INDUCED SEISMICITY AND THE O&G INDUSTRY

This presentation represents the collective thoughts of subject matter experts drawn from AXPC member companies and other Oil and Gas Industry companies. The subject matter experts include geologists, geophysicists, hydrologists, and regulatory specialists. This presentation does not represent the views of any specific trade association or company.

GWPC
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Purpose

- Provide a primer on natural and potentially induced seismicity
- Provide a general discussion on the potential of O&G induced seismicity from hydraulic fracturing and the disposal of fluids by underground injection
- Describe a framework to consider in screening, assessing, monitoring, and mitigating seismicity from fluid injection for disposal, where induced seismicity is suspected and/or there are heightened concerns due to local conditions

Seismicity 101

- Seismicity (natural or induced) is the shaking of the earth due to a slip on a fault caused by the release of stored elastic stress
- Seismicity can be induced or triggered when changes in stress or pore pressure promote a slip
- Most all seismicity is too small to be measured or felt by humans and does not cause damage to man-made structures
- The term induced seismicity is used when referring to seismicity linked to human activities

Natural Seismicity

- Seismic events occur with varying degrees of intensity…many more smaller than larger
- The energy released may reach the earth surface and cause noticeable shaking
- Damage to structures, if any, depends on the amount of energy reaching the surface, geomechanical characteristics of the soil and the condition of the structures
- The *epicenter* is the location at the surface above the slip event
- The *hypocenter* is the event's actual location in the subsurface

Measuring Seismicity

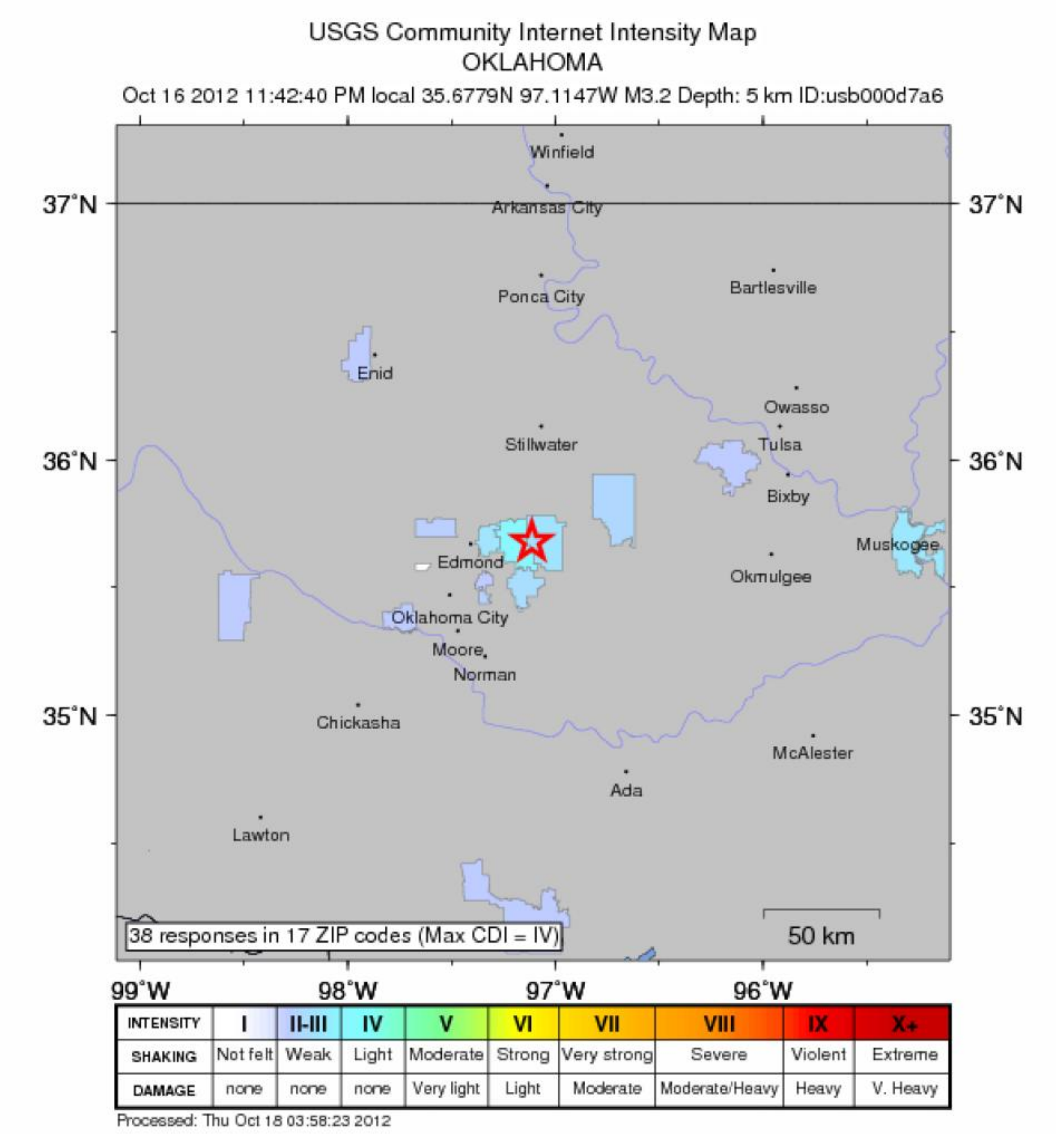
- The Richter Scale*
  - This scale is logarithmic: each increase of one unit represents a 10-fold increase in the amplitude of seismic waves measured by a seismograph (and approximately 30 times the energy released)
  - This scale has no theoretical limits: magnitude of recorded natural events typically ranges from -3 (the lower limit of micro-seismic sensor sensitivity) to 9 + (the most severe earthquake ever recorded)

** And its modern equivalents e.g. local magnitude, moment magnitude*

Measuring Seismicity

- The Modified Mercalli Index (MMI)
  - Uses the perceived effects of a seismic event on the people and structures in a given area to determine its intensity
  - Defines 12 levels of seismic event severity, ranging from imperceptible to devastating
  - MMI level is **not** synonymous with the Richter Scale magnitude, but is more useful in describing actual local effects
  - Depends upon many factors including: depth of the seismic event, distance from the seismic event epicenter, geomechanical characteristics, terrain, population density

Measuring Seismicity – Local Effects



- USGS ShakeMap
- Magnitude 3.1
- Max MMI intensity IV
- 38 Responses - 17 Zip codes

Comparison of Seismic Scales

Richter Magnitude	Description	MMI	Earthquake effect observations	World-wide occurrence
< 2.0	Micro		Micro earthquakes not felt by people and detected by sensitive instruments only.	Continual >8,000 per day
2.0 – 2.9	Minor	1	Imperceptible: Not felt except by a very few people under exceptionally favorable circumstances.	1,300,000 per year (est.)
3.0 – 3.9		2	Scarcely felt: Felt by only a few people at rest in houses or on upper floors buildings.	130,000 per year (est.)
		3	Weak: Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognized as an earthquake.	
4.0 – 4.9	Light	4	Largely observed: Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic. Walls may creak; doors, windows, glassware and crockery rattle.	13,000 per year (est.)
		5	Strong: Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed. Small objects are shifted or overturned, and pictures knock against the wall. Some glassware and crockery may break, and loosely secured doors may swing open and shut.	
5.0 – 5.9	Moderate	6	Slightly damaging: Felt by all. People and animals alarmed. Many run outside. Walking steadily is difficult. Objects fall from shelves. Pictures fall from walls. Furniture may move on smooth floors. Glassware and crockery break. Slight non-structural damage to buildings may occur.	1,319 per year
		7	Damaging: General alarm. Difficulty experienced in standing. Furniture and appliances shift. Substantial damage to fragile or unsecured objects. A few weak buildings damaged.	
6.0 – 6.9	Strong	8	Heavily damaging: Alarm may approach panic. A few buildings are damaged and some weak buildings are destroyed.	134 per year
7.0 – 7.9	Major	9	Destructive: Some buildings are damages and many weak buildings are destroyed.	15 per year
8.0 – 8.9	Great	10	Very destructive: Many buildings are damaged and most weak buildings are destroyed.	1 per year
		11	Devastating: Most buildings are damaged and many buildings are destroyed.	
9.0 – 9.9		12	Completely devastating: All buildings are damaged and most buildings are destroyed.	1 per 10 years (est.)
10.0+	Massive	>12	Never recorded, widespread devastation across very large areas.	Unknown

Created from USGS information by Wikipedia

Induced Seismicity

- Induced seismicity is seismicity due to human activity
- An increase in local seismicity that has spatial and temporal correlation with human activities raises the possibility of it being induced
- To assess whether or not the seismic activity is induced, it is necessary to evaluate the seismic data, the geophysical and geomechanical mechanisms surrounding the seismic events, as well as operational evidence
- In order for induced seismicity to take place there needs to be a critically stressed fault near the human activity

Induced Seismicity

- A small number of induced seismicity cases have been attributed to the following human activities:
  - Enhanced geothermal systems
  - Construction
  - Mining
  - Dams and reservoirs
  - Hazardous waste injection for disposal
  - Oil and Gas activities

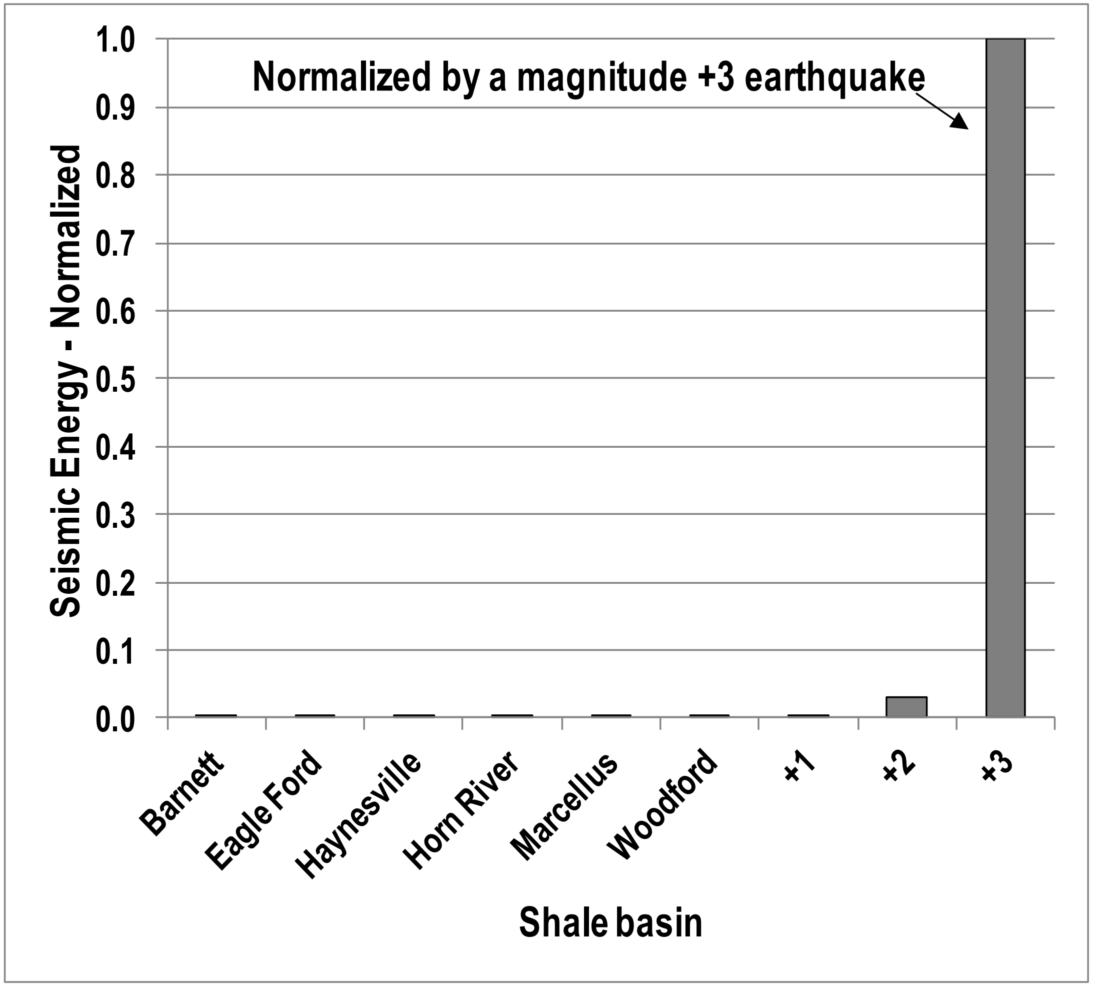
Induced Seismicity – Oil and Gas

- Production and enhanced oil recovery
  - Rare cases – water floods and production associated subsidence
  - Injection raises in-situ stress – withdrawal reduces in-situ stress
  - Has been managed by controlling injection pressures and rates
- Hydraulic fracturing
  - Short term/low volumes – process lasts 1-5 days per well
  - Process produces microseismic events, but very rarely felt at surface
    - 3 events recognized out of over 1 million fracturing operations
    - Associated with hydraulic fracturing near basement structure and/or near a critically stressed fault

"The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events" –

National Academy of Sciences - 2012

Induced Seismicity – Hydraulic Fracturing



Warpinski et al. 2012
SPE 151597

Normalized maximum microseismicity energy induced by hydraulic fracturing compared to a magnitude +3 earthquake, which is similar to the passing of a nearby truck

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Induced Seismicity

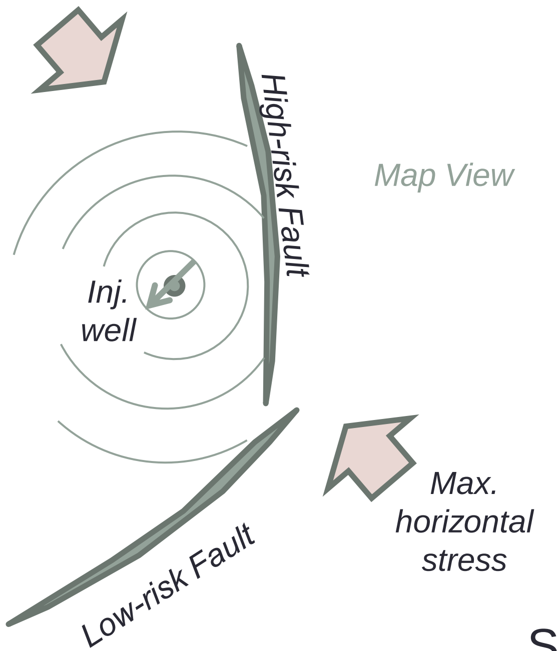
Fluid Disposal using Underground Injection (UIC Class II)

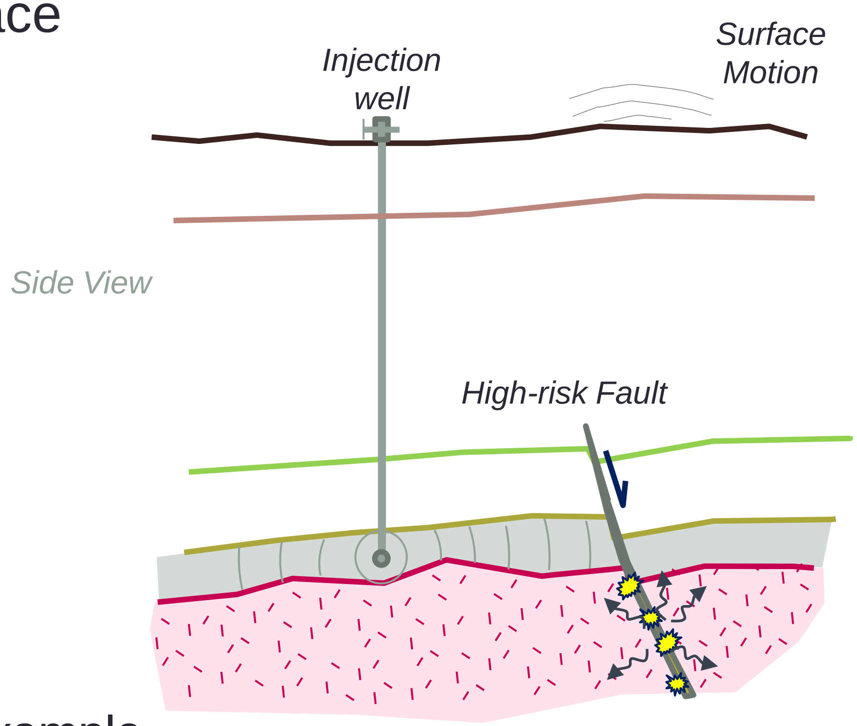
- UIC Class II wells are regulated by Federal/State Underground Injection Control Program
- There are over 30,000 UIC Class II disposal wells operating in the US……few proven cases of induced seismicity
  - Felt events are associated with injection near basement* structure and/or a critically stressed fault
  - Induced seismicity can be managed with operations monitoring and modulation of injection pressures and rates

* The term “basement” is used to define any rock below sedimentary rocks or sedimentary basins that are metamorphic or igneous in origin.

Induced Seismicity – Fluid Injection

- Fluid injection: raises pore pressure in subsurface
- Increased pressure reaches a nearby critically stressed fault with a high-risk orientation
- Fault reacts: brittle deformation, especially in basement rock, radiates seismic waves
- Ground motion may result at surface





Schematic example

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Induced Seismicity – Fluid Injection for Disposal

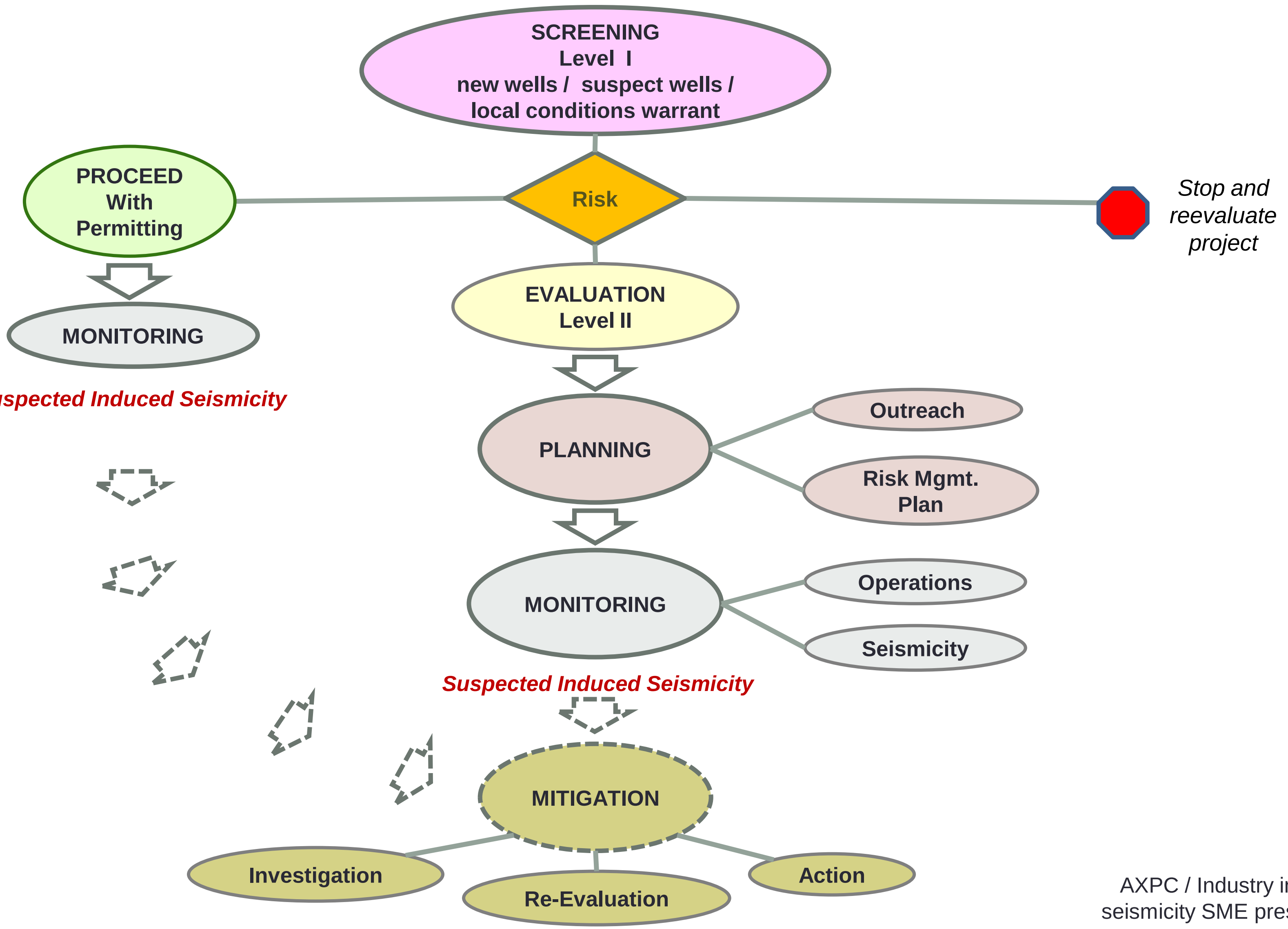
Framework for screening, evaluation, planning, monitoring, mitigation

- Risk management process for fluid disposal wells (UIC Class II)
  - Where significant induced seismicity is suspected and/or concerns due to local conditions – MOST ALL DISPOSAL WELLS HAVE NO SEISMICITY

- Highlights:
  - Proactive approach addressing public and regulatory concerns
  - Screening for siting new disposal wells
  - Not intended for legacy wells not suspected of induced seismicity
  - Scalable process for varying local conditions including: geology, operations, demographics
  - Dynamic – evolves as conditions change
  - Plan for mitigation, if and when, potentially induced seismicity occurs

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



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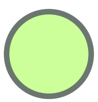
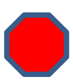
Screening – Level I

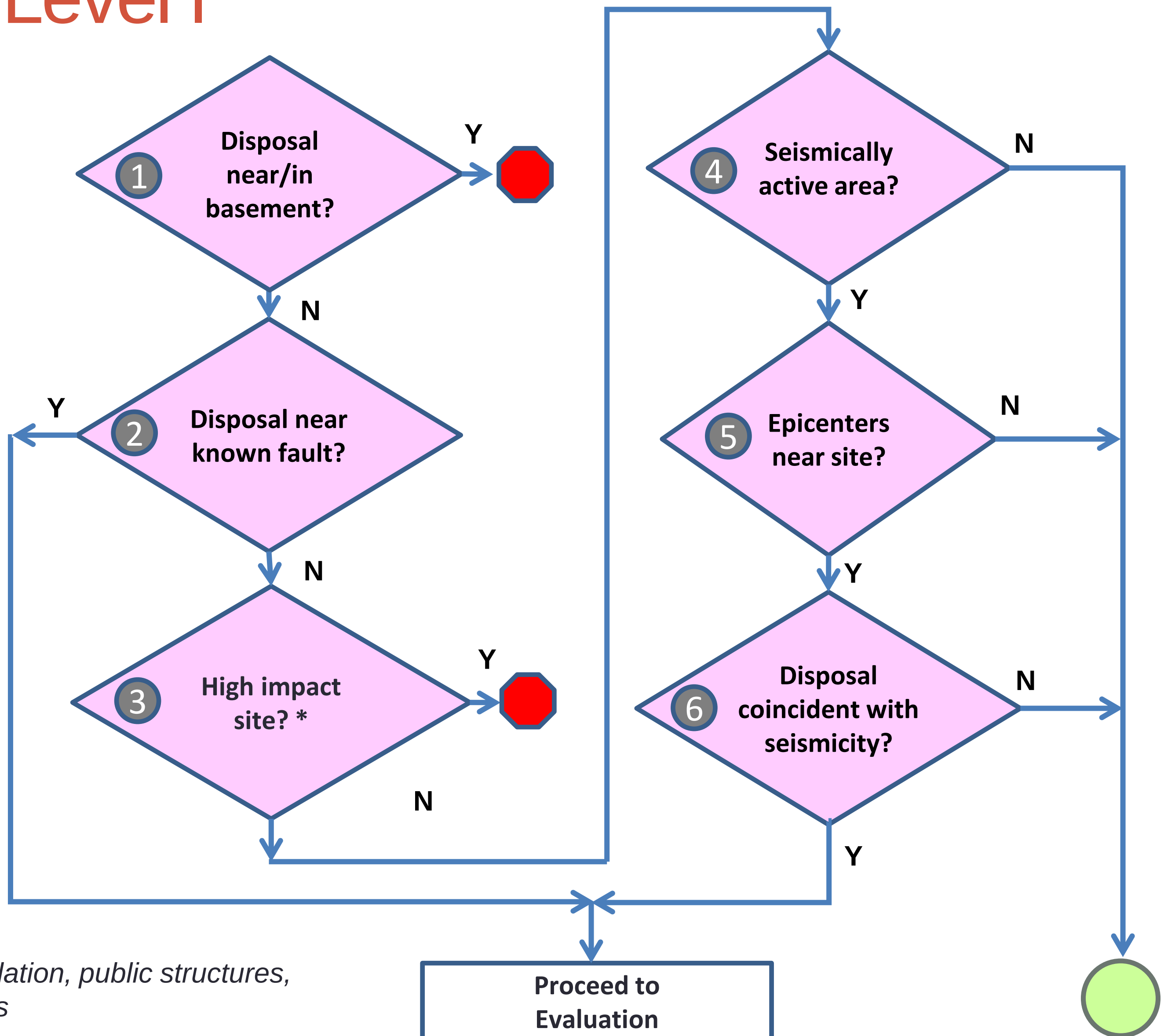
- New wells
- Wells suspect of induced seismicity
- Local conditions warrant



Proceed with permit process



Stop and reevaluate project



** e.g. Proximity to dense population, public structures, environmentally sensitive sites*

Test criteria modified from Davis & Frohlich 1993

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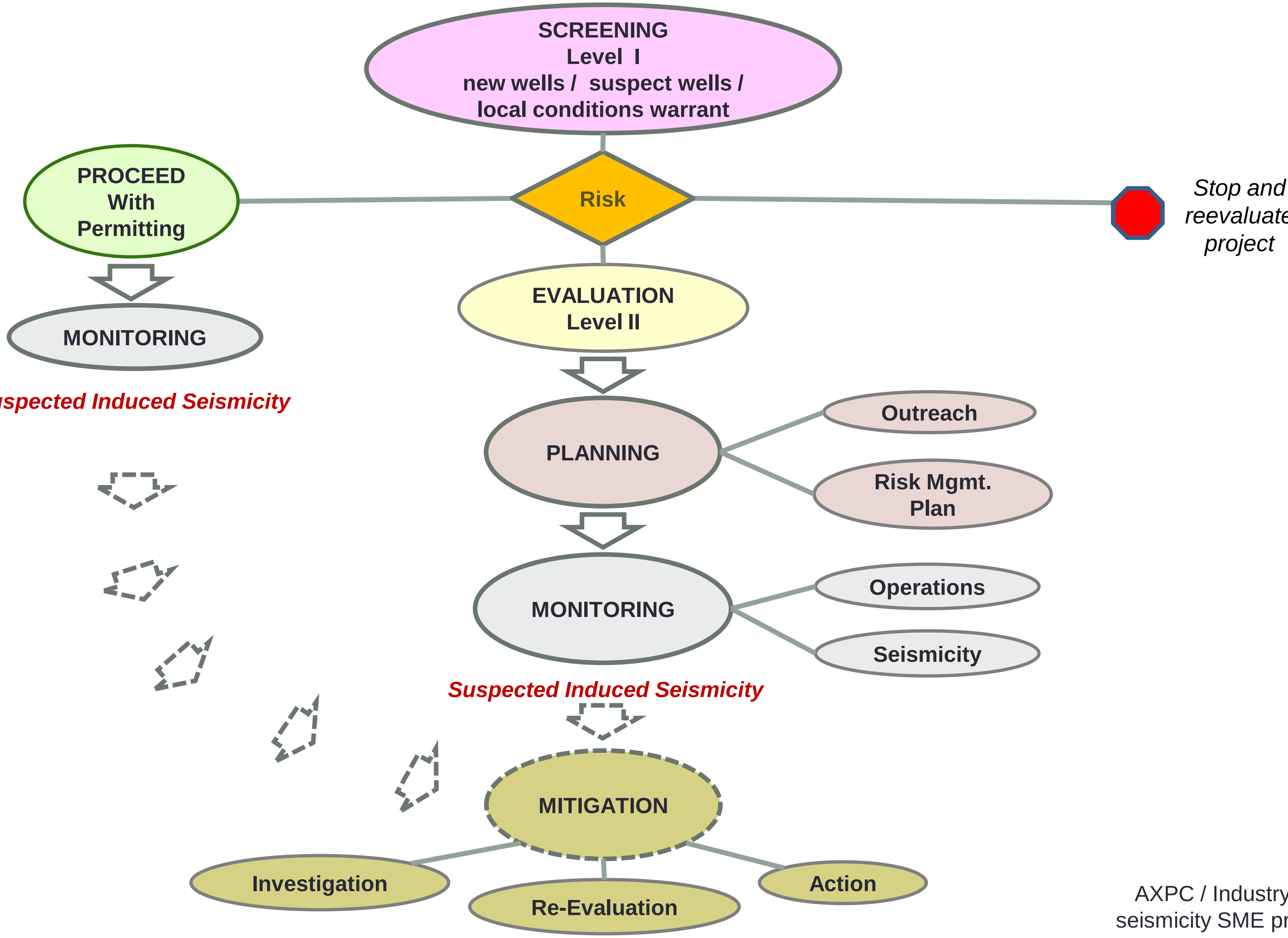

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Evaluation - Level II

- Hazard – The possibility of seismic events and ground motion occurring as a result of fluid disposal

- Impact – The effect on local population, property, or environment, including distress, damage, or loss

Evaluation Level II – technical considerations

Hazard
1. Local seismicity – location, depth
2. Local geologic stress and faults
3. Geomechanical modeling
4. Reservoir characteristics
5. Seals and boundaries, separation from basement
6. Pore pressure and fracture gradient
7. Ground conditions and expected seismic motion
8. Planned disposal volumes, rates, and pressures

Impact
1. Susceptibility of population, infrastructure, environment
2. Shake maps and damage models
3. Operator and stakeholder losses and liabilities
4. Probabilistic analyses of hazard and impact

Evaluation - Hazard Evaluation Toolbox *

Item	Data, Resources and Tools
Key geologic horizons and features	Data from existing wells, reflection/refraction seismic data, and gravity/magnetic data. Fault presence assessment from mapped horizons and coherency 'ant tracking'.
Regional stress assessment	World stress map, Stress literature, physical measurement, stress estimates from seismic and/or nearby well logs. Model effect on the reservoir and surrounding rocks from stress changes associated with fluid injection.
Surface features	USGS geological maps, published reports.
Ground conditions	Consolidation, saturation, composition, proximity to basement from State and USGS maps.
Ground response	Expected peak velocities, acceleration, and spectral frequency. Refer to local civil engineering codes. Models from USGS, state agencies and academia.
Local seismic events	Academic (e.g. IRIS), State, and industry surveys. If not available then regional or local dedicated network of seismometers and ground motion sensors. Establish magnitude, frequency of occurrence, and ground motion relationships.
Reservoir characterization	Rock type, facies, age, matrix composition, porosity types, depth, thickness, and petrophysical properties. Lateral extent and continuity, proximity to outcrop, proximity to basement, lateral barriers and conduits, compartments, bounding layers and intervening formations to basement, sealing rocks in system.
Reservoir properties	Permeability, porosity, natural fracture porosity, storativity. Mechanical properties: fracture gradient, closure pressure (ISIP), Young's Modulus, Poisson's Ratio, cohesion, coefficient of friction, pore pressure, lithostatic pressure, hydrostatic pressure, horizontal stress magnitudes and azimuth.
Disposal conditions	Initial saturation, salinity, pore pressure, static fluid level. Fluid injection rates, pressures, cumulative volumes

** Toolbox contains various scalable tools user can select to fit for purpose*

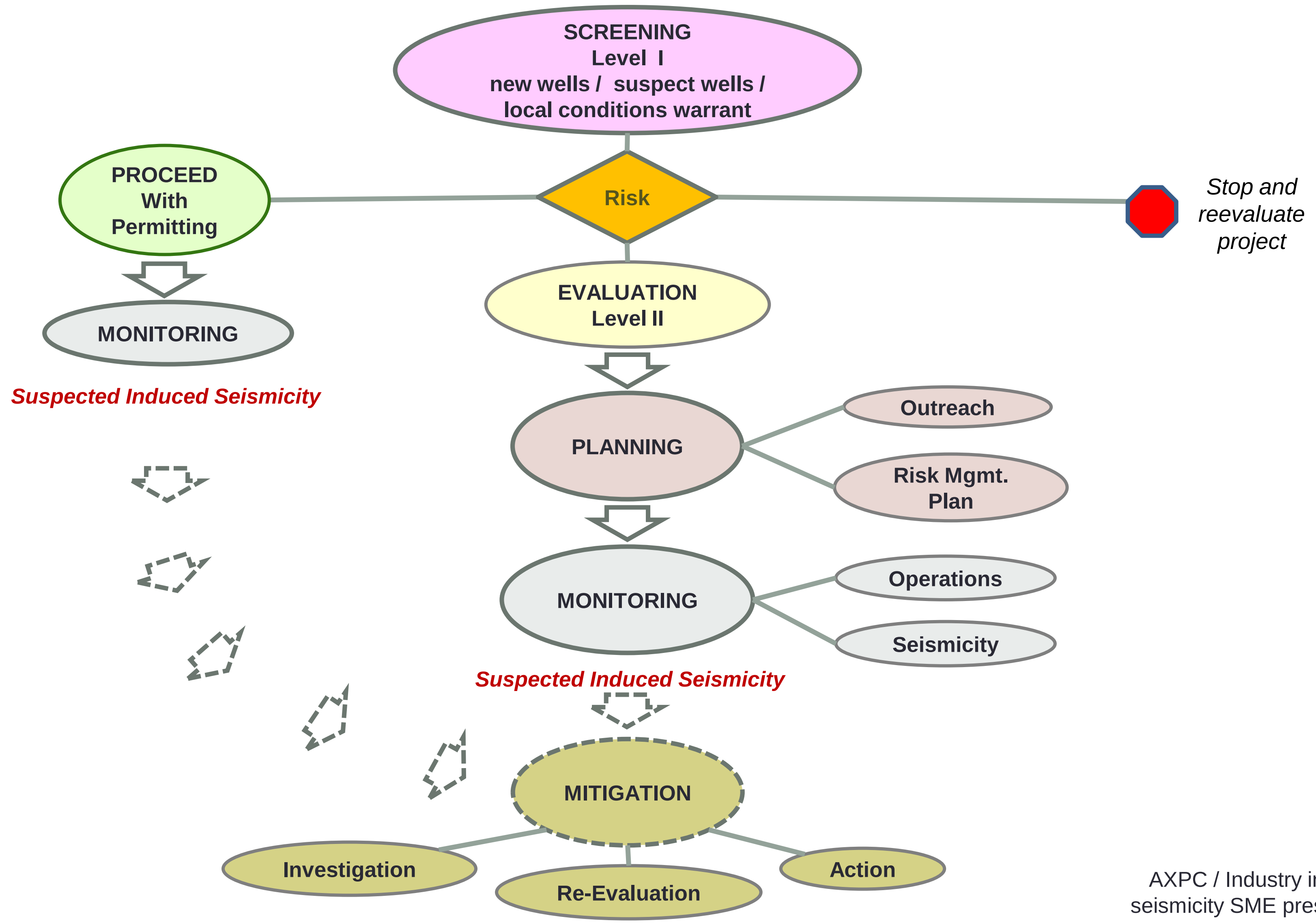
Evaluation – Impact Evaluation Toolbox *

Item	Data, Resources and Tools
Population	Survey 10 mile radius, nearby population centers. Assess the regional population density. Comfort or familiarity with seismic events – assess potential nuisance thresholds
Structures and Infrastructure	Summary of buildings, roads, pipelines, electric grid Critical infrastructure – e.g. Hospitals, schools, historical sites Construction practices, materials Local codes, seismic event ready?
Dams, Lakes, Reservoirs	Presence of dams, reservoirs. Ages, type of impoundment History of fill/drawdown Substrate – material and known faults
Environmental	General description of local ecology Special environmental hazards, protected species
Intangible	Goodwill, trust, reputation
Risk	Probabilistic models with both chance of occurrence and estimated ranges of potential outcomes for damage assessments, e.g. from HAZUS (USGS)

** Toolbox contains various scalable tools user can select to fit for purpose*

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



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Planning

- Scalable and fit for purpose for the risk of induced seismicity
- Key elements in plan:

1.Conduct **Outreach** to partners and regulators
2. Establish motion thresholds for **Risk Management Plan** “Traffic Lights”

Planning - Outreach

- Communications plan – community and agencies

1. Identify local, State, and Federal agencies and expectations
2. Know regulatory requirements
3. Notification plan – whom, messages, response

Plan adaptable to local conditions and rules

Planning - Risk Management Plan: Traffic Lights

Green — Continue operations – no seismicity felt at surface (MMI I-II)*

Amber — Modify operations – seismicity felt at surface (MMI II-III+)*

Red — Suspend operations – seismicity felt at surface with distress and/or damage (MMI V+)*

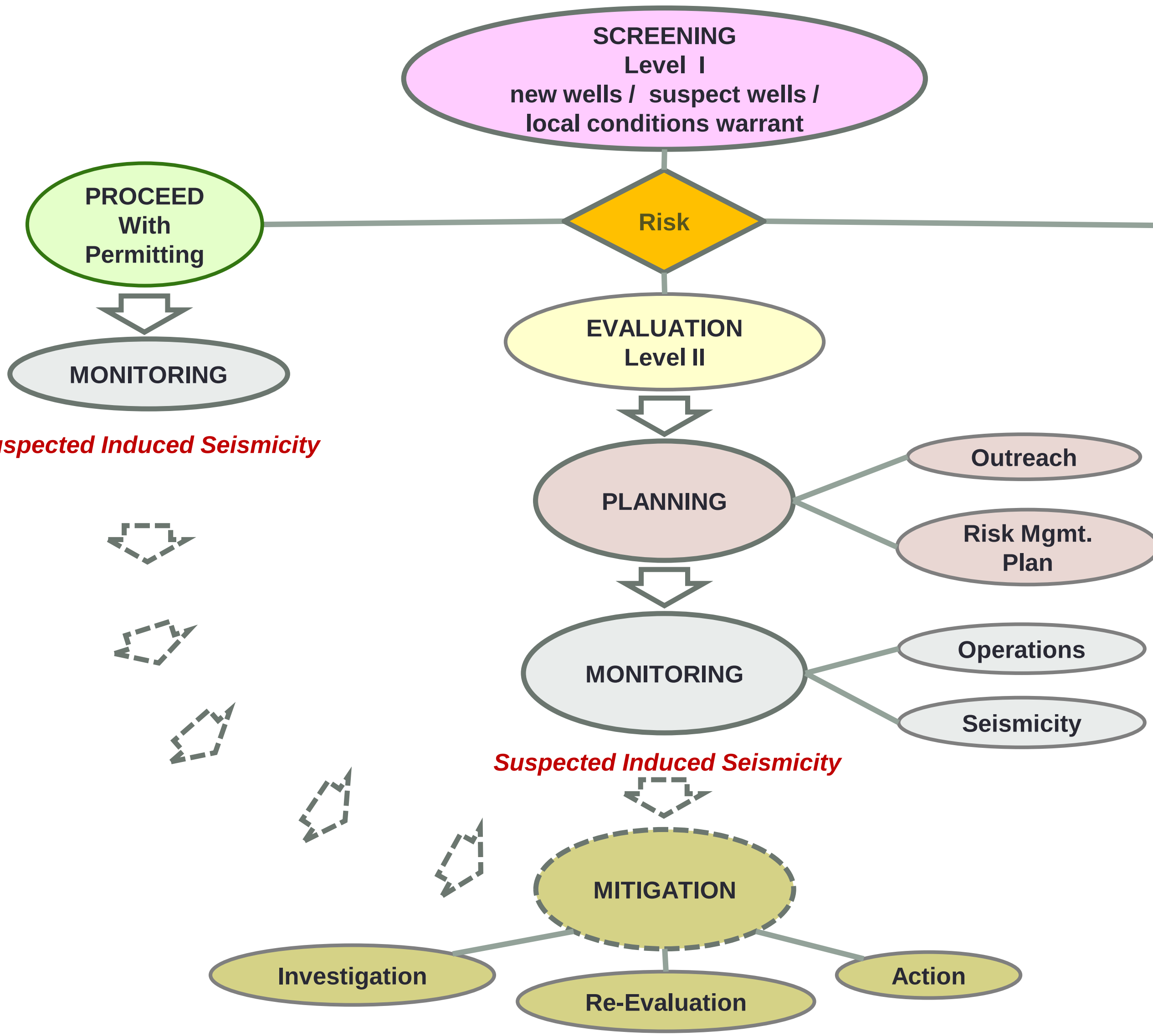
Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	none	none	none	Very Light	Light	Moderate	Moderate Heavy	Heavy	Very Heavy
Peak Acceleration (%g)	<0.17	0.17 to 1.4	1.4 to 3.9	3.9 to 9.2	9.2 to 18	18 to 34	34 to 65	65 to 124	>124
Peak Velocity (cm/s)	<0.1	0.1 to 1.1	1.1 to 3.4	3.4 to 8.1	8.1 to 16	13 to 31	31 to 60	60 to 116	>116
Magnitude	1 – 2.9	3 – 3.9	4 – 4.4	4.5 – 4.9	5 – 5.4	5.5 – 5.9	6 – 6.4	6.5 – 6.9	7.0+
Modified Mercalli	I	II to III	IV	V	VI	VII	VIII	IX	X+

Traffic Lights *

* *Established based upon local conditions, demographics and codes*

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



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Monitoring

- Operations
  - Injection volume daily, cumulative
  - Injection pressure
  - Reservoir engineering evaluation
- Seismicity
  - Public monitoring
- Scalable and fit for purpose for the risk of induced seismicity
- Integrated with Risk Management Plan
  - Thresholds for ground motion
  - Seismic alerts (e.g. from USGS, local arrays)

Monitoring – Toolbox *

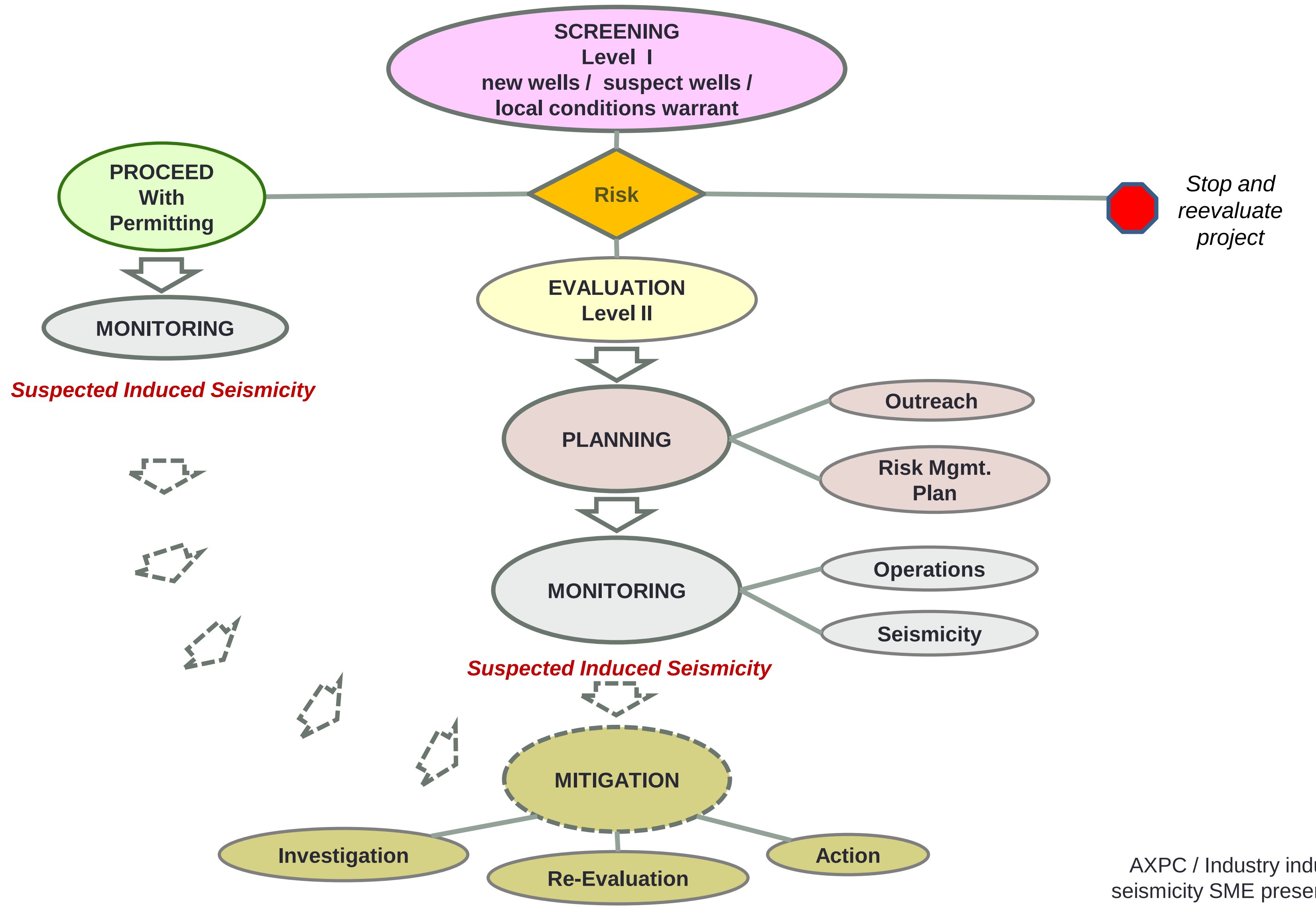
- Data, resources and tools for **Monitoring** evaluation

Item		Data, Resources and Tools
Operations	Fluid parameters	• Continuous monitoring and recording of injection rates, and pressures. • Daily and cumulative injection volumes measured and recorded. • Injectant properties noted: e.g. salinity, chemistry.
	Reservoir	• Fluid levels, shut-in pressure, pore pressure, changes in conditions. • Pressure transient behavior – e.g. falloff, step rate tests • Well performance and reservoir flow behavior (Hall plots, Silin plot) Storage/transmissivity
Seismicity	Regional	• Establish baseline conditions from USGS and other regional sources. • Maintain catalog of events from USGS and other regional sources. • Identify excursions from historical trends (temporal and spatial). • Note surface effects from seismic events recorded.
	Local	• (Level II) Install local array sufficient to locate events in the subsurface near the injection zone. • (Level II) Deploy sensors capable of measuring peak ground acceleration and velocity in the vicinity of the injection site. • Monitor possible "traffic light" events within 10 miles of well. • Evaluate whether any observed seismic events are induced or naturally occurring. • Report potentially induced threshold events established in the Risk Management plan that initiate mitigation steps.

** Toolbox contains various scalable tools user can select to fit for purpose*

Induced Seismicity – Fluid Injection for Disposal

Framework for screening, evaluation, planning, monitoring, mitigation



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Risk Mitigation

- **If, <u>and only if,</u>** induced seismicity suspected
- **<u>And</u>** if surface motions exceed thresholds: amber/red traffic light
- Goal is to manage and continue operations safely

<u>Investigation - steps</u>

1. Characterize event – magnitude, location, depth
2. Assess surface effects – motion, impact (distress, damage)
3. Calibrate seismicity to operations
4. Re-visit subsurface data – faults?
5. Improve monitoring

<u>Action</u>

1. Take steps defined in Risk Management Plan ("Traffic Lights")
2. Expand data gathering, monitoring, and analysis
3. Implement outreach plan
4. As necessary modify injection parameters

<u>Re-evaluation - steps</u>

1. Refresh evaluation – re-analyze
2. Analyze impact – ground motion studies, damage
3. Perform geomechanical and hydrologic analysis & modeling
   - Fault, stress, connection route of fluids
   - Pore pressure analysis
4. Explore all possible causes – e.g. geothermal, meteorological, production, volcanic
5. Catalog findings to inform mitigation actions

As necessary, utilize evaluation tool boxes

SUMMARY

- Induced seismicity is seismicity due to human activity
- Induced seismicity risk from hydraulic fracturing is negligible
- Induced seismicity from fluid disposal has occurred in very few, isolated cases
- Appropriate measurement of seismicity is local ground motion and its intensity
- The risk of induced seismicity from fluid disposal can be managed within a fit for purpose framework