Characterizing and Responding to Seismic Risk Associated with Earthquakes Potentially Triggered by Fluid Disposal and Hydraulic Fracturing

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INTRODUCTION AND CONTEXT

For nearly a century, earthquakes apparently triggered by fluid injection have been observed in many parts of the world (National Research Council [NRC], 2012). Although injection-related seismicity is a well-known phenomenon, recent years have seen a dramatic increase in earthquake occurrence apparently associated with oil and gas development. This increase has been most notable in the central and eastern United States (Ellsworth, 2013). Recent occurrences of felt events in areas of significant populations have brought attention to this issue from the public, oil and gas operators, regulators, and academics.

Though fluid disposal and hydraulic fracturing both have the potential to trigger earthquakes, it has become clear that the potential for induced seismicity is higher for fluid (usually saltwater) disposal than for hydraulic fracturing. For instance, saltwater disposal involves very long injection times (years to decades) and very large injection volumes (often thousands to tens of thousands of m^3 per day). This leads to much more extensive pressure perturbations than hydraulic fracturing operations, in which 1000 m^3 might be injected over an $\sim$2 hr period. The inherent differences in injection practices between these two different types of fluid-injection operations, and the apparent differences in the potential for triggering earthquakes, mean that appropriate procedures for risk assessment associated with each of these two types of fluid injection need to be developed, as described below. In this work, we focus our discussions on saltwater disposal and hydraulic fracturing, though the concepts presented can be generally applied to other types of fluid disposal.

The primary physical processes responsible for injection-related seismicity are generally well known (see reviews by Suckale, 2009; NRC, 2012). Simply put, the normal effective stress resists fault slip by acting perpendicular to a fault, essentially clamping it shut. As pore pressure increases, the effective normal stress on a fault is reduced, potentially triggering the release of accumulated strain energy on a pre-existing fault that is already close to failure (NRC, 2012). These faults are often referred to as critically stressed. Earthquakes on critically stressed faults influenced by fluid injection are referred to as triggered because relatively small perturbations release already-stored energy through an earthquake (McGarr *et al.*, 2002). The pressure change resulting from fluid injection simply triggers its release.

As the increase in triggered earthquakes becomes more problematic, it is clear that it would be advantageous to develop an initial seismic risk assessment to apply to proposed and pre-existing fluid-injection sites (The Royal Society, 2012). Earthquake hazard and risk assessments are well established but have historically focused on natural earthquakes and rarely anthropogenic earthquake triggering. Our work builds largely on previously published work but differs in that we present a comprehensive framework that considers the scientific factors necessary for a hazard and risk-assessment workflow in a format that is site adaptable and can be updated as hazard and risk evolve with time. This changing hazard and risk may be due to a new geological understanding, updates made to the operational factors, changes in the exposure, or changes to the tolerance for risk at the site.

We offer suggestions for how to incorporate anthropogenic factors, which we term "operational factors," that may influence the occurrence of triggered seismicity in a site-specific manner, as well as the exposed populations, properties, structures, and infrastructure. In addition, we discuss the use of risk-tolerance matrices that take into consideration the level of tolerance the affected groups have for earthquakes triggered by fluid injection, including the operators, regulators, stakeholders, and public, in the context of the expected benefit of the oil and gas operations. These concepts are discussed more thoroughly in an expanded document available online at the Stanford Center for Triggered and Induced Seismicity webpage (https://pangea.stanford.edu/scits/sites/default/files/scitsguidelines_final_spring2015_0.pdf; last accessed May 2015).

HAZARD AND RISK-ASSESSMENT WORKFLOW

Our proposed hazard and risk-assessment workflow for earthquakes triggered by hydraulic fracturing and saltwater disposal

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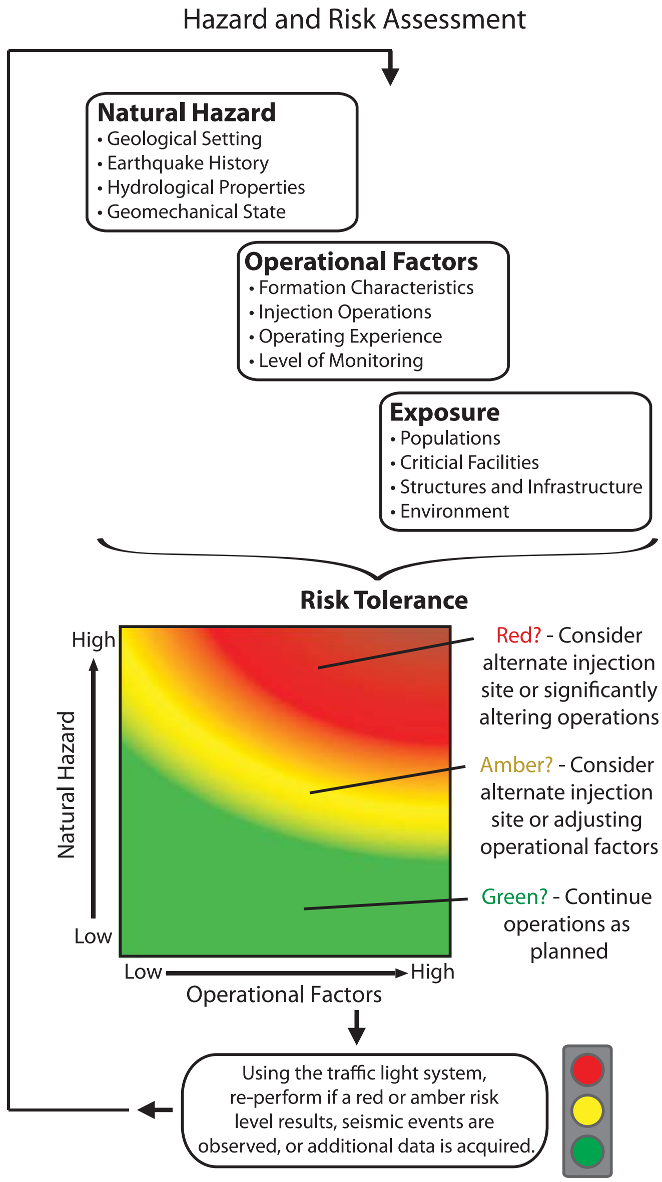


▲ **Figure 1.** Hazard and risk-assessment workflow. In concept, the hazard, operational factors, exposure, and tolerance for risk are evaluated prior to injection operations and reflected by shifting the green to red color spectrum in the risk-tolerance matrix. After injection begins, the occurrence of earthquakes in the region and additional site-characterization data could require additional iterations of the workflow. Below, we show different risk-tolerance matrices for different levels of exposure.

is meant to be site specific and adaptable (Fig. 1). It includes an analysis of the earthquake hazard at a site using the known geology, hydrology, earthquake history, and geomechanics of the area that, when used with a probabilistic seismic-hazard analysis (PSHA) (e.g., McGuire, 2004), is the basis for determining the probable level of natural seismic hazard. In some cases there may be significant uncertainty in determining the level of hazard in an area due to data quality or resource availability and this should be considered in the risk assessment. The determined natural hazard is then used in conjunction with operational factors that influence the potential for the occurrence of triggered earthquakes, including specific injection practices, the operating experience in the area and of the company responsible, and the formation characteristics. Once probabilities of experiencing various levels of ground motions have been estimated based on possible triggered earthquake source locations and source sizes, they can be combined with the associated likely consequences to evaluate risk. Consequences depend upon the level of exposure of the site and surrounding area and the contributing operational factors. As such, risk assessment and planning need to occur jointly with planning of operations that might affect risk. Both the operational factors and exposure are described further below.

The proposed workflow is intended to be implemented prior to injection operations and then used iteratively as new information related to the hazard and risk becomes available. Although this process may be difficult in practice, it is important to reflect upon examples of injection operations where a risk-tolerance assessment could have prevented triggered events, such as the earthquakes triggered by injection in Basel, Switzerland (Deichmann and Giardini, 2009). In cases where the risk is non-negligible, mitigation can include additional monitoring and data collection (Nygaard *et al.*, 2013). In severe cases, particular areas may be identified as having unreasonably high hazard and subsequent risk for fluid injection.

OPERATIONAL FACTORS

Along with the earthquake history and geologic, hydrologic, and geomechanical characteristics of a site, a number of operational factors also contribute to the potential for triggered seismicity (Fig. 2). It is the responsibility of the operators and regulators to determine the level of impact that the operational factors have on the risk level of a project. Operational factors are specific to triggered seismicity and not included in standard seismic hazard and risk calculations. Because these operational factors are not included in current PSHA procedures, we account for them separately in the formation of a project's risk-tolerance matrix. Conceptually, we would like to quantify factors that influence the likelihood of earthquake occurrence in terms of the seismic source model of the hazard analysis calculation. However, because it is currently difficult to link these operational factors in a quantitative or causative manner to earthquake occurrence, we take an indirect approach and consider operational factors as a separate metric to be used when assessing risk.

First, there are particular formation characteristics that may affect the risk at a site in addition to choosing injection well locations sufficiently far from potentially active faults. Specifically, examining whether the injection interval is in communication with the basement (i.e., a crystalline formation underlying sedimentary rocks) or an underpressured (subhydrostatic) environment. If the injection formation is located directly above the basement without the presence of a sealing formation or if it appears as though a permeable path may be connecting the injection formation with the basement, the

Operational Factors	Formation Characteristics	Injection Operations: Wastewater Injection	Injection Operations: Hydraulic Fracturing	Operating Experience
Significant	Injection horizon likely in communication with basement, underpressured injection interval	High cumulative injection volumes and rates	High fluid injection volumes and pressures near active faults, no flowback performed	Limited injection experience in region, past earthquakes clearly or ambiguously correlated with operations
Moderate	Injection horizon potentially in communication with basement, slightly underpressured injection interval	Moderate cumulative injection volumes and rates	Moderate fluid injection volumes and pressures near active faults, flowback possibly performed	Moderate injection experience in region with no surface felt ground shaking
Minor	Injection horizon not in communication with basement	Low cumulative injection volumes and rates	Low fluid injection volumes and pressures remote from active faults, flowback possibly performed	Extensive injection experience in region with no surface felt ground shaking

▲ **Figure 2.** The factors related to operations that contribute to the level of risk at an injection site.

Exposure	Critical Facilities	Structures and Infrastructure	Environment	Populations
High	Facilities in the immediate vicinity with the potential to suffer damage	Few designed to withstand earthquakes based on current engineering practices	Many historical sites, protected species, and/or protected wildlands	High population density and/or total population
Moderate	Facilities in the nearby area	Many designed to withstand earthquakes based on current engineering practices	Few historical sites, protected species, and/or protected wildlands	Moderate population density and/or total population
Low	No facilities in the area	Most designed to withstand earthquakes based on current engineering practices	No historical sites, protected species, and/or protected wildlands	Low population density and/or total population

▲ **Figure 3.** The technical factors that contribute to the level of exposure at an injection site.

earthquake risk for the project may increase significantly (Zhang *et al.*, 2013).

Second, the specific injection operations also have the potential to affect the level of risk associated with a project and site. The injection rates and volumes at single wells may be correlated with earthquake activity at a site. An increasingly significant operational consideration for saltwater disposal wells is the rate of injection of a well or a group of wells in close proximity. Moreover, high rates of injection in neighboring wells can cause a cumulative effect in the form of an unusually large pressure halo that could trigger slip on potentially active faults in the area. Modeling by Keranen *et al.* (2014) showed that the pressure generated by four very high-rate injection wells is expected to be significant in the vicinity of the wells. The diffuse seismicity now occurring in Oklahoma appears to be the result of increased pressure in the Arbuckle saline aquifer and underlying basement rocks as a result of cumulative injection from many injection wells over a number of years (Walsh and Zoback, 2015).

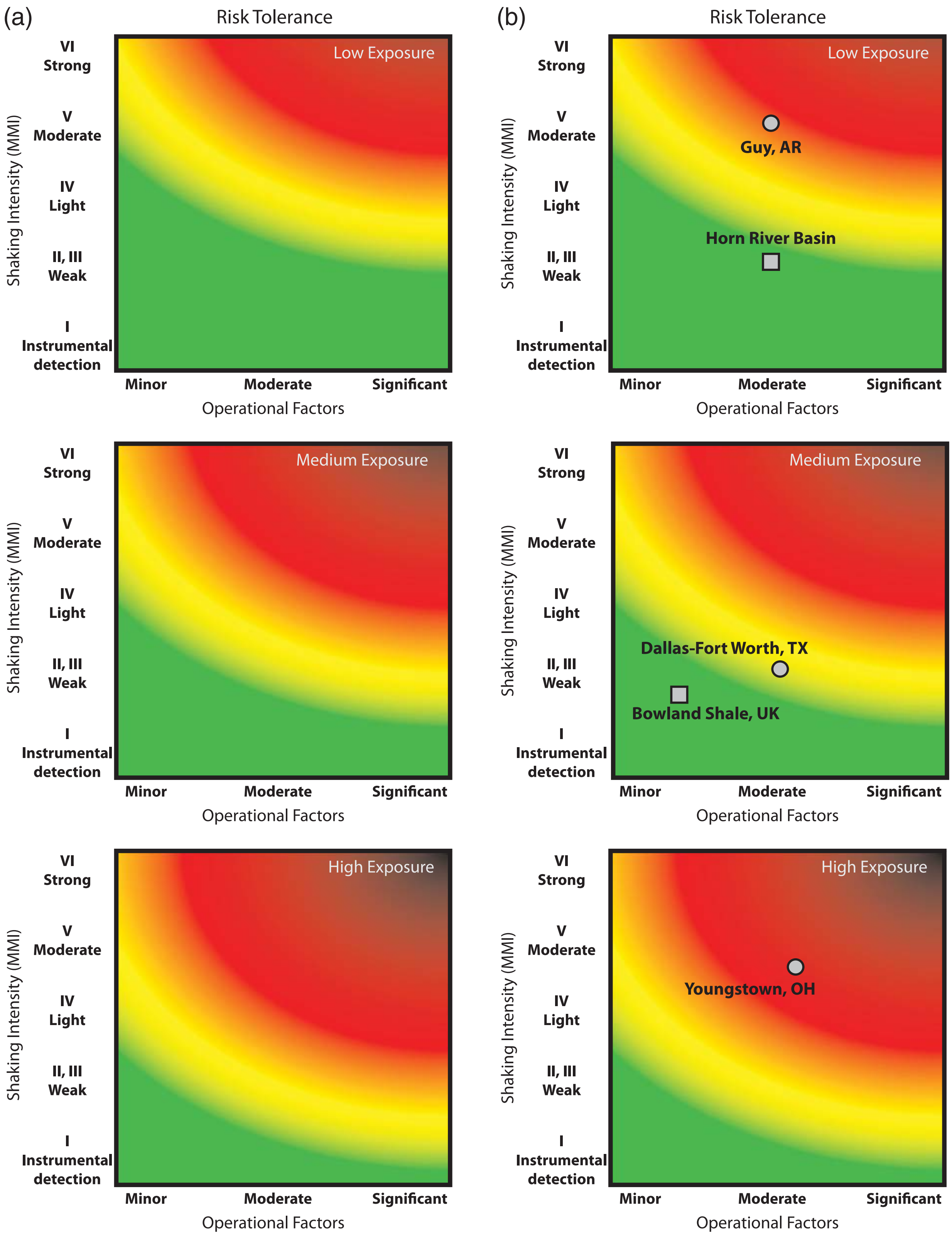
EXPOSURE

The exposure associated with a particular site depends on the number, proximity, and condition of critical facilities, local structures and infrastructure, the size and density of the surrounding population, and protected sites that have the potential to experience ground shaking as a result of fluid injection. Specific items to identify include populations, hospitals, schools, power plants, dams, reservoirs, historical sites, hazardous materials storage, and natural resources influenced by ground shaking (American Exploration and Production Council [AXPC], 2013). If an injection project is proposed near one or more of these items, the risk for the project increases commensurately. For example, it may be unreasonable to perform fluid injection very near critical facilities such as refineries, power plants, or hospitals (structures with potentially significant consequences given a particular level of ground shaking). In general, it is important to consider whether nearby structures and infrastructure are capable of withstanding ground motion that could be caused by a triggered seismic event, keeping in mind that standards of construction vary widely depending on the year of construction, applicable building codes, and other factors. Structures and infrastructure may include buildings, roads, pipelines, and electrical distribution systems (AXPC, 2013). Figure 3 offers a summary of details related to exposure to consider when determining the level of impact these parameters have on the overall risk.

The area of concern for factors related to exposure will be site dependent. The AXPC (2013) suggests considering populations that are within a 10-mile radius of the injection site. However, earthquakes can potentially be triggered at some distance away from an injection site, and ground shaking from a moderate earthquake can be felt over a wide region. Determining this area of concern could be done in a way that incorporates the site-specific conditions of the geology, hydrology, geomechanical characterization, earthquake history, and exposure to risk, as well as whether injection from neighboring operators may have a cumulative contribution to the risk in the area.

RISK MATRICES

Once the seismic hazard, exposure, and operational factors are determined for a given project, operators and regulators can aggregate the results using a risk-matrix method. Figure 4 shows how the results from the hazard assessment via PSHA (vertical axis), the operational factors (horizontal axis), and the exposure (top, middle, or bottom figure) can be aggregated to perform such an evaluation, as expanded upon from concepts proposed by Nygaard *et al.* (2013). Figure 4a shows generalized risk-tolerance matrices for areas of low exposure, medium exposure, or high exposure. In our proposed risk-tolerance matrices, the green regions would be considered favorable given appropriate operational practices; amber regions would be considered acceptable but may require enhanced monitoring, restricted operational practices, and real-time data analysis; and



▲ **Figure 4.** Risk-tolerance matrices. (a) Generalized risk-tolerance matrices associating the level of hazard (probable shaking intensity determined using PSHA), the operational factors (Fig. 2), exposure (Fig. 3), and the tolerance for risk of a particular injection project. (b) Examples of projects being plotted on the risk-tolerance matrices in light of what we know after events have occurred. The squares represent hydraulic fracturing projects and the circles represent saltwater disposal projects.

red regions would require significant mitigating actions or potential site abandonment.

An understanding of the risk that exists for a particular project will allow the affected parties to determine the level of tolerance they have for the estimated risk. The tolerance for potential ground shaking will be shaped by the political, economic, and emotional state of the populations involved, making it inherently site specific. In high-risk cases or for those who have a low tolerance for the determined risk, injection may not be allowed to proceed in certain locations. Alternatively, in other areas, the tolerance for risk may be sufficiently high to not interfere with the proposed injection project. Of course, how one determines the exact levels of exposure, operational factors, hazard, and subsequent risk to inform the specific risk-tolerance matrix used for a particular project is somewhat subjective and requires collaboration among the stakeholders.

We consider several examples of actual injection operations to illustrate the use of the risk-tolerance matrix in Figure 4b. In each case, we only performed a rough analysis to provide context based on the current scientific literature. When this workflow is implemented, a more thorough analysis should be performed, including the use of PSHA to determine the probable hazard for a given project. For PSHA results to be utilized in this matrix, the ground shaking intensity with a given exceedance rate will need to be determined. In natural earthquake hazard applications, the focus is often on strong but rare ground-motion intensities (particularly for determining building codes). In addition to these rare ground motions, triggered seismicity applications also focus on the more frequent (i.e., higher-exceedance-rate) but smaller intensity ground motions. We estimate the probable hazard in light of what we know after each of these earthquakes occurred (Fig. 4b). It is important to note that each project will have its own risk tolerance that will be determined by the public and stakeholders that are directly impacted. In order to reflect these differences in risk tolerance, the colored portions of the risk-tolerance matrices should shift either up or down (to become more lenient or strict, respectively).

In a low-exposure area, we consider the Horn River basin hydraulic fracturing project in British Columbia, shown in Figure 4b, to describe the qualitative strategy used to determine the project's location on the risk-tolerance matrix. The Horn River basin area is a remote location with very low exposed population and little-to-no built infrastructure. It had experienced no significant earthquakes between 1985 and 2007 when development began (Nygaard *et al.*, 2013). In April 2009 and December 2011, 38 earthquakes were recorded between **M** 2.2 and 3.8 on the National Resources Canada (NRCAN) seismic network. Following Nygaard *et al.* (2013), we consider the probable ground shaking to be between MMI II and V. In Figure 4b, we plot the Horn River basin example in the green shaded region in the low-exposure risk-tolerance matrix, suggesting that additional mitigation efforts may not be needed.

If we imagine the Horn River basin case occurring in a medium-exposure area, the project would be located in the amber portion of the medium-exposure risk-tolerance matrix, suggesting that heightened monitoring and data analysis, in addition to potentially adjusting injection operations, may be appropriate. If we extend this and imagine the Horn River case in a high-exposure level, the project would be in the red portion of the high-exposure risk-tolerance matrix. This suggests that limiting injection or potentially abandoning the well, extending earthquake monitoring and analysis, and communicating with area regulators and neighboring operators may be appropriate.

In addition to the Horn River basin, we consider the possible placement of other projects onto the risk-tolerance matrices, including the Guy, Arkansas, saltwater disposal site (Horton, 2012), the Dallas–Fort Worth saltwater disposal site (Frohlich *et al.*, 2011), the Youngstown, Ohio, saltwater disposal site (Kim, 2013), and the Bowland Shale (Preese Hall) hydraulic fracturing site (Green *et al.*, 2012; Clarke *et al.*, 2014). The Guy, Arkansas, wastewater disposal project was placed in the red portion of the low-exposure risk-tolerance matrix because it is located in an area with a low population density and few structures and infrastructure, but there was an **M** 4.7 earthquake with an extended lineation of earthquake epicenters in 2011 (Horton, 2012). The Dallas–Fort Worth saltwater disposal site experienced several earthquakes of **M** 3.3 and below between October 2008 and May 2009 (Frohlich *et al.*, 2011). We considered the site to be of medium exposure because of the close proximity of the Dallas–Fort Worth airport, resulting in the project being located in the amber portion of the medium-exposure risk-tolerance matrix. The Youngstown, Ohio, saltwater disposal site was placed in the red portion of the high-exposure risk-tolerance matrix due to its proximity to the Youngstown, Ohio, urban area and the occurrence of an **M** 3.9 earthquake in December 2011 (Kim, 2013).

The Bowland Shale hydraulic fracturing project was placed in the green portion of the medium-exposure risk-tolerance matrix because the project used a fairly unaggressive injection strategy located in a moderately populated area that experienced an **M** 2.3 earthquake in 2011 (Green *et al.*, 2012; Clarke *et al.*, 2014). However, it is clear that the stakeholders involved in hydraulic fracturing operations in the United Kingdom have a very low tolerance for risk and might consider the medium-exposure risk-tolerance matrix we show here to be not strict enough. Therefore, they may produce risk-tolerance matrices for their sites that show the transitions between the green, amber, and red portions occurring at lower possible shaking intensities.

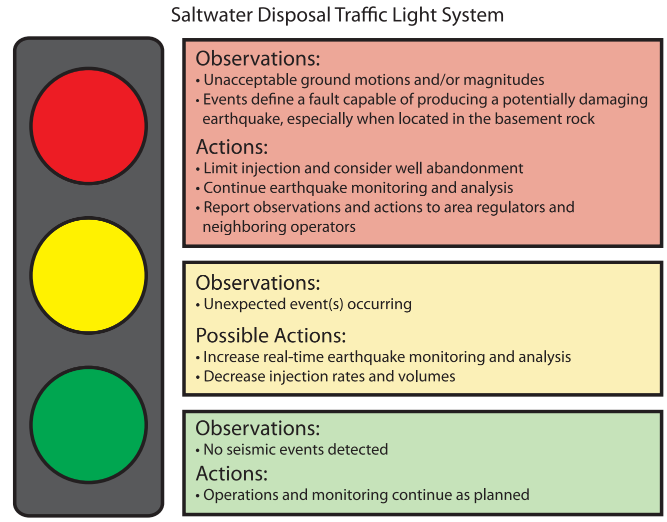
TRAFFIC-LIGHT SYSTEMS AND RAPIDLY CHANGING RISK

Traffic-light systems are a risk management tool that can be used to address the possibility of seismic risk changing with time due to the occurrence of unexpected seismicity in an area of saltwater disposal or hydraulic fracturing. Traffic-light systems have historically been used in enhanced geothermal settings and have been based on ground shaking or magnitude thresholds to signify whether the injection project should continue as planned (green), modify operations due to heightened risk (amber), or suspend operations due to severe risk (red) (Majer *et al.*, 2012; NRC, 2012; Department of Energy and Climate Change of the United Kingdom [DECC], 2013). These systems have the potential to provide an excellent means of communication between the operating companies, regulators, the media, and the public. They allow private companies and responsible state and federal agencies to communicate (1) the possible significance of the unusual seismic activity, (2) the steps that should be taken to better understand the risk associated with the seismicity, and (3) the conditions under which remedial action might be taken.

The standards used by individual projects for traffic-light systems would be most effective if they were tailored to be site specific and dependent on the risk assessment, rather than fixed for all circumstances. Development of the systems could take into account all aspects of hazard and risk and could be developed with guidance from regulators, local geologic surveys, or operators (Canadian Association of Petroleum Producers [CAPP], 2012; Nygaard *et al.*, 2013). Early in the development of the traffic-light system, it is important to use the outcome of the risk-tolerance assessment to decide whether earthquake monitoring is necessary and, if so, how the seismic data will be observed and analyzed. It may be beneficial to consider not only earthquake magnitude thresholds and ground shaking but also particular geological observations, such as whether small magnitude events highlight a fault capable of producing a relatively large earthquake or whether small magnitude events migrate into the basement rock, in an attempt to be more proactive in mitigating triggered earthquake risks. In cases of high risk, this may include the continual performance of in-depth, real-time analysis of microseismic data that would aim to identify particular event characteristics that could foreshadow felt or damaging earthquakes, as discussed below.

Traffic-light systems are dependent on the level of monitoring used at the site, which is determined by the outcome of the risk assessment. Earthquake monitoring is beneficial and appropriate at injection sites with sufficient levels of risk. This monitoring could be done using data from regional or local arrays, or operational arrays specific to the injection site. How frequently data are requested and collected from the local arrays or acquired from operational arrays and then analyzed will be based on the seismic hazard and risk assessment. In cases of significantly high risk, it may be necessary to have a real-time telemetry system in place that allows for the constant delivery of data to an automated event-analysis system. An automated system that detects, locates, and estimates the magnitude of the earthquakes in the region would allow for an efficient means of determining if any events have characteristics such as events highlighting faults and determining if the events have a larger spatial coverage and faster migration rate than expected. In cases of low risk, it may not be necessary to have a real-time automated system, but instead a system that allows the data to be requested or collected as needed or periodically.

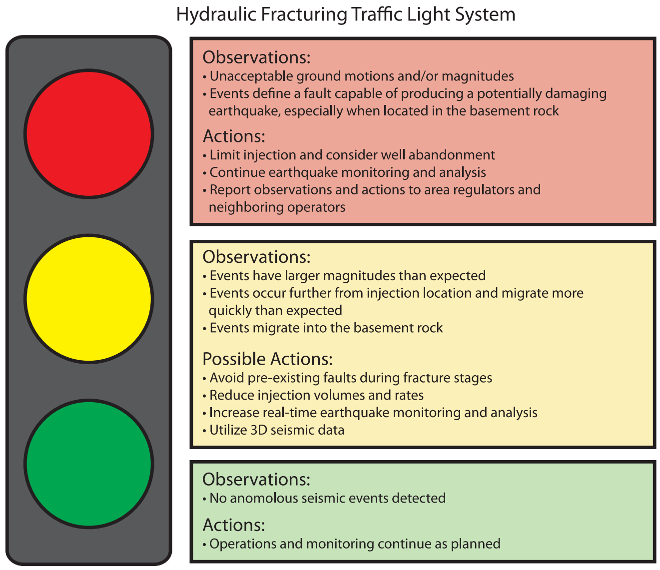
The traffic-light systems we present here focus on two project types (saltwater disposal [Fig. 5] and hydraulic fracturing [Fig. 6]) and encourage a site-specific, risk-informed, real-time risk-management system that could be increasingly effective when updated as new data become available. The level of risk at a site informs the level of the seismic monitoring network used and any necessary operational adjustments. Our proposed system incorporates often subtle, but potentially diagnostic, geological and geophysical characteristics that may indicate a potentially larger event to come. This is done by focusing on specific observations that suggest the presence of a fault large enough to host a significant triggered earthquake. For the two project types, different observations may cause operators to transition between the green and amber zones of the traffic light; however, we suggest that the same observations may cause injection operations for both saltwater disposal and hydraulic fracturing to move into the red zone of the traffic light.



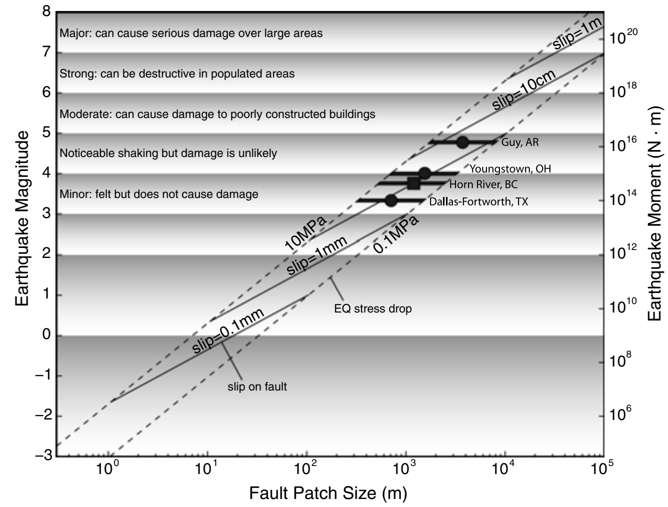
▲ **Figure 5.** Traffic-light system applicable to saltwater disposal. The green, amber, and red panels represent the levels of heightened awareness frequently represented in traffic-light systems. Within each panel, we suggest what observations might be considered and possible actions to take.

Of particular concern, and a key observation in mitigating risk, is whether there is the potential for triggered earthquakes to occur on relatively large, critically stressed, pre-existing basement faults. Over the life of an injection project, it is thought that pore pressure perturbations have the potential to migrate toward critically stressed, permeable faults in the crystalline basement. A relatively simple conceptual model involving the migration of pressure perturbations from injection horizons in Oklahoma to active basement faults has begun to evolve that shows how long-duration fluid injection has the potential to trigger slip on relatively large faults (Keranen *et al.*, 2013; Zhang *et al.*, 2013).

Figure 7 illustrates well-documented earthquake scaling relationships of relatively large triggered earthquakes based on their reported magnitudes (as summarized in Stein and Wysession, 2009). From these scaling relationships, we can see that an **M** 4.7 earthquake, the largest magnitude event that occurred at



▲ **Figure 6.** Traffic-light system applicable to hydraulic fracturing. The green, amber, and red panels represent the levels of heightened awareness frequently represented in traffic-light systems. Within each panel, we suggest what observations might be considered and possible actions to take.



▲ **Figure 7.** Scaling of earthquake source parameters showing the relationship between earthquake magnitude, the size of the fault patch that slips in the earthquake, and the amount of fault slip using principles summarized in Stein and Wysession (2009). Triggered earthquakes are plotted based on their reported magnitudes using circles for saltwater disposal and a square for hydraulic fracturing (Frohlich *et al.*, 2011; BCOGC, 2012; Horton, 2012; Kim, 2013).

Guy, Arkansas (Horton, 2012), suggests slip on a fault that is a kilometer in length. Fault patch sizes this significant are often larger than the thicknesses of the formations in which fluids are being injected, suggesting that fluids are migrating toward other formations (i.e., crystalline basement) that are capable of hosting such faults.

Previously unidentified faults large enough for potentially damaging triggered earthquakes may be identifiable using observations outlined in the proposed traffic-light system. These observations include considering whether event locations highlight faults (either previously identified or not), whether those faults are preferentially oriented for shear failure in the current state of stress, whether the events have a larger spatial coverage and migrate faster than expected, or whether the events have higher magnitudes than expected.

As fluids are injected into the subsurface and microseismic events are monitored, there are two observations that may indicate the presence of active faults. First, events may migrate farther from the injection zone than expected, indicating that fluid is potentially migrating through a permeable, active fault. Second, small earthquakes may illuminate a planar feature, suggesting the presence of a potentially active fault. Further analysis and a degree of caution would be appropriate through a continued examination of historical seismic data, microseismic data, or any available 3D seismic data. If an illuminated feature is preferentially oriented for failure, then the seismic hazard may increase and the operational factors may need to be adjusted accordingly, with the consideration of well abandonment in severe cases.

Ideally, all injection operations will begin in the green zone of the risk-tolerance matrix and the traffic-light system, where operations and monitoring would be carried out as planned based on the outcome of the initial risk assessment. For saltwater disposal, as long as no earthquakes are detected, the project remains in the green zone. For hydraulic fracturing, we would expect to observe very small magnitude earthquakes, but if an anomalous seismic event(s) was detected, the project may transition to the amber zone. Any time a project moves out of the green zone and into the amber or red zone, it would be beneficial to quickly evaluate to what extent operation practices might be adjusted or halted and what analysis might be performed (CAPP, 2012; NRC, 2012; AXPC, 2013). Operators and regulators may work together to determine the extent of the event(s), perform these evaluations and preliminary analyses of the event(s), and maintain open communication with each other and nearby operators (CAPP, 2012).

If a project begins in the amber zone of the risk-tolerance matrix and traffic-light system, or moves into it due to the occurrence of unexpected events, then caution should be exercised at all times in the form of heightened awareness, enhanced monitoring, and/or the real-time data analysis. We stress that the amber zone of the traffic light should neither be necessarily interpreted as a disadvantageous phase nor should it be thought that a project would inevitably move to the red zone of the traffic light. Example actions are slightly different for saltwater disposal and hydraulic fracturing. In the case of saltwater disposal, it may be reasonable to decrease injection rates, volumes, and pressures, while for hydraulic fracturing, avoiding pre-existing faults during individual fracture stages, reducing injection rates and volumes, and utilizing 3D seismic data to identify faults in the subsurface may be considered.

Observations that may cause a project to move into the red zone of the traffic-light system for both saltwater disposal and hydraulic fracturing projects include the detection of unacceptable levels of ground shaking or magnitudes, events defining a fault capable of producing a potentially damaging earthquake, and events migrating into the basement rock. Actions that could be considered if any of the above observations occur include limiting injection and considering well abandonment, continuing earthquake monitoring for the duration of the examination or sometime after the injection has ceased, and reporting observations and operational practices to area regulators and neighboring operators. In these cases, it is important to continue monitoring for additional earthquakes that may occur postinjection because the events may provide valuable insight for hazard and risk assessments for ongoing and future injection projects in the area.

It is important to note that after a project moves to amber or red, it may be possible to transition back to a lower risk level after a thorough evaluation of changes to the hazard and risk at the site. This may include engaging engineers and subsurface geological and geophysical experts to review available subsurface data and, if necessary, to design and conduct engineered trials to adjust operating procedures as appropriate with respect to injection volumes, rates, and locations (CAPP, 2012). It would be critical to re-evaluate the tolerance for risk at the site in light of the observations that caused the project to transition to the amber or red portion of the traffic-light system.

If triggered events occur, all area operators and regulators have the opportunity to increase their understanding of the potential to trigger or induce events in the future. Sharing information such as the time, location, magnitude, the focal mechanism (if the operator is able to calculate this information given the monitoring), and the injection history leading up to the event with regulators and other area operators may be necessary. Enhancing the seismic monitoring at a particular site, even if a project moves into the amber or red zone of the traffic light or if a project is abandoned, allows for a more detailed evaluation of any future events (AXPC, 2013).

SUMMARY AND DISCUSSION

To date, there are many different guidelines, regulations, and studies that have been published or put into practice that focus on triggered earthquake risk. Many of these are *ad hoc*, prescriptive, and reactionary. We present here a framework for risk assessment for triggered seismicity associated with saltwater disposal and hydraulic fracturing and offer systematic recommendations for factors to be considered. This framework includes an assessment of the site characteristics, seismic hazard, operational factors, exposure, and tolerance for risk. The process is intended to be site specific, adaptable, and updated as new information becomes available. We describe factors that are not currently included in standard earthquake hazard and risk-assessment procedures, including considering the necessary anthropogenic factors that are inherent in fluid-injection operations. We use risk-tolerance matrices as a means for including all aspects that influence the tolerance risk regulators, operators, stakeholders, and the public have for triggered earthquakes. The hazard and risk-assessment workflow includes the use of a traffic-light system that focuses on geologic and geophysical observations, rather than only earthquake magnitudes or ground motions, as the determining factors for whether a particular site needs to consider enhanced monitoring and decreased injection practices or possible injection-well abandonment.

The risk-assessment workflow offered in this document is meant to provide a framework for which oil and gas operators and regulators can build upon in order to reduce the risk of earthquakes triggered by fluid disposal. In order to implement this workflow, the parties responsible for each component of the risk assessment would need to be identified and the differing tolerances to risk between the stakeholders would need to be addressed. Future work may include determining how to implement a hazard assessment that considers the factors pertinent to earthquakes triggered by fluid injection.

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