

Hindcast simulations of $M \geq 4$ events and anticipated ground shaking for induced seismicity in Montney, British Columbia

Raisha Pradisti and Mirko van der Baan

Department of Physics, University of Alberta

Summary

Recent increases in induced seismicity in northeastern British Columbia following the development of the unconventional hydrocarbon in the Montney Play has raised concerns about the local and regional seismic hazard potential. While conventional Probabilistic Seismic Hazard Analysis (PSHA) using observed historical data has paved the way to assess seismic hazard, Monte Carlo simulation provides an alternative to quantify the seismic hazard by allowing multiple scenarios that may have otherwise been poorly constrained in the historical data. In this study, we hindcast the likelihood of magnitude $M \geq 4$ events using the Monte Carlo simulation based on the estimated Gutenberg-Richter (GR) parameters obtained from the observed catalog. We found that the rates and probability occurrences of the moderate magnitude events were trickier to simulate due to the inherent uncertainty associated with their rare observed occurrence. When uncertainty is considerable, we are inclined towards overestimated rates and cautionary occurrence scenarios, as they may prepare better for the potential of getting at least one magnitude $M \geq 4$ event.

In addition, we also compare three different Ground Motion Prediction Equations (GMPEs) developed for different cases of seismicity and different ranges of magnitude and distance range applicability to find the suitable GMPEs for accurate ground motion estimation. We found that the site-specific, induced seismicity GMPE, which incorporated more geologic information and site-specific factors, predicts a more complex variation of local ground shaking intensity compared to more general GMPEs developed based on natural seismicity.

Methods

1. Monte Carlo simulation to hindcast $M \geq 4$ events

We use a merged catalog covering the Montney Play published by the British Columbia Energy Regulator (BCER) and Geological Survey of Canada (GSC). We follow the workflow by Reyes Canales et al. (2022) and the references therein to obtain the seismicity rates from the observed catalog.

Using the observed seismicity rates, we apply Monte Carlo simulation and a logic-tree approach to generate the annual synthetic catalogs. The metrics to assess the resulting synthetic catalogs were done by comparing the annual rate of exceedance plots and the probability of occurrence plots between the observed and synthetic catalogs.

2. GMPE comparison

We explore three GMPEs in this study, with the summary of each GMPEs outlined in Table 1.

Table 1. Summary of the GMPEs explored.

GMPE	Developed for	Magnitude range applicability	Distance range applicability	Site conditions
Atkinson and Adams (2013; AA13)	Natural seismicity	$M_w \geq 4.5$	$10 \text{ km} \leq R_{\text{hypo}} < 800 \text{ km}$	Reference site conditions (soft rock)
Atkinson (2015; A15)	Induced seismicity	$M_w 3$ to $M_w 6.0$	$R_{\text{hypo}} \leq 300 \text{ km}$	Reference site conditions (rock)
Nanometrics (2023; NMX23)	Induced seismicity in the Kiskatinaw area	$M_w 1.25$ to $M_w 6.0$	$R_{\text{hypo}} \leq 50 \text{ km}$	Depends on bedrock depth, surficial geology, and Vs30.

We compare the three GMPEs by how well they recreate the natural seismic hazard maps of Canada based on seismicity rates from Halchuk et al. (2014), and how well they recreate the local shakemaps based on scenario earthquakes from Nanometrics (2024).

Results

Likelihood of $M \geq 4$ induced events

Figure 1 shows the example of the annual rates of exceedance and the probability of occurrences for events in the small magnitude range ($M \sim 2$ to 3) and magnitudes $M \geq 4$ for the 2021 South West Montney cluster. Predicting the likelihood of small magnitude events is straightforward, but less so for moderate magnitude events. The observed seismic catalog is usually rich in the more frequent small magnitude events; thus, it is easier to predict the rates of the small magnitude events. The rates of moderate to large magnitude events are subject to inaccuracies of extrapolation due to their less common nature.

Kinks in the frequency magnitude distributions also jeopardize the accuracy of seismic rates estimation. Commonly, the GR parameters are estimated for the distribution above a minimum magnitude above which all earthquakes are reliably recorded, called the magnitude of completeness. Different minimum magnitudes may result in different estimated GR parameters. An alternative approach is to use a minimum magnitude of interest in excess of the magnitude of completeness in the estimation as small events are unlikely to cause damage, and thus less important.

Comparison of different GMPEs

Figure 2 shows the scenario shakemaps from a hypothetical $M_w 4.20$ event near Fort St. John, estimated using the three GMPEs. Overall, the shakemaps show PGA values that vary radially,

because the expected ground shaking decreases generally with increasing source-to-site distance. The NMX23 GMPE shakemaps showed the most complex distribution of ground motion variation due to the additional site condition term. On the other hand, the AA13 and the A15 GMPE shakemaps show a relatively uniform distribution of ground motion variation, as the two GMPEs applied a site correction term that only depends on the V_{S30} velocity which is here taken as constant for the region.

The shakemaps predicted using the NMX23 GMPE also showed the highest PGA values closer to the epicenter, whereas the AA13 and A15 shakemaps predicted a moderate PGA values around the epicenter. The wider single-PGA value near the epicenter observed in AA13 shakemap is also a result of the GMPE's inability to resolve the ground motion estimation for near-distance. This study shows how different GMPEs lead to varying predictions of ground motion, underscoring the need to choose the appropriate GMPE for accurate seismic hazard assessment.

Conclusions

Monte Carlo simulation for probabilistic seismic hazard analysis (PSHA) allows us to hindcast the likelihood of moderate magnitude events given the estimated seismic parameters from the observed catalog. However, the hindcasted rates are subject to uncertainty for moderate magnitude events, particularly when the observed catalog lacks these.

Comparison of the different GMPEs reveals the importance of selecting the appropriate GMPE for accurate seismic hazard assessment in Montney, British Columbia. Several factors to consider are the ability to predict small-to-moderate magnitude of induced events, and the ability to address the complexity of the site conditions that has been the case for Montney, British Columbia. We recommend using a logic-tree approach, combining local site-specific GMPE based on observed induced seismicity with regional GMPEs from natural seismicity observed at larger distances.

Acknowledgements

The author would like to thank the sponsors of the Consortium for Distributed and Passive Sensing for the financial support. The authors would also like to thank Mauricio Reyes Canales (Alberta Geological Survey/Alberta Energy Regulator) for providing the Monte Carlo simulation package, and Nanometrics for providing their GMPEs.

References

- Atkinson, G. M., & Adams, J. (2013). Ground motion prediction equations for application to the 2015 Canadian National Seismic Hazard Maps. *Canadian Journal of Civil Engineering*, 40(10), 988-998.
- Atkinson, G. M. (2015). Ground-motion prediction equation for small-to-moderate events at short hypocentral distances, with application to induced-seismicity hazards. *Bulletin of the Seismological Society of America*, 105(2A), 981-992.
- Halchuk, S., Allen, T. I., Adams, J., & Rogers, G. C. (2014). Fifth generation seismic hazard model input files as proposed to produce values for the 2015 National Building Code of Canada. *Geological Survey of Canada Open File*, 7576(18). <https://doi.org/10.4095/293907>.
- Nanometrics. (2023). Integration of ground motions into induced seismicity risk management in the Kiskatinaw area, Northeast B.C. *BC Oil and Gas Research and Innovation Society (ER-Seismic-2022-01)*.

Reyes Canales, M., Yusifbayov, J., & van der Baan, M. (2022). Evolution of short-term seismic hazard in Alberta, Canada, from induced and natural earthquakes: 2011-2020. *Journal of Geophysical Research: Solid Earth*, 127(2), e2021JB022822.

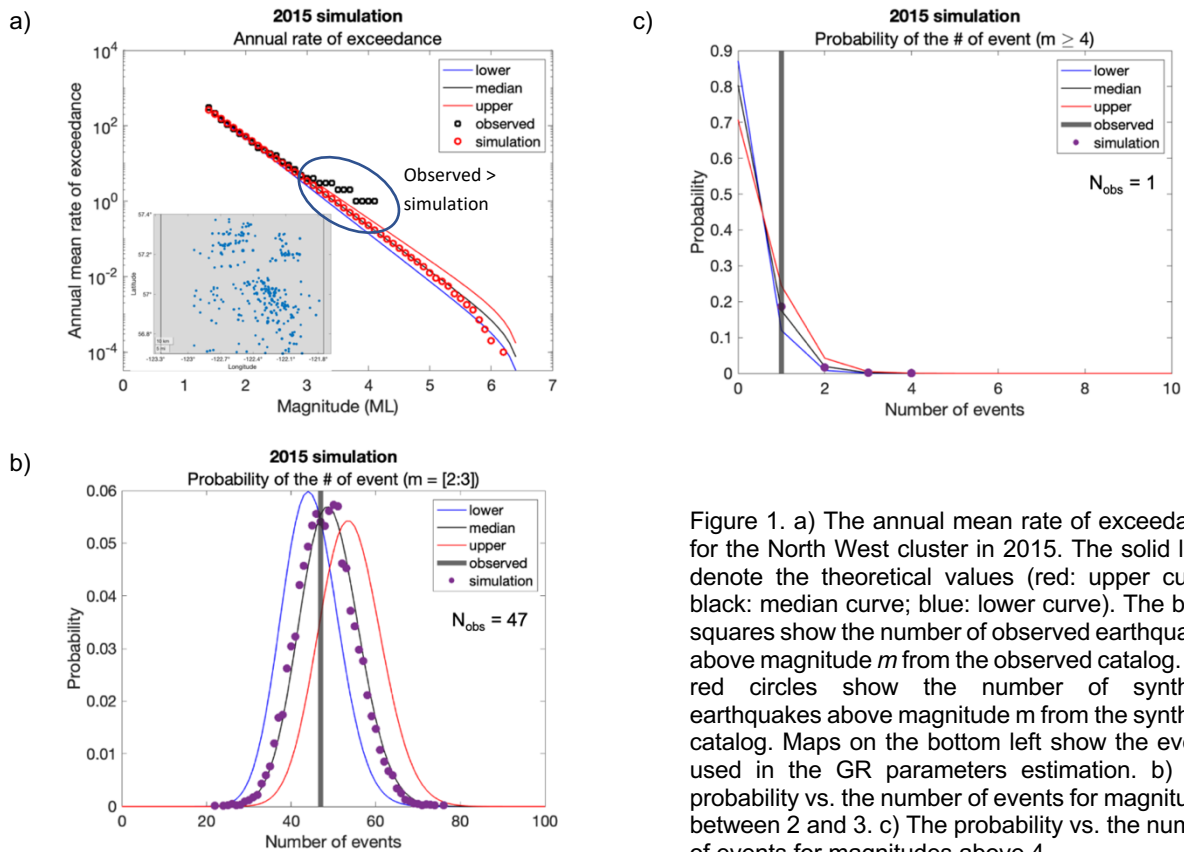


Figure 1. a) The annual mean rate of exceedance for the North West cluster in 2015. The solid lines denote the theoretical values (red: upper curve; black: median curve; blue: lower curve). The black squares show the number of observed earthquakes above magnitude m from the observed catalog. The red circles show the number of synthetic earthquakes above magnitude m from the synthetic catalog. Maps on the bottom left show the events used in the GR parameters estimation. b) The probability vs. the number of events for magnitudes between 2 and 3. c) The probability vs. the number of events for magnitudes above 4.

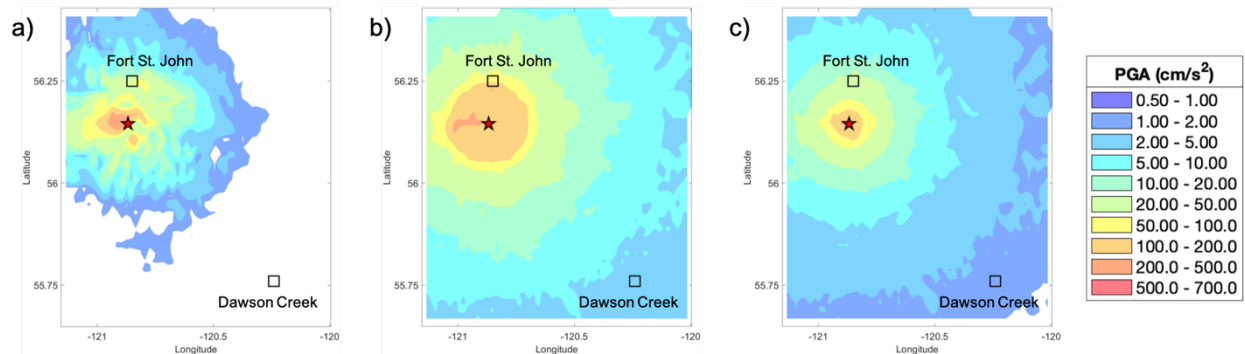


Figure 2. Shakemaps of an M_w 4.20 event (red star) at 56.165°N and 120.868°W . a) Predicted using NMX23 GMPE (benchmark). b) Predicted using AA13 GMPE. c) Predicted using A15 GMPE. All shakemaps have the same color legend for the PGA values, as shown on the right-most color legend.