OHMM | @ 75 DEGF | @ | |
| RMF AT MEAS. TEMP. | | 0.037 OHMM | @ 75 DEGF | @ | |
| RMC AT MEAS. TEMP. | | 0.061 OHMM | @ 75 DEGF | @ | |
| SOURCE OF RMF | RMC | CALCULATED | CALCULATED | | |
| RM AT BHT | | 0.012 OHMM | @ 133.7 DEGF | @ | |
| TIME SINCE CIRCULATION | | 5 HRS | | | |
| MAX. RECORDED TEMP. | | 133.7 DEGF | | | |
| EQUIP. NO. | LOCATION | ML4257 | CANTON,OH | | |
| RECORDED BY | | D.ASHWORTH | | | |
| WITNESSED BY | | TOM TOMASTIC | | | |




Source: ALL Consulting, 2017

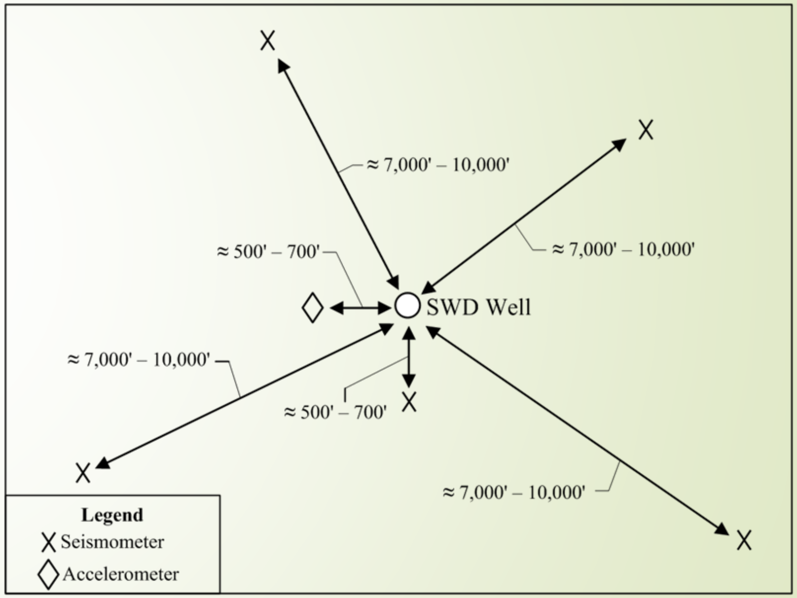
# Seismic Monitoring - Continued

- For highest location accuracy, multiple arrival times from seismic stations distributed evenly around the seismic event is most desirable.
- Epicenter depths, another critical element for determining induced versus natural tectonic seismic events, is hard to constrain without seismic stations being within the distance equivalent to the seismic event focal depth.
- In all reality, most regional or local seismic networks are not sufficiently dense enough to obtain accurate focal depths.

Source: Wong et al, 2015

# Local Seismic Monitoring Network

- Four seismic units are installed in an array around the disposal well at or near 90-degree angles and at a distance approximately equal to the depth of the disposal well.
- A fifth unit is installed within 500 to 750 feet of the wellhead to facilitate accurate focal depth determinations.
- Additionally, since ground motion is one of the primary concerns of induced seismicity, a strong motion accelerometer is installed near the wellhead to record peak ground acceleration at or near the site.




Source: ALL Consulting, 2016

# Seismic Monitoring Equipment

- **Three Component Seismic Velocity Unit:**
  - Three channel digitizers and three-directional sensors;
  - Sensors with frequency range of 0.1 to 1,000 hertz with a natural frequency of two hertz; and
  - Installed at depths of seven to ten feet below the surface to reduce surface noise effects.

- **Strong Motion Accelerometer:**
  - High resolution state-of-the-art accelerometer that measures various low frequency and ultra-low frequency ground motion;
  - Advanced features include high sensitivity with large linear and high dynamic range; and
  - Typically installed at a depth of about 2.5 feet below the surface.

# Types of Equipment


RefTek three-channel digitizer


ISES Three-directional sensor

Trimble REF TEK 147A Accelerometer

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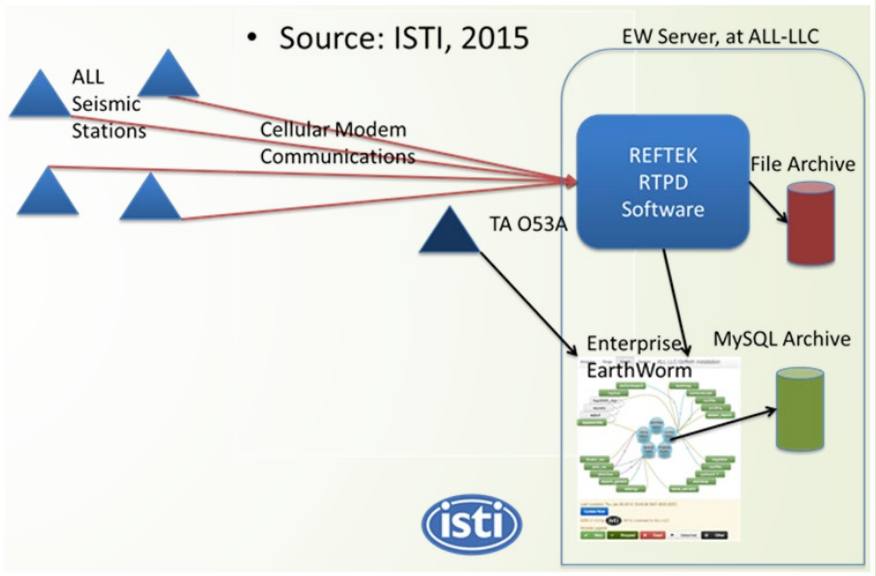
# Seismic Monitoring Equipment Maintenance

- Routine periodic inspections and maintenance need be conducted to ensure equipment remains in good operational condition.
- Frequency of inspection, calibration, and maintenance should be performed in accordance to manufacturer's recommendations.
- Inspection and maintenance records should to be maintained for at minimum of three years.

# Seismic Data Processing

- Data transmission;
- Data analysis;
- Monitoring of the system;
- Automated e-mail alerts; and
- Data Management.




Source: ISTI, 2015

# Real-Time Monitoring

- Errors in depth, location, and origin time are calculated using seismic computer location programs.
- The azimuthal gap, root mean square error (between the calculated and actual travel times at all seismic stations), minimum distance, and number of stations used by the programs are also calculated.

Source: Wong et al, 2015

## Example automated email

If the Earthworm system detected and located an event, it would have sent an email similar to the following:

Source: ISTI, 2015

# Location Quality

- The quality of the location accuracy is typically assigned a letter from A to D, based on a combination of parameters, with A being excellent and D being poor.
- The smaller the seismic event, generally the poorer the location, as fewer seismic stations will detect and record ground shaking and arrival times can be harder to pick.
- If adequate seismic station coverage exists and can clearly record P-wave motions with good station distribution around the seismic event, then the orientation of the fault plane(s) can be determined.

Source: Wong et al, 2015

| EW Event ID: 6794 | |
|---|---|
| Origin time: | 2015.08.01 21:03:26 |
| Latitude: | 39.7525 |
| Longitude: | -82.4553 |
| Depth: | 10.0 km |
| Coda Magnitude: | 3.1 Md nobs=1 |
| Local Magnitude: | 1.6 ±0.6 ML nobs=52 |
| RMS Error: | 0.18 s |
| Horizontal Error: | 1.08 km |
| Depth Error: | 2.92 km |
| Azimuthal Gap: | 161 Degrees |
| Total Phases: | 8 |
| Total Phases Used: | 7 |
| Num S Phases Used: | 0 |
| Quality: | C |


Source: Cambrian Well Services, 2016

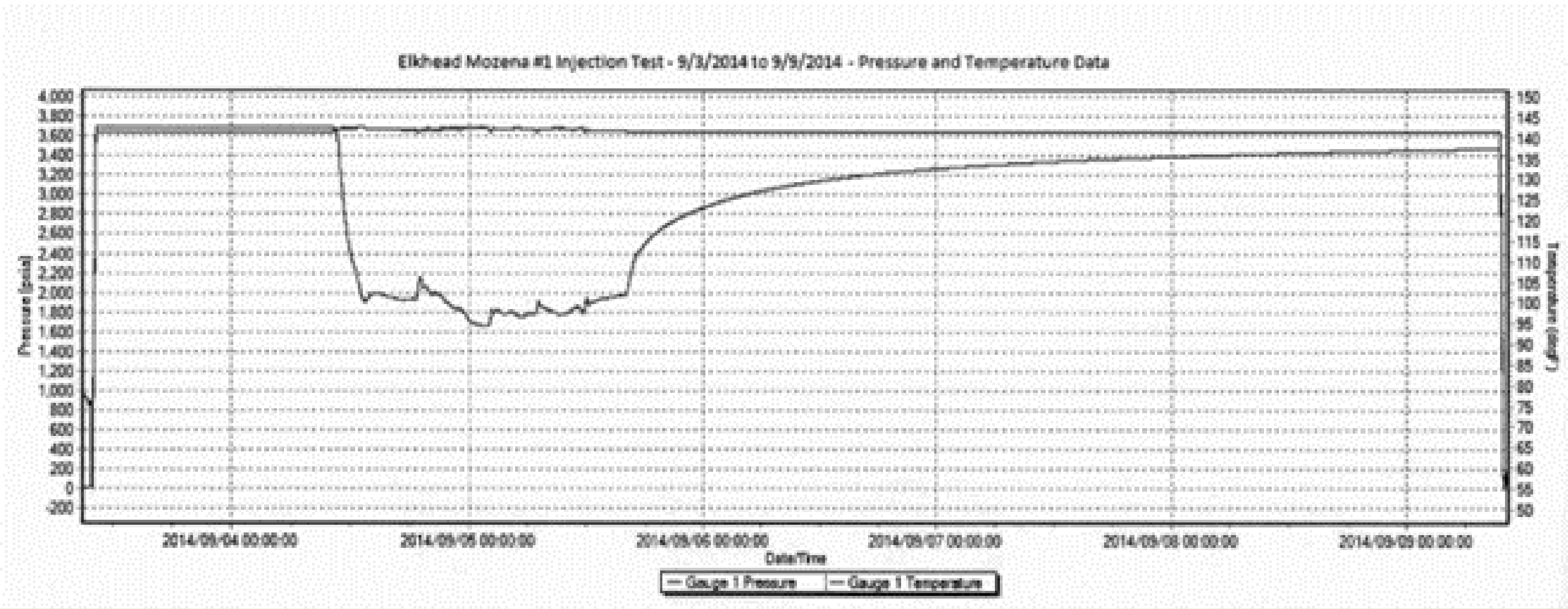
# Development of Area of Interest

- An Area of Interest (AOI) around a Class II disposal well should be established based on applicable state regulations and risk assessment findings.
- Additional considerations for a practical AOI should also include:
  - Site-specific geology and hydrology;
  - Cumulative injection history for existing wells;
  - Proximity to the Precambrian basement rocks; and
  - Historical seismic activity within the vicinity of the AOI.

# Mitigation of Induced Seismicity

- Mitigation planning should include both existing and proposed Class II disposal well operations.
- The plan should be proactive in its approach and based on local conditions such as:
  - Existing infrastructure;
  - Population density; and
  - Risk level, with considerations to public sensitivity and tolerance.
- Additional considerations in the plan should include:
  - Injection pressure and volumetric monitoring and reporting; and
  - Periodic pressure fall-off testing to assess injection zone performance.

# Example of Pressure Fall-off Test




Source: DOGRM, 2014





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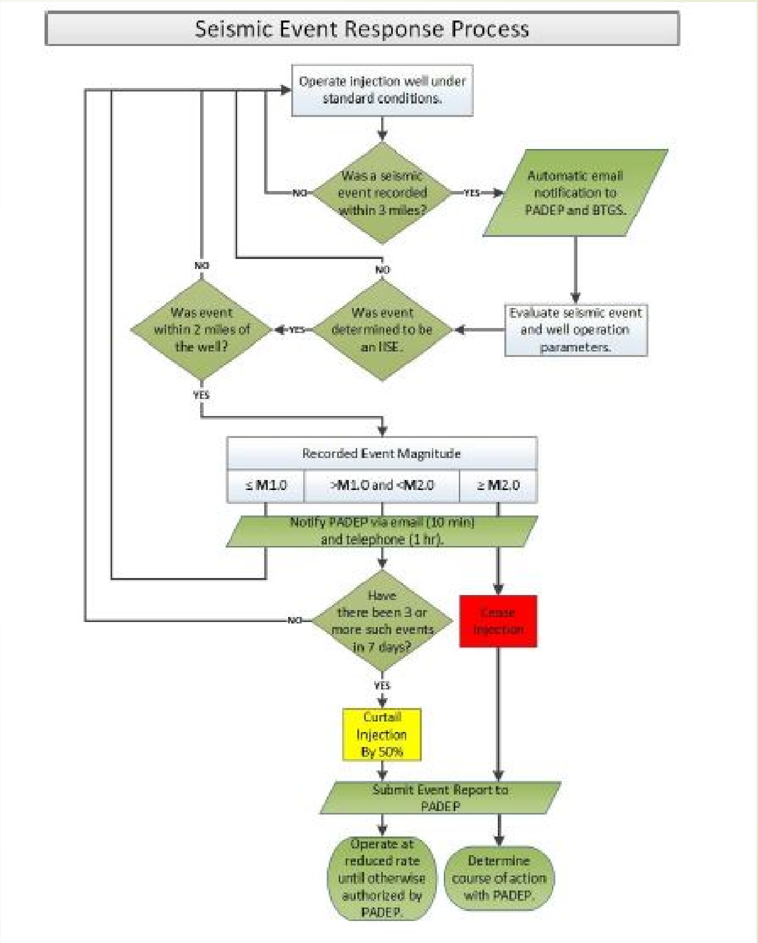
# Event Mitigation and Contingency Planning

- Planning should include notification requirements and a seismic event response process diagram.
- Key mitigation strategies, which would likely involve a phase approach such as a traffic light system, would include operational changes such as:
  - Reduction in injection rate; and/or
  - Injection pressure reduction.

# Seismic Event Response Process




Source: ALL Consulting, 2017





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# Plan Maintenance and Review

- To ensure the Seismic Monitoring and Mitigation Plan stays current and effective, the following should be considered:
  - Reviewed and updated at least annually;
  - When there are significant changes in activities or operations; or
  - Implementation of mitigation measures to address injection-induced seismic event(s).

# Regulatory Reporting

- Seismic monitoring data reporting;
- System change reports;
- Event notification; and
- Disposal well monitoring and reporting requirements.

OHIO DEPARTMENT OF NATURAL RESOURCES
DIVISION OF OIL & GAS RESOURCES MANAGEMENT
2045 Morse Road, F-2 • Columbus, OH 43229-6693
(614) 265-6922

*This report must be submitted annually by April 15 for each Saltwater Injection Well or Enhanced Recovery Project.*

**Annual Report (Form 204)** Rev. 01/17

**For Calendar Year:**

**1. Owner #:**

**2. Owner Name, Address and Telephone:**

**3. API Number:**

**4. Lease Name:**

**5. SWIW or ERP Number:**

**6. County:**

**7. Civil Township:**

**8. Type of Well:** *Choose one.*
- ☐ Saltwater Injection Well (SWIW)
- ☐ Enhanced Recovery Project (ERP)
- ☐ Other *Specify:*

**9. Type of Fluid:** *Choose all that apply.*
- ☐ Freshwater
- ☐ Saltwater
- ☐ Gas *Specify:*
- ☐ Other *Specify:*

**10. Injection Pressure (PSI) and Volume (BBL or MCF)**

| MONTH | DAYS IN OPERATION | TOTAL VOLUME INJECTED | INJECTION PRESSURE | |
|---|---|---|---|---|
| | | | MAXIMUM | AVERAGE DAILY |
| January | | | | |
| February | | | | |
| March | | | | |
| April | | | | |
| May | | | | |
| June | | | | |
| July | | | | |
| August | | | | |
| September | | | | |
| October | | | | |
| November | | | | |
| December | | | | |

DNR 744 Form 204 Rev. 01/17

Source: DOGRM, 2017

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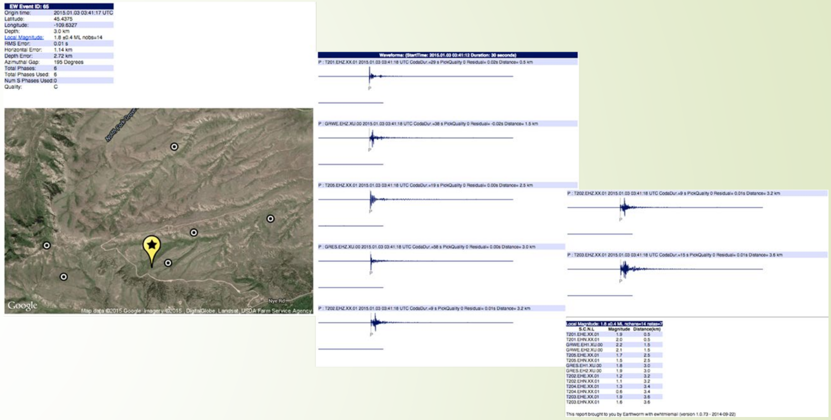
# Event Notification

- Reporting includes:
  - Magnitude;
  - Epicenter and hypocenter locations; and
  - Preliminary seismic event analysis.



Source: ALL Consulting, 2015

# Issues with Regulatory Mitigation Measures

- There are several problems with relying on seismic magnitude for defining mitigation measures or Traffic Light System (TLS) levels.
- These problems include:
  - Large uncertainties in determining magnitudes particularly at small values.
  - Magnitudes can differ by upwards of one unit not only due to differences in instrumentation but also path and site effects.
  - There are also issues with the different magnitude scales used by the various agencies and often they do not necessarily agree.
- Magnitude levels for TLS can have significant economic losses to the disposal well operator by shutting down operations needlessly where there is no threat to the public or infrastructure.
- By addressing TLS levels using ground motion, the issues mentioned above can often be avoided.

Source: Wong, et al, 2015

# Summary

- Seismic monitoring and mitigation needs to be based on sound, scientific principals.
- Key mitigation strategies should be proactive and include a phased approach such as a traffic light system (TLS).
- Both ground motion and magnitude should be used for defining TLS thresholds, with priority on ground motion.
- TLS levels should be defined on a site-specific basis that allows for:
  - Higher levels in unpopulated areas; and
  - Lower levels in areas of vulnerable population and infrastructure.

# Questions

Thomas E. Tomastik, Senior Geologist and Regulatory Specialist,
ALL Consulting
10811 Keller Pines Court
Galena, OH 43021
ttomastik@all-llc.com
www.all-llc.com

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