

The Induced Seismicity Team

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Policy Paper



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A Study of the Traffic Light System for Induced Seismicity

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Abstract: Induced seismicity is mainly due to various industrial operations, such as hydraulic fracturing and wastewater injection during oil and gas production. Even though these seismic events are generally low in magnitude ($< M_L 1$) and hardly felt, unexpected large induced earthquakes can still happen. One of the possible reasons is operating near fault zones. These large induced seismic events damage property and cause panic among the public. Hazard analysis is used to study the potential risks of induced seismic events. Possible damage an earthquake can cause, such as infrastructure damage, and human anxiety are considered as factors in the risk analysis of induced seismicity. The Traffic Light System (TLS) is the mitigation method implemented for operations in Alberta and British Columbia, Canada. The operators are required to react differently depending on the recorded magnitude and if the magnitude reaches certain thresholds. Reports show that TLS partially mitigates the impact of induced seismicity, but large earthquakes still occur at operation sites. In this paper, we studied the possible causes of these large induced earthquakes and the possible risks of induced seismicity and gave our opinions on the policy regarding the current TLS. We first examined the

effectiveness of TLS based only on magnitudes. Then we analyzed the practicability of including other parameters in TLS, such as peak ground velocity and peak ground acceleration, specific regions, and population density. Based on our study, we gave some suggestions to improve the evaluation and mitigation of induced seismic events.

1.0 Introduction

Many human activities, such as reservoir impounding, wastewater disposal into the ground, extraction of natural gas and hydrocarbons, or mining, can cause induced seismicity (Ellsworth, 2013). Davies et al. (2013) compiled 198 possible examples with magnitudes equal to or greater than moment magnitude (M) 1.0 that occurred since 1929. The highest local magnitude (M_L) was $M_L 7.9$, which was due to reservoir impoundment in China. Hydraulic fracturing (hydrofracking) used to explore unconventional reservoirs is one of the major causes of induced seismicity.

Most of the data from hydrofracking in the United States of America (USA) show that when fault reactivation occurs, the earthquake magnitudes tend not to exceed $M_L=1$. According to Davies et al. (2013), most of the earthquakes that were felt by the public were caused not by hydrofracking, but by wastewater re-injection. The risk that the injection of waste fluids poses is greater than the risk posed by hydrofracking, but it's still low and can be minimized through careful site selection, monitoring, and management. Although the largest induced earthquakes were associated with wastewater disposal, confusion in the public and the media regarding the distinction between the process of hydraulic fracturing and the disposal of its wastewater has led to intense scrutiny of hydraulic fracturing, particularly from regulatory agencies.

In addition, induced earthquakes that were felt and even caused damages have caught more attention from researchers, operators, regulators, and the public. In the USA, damage to structures has been documented in at least three potentially induced earthquake events: the M_L

5.7 Prague, Oklahoma earthquake; the 2011 M 5.3 Trinidad, Colorado earthquake; and the 2012 M_L 4.8 Timpson, Texas earthquake (Wong et al., 2015). If pre-existing faults are connected via the hydraulic fractures or if there is direct injection into the faults intersecting treatment wells, injection can lead to fault reactivation. Fault reactivation can cause earthquakes with magnitudes larger than expected for fracture propagation (Becklumb et al., 2015). For example, studies have shown that the earthquakes that happened in the Eola Field, Oklahoma, USA in 2011 with magnitudes up to 2.3 (Holland, 2011) and in Lancashire, UK in 2011 with magnitudes up to 2.8 (de Pater and Baisch, 2011) are related to fault reactivation by hydraulic fracturing.

2.0 Risk factor regarding induced seismicity

Risk is defined as the chance/probability of being exposed to a hazard. Hazards associated with earthquakes depend on proximity to potential earthquake sources, magnitudes of the earthquakes, and rates of occurrence and are usually expressed in probabilistic terms. Earthquake hazards can include ground shaking, liquefaction, surface fault displacement, landslides, tsunamis, and uplift/subsidence for very large events ($M_L > 6.0$). Because induced seismic events, in general, are smaller than M_L 5.0 with short durations, the primary concern is ground shaking.

Ground shaking can result in structural and nonstructural damage to buildings and other structures and can result in human anxiety. It is commonly accepted that structural damage to modern engineered structures happens only in earthquakes larger than M_L 5.0. The main parameter in structural damage is peak ground velocity (PGV), while the most common ground shaking is measured as peak ground acceleration (PGA) in seismology and earthquake engineering. When PGA is greater than 18-34% of g, moderate structural damage is possible, and very strong shaking can be perceived (Bommer, 2015). In rare cases, nonstructural damage has been reported in earthquakes as small as M_L 3.0.

Human anxiety, or the human concern created by low-level ground shaking, is another factor in determining the risks posed by induced seismicity. Because injection-induced seismicity generally has a small magnitude and short duration, human anxiety is often the only or primary hazard associated with felt events.

3.0 Policy options regarding the Traffic Light System for induced seismicity

Regarding the hazards of induced seismicity, the Traffic Light System (TLS) has been implemented for regulating industrial operations and mitigating the impacts of induced seismic events. TLS was first implemented by Bommer (2006) in an enhanced geothermal plant. Traffic Light System (TLS) is a calibrated control system served as a direct mitigation method for induced seismicity. Its merits consist of providing continuous and real-time monitoring and management of ground shaking of induced seismicity. Hazards of induced seismicity are characterized into three levels: green, amber (yellow), and red, and the reactions vary based on the characterization (Figure. 2). Three factors were incorporated into TLS: 1) public response, 2) magnitude, and 3) PGV. TLS used in Basel, Switzerland did not stop four M 3 earthquakes from happening, but it may have prevented larger events.

One way to define TLS thresholds is to adopt the ground motion-based approach that Bommer et al. (2006) used in the Berlin geothermal field: The green light is based on the threshold of general detectability. The yellow light is based on ground motion levels at which people are aware of the seismicity, but damage is unlikely. Finally, the red light indicates ground shaking at levels where building damage is expected. Moreover, ground shaking levels vary from area to area because they are dependent on area-specific factors, which include the nature of the induced seismicity, path effects, attenuation, and local site conditions. Bommer et al. (2006) considered this in defining the TLS thresholds as a PGV range of 0.04 to 0.12 cm/sec. Thus, a

yellow light could be set at the lower end of this range. The red light might be initially set at some value in the range of 0.5 to 1 cm/sec. The PGV corresponding to a Modified Mercalli Intensity V is about 0.5 to 1.2 cm/sec. The threshold for the onset of damage, such as the cracking of plaster walls, is defined as 0.127 cm/sec (Siskind et al., 1980). The uncertainties are large and so any initial thresholds should be considered preliminary and will require calibration with actual observations.

In addition, TLS should consider the population density variance. If induced vibrations cause disturbance or distress to those living or working in proximity to the source of the excitation, it is likely that there will be complaints or protests, which, depending on the legal framework of the country in question, could lead to the suspension of the activity or litigation resulting in financial compensation to those affected. For example, in the seismically active Geysers geothermal area, the local population tolerates earthquakes up to M 4.5 and so no TLS is even in place. The area is a rural area with a relatively small population. Therefore, whether a specified population considers detectable low levels of ground motion acceptable or not is highly subjective and varies from site to site. TLS ground motion levels should be defined on a project-specific basis accounting for hazard and risk.

The current TLS systems were implemented in Alberta and British Columbia (Canada), Basel (Switzerland), and Oklahoma (USA). The Oklahoma Corporation Commission (OCC) require TLSs on a number of selected wells in Oklahoma, but there is no state-wide regulation. The thresholds range from a M_L 1.8, which is the smallest event that has been felt in south-central Oklahoma, to M_L 3.7. There are no published guidelines specifically on the control or definition of acceptable levels of induced seismic ground shaking. Further, there are different thresholds in different jurisdictions. Most of the time the threshold is stated in terms of magnitude. Uncertainty in magnitude and its large dependence on other parameters, such as

scaling, location of recording, and measurements, are issues for TLS, and hence, one of the reasons why magnitude is not the best parameter to use in TLS (Kao et al., 2016). The TLS lights should be based on the apparent risk. Risk is a direct consequence of hazard, and hazard is best defined by ground shaking levels. Thus, we think ground motions should be the primary basis for TLS.

Both PGA and PGV should be used in TLS as ground motion parameters if ground shaking is used as the TLS threshold. Currently, only models built from natural earthquakes are available to change M_L to PGA and PGV. More data from induced seismic events need to be collected to build a new model that can predict ground motions for induced seismicity. The TLS threshold can then be established from the predicted risk level.

Two important issues in dealing with TLS are the mitigative steps that need to be taken to continue operating under an amber light and the steps necessary to resume operations after reaching a red light. The mitigative steps are operation-specific and ambiguous, and their purpose is to prevent the occurrence of a damaging earthquake or, in some public-sensitive cases, to maintain ground shaking levels to below the threshold. The British Columbia Oil and Gas Commission (BCOGC) have steps in their TLS that enable the operator to resume activities if “a plan for mitigation aimed at reducing the seismicity” is developed (BCOGC, 2014). It seems this requirement is purposefully very general. Another problem is to evaluate the success of these procedures because of the many operational parameters at play and the anecdotal nature of the results (BCOGC, 2014).

As stated by Bommer et al. (2015), TLS is seldom an effective tool for reducing hazards associated with induced seismicity. It can, however, be an effective component of a more comprehensive risk management program. Such a program is described in the DOE Protocol (Majer et al., 2012) and in Bommer et al. (2015).

In our view, the ideal mitigative action requires the deployment of a dense, high-resolution microseismic network that is often used to map the microseismic events associated with hydraulic fracturing stages. Such a network can map almost in real time the migration of microseismic events and when these events may encounter a fault resulting in potentially larger fault-related seismic events. Such microseismic monitoring is expensive and is generally only done in a fraction of hydraulic fracturing projects.

Although we advocate that TLS levels be based on ground shaking, we also recommend that magnitude and public perception be considered as secondary factors as was the case for the Basel EGS Project. There is still value in considering magnitude because that parameter still provides valuable insight into the magnitude-frequency relationship, which is needed to predict the sizes and rate of future seismicity. As mentioned earlier, public perception is important as indicated by the case of The Geysers

The TLS ground motion levels should be defined on a project-specific basis accounting for hazard and risk. In unpopulated areas, the ground motion levels can be high, and in areas with a vulnerable population and buildings, the levels need to be lower. If public perception is an issue, that has to be accounted for in defining the ground motion levels.

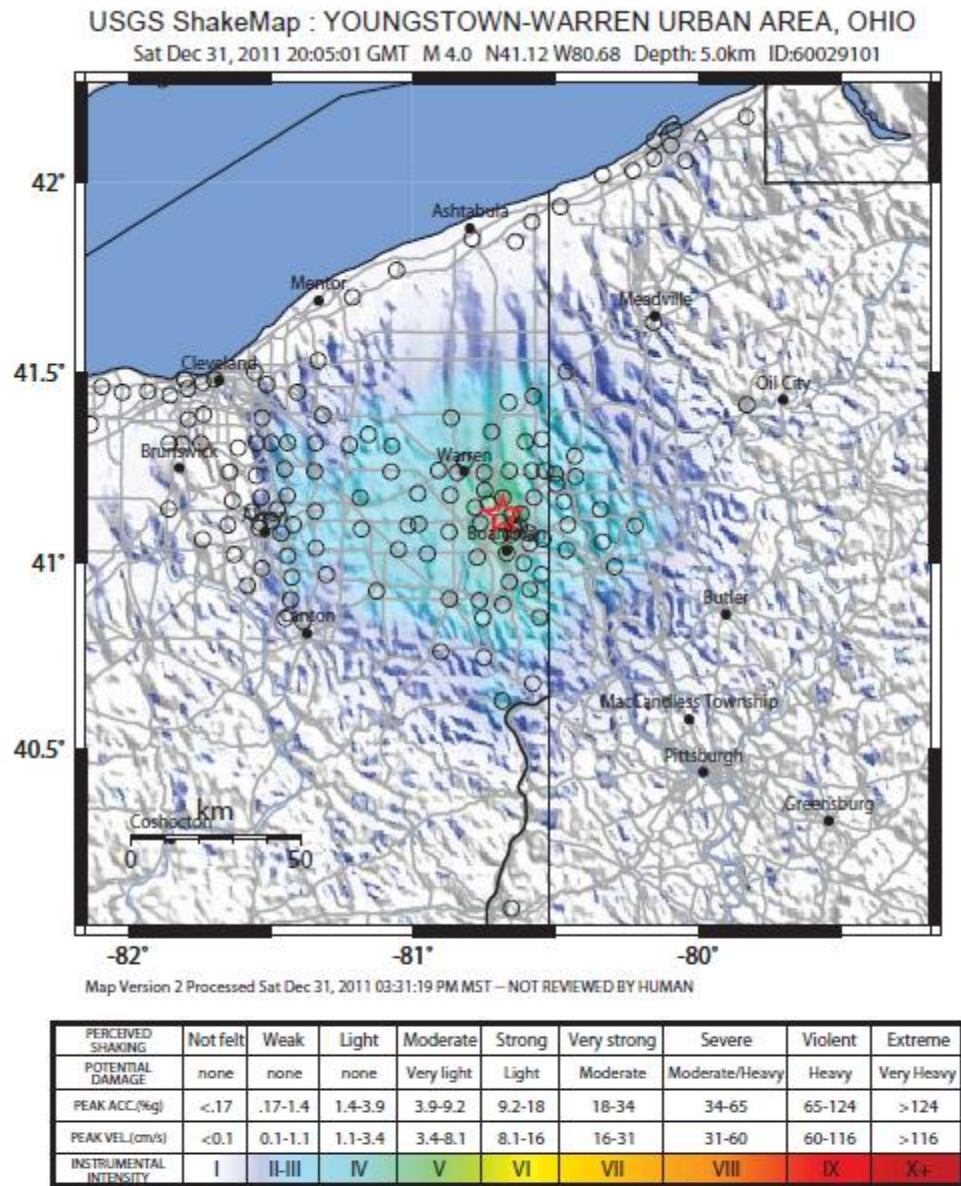
4.0 Conclusions

The following should be considered to better evaluate and mitigate risks associated with induced seismicity caused by hydraulic fracturing:

- More comprehensive geophysical studies should be conducted for a better understanding of the fault system of the potential areas for oil and gas productions.
- More transparency on induced seismicity can put the public at ease and remove the negative conception.

- Traffic light systems are good mitigation systems even though they are reactive.
- There is a lag time between injecting fluid and the resulting seismic activity; therefore, the efficiency of TLS may be questionable.
- In the long term, TLS will be more efficient and economical as unnecessary stoppages based on a state-wide uniform threshold will be minimized or avoided, particularly a threshold based on magnitude.
- TLS levels should be based on ground shaking, and magnitude and public perception should be considered as secondary factors.
- As a first step, PGA and PGV levels can be used to establish TLS thresholds, but those levels need to be adjusted for the area-specific characteristics of the induced seismicity, local population, and site conditions.
- TLS is based on a range of PGV thresholds using information on human sensitivity to vibration caused by blasting and on vulnerability curves for expected structural damage to local buildings.
- A more comprehensive risk management system needs to be established that uses ground motion prediction models based on more induced seismicity data from hydraulic fracturing instead of natural earthquakes.

5.0 Tables and Figures



	Project No. 26819152	SHAKEMAP OF THE 2011 M4.0 YOUNGSTOWN EARTHQUAKE	Figure 2-6
	Ohio Oil and Gas Ohio		

Figure 1. U.S. ShakeMap suggested by USGS. (Wong et al., 2015).

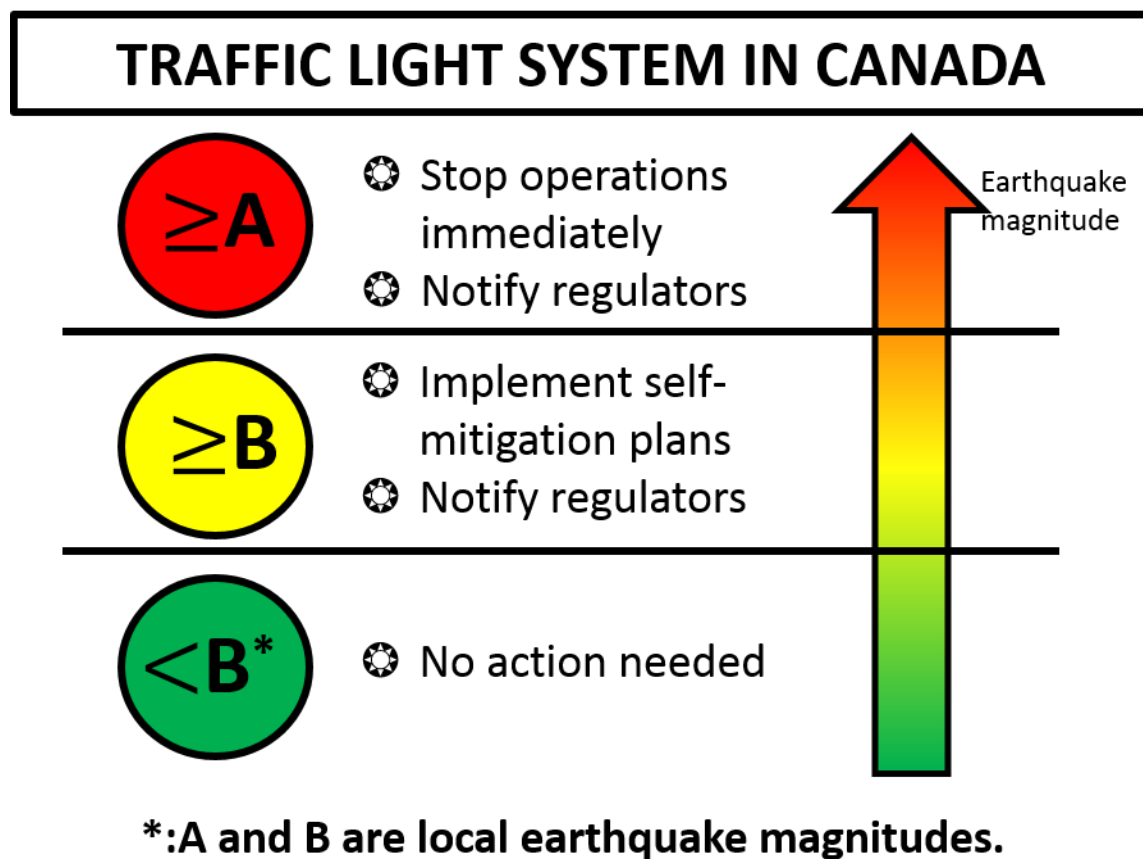


Figure 2. An illustration of Traffic Light System in Canada.

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