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IMPACT OF THE GROUND MOTION PREDICTION EQUATION CHANGES ON EASTERN CANADA HAZARD MAPS

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ABSTRACT

Accurate seismic hazard assessment is one of the most important steps on the way to reduce seismic risk. Probabilistic Seismic Hazard Assessment (PSHA) (Cornell, 1968; McGuire, 2004, 2008) is most common method used today in national seismic codes, including the National Building Code of Canada (NBCC) and National Building Code of United States of America. The new generation of Canadian seismic hazard maps was released in 2015 as a basis for updated seismic provisions of NBCC 2015. Its application implemented a new set of representative ground-motion prediction equations proposed by Atkinson and Adams, 2013, in which a set of three alternative weighted ground motion prediction equations (GMPE) are used to describe epistemic uncertainty. Here sensitivity tests have been performed with the aim to compare the proposed GMPE model with different weights in the probabilistic logic tree (±25-75% weight change applied) and to examine the total amplitude range of ground motion data represented on hazard maps at 0.5, 1.0 and 5.0 Hz frequency. The results of this study show the importance of a correct epistemic uncertainty estimation in PSHA in general and for the Eastern Canada region in particular. Weight changes in each node of the GMPE logic tree for Eastern Canada leads to the significant changes in ground motion values on the hazard maps. In particular, at 5.0 Hz frequency, the difference from the initial base model varies between 14.73% to 64.6% and 19.44% to 100% at 1.0 Hz frequency. At 0.5 Hz frequency the results are even more sensitive and show a 25.71% to 142.85% difference in ground motion estimation.

Keywords: PSHA, hazard maps, sensitivity analysis, representative GMPE

1. INTRODUCTION

Seismic hazard maps are a series of maps in different frequency bands calculated in terms of probability of exceeding a certain ground motion level at many points across a region. The maps are probabilistic because they take into consideration the uncertainties in the earthquake magnitude, location and the resulting ground motions that can affect a set of sites. There are many practical applications of hazard maps, the most important among them are the production of earthquake resistant construction standards, insurance rate calculation, structural stability estimation, potential hazard and the associated response assessment. The national seismic hazard maps for Canada are under continuous improvement by the Geological Survey of Canada (GSC). As a result, several seismic hazard models have been proposed and five generations of seismic hazard maps have been created (NRCC, 1953, 1970, 1985, 2005, 2010).

Canada has a vast territory and a variety of tectonic regimes. As a result, the production of seismic hazard maps takes into account the country divided into eastern, western and stable (central) regions (Adams and Atkinson, 2003). Each region has its own particular qualities, principles and approaches of hazard mapping. This study describes models, approaches and results only for Eastern Canada, which is known as a region of moderate seismicity. Despite the fact that detailed source characteristics and wave propagation properties of particular active fault sources are generally unavailable in this region, several generations of the source zone models, earthquake occurrence patterns and ground motion relations have been developed to quantify seismic hazard characteristics in the region. The variety of proposed models increases the resulting level of uncertainty and results in potential error in the decision making process, related policies and standards. As a result, there is a strong interest in the sensitivity analysis of hazard maps as they relate to the main input model parameters.

The most important input models for hazard map production are the seismic source zone model and the GMPE model. The seismic source zone model contains detailed seismicity specifications for a region, allowing for uncertainty, while a GMPE model is a statistical model developed for different tectonics regions to predict ground shaking at any site in a region. Previously, Atkinson and Goda (2011) investigated the effect of seismicity models and a new GMPE on seismic hazard assessment for four Canadian cities (Ottawa, Montreal, Quebec City, Vancouver) and concluded that the selection of correct GMPE model has an important effect on the resulting hazard assessment. Atkinson and Adams (2013) proposed a new set of GMPE for the 2015 National Seismic Hazard Maps. The main difference between the newly proposed GMPE model and other traditional models is in the means of quantifying epistemic uncertainty. In the past, the existing peer-reviewed GMPE models used different assigned weights representing that uncertainty and the relative confidence in each model (Atkinson, 1995). The updated method proposes using of existing peer-reviewed GMPEs to construct a set of three weighted equations (central, upper and lower) for each region and event type. The central GMPE is a representative GMPE and the upper and lower bounding equations quantify the uncertainty in the central GMPE. All three sets of GMPEs have different weights assigned to the logic tree used in PSHA. Each of these approaches has advantages and disadvantages (Atkinson, 2011). The first approach is more traditional and widely used than the representative model. However, in Canada the representative approach has been approved to the 2015 seismic hazard map production process (Atkinson and Adams, 2013).

Our motivation in this study is to expand the boundaries of the sensitivity analysis of hazard maps to the new GMPE model. The sensitivity tests performed in this study compared the complex effect of changes to GMPE models not for one particular site, as has been done before, but on a number of sites (hazard map). For high-resolution hazard map production calculations must be carried out on a large number of sites, and this requires powerful computational resources. Kropivnitskaya et al. (2015) demonstrated that these steps in the hazard mapping process, such as Monte Carlo simulations and resolution mapping, can be split and distributed into pipelines in parallel. Near real-time and low-latency parallel computing of hazard maps have been achieved by using streaming and pipelining computing paradigms through IBM InfoSphere Streams platform (IBM, 2015) which reads input data and models from external sources (in our case www.seismotoolbox.ca), executes hazard calculations in parallel on a number of sites and visualize resulting hazard map (Kropivnitskaya et al., 2015).

2. HAZARD MAPS PRODUCTION METHODOLOGY

Seismic hazard analysis provides an estimate of the effects from natural earthquakes on the man-made structures at a given site of interest. There are two widely used seismic hazard analysis approaches: deterministic and probabilistic. In the deterministic methodology, hazard is estimated for a specific magnitude at a fixed source-to-site distance (Reiter, 1990; Anderson, 1997; Krinitzsky, 2002). The probabilistic approach quantifies the probability of exceeding various ground-motion levels at a site or a map of sites given by all possible earthquakes in a region (Cornell, 1968; McGuire, 1977). PSHA is a powerful tool for seismic hazard map production (Adams and Atkinson, 2003; Trifunac, 1990). The classic probabilistic hazard calculation is relatively simple. Given that the seismic hazard source model and attenuation relationships are known or assumed, PSHA is performed in the following steps:

1. Determine the seismic hazard source model that provides N earthquake scenarios E_n for magnitude (m_n), location (L_n), and rate (r_n);
2. Determine the distance D_n to the site of interest;
3. Calculate the distribution of possible ground-motion levels for the scenario (Eq. 1):

$$[1] \qquad p_n(\ln PGA) = \frac{1}{\sigma_n\sqrt{2\pi}} e^{-\frac{(\ln PGA - g(m_n, D_n))^2}{2\sigma_n}},$$

where

lnPGA is a natural logarithm of peak-ground acceleration;
$g(m_n,D_n)$ is the mean of lnPGA given by attenuation relationship;
σ_n is the standard deviation of lnPGA given by the attenuation relationship.

4. Find the probability of exceeding each lnPGA by integration (Eq. 2):

$$[2] \qquad P_n(>\ln PGA) = \frac{1}{\sigma_n\sqrt{2\pi}} \int_{\ln PGA}^{\infty} e^{-\frac{(\ln PGA - g(m_n, D_n))^2}{2\sigma_n}} d\ln PGA;$$

5. Obtain the annual rate at which each lnPGA is exceeded R_n due to the scenario (Eq. 3):

$$[3] \qquad R_n(>\ln PGA) = r_n P_n(>\ln PGA);$$

6. Calculate the total annual rate of exceeding each lnPGA (Eq. 4):

$$[4] \qquad R_{total}(>\ln PGA) = \sum_{n=1}^{N} R_n(>\ln PGA) = \sum_{n=1}^{N} r_n P_n(>\ln PGA);$$

7. Compute the probability of exceeding each ground-motion level in the next T years of this annual rate using the Poisson distribution (Eq.5):

$$[5] \qquad P_{Poissonian}(>\ln PGA, T) = 1 - e^{-R_{total}T}.$$

An alternative procedure to perform PSHA proposed by Musson (1999) uses Monte Carlo simulations, where in the first stage a long-time synthetic earthquake occurrence catalogue is simulated. This synthetic catalogue is used to estimate a distribution of ground motions at any site from selected GMPE. Today there are a number of free and commercial software tools available to perform PSHA including Monte Carlo simulation approach (EQRISK, FRISK (McGuire, 1978), SeisRisk (Bender and Perkins, 1987), Fortran codes produced by National Seismic-Hazard Mapping Project by the USGS, CRISIS (Ordaz et al., 2013), EQRM (Robinson et al., 2005, 2006), OpenSHA (Field et al., 2003). One such tool is the EqHaz software suite of open-source FORTRAN programs developed by Assatourians and Atkinson (2013). This suite consists of three programs. EqHaz1 creates the synthetic earthquake catalogues generated by the user-specified seismicity parameters. EqHaz2 produces the ground motion catalogues and mean hazard probability curves at a site, as well as mean hazard motions at specified return periods calculated for a grid of points. These modules have some calculation limits that do not allow their use these modules for PSHA mapping purposes. In particular, the number of records in the each synthetic catalog is limited to 1,000,000 and hazard map produced by EqHaz2 could have no more than 100,000 points that for Eastern Canada means the maximum hazard map resolution that can be obtained is about one value per 25 kilometers. EqHaz3 de-aggregates the hazard, estimating the relative contributions of the earthquake sources in terms of distance and magnitude. Kropivnitskaya et al. (2015) took the EqHaz1 and EqHaz2 Fortran source code, compiled them into system object libraries and implemented the base PSHA procedures and functions in the streaming environment IBM InfoSphere Streams. As a result, pipelining and parallel execution on the experimental environment of a cluster of four machines, each with dual Xeon quad-core 2.4 GHz CPU, 16 GB RAM and running Linux overcame the EqHaz limitations mentioned above. In particular, the number of sites for hazard maps are stepped-up to 2,500,000 sites that gives a hazard map with resolution about one value per kilometer. The number of records in the synthetic catalog has been increased in 10 times up to 10,000,000 records (Kropivnitskaya et al., 2015). These achievements allowed the creation of hazard maps for a sensitivity testing in near-real time for the entire territory of Eastern Canada with relatively high resolution.

3. HAZARD MAPS PRODUCTION METHODOLOGY

3.1 Seismic Source Zone Model

Eastern Canada has a relatively low rate of earthquake activity, the result of its location in a stable continental region within the North American Plate. Approximately 450 earthquakes occur in this region every year. On average, four of those are M > 4 and thirty of M > 3 per year, three events of M > 5 every decade. Approximately twenty-five are reported as felt events. In most cases an M > 3 event is strong enough to be felt while an M > 5 event is the threshold for damage in this region. The GSC manages a seismograph network that can detect all events in Eastern Canada of M > 3 as well as all events with M > 2.5 or more in areas with a high density population (Halchuk, 2000). As of today, there is no solid understanding of what causes earthquakes in Eastern Canada. This region is the part of the stable interior of the North American Plate. Therefore, there is no correlation between plate interaction and the seismic activity rate and magnitude in this region (Halchuk, 2000).

The seismicity zoning and occurrence model used in this work as input for synthetic data generation are a composite model of thirty-nine Eastern Canada zones provided by GSC (Adams an Halchuk, 2003, 2004; Halchuk and Adams, 2008) shown in Fig. 1. The model includes regional geological and seismological features and consists of two alternative source zone models: the H model, which is based on historical seismicity, and the R model, which is based on regional tectonic structure.

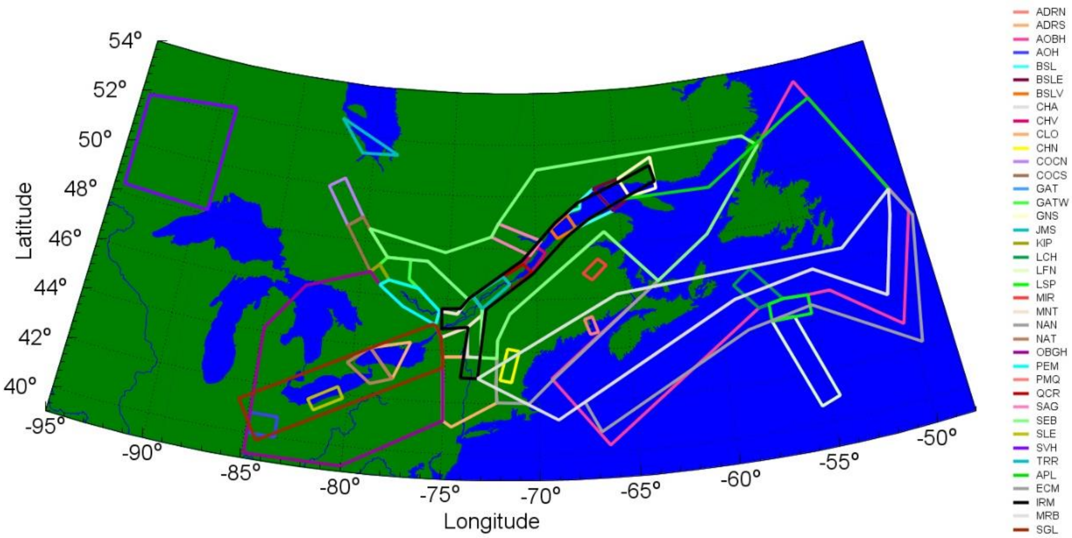

Figure 1: Eastern Canada Seismic Zones Composite Model.

3.2 GMPE Model

A GMPE represents the shaking amplitude as a function of earthquake magnitude, distance from the source, site conditions, and other variables and are calculated for peak ground acceleration and velocity. The selection of the correct GMPE model is a critical step in PSHA containing two types of uncertainty. The first is aleatory uncertainty, random variability of amplitudes about a median prediction equation. This type of GMPE uncertainty is handled by integrating over the distribution of ground-motion amplitudes about the median. The second type is epistemic uncertainty, which affects the correct value of the median, and in most cases is handled by considering alternative GMPEs in a logic tree format (e.g., Bommer and Scherbaum, 2008). The logic tree model is based on branches with alternative models and then weights assigned to each of those. As a result, the branches and their weights are intended to represent the underlying continuous distribution of possible ground motions. There are two alternative approaches for epistemic uncertainty estimation in GMPEs by using logic trees. One of them uses multiple existing peer-reviewed GMPEs, with weights assigned to each GMPE based on the judgment of the analyst concerning their relative merits or applicability. Another method uses existing peer-reviewed GMPEs, data analysis, and judgment to define a representative suite of models to capture the uncertainty, including one or more central model along with high and low alternatives. Atkinson (2011) argued that the development of a representative suite is a superior approach to building ground-motion characterization logic trees, in comparison with the more widely practiced use of multiple GMPEs drawn from the literature.

Three sets of representative GMPE (central, low and high) have been developed in Eastern Canada based on five peer-reviewed equations Pezeshk, Zhandieh and Tavakoli (2011), Atkinson and Boore (2006), Atkinson (2008), Silva, Gredor and Daragh (2002) with single corner (variable stress), Gredor and Daragh, (2002) with double corner (with saturation). In Figure 2 examples of several GMPE equations are shown with pseudo spectral acceleration at different period of time for event with different magnitude. Spectral acceleration is the most commonly used measure of ground motion intensity in building engineering practice. For specified natural period and damping level, spectral acceleration represents the maximum acceleration that a ground motion will cause in a linear oscillator. In other words, pseudo spectral acceleration (PSA) is equal to spectral displacement times the square of the natural frequency (Baker et. al, 2006). The representative central equation developed shows the geometric mean ground motions of the five alternatives. It can be used as input for ground motion estimation for all site classes B, C conditions (the average shear-wave velocity in the top 30 m Vs30=760 m/s) in Canada. Atkinson (2011) demonstrated that the representative equation method is comparable to the alternative equations approach, but the weights of each GMPE in the logic tree for PSHA calculations must be selected in a consistent manner.

For Eastern Canada the proper logic tree weights proposed are 0.5, 0.25, and 0.25 for the central, low and high equations weight, respectively. This weights schema is used and designated as the base model in this study. To obtain the relative performance of the models and to study the representation of epistemic uncertainty, three sensitivity exercises were performed here. In particular, a set of hazard maps were created considering different weights in the PSHA logic tree for central, low and high equations in the representative set (listed in the Table 2). In each case the weight difference in the each node of the logic tree comparing with basic model equals ±25%-75%. During the first test the weights of low and central equations in the logic tree have been decreased up to 25% and 50% relatively to teach 0 and high equation weight has been increased by 75% and reached the maximum weight equals 1. During the second test the maximum weight has been assigned to the central equation when at the same time for low and high equations 0 weight has been assigned. The third test represent the case in which the low equation received the maximum weight and high and central equation have not been taken into account.

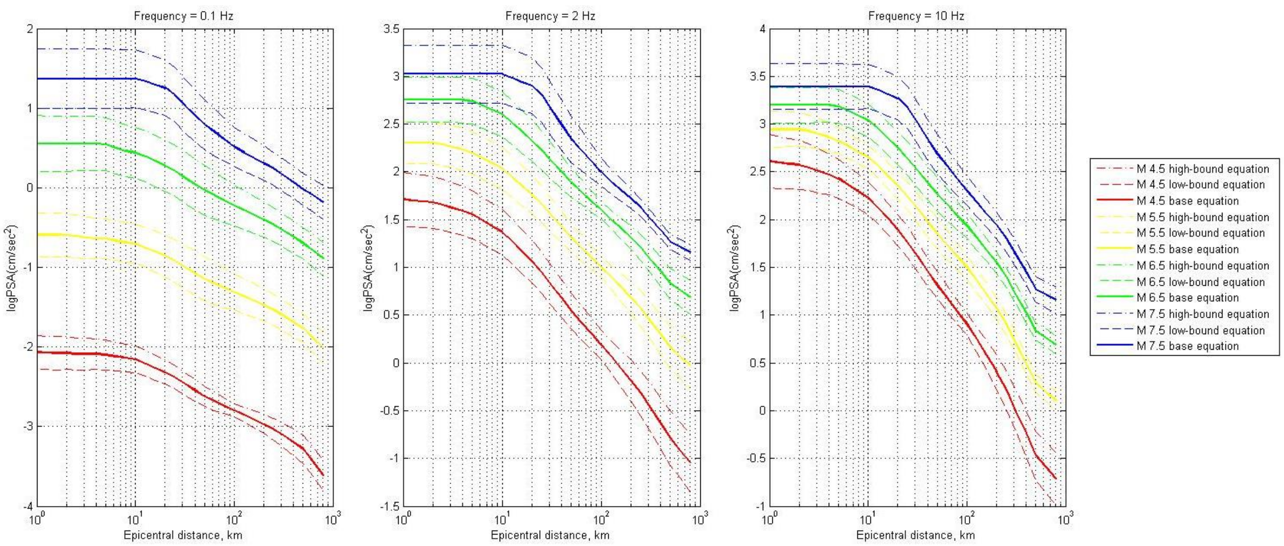

Figure 2: PSA values at 0.1Hz, 2Hz and10 Hz for Eastern North America GMPE versus epicentral distance.

4. RESULTS

The mean hazard maps of predicted PSA with 2475 year return period were calculated based on the input parameters explained above. 2475 year return period represents 2% exceedance probability in 50 years. This return period is commonly used in building design because of its ability to capture the effects of rare but large earthquakes. The hazard maps produced with input base model are shown on Fig.3, representing PSA at three different periods equal 0.2 sec, 1.0 sec and 2.0 sec.

Three sensitivity tests have been performed for different GMPE models. The effects of modification in the GMPE model are significant at every vibration period in all three sensitivity tests. Test 1, presented in Fig. 4, compared predicted spectral acceleration calculated for the base model with predicted spectral acceleration calculated for the model with maximum weight assigned to the high-bound GMPE of the representative set. As expected, the difference of the estimated level of ground motion with the high-bound model is generally positive in all cases and varies in the range from 1.81 to 58.47 cm/sec^2 at 0.5 Hz frequency, from 3.6 to 128.53 cm/sec^2 at 1.0 Hz frequency, from 4.76 to 398.89 cm/sec^2 at 5.0 Hz frequency.

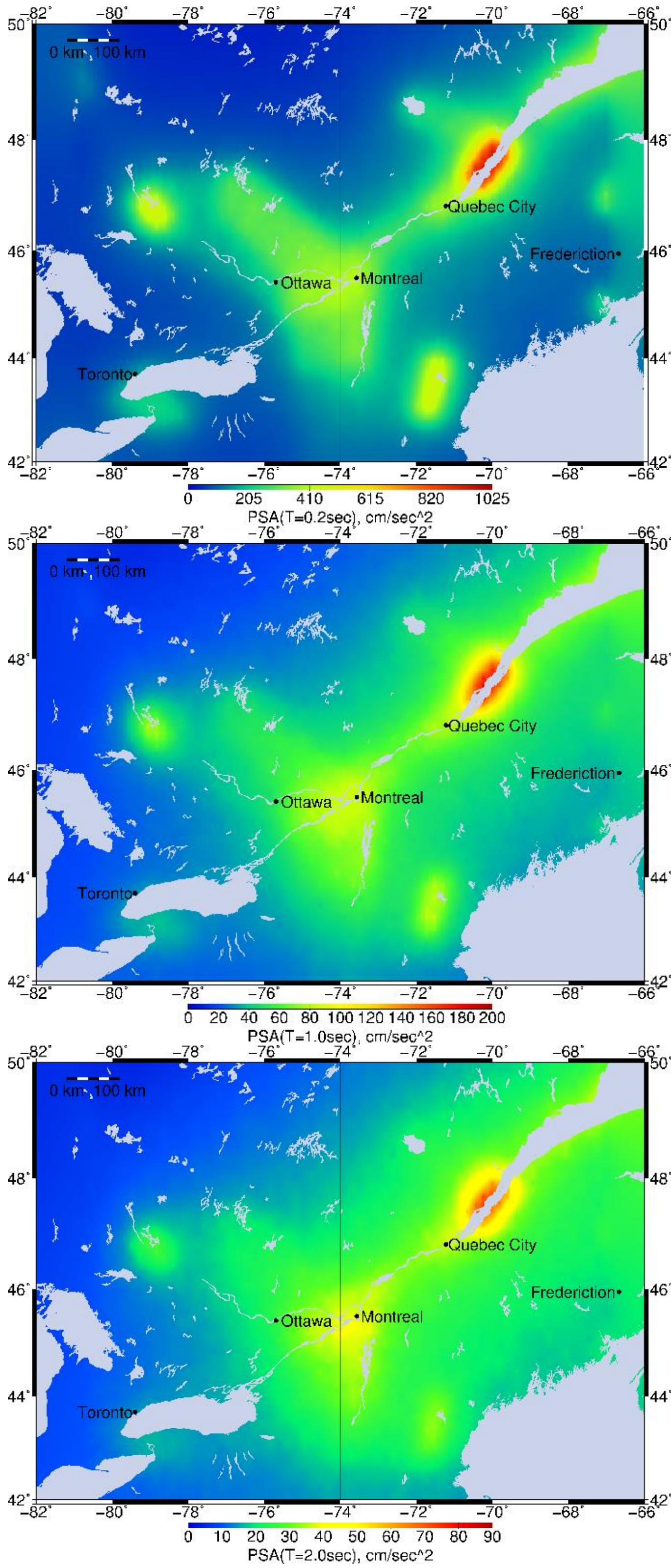

Fig 3. 2475 year return period mean hazard maps (with base GMPE model).

During the second test (Fig. 5), maximum weight was assigned to the central GMPE of the representative set. The results obtained in this case are also significantly different when compared to the base model results. The estimated difference varies from 0.00063 to 17.92 cm/sec^2 at 0.5 Hz frequency, from – 0.00059 to 36.37 cm/sec^2 at 1.0 Hz frequency, and from 0.0011 to 142.95 cm/sec^2 at 5.0 Hz frequency.

In the third test (Fig. 6) the maximum weight has been assigned to the low-bound GMPE and results have been compared with the results of the base model. This test results in a negative difference that is in the range of -49.3 to -1.79 cm/sec^2 at 0.5 Hz frequency, from -100.06 to -4.08 cm/sec^2 at 1.0 Hz frequency, from -756.84 to -11.67 cm/sec^2 at 5 Hz frequency.

The mean changes on every vibration period for each test performed also were analyzed. The maximum change occurs in Test 1, in which 100% weight in the GMPE logic tree has been assigned to the high-bound equation of the representative GMPE set. The minimum mean difference appeared in the Test 2 case in which the medium equation of the representative GMPE set was applied. In general, the predicted spectral acceleration is more sensitive to the applied changes at low frequencies and close distances than at high frequencies and far distances.

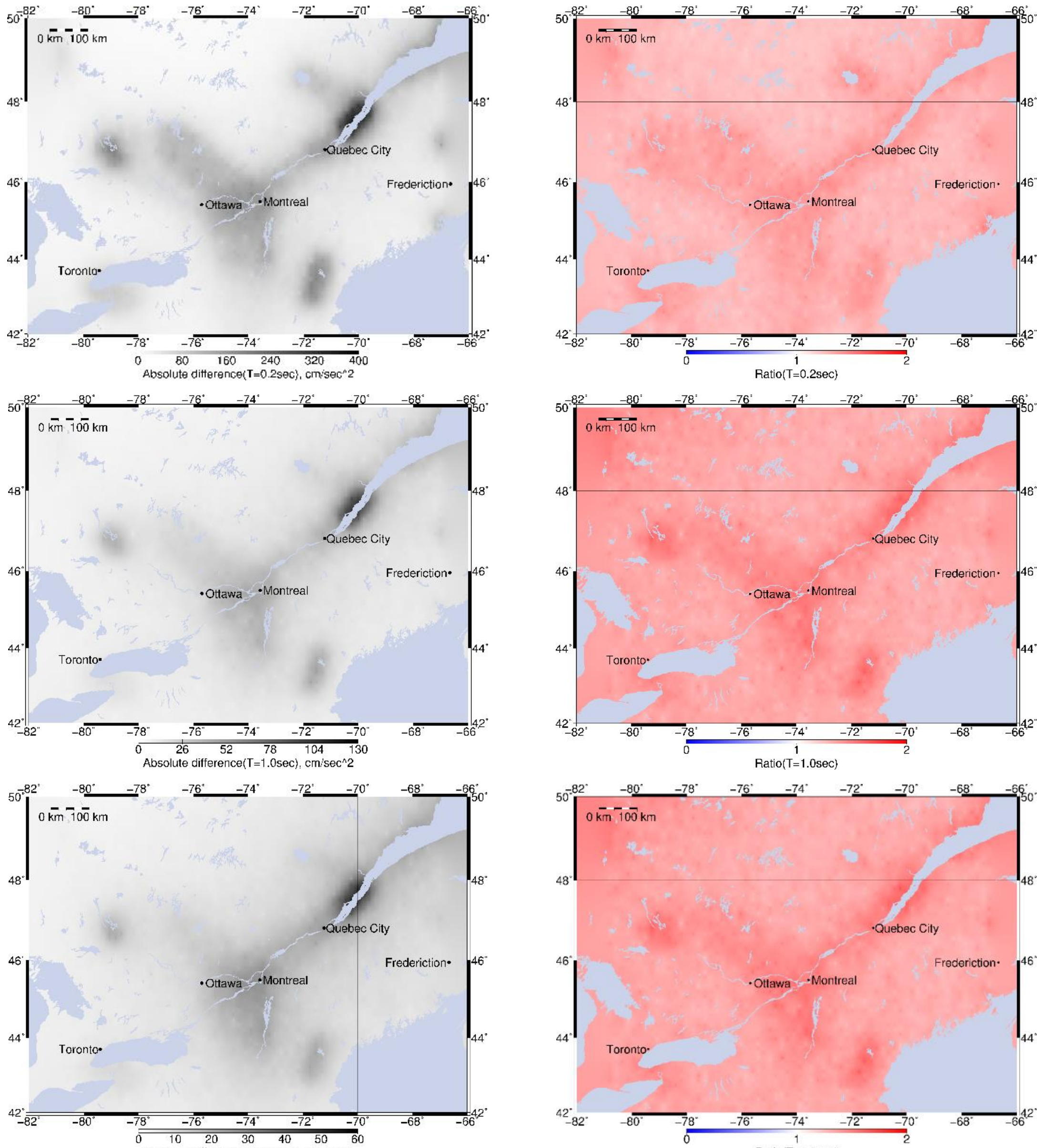

Figure 4: Sensitivity test of 2475 year return period mean hazard maps with high-bound GMPE.

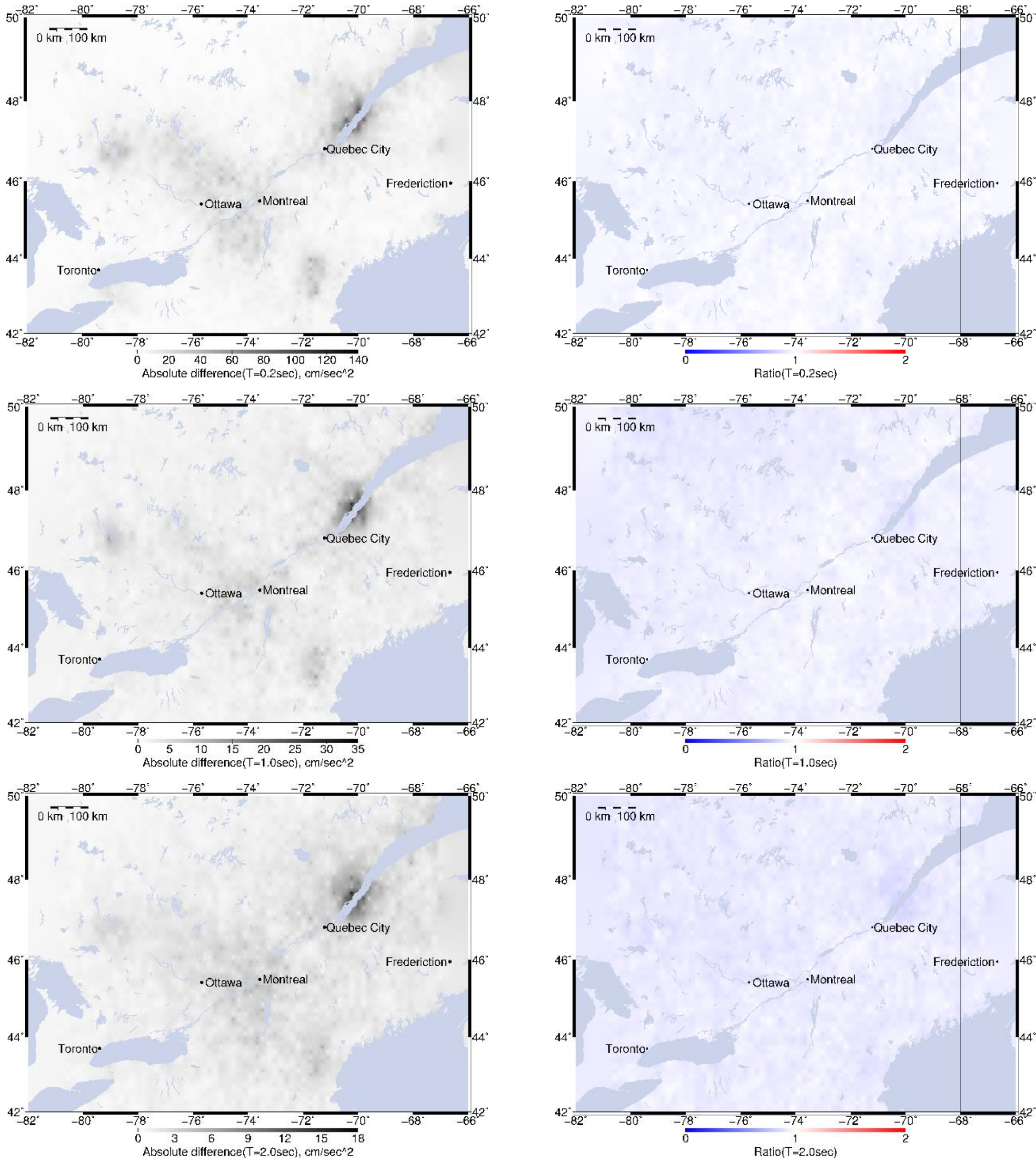

Figure 5: Sensitivity test of 2475 year return period mean hazard maps with medium GMPE.

5. CONCLUSIONS

Hazard maps have important significance in the seismic risk mitigation programs. Both overestimation and underestimation of the true seismic hazard and risk may significantly increase economic and human losses. Attention should be paid to the development and sensitivity analysis of key input models for PSHA. GMPE models play an important role in ground-motion characterization and seismic hazard map production. In particular, the correct representation of epistemic uncertainty through weights assigned in the representative set of GMPE logic tree has a significant impact on the seismic hazard assessment and, as a result, is one of the most important factors in PSHA and should be handled carefully according to the experts' recommendations.

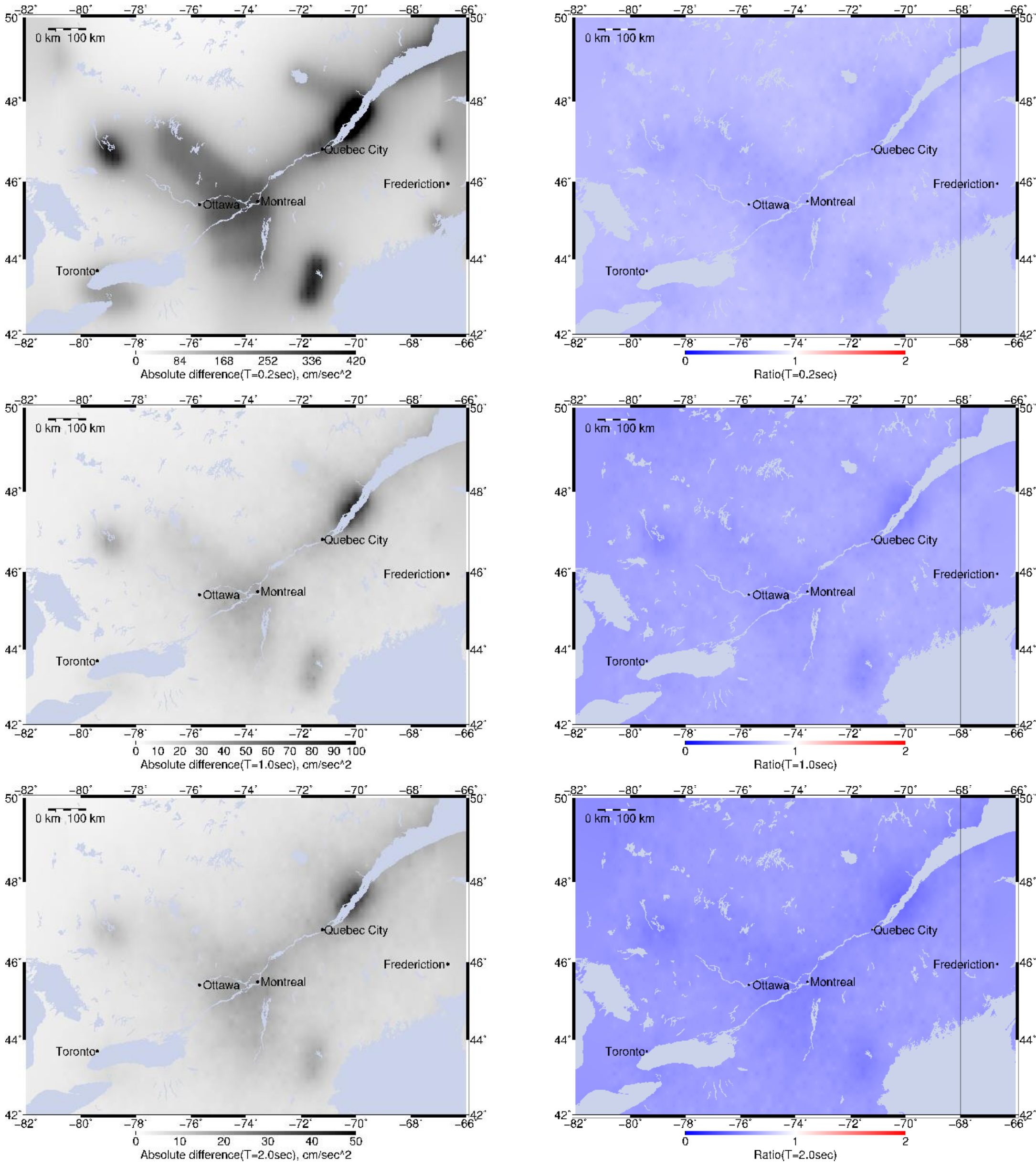

Fig 6. Sensitivity test of 2475 year return period mean hazard maps with low-bound GMPE.

6. REFERENCES

Adams J., and Atkinson, G. 2003. Development of seismic hazard maps for proposed 2005 National Building Code of Canada. *Canadian Journal of Civil Engineering*, 30 (2): 255-271. doi: 10.1139/102-070.

Adams, J., Halchuk S., 2003. Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada. *Geological Survey of Canada Open File 4459*: 1-155.

Adams, J., Halchuk S., 2004. Fourth-generation seismic hazard maps for the 2005 national building code of Canada. *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Canada. Paper 2502 on CD-ROM.

Anderson, J.G. (1997). “Benefits of Scenario Ground Motion Maps”, *Engineering Geology*, Vol. 48, No. 1, pp. 43–57.

Assatourians, K., and G. M. Atkinson (2013). EqHaz: An open-source probabilistic seismic-hazard code based on the Monte Carlo simulation approach. *Seismol. Res. Lett.* 84, no. 3, 516–524.

Atkinson, G. (1995). Ground motion relations for use in eastern hazard analysis. In Proceedings, *7th 650 Canadian Conference on Earthquake Engineering*, Montreal, June 1995, p. 1001-1008.

Atkinson, G. (2008). Ground-motion prediction equations for eastern North America from a referenced empirical approach: implications for epistemic uncertainty, *Bull. Seism. Soc. Am.*98, 1304-1318

Atkinson G. 2011. An empirical perspective on uncertainty in earthquake ground motions. *Canadian Journal of Civil Engineering* 38(9): 1002-1015

Atkinson, G. and J. Adams (2013). Ground motion prediction equations for application to the 2015 national seismic hazard maps of Canada. *Canadian Journal of Civil Engineering*, 40, 988-998.

Atkinson, G. M., and D. M. Boore (2006). Earthquake ground-motion prediction equations for eastern North America, *Bull. Seism. Soc. Am.*96, 2181-2205.

Atkinson, G. and K. Goda (2011). Effects of seismicity models and new ground motion prediction equations on seismic hazard assessment for four Canadian cities. *Bull. Seism. Soc. Am*., 101, 176-189.

Bender, B., and D. M. Perkins (1987). SEISRISK III: A computer program for seismic hazard estimation. *U.S. Geol. Surv. Bull*. 1772.

Bommer, J. and F. Scherbaum (2008). The use and misuse of logic trees in probabilistic seismic hazard analysis. *Earthquake Spectra*, 24, 997-1009.

Cornell, C. A. (1968). Engineering seismic risk analysis. *Bull. Seismol. Soc. Am*. 58, no. 5, 1583–1606.

Field, N., T. A. Jordan, and C. A. Cornell (2003). OpenSHA: A developing community-modeling environment for seismic hazard analysis. Seismol. Res. Lett. 74, no. 4, 406–419.

Gregor, N. J., W. J. Silva, I. G. Wong, and R. R. Youngs (2002). Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model, *Bull. Seism. Soc. Am.*92, 1923-1932.

Halchuk, S., (2000) Earthquake zones in Eastern Canada http://www.earthquakescanada.nrcan.gc.ca/ zones/eastcan-eng.php

Halchuk, S., and J. Adams (2008). Fourth generation seismic hazard maps of Canada: maps and grid values to be used with the 2005 National Building Code of Canada, *Geological Survey of Canada, Open File 5813*.

IBM (2015) IBM Knowledge Center http://www-01.ibm.com/support/knowledgecenter/

Krinitzsky, E.L. (2002). "How to Obtain Earthquake Ground Motions for Engineering Design", *Engineering Geology*, Vol. 65, No. 1, pp. 1–16.

Kropivnitskaya Y., Qin J., Tiampo K., Bauer M. (2015). A Pipelining Implementation for High Resolution Seismic Hazard Maps Production. *International Conference On Computational Science, ICCS 2015 — Computational Science at the Gates of Nature.* Volume 51:1473–1482

McGuire, R. (1978). FRISK: Computer program for seismic risk analysis using faults as earthquake sources. *U.S. Geol. Surv. Open-File Rept.* 78-1007.

McGuire, R. (2004). *Seismic Hazard and Risk Analysis.* Earthquake Engineering Research Institute, Oakland, California.

McGuire, R. (2008). Probabilistic seismic hazard analysis*: Early history. Earthq. Eng. Struct. Dyn*. 37, 329–338.

Musson, R.M.W (1999). Determination of design earthquakes in seismic hazard analysis through Monte Carlo simulation. *J.Earthquake Eng*., 3, 463-474.

NRCC. 1953. 1960. 1965. 1970. 1975. 1977. 1980. 1985. 1990. 1995. 2005. 2010. National Building Code of Canada, *Associate Committee on the National Building Code, National Research Council of Canada*, Ottawa, ON.

Ordaz, M., F. Martinelli, V. D'Amico, and C. Meletti (2013). CRISIS2008: A flexible tool to perform probabilistic seismic hazard assessment*. Seismol. Res. Lett*. 84, no. 3, 495–504, doi: 10.1785/0220120067.

Pezeshk, S., A. Zandieh and B. Tavakoli (2011). Ground-motion prediction equations for eastern North America from a hybrid empirical method. *Bull. Seism.Soc. Am*.

Reiter, L. (1990). *Earthquake Hazard Analysis: Issues and Insights*, Columbia University Press, New York, U.S.A.

Robinson, D., T. Dhu, and J. Schneider (2006). Practical probabilistic seismic risk analysis: A demonstration of capability. *Seismol. Res. Lett.* 77, no. 4, 453–459.

Robinson, D., G. Fulford, and T. Dhu (2005). *EQRM: Geoscience Australia's Earthquake Risk Model: Technical Manual: Version 3.0*, GA Record 2005/01, Geoscience Australia, Canberra, 148 pp.

Silva, W. J., N. J. Gregor, and R. Darragh (2002). *Development of regional hard rock attenuation relations for central and eastern North America*, Technical Report, Pacific Engineering and Analysis, El Cerrito, CA.