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Abstract

A technical meeting was held on October 6, 2015, at the downtown campus of the University of Calgary to discuss the effectiveness of the traffic light protocol (TLP) approach for management of risks from induced seismicity. The meeting was attended by 64 participants from industry (55%), various government agencies (25%), academia (10%), and professional societies (5%). The role of TLP in the mitigation of seismic hazards from induced seismicity and its challenges were examined. Three major issues with the current magnitude-based TLPs were identified: (1) possible confusion due to the magnitude uncertainty for an induced seismic event, (2) lack of a link to the impact/consequences of reported seismic event(s), and (3) need to integrate other potential hazard indicators. To improve the effectiveness of existing TLPs, the following changes are recommended: (1) incorporate ground motion information into TLPs such that decisions can be made based on better assessment of the actual risk, (2) develop a standardized approach for earthquake magnitude calculation, and (3) make the TLPs more adaptive to local hazard conditions through research and incorporation (as appropriate) of other hazard indicators. A number of action items were brought forward at the workshop: (1) establishing a uniform standard for seismic data collection and assessment, (2) establishing a coherent framework of data sharing for induced seismicity monitoring and research, (3) sharing other types of data, such as locations of known faults, and (4) taking more proactive approaches to establish best practices and to mitigate seismic risk from induced seismicity. These actions will greatly strengthen the reputation of the hydrocarbon industry with respect to proactive, sensitive and responsible development of unconventional sources. If these steps can be implemented in a timely and effective manner, Canada has the potential to be a world leader in monitoring, understanding and mitigating hazards and risks from injection-induced seismicity.

Introduction

In response to the occurrence of relatively large (and felt) earthquakes that are potentially induced by man-made activities, there is an increasing trend for the industry and government regulators to include a "traffic light" system in their decision-making process. Traffic light systems were first developed as a tool for enhanced geothermal systems [*Bommer et al.*, 2006], and has since been widely adapted for seismic risk mitigation associated with a variety of injection operations. Despite its significant implications for the cost of operations and the protection of public safety, the protocol that defines the different scenarios for different lights ("green", "yellow", or "red") has not been thoroughly examined with respect to its effectiveness as a risk-mitigation measure. Most government regulators adopt a traffic light protocol (TLP) that depends on both the magnitude of the earthquake and local community reports. Ground-shaking information is rarely included in TLPs for induced seismicity, yet it is the intensity of shaking, in combination with the proximity of vulnerable infrastructure that will determine the risk.

It is well known that the estimate of an earthquake's magnitude can have some uncertainty. The source of magnitude uncertainty can be attributed to multiple factors, including the widespread use of different magnitude scales (M_L, M_w, M_s, m_b, M_N, etc.), choice of stations used (i.e., different distance and azimuthal coverage), amplitude variation as a function of frequency due to different combinations of seismic moment and stress drop, and different attenuation correction functions. While an uncertainty of ±0.2 in magnitude is understandable and generally accepted by the seismological community, even an uncertainty of this level can create a serious problem when the value of magnitude is used to determine whether or not an injection operation should be suspended. Recent examples of magnitude 4 and larger earthquakes in northeast BC and western AB that are possibly induced by injection operations have highlighted possible deficiencies of existing TLPs for induced seismicity.

To identify specific issues of TLPs and how they should be addressed, a one-day technical meeting was organized by a group of researchers involved in the study of induced seismicity. The main purpose of this technical meeting was to gather stakeholders from government agencies (regulators, scientists, research managers, etc.), industry, and academia to engage in a focused discussion on TLPs for induced seismicity. The themes of this meeting included:

1. To outline the expected benefit of implementing a TLP in the decision/policy-making process and to examine the practicality of such measures;
2. To review deficiencies of current TLPs for induced seismicity and to explore innovative ways of improvement;
3. To seek possible alternatives that could achieve a better balance between the protection of public safety and the economic benefit of developing natural resources; and
4. To build toward a consensus among government, industry and academia for future scientific collaboration on induced seismicity research.

One goal of this meeting was to produce technical documentation to inform/improve decision-making at all levels. This report summarizes the format of the meeting, results of discussion during the meeting, and the meeting's main conclusions. Specific recommendations on how to improve existing TLPs and promote research efforts and collaborations to ultimately develop best practice of unconventional oil and gas development are also presented.

Timeline and Program

This technical meeting was originally planned by the Geological Survey of Canada (GSC) to be held on October 6, 2015, at the Sidney, BC, office (also known as the Pacific Geoscience Center, PGC).

The first announcement was sent out on August 5, 2015, to a group of 54 potential participants. Due to the sensitive nature of the meeting topic during the course of a federal election (August 4 – October 19, 2015), the Natural Resources Canada (NRCan) proposed to postpone the meeting until after the election. After consulting a group of potential participants, a consensus was reached to hold the meeting as originally scheduled under the condition that NRCan does not assume the role of hosting organization. Despite the short notice, the University of Calgary generously announced on September 4, 2015, to host this meeting at its downtown campus. Relocation of the meeting place made it somewhat easier for industry representatives to participate. As a result, the organization committee turned down many late requests due to the limited capacity of the meeting room.

Overall, there were 64 participants: 35 (55%) from the industry, 16 (25%) from various government agencies, 10 (15%) from academia, and 3 (5%) from professional societies (Figure 1). The assembly thus had a well-balanced mixture of expertise, including field operation experts, corporate executives and administrators, government regulators, researchers, and funding managers.

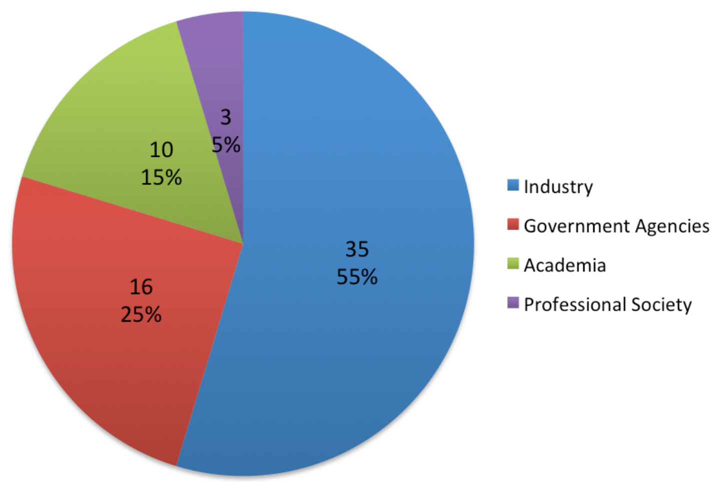

Figure 1. Participants of the Technical Meeting on Traffic Light Protocols for Induced Seismicity.

The meeting began with welcome remarks given by Prof. David Eaton (University of Calgary). Dr. Honn Kao (NRCan) was the first speaker to present an overview of the standard operation procedures on earthquake monitoring in Canada. Dr. Todd Shipman and Mr. Dan Walker then gave talks to introduce existing TLP regulations in Alberta (AB) and British Columbia (BC), respectively. These presntations were followed by a session of question-and-answer and group discussion.

The second part of the morning's session was led by a panel of experts in field operation and service to present the industry's perspective on the TLP for induced seismicity. Dr. Shawn Maxwell (IMaGE) was the moderator to facilitate the discussion.

The afternoon's session began with three talks given by university researchers (Dr. Amanda Bustin, University of British Columbia; Prof. David Eaton, University of Calgary; and Prof. Gail Atkinson, University of Western Ontario) to provide some insight from a research point of view. This was followed by the second panel discussion, also moderated by Dr. Shawn Maxwell, to focus on the perspective of regulatory, academic, and legal concerns.

A session of open discussion was arranged at the end of this meeting to gather ideas on how to define a path toward efficient mitigation of seismic risk associated with induced seismicity. It also included sharing experiences of effective communication to the media and the general public. The meeting ended with a brief presentation by Prof. Gail Atkinson to summarize results of discussion and key conclusions. A copy of the meeting's program is attached at the end of this report as an Appendix.

In an effort to encourage presenters and participants to speak freely, all meeting attendees agreed to adhere to the Chatham House Rule, i.e., all participants are free to use the information received, but neither the identity nor the affiliation of the speaker(s), nor that of any other participant, may be revealed. Consequently, all materials presented in this report are considered the collective result of this technical meeting. No opinion from individual participants is implied.

Brief Review of Existing TLPs

The concept of a "traffic light" system is widely used nowadays by governments, organizations, and private companies to characterize the level of a particular threat as well as a set of specific actions in response. In this technical meeting, we define a TLP as a site-specific, real-time, risk management system with multiple discrete response levels. Each TLP level is determined using observable criteria and invokes specific actions designed to mitigate the associated risk.

The first TLP for induced seismicity was proposed for the operations of hydraulic stimulations of enhanced geothermal systems [*Bommer et al.*, 2006]. Based on the level of peak ground velocity (PGV) and the occurrence rate of induced events, the tolerable ground motion was classified into three zones: the "Green" zone corresponds to the level of ground motion either below the threshold of general detectability or, at higher ground motion levels, the occurrence rate lower than the already established background activity level in the area; the "Amber" zone corresponds to the level of ground motion at which people would be aware of the seismic activity associated with the stimulation, but damage would be unlikely; and the lower bound of the "Red" zone is set at the level of ground shaking at which damage to buildings in the area is expected to set in.

Taking such an approach, a 4-level TLP (green, yellow, orange, and red) was established for the enhanced geothermal system in Basel, Switzerland, with each level corresponding to a predefined range of PGV, magnitude threshold, and the number of felt reports from the public [*Häring et al.*, 2008]. Specifically, a green light is given under the condition of PGV <0.5 mm/s, the local magnitude (M_L) of the seismic event <2.3, and there are no felt reports. In this case, the pumping and all operations can continue as planned. A yellow light corresponds to the case of PGV ≤ 2.0 mm/s, $M_L \geq 2.3$, and few felt reports received. It requires the operators to inform regulators/supervisors and the pumping rate should stop increasing. An amber light corresponds to the case of PGV ≤ 5 mm/s, $M_L \leq 2.9$, and many felt reports received. In addition to informing regulators/supervisors, the operators must maintain wellhead pressure below the stimulation pressure by reducing (or even stopping) pumping or by bleeding the well(s). At the red light (PGV >5 mm/s, $M_L >2.9$, and generally felt in the source area), pumping should be stopped and the well(s) should be bled off to minimum wellhead pressure [*Häring et al.*, 2008].

For induced seismicity associated with the development of unconventional oil and gas, the most restricted TLP of the world is probably the one established in the UK in 2013 (https://www.gov.uk/government/publications/traffic-light-monitoring-system-shale-gas-and-fracking). This TLP depends entirely upon the magnitude of the induced event(s) and sets the yellow and red light conditions at $M_L \geq 0.0$ and $M_L \geq 0.5$, respectively.

In the US, different states have implemented different TLPs based on the maximum magnitude of the induced events, the level of ground shaking, the distribution of geological faults, and background seismicity [*Wong et al.*, 2015]. For example, Colorado requires companies to modify operations if triggered events are felt at surface and to suspend operations in an event of $M_L \geq 4.5$. Ohio has established buffer zones around higher risk areas and requires operators to monitor hydraulic fracture operations inside the buffer zones and have a seismicity mitigation plan in place. The monitoring must have a detection threshold of M_L 1.0 or less. If any event with $M_L \geq 1.0$ is detected, operations must be suspended and the company is required to meet with the Ohio Conservation Commission to discuss a plan to resume injection [*Wong et al.*, 2015]. In Oklahoma, the Oklahoma Corporation Commission (OCC) has defined "areas of interest" as 10 km from any M_L 4+ events or earthquake swarms consisting of at least two M_L 3+ events (http://earthquakes.ok.gov/what-we-are-doing/oklahoma-corporation-commission). The specification of OCC's TLP thresholds is defined on a well-to-well basis as permit condition evolves, ranging from 1.8 to 3.7 in M_L [*Wong et al.*, 2015].

For Canadian provinces, the Alberta Energy Regulator (AER) issued Subsurface Order No. 2 on February 19, 2015 to require all operators in the Fox Creek area to establish seismic monitoring arrays capable of detecting M_L 2+ event within 5 km of an injection well. A yellow light is triggered if an earthquake of M_L between 2 and 4 is observed. A red light condition, which requires immediate suspension of injection operations, takes effect when the induced earthquake has an M_L value of 4 or larger.

In BC, the BC Oil and Gas Commission (OGC) has established a similar TLP for induced seismicity. All companies are required to suspend their injection operations if an M_L 4 or larger earthquake occurs within 3 km of the well(s). Operations are allowed to resume only after a mitigation plan is submitted and approved by the OGC. Due to the more frequent occurrence of relatively large induced seismic events in the northern Montney Play, the OGC now is in the process of requiring the installation of seismic monitoring instruments as part of the permit condition in a predefined "high-risk" area. The installed seismic array must be capable of real-time monitoring with a hypocenter resolution of 500 m. Earthquake catalogues must be submitted to the OGC every two weeks. As the regulations are still evolving, the specified measures may/will be adjusted in the future when new information becomes available.

TLP from Regulator's Perspective

In general, regulators deal with any form of risk in three steps: identification, analysis, and treatment. Specifically in terms of seismic risk associated with induced seismicity, the identification part mainly involves enhanced and improved monitoring of local earthquakes, such as densification of regional and local seismic networks to lower the detection threshold of regional seismicity, timely automatic determination of earthquake source parameters (origin time, epicenter, depth, and magnitude), and integration of seismic data collected by various agencies.

The main purpose of seismic risk analysis is to provide an estimate of potential loss or damage due to the occurrence of earthquakes. Since the level of risk is represented by the product of hazard, exposure, and its vulnerability to said hazard, it is possible to have very low risk even if the hazard is high (i.e., when the exposure or consequences are exceptionally low). Conversely, it is possible to have high risk even if the hazard is low (i.e., when the exposure or consequences are high). One of the key functions of a regulator is to incorporate the information/knowledge of potential seismic risk due to induced earthquakes into the policy-making process to achieve a balance between economic benefits and the protection of public safety.

Depending on the nature of actions, risk treatment can be classified as reactive, proactive, and predictive. A reactive risk treatment mainly involves the management and response to a known risk. In this regard, the TLP is considered a reactive risk management tool. The proactive risk treatment, on the other hand, would consider known factors, such as the distribution and geometry of geological faults, or the exposure of population or infrastructure. One example of proactive risk treatment is regional zoning according to established hazard and risk assessment. Predictive risk strategies are a longer-term goal requiring better understanding of induced-seismicity processes. Regulatory agencies are working closely with research communities to explore models with some predictive capability. Mapping the distribution and characteristics of regional tectonic stress, for example, is helpful in finding injection sites that avoid high-risk areas [e.g., *Alt and Zoback*, 2014; *Hurd and Zoback*, 2012].

In general, seismic damage can happen when the peak ground acceleration (PGA) exceeds 5–10% of the Earth's gravity (g), depending on the vulnerability of exposed structures and other factors. For an induced seismic event at 3 km depth, this level of PGA can be easily reached at the site directly above the source, even for small earthquakes (M<4). For events of M>4, damage could well occur if vulnerable infrastructure is exposed. Currently, NRCan has a staff seismologist on call 24/7 to respond to any M4+ earthquakes that occurs inside or in the vicinity of Canada. Immediate on-call response will also be initiated for seismic events with M<4 if they are widely felt in populated areas. From this perspective, setting the suspending-operation threshold (i.e., the red light) at M=4 is convenient.

However, it does not address ground motion consideration, nor risk that may be signalled by operational conditions such as accelerated occurrence of lower magnitude events. In this scenario, an unusually large number of $M2+$ events may provide a seismological indicator that a larger event could be imminent.

The ultimate goal of implementing a TLP for induced seismicity is to ensure a quick and effective reduction in both the number and size of earthquakes when their occurrence is potentially linked to injection operations. It is not clear if such a goal is necessarily achieved by reducing the injection rate and/or pressure or by suspending injection operations altogether. Nonetheless, the overall strategy of reducing the level of injection in case of increasing seismic activity is a practical approach to respond to induced earthquakes in most situations. In some high-risk situations, risk-avoidance may be the best approach.

The TLP currently implemented by the AER appears to have worked well. Since its implementation in February 2015, the AER has dealt with more than 270 cases of induced earthquakes (up to the end of September 2015). Most of these triggered yellow light conditions without any subsequent $M>4$ events. Only one case triggered a red light (June 13, 2015, in the Fox Creek area). In BC, the OGC has issued suspension order in two cases (August 4, 2014, and August 17, 2015; both in the northern Montney Trend). After the operators submitted mitigation plans with different operation parameters, the injections were allowed to resume at a reduced scale.

TLP from Operator and Service Provider's Perspective

The Canadian Association of Petroleum Producers (CAPP) published a document in 2012 to address the issues of assessment, monitoring, mitigation and response for anomalous induced seismicity related to hydraulic fracturing operations [*Canadian Association of Petrolium Producers*, 2012]. Operators can assess the potential for anomalous induced seismicity by analyzing the geological setting and geomechanical conditions, collecting historical seismic patterns, and understanding the local context such as the distribution of population and infrastructure, the types of buildings and local structures, and the environment. The TLP falls in the categories of monitoring, mitigation and response. When anomalous induced earthquakes occur, certain mitigation procedures should be implemented as listed in CAPP's document. In case of the anomalous induced seismicity escalating to unanticipated levels, the on-site personnel could immediately suspend operations and report to the regulator.

From an operator's point of view, the TLP is a part of the decision-making process to better assess and mitigate the potential risk due to induced seismicity and to establish more effective communication with the regulator. One benefit of a TLP based on the magnitude of a seismic event is that it is easy to develop and implement. The simple definition also makes it transparent and straightforward to understand and communicate. However, there are significant challenges that must be addressed, including the lack of standardization if the TLP is going to be implemented for wide applications, the complexity associated with real-time data streaming and processing, the variability in the seismic array design to satisfy reporting criteria, and the lack of validated procedures for the mitigation defined in the TLP. As a result, it is common for different operators to have their own internally developed response procedures.

It is important to point out that operators have to deal with many risk factors other than just induced seismicity. For example, wind load due to winter storms may have far more chance to cause damage to drilling facilities than induced seismicity. Ultimately, the economic reality is that producing wells must be profitable.Thus, it is absolutely critical for industry to establish an optimal balance between economic returns and acceptable level of seismic risk. Setting TLP thresholds at levels that are too restrictive may effectively render an unconventional play to be uneconomic. On the other hand, making it too unrestrictive may unduly increase the possibility of more frequent occurrence of relatively large (felt) induced earthquakes or significant damage, which could have negative economic and sociopolitical consequences.

Major Deficiencies of Current TLPs

As most TLPs implemented by regulators are based on the magnitude of induced earthquakes, they can have serious deficiencies in serving the purpose of mitigating seismic risks. Three major deficiencies were identified at this meeting.

- **Possible confusion due to the magnitude uncertainty of an induced seismic event**

While the existence of some level of magnitude uncertainty (e.g. 0.2 magnitude units on average) is generally known and regarded as unavoidable by the seismological research community, this becomes a critical issue if the magnitude value is used in a TLP, especially when the computed magnitude of an earthquake falls just above the threshold of a red light. Taking the August 17, 2015, earthquake in the northern Montney Trend, BC, for example, the local magnitude (M_L) listed in NRCan's national earthquake catalogue is 4.48. This value was derived from M_L measurements at 15 Canadian National Seismograph Network (CNSN) stations with values ranging from 3.37 to 5.32. The corresponding one standard deviation is 0.47. The GSC moment-tensor solution for this event gave a moment magnitude (M_w) of 4.6 initially, later revised to 4.5. Moreover, magnitude differences between agencies and scales are often much larger than this, often resulting in a lack of clarity as to whether a red light event has occurred.

It is common for different agencies or organizations to report different values of magnitude for the same seismic event. Many factors can contribute to the magnitude discrepancy, including the use of different magnitude scales (M_L, M_w, m_b, M_N, etc.) and methodology, different choice and availability of data (e.g., local arrays vs. regional or global networks; private data vs. public data; short-period seismometers vs. broadband instruments), possible effects due to different source characteristics (seismic moment, stress drop, and focal mechanism), application of different attenuation/distance corrections, and different site effects at recording stations due to the variation of local geology. At this moment, the NRcan estimate tends to be the accepted value, even though other arrays may have better data leading to more accurate magnitude estimates. Unless the data used in magnitude calculation are opened to the public such that the derived magnitude can be independently verified, values determined from local arrays should not be used for regulatory purposes. A good alternative is to establish a data-sharing framework with contributions from both public and private networks. This is a topic to be discussed next.

- **Lack of a link to the impact/consequences of reported seismic event(s)**

Although magnitude is a good indicator for the size of a seismic event, it does not provide a complete picture of the actual ground motion. Since seismic hazards are closely associated with the level of ground shaking, knowing an earthquake's magnitude alone is not necessarily sufficient to estimate its potential hazard impact.

Given the same magnitude, seismic events may result in dramatically different hazard scenarios depending on many other factors. For examples, the distance between an epicentre and densely populated communities or high-consequence infrastructure, the source depth, the soil conditions, the frequency content of propagating waves, and the radiation pattern of the source can all affect the level of shaking at a given site. An M~3.8 earthquake that occurs in or close to town may cause far more public concern and attract immediate media attention than an M~4.3 event in a remote area. In terms of the likely seismic hazards, the M~3.8 event might have a higher chance to cause minor injuries and/or cosmetic damages to buildings than the M~4.3 one. Yet under the current TLPs in both BC and AB, a red light (immediate suspension of injection operations) will be issued for the remote M~4.1 event while injection in the vicinity of the M~3.9 earthquake will be allowed to continue with some modification. The lack of a direct link between an earthquake's magnitude and the impact or consequences (including injuries and seismic damages) it may cause is considered a major deficiency of the existing magnitude-based TLPs.

- **Need to integrate other potential hazard indicators**

Seismological studies have reported observations that may be indicative of the likelihood of occurrence of relatively large events. One such indicator is the change of seismic patterns (known as the Pattern Informatics index) that may have demonstrated some limited capability in intermediate- and short-term earthquake forecasting [e.g., *Tiampo et al.*, 2002]. Another indicator is the change of the frequency-magnitude distribution (i.e., the *b*-value) both in time and space with respect to the injection operations [*Bachmann et al.*, 2012]. A systematic migration of earthquake hypocenters either toward or away from the injection site could be the other important observation indicative of strong interaction between injection operations and the perturbation of regional tectonic stress field.

Another potentially useful indicator is a spatial correlation between induced seismicity and geological structures, especially shallow crustal faults. For example, close attention should be paid if clusters of induced seismicity are observed along favourably-oriented faults in the basement extending deep into the crust. Theoretically, such faults may have larger capacity in storing tectonic strain, and thus could result in larger earthquakes if shear dislocation is induced due to an increase in pore pressure. The current magnitude-driven TLPs provide no discrimination in the geological structures associated with the induced seismicity.

Effective Ways to Improve Current TLPs

There are several ways to effectively improve the current TLPs. In this meeting, three major directions are pointed out and discussed in detail. They are: (1) to incorporate ground motion information into TLPs; (2) to standardize magnitude calculation; and (3) to make the TLPs more adaptive.

- **Incorporate ground motion information into TLPs**

This strategy would address one of the major deficiencies mentioned in the previous section (i.e., not linked to the impact/consequences of reported seismic event(s)). The biggest merit of incorporating ground motion information into TLPs is that decisions can be made based on better assessment of the actual risk(s) associated with the induced event, in particular locations of interest. Ground motion measurements can be derived directly from seismic instrumentation without the need to estimate source characteristics such as magnitude with the associated technical challenges. The intensity of ground shaking at some key locations, such as the injection sites, critical infrastructure locations, pipelines, community centers and densely populated areas, can be particularly helpful in determining whether consequential effects are probable. It can also be used to estimate the level of concerns from both the media and the general public.

The most critical challenge is how to establish an accurate characterization of the ground motion field. As the level of ground motion can vary significantly from one site to another depending on local site conditions, having strong ground shaking measured at some particular locations does not necessarily imply strong shaking for the event in general, nor does it ensure non-consequential motions at other locations. Therefore, an accurate characterization of the ground motion field would need high station density with sufficient sampling at both local and regional distances. Since it is unrealistic to expect any single organization to establish regional networks at the required density, establishing an effective strategy for data sharing would be the most realistic model to achieve sufficient network density. This topic will be further discussed in the next section.

Another important task to make ground-shaking measurements more useful to hazard assessment is to develop and improve ground motion prediction equations (GMPEs) and their integration into real-time ShakeMap calibration [e.g. *Atkinson et al.*, 2015a, b; *Wald et al.*, 1999; *Worden et al.*, 2010]. In addition to obtaining a better dataset containing samples at various distances from multiple events of different magnitudes, good calibrations are needed to accurately prescribe the source effect, attenuation (or distance) effect, and the effect due to site amplification. Utilizing the expertise of the research community is needed to ensure realistic ground-shaking estimates for future events.

- **Standardize magnitude calculations**

As mentioned earlier, the discrepancy among different magnitude values reported by various agencies or organizations can come from the choice of different magnitude scales, methodology, calibration and/or data. Thus, one of the most effective ways to minimize such discrepancy is to standardize the calculation of earthquake magnitude. There are three aspects to be considered.

The first one is the instrumentation. It is important that seismic data used in the magnitude calculation should meet certain criteria to enable consistent and reliable results. For example, the seismograph instruments must have sufficient dynamic range with respect to the expected magnitude and distance ranges. In the case of induced seismicity relevant to injection operations, the magnitude range observed to date is 0–4.5 and the distance range is from a few kilometers to hundreds of kilometers. In other words, it is expected that the seismograph instruments can perform equally well for an M~4 event located at close distance and another M~1 located more than 100 km away.

Another instrument requirement is sufficient spectral band. Broadband instruments with a flat spectral response between 0.1 and 50 Hz or wider are needed. This is because earthquake source spectrum can vary significantly with source dimension. In general, the long-period (>10 s) component becomes more predominant as the source dimension increases. This means that the narrow-band geophones commonly used by the industry in seismic prospecting are not the ideal instruments for recording seismic data to be used in magnitude or ground-motion calculations.

One final concern about the instrument is the level of self-noise. This is related to the instrument's ability to record small earthquakes at far distances. For the expected magnitude and distance ranges of induced seismicity, the instrument should have a self-noise level of -100 dB or better.

The second aspect of standardization is the choice of magnitude scale. NRCan determines the local magnitude (M_L) of an earthquake in western Canada based on the formula outlined in *Richter* [1935]. For seismic events located east of the line connecting (60ºN, 128ºW), (49ºN, 113ºW) and (40ºN, 102ºW), i.e., east of the Canadian Rockies inside the Canadian Shield, the formula developed by *Nuttli* [1973] and later revised by *Stevens et al.* [1976] and *Drysdale et al.* [1985] are used to determine the magnitude values, known and listed in the Canadian National Earthquake Catalogue as M_N. These magnitude calculations are generally calibrated for regional monitoring distances, while local arrays are often used to monitor induced seismicity at close distances. The corresponding moment magnitude (M_w) is reported after a successful moment-tensor inversion is completed, as described in *Kao et al.* [2012].

In general, M_w is considered the most reliable magnitude measurement, as it does not suffer from the effect of amplitude saturation associated with the increase of source dimension. However, M_w is not listed in the Canadian National Earthquake Catalogue for most of the smaller earthquakes (M_L <~4) due to the lack of high-quality long-period waveforms at regional distances for moment-tensor inversion. Although alternative ways of M_w determination have been proposed for smaller events in the literature [e.g., *Atkinson et al.*, 2014], they are still considered experimental and have not been implemented by earthquake monitoring agencies such as NRCan as part of the routine process.

The final aspect is the parameters used in magnitude calculations. While NRCan scientists have made presentations in various meetings, workshops, and conferences to illustrate the procedures and parameters used in routine processing, those used by other agencies or organizations might be less certain. This is especially true for individual local array operators who often determine the source parameters of local earthquakes with more detailed velocity models based on high-resolution seismic surveys. Applying waveform filters and/or station corrections can also affect the magnitude calculation. To eliminate, or at least minimize, the magnitude discrepancy among different reported solutions, it is important to agree on a standard set of parameters used in the calculation.

- **Make the TLPs more adaptive to local hazard conditions**

In a recent National Energy Board document [*National Energy Board*, 2013], it is recommended that operators of hydraulic fracturing should acquire enough details on potential hazards, including that associated with seismicity. During the entire operation period, operators need to have a monitoring plan for seismic events and a safety termination plan should a suspected seismic event result in a shutdown or disruption to operations. Based on a recent study of induced seismicity in western Canada, the vast majority of injection operations were not associated with the occurrence of M_L 3+ earthquakes [*Atkinson et al.*, 2016], but it remains difficult to predict such occurrences in advance. Consequently, a one-size-fits-all TLP may not be the best tool to characterize the seismic risk from induced seismicity.

One alternative is to establish TLPs for specific zones where the seismic risk from induced events is deemed to be relatively high, due to increased likelihood or increased exposure (i.e., TLP zoning). To a certain degree, this has already happened in AB as the subsurface order #2 was issued for a specific area. It is theoretically possible for the same province to have different TLPs for different sites of development depending on local conditions such as the population density and the distribution of active faults. Various TLPs might also have different lists of primary mitigation measures that are tailored to site-specific characteristics and operational details.

Characterizing seismic risk associated with fluid injection in a format that is site-adaptable and can be updated as hazard and risk evolve with time has been recently proposed in the seismological literature [*Walters et al.*, 2015]. Specifically, the risk-tolerance matrices must consider the tolerance levels of various groups involved in the injection operations, including operators, regulators, stakeholders and the public, in addition to the analysis of earthquake hazard based on known geology, hydrology, seismicity history, and geomechanics of the site. Such a matrix approach that takes the probabilistic analysis of seismic hazard and operational factors into account, in addition to risk tolerance considerations, could lead to more adaptive TLPs that might be more effective in seismic risk management.

Setting A Path Forward

Meeting participants recognized and appreciated the necessity of mitigating seismic risk associated with induced seismicity. To successfully achieve such a goal, improvements to current TLPs are recommended. Four major aspects are raised and discussed in detail. They are: (1) to establish a uniform standard for seismic data collection; (2) to establish a framework of data sharing for induced seismicity monitoring and research; (3) to share other types of data; and (4) to take more proactive approaches.

- **Establish a uniform standard for seismic data collection and assessment**

Obtaining high-quality seismic data is the foundation for any seismological studies. Specifically for the purpose of TLP, it is important to set a uniform standard for data quantity, quality and accessibility.

  - *Data quantity*

To validate ground motion prediction equations, it is recommended to have at least 4 broadband stations available for each seismic event in each of the following distance ranges: <10 km, 10–30 km, 30–60 km, 60–150 km, and 150–400 km. Seismograph stations must be deployed for sufficiently long period of time to be able to collect multiple events. Such practices can ensure the construction of reliable GMPEs, including site response characterization, for accurate seismic hazard assessment.

- *Data quality*
  The ground motion must be recorded without voltage clipping at all distance ranges. This means that high-quality strong-motion accelerometers should be deployed at close range (less than 30 km from the injection wells) in addition to more sensitive broadband seismometers.
- *Data accessibility*
  It is important for different groups to have access to the same set of high quality data so that key parameters (such as earthquake source epicenter, depth, magnitude, ground-motion amplitudes) can be reproduced. The key concepts in data accessibility are transparency and collaboration in data sharing (a topic elaborated next).

- **Establish a coherent framework of data sharing for induced seismicity monitoring and research**

For a TLP to be most effective, the seismograph network must be able to detect small-magnitude events that might precede the occurrence of relatively large ones. This objective would require dense station distribution in development areas of concern. Many operators in the region have already established dense seismograph arrays for their own earthquake monitoring purposes. At present, much of the data recorded by these dense local arrays is released due to proprietary concerns. As a result, there are cases in which different companies establish rstations in close proximity along operation boundaries. From the industry's point of view, this represents a redundant investment on local earthquake monitoring. Meanwhile, such investment does not contribute to higher accuracy of earthquake source parameters unless the data are available to regional seismograph network operators, nor does the investment result in improved scientific understanding of induced-seismicity processes and effects, as the research community that is working on these problems do not have access to the data they require to make progress.

The goal of data sharing is to set up a level playing field such that every contributor will provide the same set of information in a standard and widely accessible format to facilitate data transparency, robustness, and leveraging of data through use in multiple induced-seismicity research programs. The main purpose is for interested groups, private or public, to reproduce and validate key parameters, including the event's location, magnitude, and the distribution of ground motion.

It is important to emphasize that data sharing is most important for larger anomalous events with hazard implications. From a TLP's point of view, microseismic data (e.g., recorded by dense arrays consisting of a large number of geophones) of the type that are commonly used for imaging hydraulic fracturing operations are not required for this purpose.

The practice of data sharing should be outcome-oriented. For relatively large events (e.g., M>1.5), real-time posting of key event and ground-motion parameters (e.g., pseudo spectral acceleration at 0.3, 1, 3, 10 Hz; peak ground acceleration; peak ground velocity; phase picks; magnitude by agreed formula; hypocentral location and the corresponding error range) should be made in standardized format. Waveforms and metadata for a subset of stations that individual companies or organizations agree to contribute should pass vigorous quality-control procedures and be archived at publicly accessible data centers for distribution.

In addition to source parameters, the distribution of ground motions (a.k.a. the shakemap) associated with relatively large events could also be a very useful outcome of data sharing. Real-time shakemaps could provide better and more accurate information on seismic hazard assessment, which could be incorporated into the TLP for induced seismicity. There are several real-time shakemap-generating packages in operation, such as the one used by the U.S. Geological Survey. The Automatic Response System developed by the University of Western Ontario for seismic safety monitoring of nuclear power plants in southern Ontario is another good example.

It is important to recognize that companies are very sensitive to sharing proprietary information, including seismic data. Thus, it might make data sharing much easier if formal agreements are in place. Mechanisms of cost sharing and a forum for communication/discussion already exist under the framework of CAPP. Thus, CAPP can play an important role in this regard.

- **Sharing of other types of data**

Other types of data could also be useful to the study of induced seismicity and the implementation of an effective TLP, including key parameters of injection operations (well locations, injection intervals, rate and total volume, pressure, and time history), the distribution and geometry of geological faults, and information about the regional tectonic stress. Sharing these data sets might not be as easy as sharing seismic data of relatively large events.

Currently, key parameters of injection operations are already made available to the general public with a time delay of approximately one year. A reduction in this time lag would speed research progress. Sharing information on geological structures/faults for the Fox Creek area, AB, has already happened among members of CAPP. The AER is also working on a detailed stress map and the fault distribution map of the Western Canada Sedimentary Basin.

At this moment, there is no established channel for research organizations to gain access to proprietary datasets. Having confidentiality agreements established under the framework of research collaborations is the standard way for the industry to share other types of data with the research community.

- **Take more proactive approaches to establish best practices and to mitigate seismic risk from induced seismicity**

Meeting participants pointed out a number of specific recommendations on how more proactive approaches could be implemented. Overall, these can be classified into four major categories: (1) targeted research to identify and characterize seismic risks associated with induced seismicity, (2) prevention and mitigation of seismic risks due to induced seismicity, (3) establishment and enhancement of effective collaborations, and (4) effective engagement and communication with the media and the general public.

  - *Targeted research to identify and characterize seismic risks associated with induced seismicity*

    The identification and characterization of seismic risks associated with induced seismicity is considered one of the biggest knowledge gaps in seismology. It is recognized that the current TLP approach is not necessarily capable of interrupting an earthquake sequence once it has started. This is partly because of lack of detailed understanding of the underlying physical model. Furthermore, we do not know whether the factors affecting the occurrence of small events are the same as those that control larger events.

    In terms of specific research tasks, one promising direction is to take a probabilistic approach in characterizing seismic hazard and risk and incorporate such information in the TLP. A variety of scientific inputs (the distribution of geological faults, history and magnitude of regional seismicity, induced-seismicity activation rates and patterns, regional ground motion processes, and earthquake activation mechanisms, etc.) can be used to calculate the short-term hazard and risk factor. Some preliminary studies of this nature have already been performed (e.g. *Atkinson et al.*, 2015a; *Bourne et al.*, 2015; *Petersen et al.*, 2016). The TLP is setup to reflect the risk exposure and tolerance thresholds that are acceptable to the regulatory agencies. In this case, a yellow or red light can be triggered without the actual occurrence of a relatively large earthquake, as long as the probability of risk exceeds a predefined level.

It is also possible to take a deterministic approach by identifying specific parameters that are indicative of increasing risk. One particularly interesting example is a drop in *b*-value during an earthquake sequence A change in b-value from ~2 to ~1 could be the manifestation of activating a tectonic fault, and thus may imply a higher probability of generating larger events [e.g., *Urbancic et al.*, 1992; *Eaton and Maghsoudi*, 2015).

Ultimately, the goal of this line of research is to develop an effective early detection system for forecasting induced seismicity in northeast BC and western AB. It requires a multi-disciplinary approach.

- *Prevention and mitigation of seismic risks due to induced seismicity*
  Definition of industry best practices to lessen seismic risk would provide clarity to operators. Various operational scenarios are currently being utilized. Given the known location of geological faults, well placement might be a good mitigation scheme to minimize (or avoid) the effect of injection on pre-existing, critically stressed faults. However, experiences in the Fox Creek area have indicated that significant induced seismicity often does not occur along previously mapped faults. In other words, placing wells away from known faults does not necessarily translate into fewer occurrences of induced events. More research is needed to understand the relationship between geological structures and induced seismicity. In the meantime, risk avoidance involves avoiding injection locations in close proximity to vulnerable high-consequence infrastructure.
- *Effective collaborations*
  Collaboration is recognized as an essential ingredient in the proposed research framework. For research collaborations to be more effective, forming focused subgroups with common interest(s) and interdisiplinary expertise might be helpful. These induced seismicity research subgroups can be formed in terms of geographic locations (e.g., the Fox Creek area, the northern Montney Trend, etc.), event types (e.g., hydraulic fracturing, wastewater disposal, or reservoir impoundment), or a combination of both.
- *Effective engagement and communication with the media and the general public*
  The industry recognizes that the issue of induced seismicity may cause "reputational" damage in addition to actual "physical" or "structural" damage. Taking the UK case for example, the occurrence of one small *M* 2.3 earthquake due to hydraulic fracturing facilitated the implementation of the most restricted TLP for induced seismicity in the world. The decision was mainly politically driven and effectively caused a complete shutdown of UK's shale gas development. To avoid a similar outcome to happen in Canada, the following activities are recommended.
  a) Increase transparency:
     A number of efforts can be made to increase the transparency of the industry's injection operations, including advanced notification and consultation with stakeholders and local communities on the schedule and operational details of hydraulic fracturing, regular open-house events for local residents, and the installation of ground motion sensors at appropriate locations, coupled with publicly-available maps of ground-shaking and effects. It is worth noting that

during recent example of events that triggered "red light" conditions, operating companies released press releases accepting responsibility.

b) Precise and adequate explanation of scientific data:
Scientific data and principles can be difficult for the general public to understand. Thus, describing scientific observations in a precise and understandable way is critical to effective communication with the media and the general public. For example, the general public might not realize the difference between microseismic events and an *M* 4 earthquake. It might be more effective to use real-life scenarios (e.g., a big truck driving by) to describe the corresponding level of ground shaking. It is also important to help the media to better elaborate scientific facts associated with hydraulic fracturing.

c) Enhanced public education:
Public education is extremely important to the promotion of healthy dialogs between the industry and the society. Universities can play an effective role in this regard as the general public tend to trust the academia more than the industry. Making understandable scientific research products available online (e.g., public websites) should be an important part of the public education effort. Furthermore, taking advantage of the rapid pace of online social media (e.g., Facebook, Tweeter, etc.) to spread new research results may be an important tool of public education.

d) Immediate response to complaints and concerns:
Effective communication begins with immediate response to complaints and concerns raised by local residents. At present, both the BC OGC and AER have standard procedures in place to respond to public inquiries and complaints. A similar system is recommended for the industry.

Concluding Remarks

The concept of a "traffic light" system is widespreadly used by governments, organizations, and private companies to characterize the level of a particular threat as well as a set of specific actions in response. In both BC and AB, a red light (immediate suspension of injection operations) is triggered when the induced earthquake has an M_L value of 4 or larger. Operations are allowed to resume only after a mitigation plan is submitted and approved by the regulatory agencies.

In general, regulators deal with any forms of risk in three steps: identification, analysis, and treatment. A traffic light protocol (TLP) for induced seismicity is considered a reactive risk management tool as part of the risk treatment process. It is important to consider proactive measures, such as risk avoidance and well placement, and predictive strategies. However, the predictive risk management is probably too premature to be included in the regulatory process at this point.

As most TLPs implemented by regulators are based on the magnitude values of induced earthquakes, they can have serious deficiencies in serving the purpose of mitigating seismic risks. These deficiencies include (1) possible confusion due to the magnitude uncertainty of an induced seismic event, (2) lack of a link to the impact/consequences of reported seismic event(s), and (3) need to integrate other potential hazard indicators.

The meeting produced three specific recommendations for effective improvement of the current TLPs. The first one is to incorporate ground motion information into TLPs such that decisions can be made based on better assessment of the actual risk. An accurate characterization of the ground motion field, including calibration of regional ground motion prediction equations, are important tasks required to improve the seismic hazard assessment. The second recommendation is to develop a standardized approach for earthquake magnitude calculation. This includes setting standards on seismic instrumentation, making a consistent choice of magnitude scale, and using the same set of parameters in the calculation. The third recommendation is to make the TLPs more adaptive to local hazard conditions. Specific activities include the establishment of TLPs for specific zones where the seismic risk from induced seismicity is deemed to be relatively high (i.e., TLP zoning) and regular update of TLPs as hazard and risk evolve with time. In addition to the analysis of earthquake hazards based on known geology, hydrology, seismicity history, and geomechanics of the site, TLPs should also consider the tolerance levels of various groups (operators, regulators, stakeholders, and the public) against induced seismicity.

Meeting participants recognized and appreciated the necessity of mitigating seismic risk associated with induced seismicity. Several specific action items were raised to set a path forward within a broader context of academic and social values. First of all, it is necessary to establish a uniform standard for seismic data collection and assessment. A list of criteria in data quantity, quality, and accessibility is proposed to ensure the facilitation of meaningful data analysis and research. Secondly, it is recommended to establish a coherent framework of data sharing for induced seismicity monitoring and research. The main purpose is for interested groups, private or public, to reproduce and validate key parameters for events of interest. It can also help to obtain a more complete understanding of ground motions related to relatively large induced events. Thirdly, sharing other types of data on a timely basis, such as key parameters of injection operations and the distribution and geometry of geological faults, is strongly encouraged. Having confidentiality agreements established under the framework of research collaborations may represent an effective way for sharing sensitive datasets that have proprietary implications.

More proactive approaches to establish best practices and to mitigate seismic risk from induced seismicity are recommended. Specific efforts include targeted research to identify and characterize seismic risks associated with induced seismicity, prevention and mitigation of seismic risks due to induced seismicity, effective collaborations, and effective engagement and communication with the media and the general public. For the identification and characterization of the seismic risk from induced earthquakes, one promising direction is to take a probabilistic approach in characterizing seismic hazard and risk and to incorporate such information in the TLPs. Some indicators may have deterministic value - such as the sudden drop of the *b*-value of an induced earthquake sequence. As for the effective engagement and communication with the media and the general public, it is important to increase the transparency of the industry's injection operations, to provide precise and adequate explanation of scientific data, to enhance public education on hydraulic fracturing and induced seismicity, and to immediately respond to complaints and concerns raised by local residents.

Finally, it is emphasized that, with development and enhancement of a collaborative multi-stakeholder framework, Canada has the potential to be a world leader in monitoring, understanding and mitigating hazards and risks from induced seismicity. Improving the TLPs could be a good starting point. Coordinated efforts and joint research works must be established among various sectors (government, academia, and the industry) to ensure public safety and the environmental protection as the responsible development of unconventional resources continues.

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Appendix: Meeting Program

UNIVERSITY OF CALGARY

Technical Meeting on Traffic Light Protocols for Induced Seismicity
8:30am – 4:40pm October 6, 2015

University of Calgary, Downtown Campus
906 8 Avenue SW Calgary
Calgary, Alberta, T2P 1H9

Agenda

Time	Activities	Presenter/Moderator
8:00 – 8:30	Arrival and Registration	
8:30 – 8:35	Welcoming Remarks	David Eaton (UCalgary)
Session I: Alireza Mahani (chair)		
8:35 – 8:50	NRCan's SOP on Earthquake Monitoring	Honn Kao (NRCan)
8:50 – 9:05	TLP regulations in Alberta	Todd Shipman (Alberta Energy Regulator)
9:05 – 9:20	TLP regulations in BC	Dan Walker & Michelle Gaucher (BC Oil and Gas Commission)
9:20 – 9:45	Questions and Discussion	
9:45 – 10:00	**Coffee Break**	
10:00 – 11:30	***Panel discussion I***: Industry Perspective	Shawn Maxwell (IMaGE)

Networking Lunch Break

Time	Activities	Presenter/Moderator
Session II: Honn Kao (chair)		
13:00-13:15	Monitoring and hazard assessment of anomalous induced seismicity in northeast British Columbia	Amanda Bustin (UBC)
13:15-13:30	Integrated monitoring to determine earthquake size and ground shaking intensity in real time	Gail Atkinson (Western U.)
13:30–13:45	Traffic Light Protocols: What? Why? How?	David Eaton (UCalgary)
13:45 – 14:00	Questions and Discussion	
14:00-14:15	**Coffee Break**	
14:15-15:45	***Panel discussion II***: Legal/Regulatory/Academic Perspective	Shawn Maxell (IMaGE)
15:45-16:30	***Open Discussion***: Defining a path toward efficient mitigation of seismic risk due to induced seismicity.	David Eaton (UCalgary)
16:30-16:40	Closing Remarks	Gail Atkinson (Western U.)

Organizing Committee:

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- Dr. Alireza Mahani (Geoscience BC, ali.mahani@mahangeo.com), or
- Dr. Shawn Maxwell (IMaGE, shawn.maxwell@itasca-image.com