

The seismic hazard model for Canada: Past, present and future

Trevor I. Allen

Geological Survey of Canada, Natural Resources Canada, Sidney, British Columbia, Canada

John Adams & Stephen Halchuk

Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario, Canada

ABSTRACT: The Geological Survey of Canada (GSC) has contributed earthquake hazard information for the National Building Code of Canada (NBCC) since the 1953 edition. The requirements for seismic hazard modelling and mapping have changed over the years as scientists' understandings of earthquakes and their effects on buildings have evolved and improved. As the knowledge of, and sophistication in, probabilistic seismic hazard modelling techniques have advanced, Canada's national mapping efforts have evolved from qualitative assessment in 1953, to fully probabilistic for the hazard model accepted for the seismic provisions of the 2015 NBCC.

The 2015 national hazard model update (the 5th Generation) yields many important advances on its predecessors, including: reconfigured seismic sources and special consideration of large rare eastern earthquakes; the use of a suite of representative backbone ground-motion models, and; explicit definition of crustal fault sources in the Yukon Territory and offshore western margin faults (north of Cascadia) based on GPS and paleoseismic slip rates. The GSC is now working towards the 2020 building code cycle with a view of rethinking the fundamental scientific questions and building on the advances made for the 2015 hazard model. In particular, we will: evaluate and adopt new hazard computation software; evaluate catalogue declustering techniques; examine, in more detail, the rationale for ground-motion model selection in specific tectonic environments; consider hazard from induced earthquakes; and explore the utility of risk-targeted ground motions for design.

1 INTRODUCTION

The Geological Survey of Canada (GSC), a sector of Natural Resources Canada, is responsible for providing seismic hazard information to key stakeholders with the ultimate aim of safeguarding Canadian citizens from the negative impacts of earthquakes. The 5th Generation Seismic Hazard Model of Canada (SHMC) has recently been prepared to underpin the seismic provisions for the 2015 National Building Code of Canada (NBCC; Adams *et al.*, 2015). The 2015 SHMC yields many important advances on its predecessors. These advances will be explained in the current contribution. The historical context for seismic hazard mapping in Canada will also be summarised. The contribution will conclude by discussing research priorities for the 6th Generation SHMC that will be explored for the 2020 edition of the NBCC.

2 HISTORICAL CONTEXT

Canada has had four epochal seismic hazard models (1953, 1970 1985 and 2005), each of which were used in one or more editions of the NBCC (Adams, 2011). The 1953 map was a qualitative assessment (Hodgson, 1956), and was primarily a zoning map rather than a seismic hazard model. The 1970 model (Milne & Davenport, 1969) was a true probabilistic seismic hazard model, one of the earliest such national models. It depicted the peak horizontal ground acceleration (PGA) to be expected at 0.01 per annum (p.a.). The 1985 maps (Basham *et al.*, 1985) were probabilistic at 0.0021 p.a. (or 10% exceedance in 50 years) and were given for both PGA and peak horizontal ground velocity (PGV). The 2005 (4th Generation SHMC) probabilistic assessment (Adams & Halchuk, 2003) was developed for 0.000404 p.a. (or 2% exceedance in 50 years), and provided four spectral acceleration parameters (at periods of 0.2, 0.5, 1.0, and 2.0 seconds) giving site-specific uniform hazard spectra for the first

time. PGA was also provided to allow continuity in geotechnical designs. A schematic overview of the evolution of the SHMC is provided in Figure 1. The development of the 2015 5^{th} Generation SHMC is discussed in the succeeding section.

3 THE SEISMIC HAZARD MODEL OF CANADA PREPARED FOR THE 2015 NBCC

The 5th Generation SHMC was developed to provide seismic design values for the 2015 NBCC (Adams et al., 2015). The model updates the earthquake catalogue (Halchuk et al., 2015b); consistently expresses earthquake magnitudes in terms of moment magnitude; revises areal earthquake sources; includes probabilistic treatment of Cascadia and other fault sources; and estimates mean ground shaking at the 2% in 50-year probability level. The model takes advantage of contemporary scientific knowledge and replaces the 4th Generation "robust" combination of alternative source models (Adams & Halchuk, 2003) used for the 2010 SHMC with a fully probabilistic model. The groundmotion models (GMMs) used represent a major advance over those used for the 4th Generation model. Seismic design values (on Soil Class C at $V_{S30} = 450$ m/s) for PGA, PGV and for Sa(T) for periods T = 0.2, 0.5, 1.0,2.0, 5.0, and 10.0 s are proposed for the 2015 NBCC. Specific highlights of the 2015 model are described below.

3.1 Seismic source models

Seismic source zones used for the 4th Generation



Figure 1: The evolution of national hazard model of Canada.

consisted of two models, distinguished primarily as historical cluster (H) and regional seismotectonic (R) models. For the 5th Generation model, this framework is preserved in northeastern Canada. In southeastern Canada, an additional type of source – hybrid between H and R [see Adams (2011) for rationale] – is used together with the updated H and R models. In western Canada, a single set of source models is used. However, these models include variability in the source geometry as appropriate (for example, in the closest down-dip approach of the Cascadia subduction zone to southwestern British Columbia; Rogers *et al.*, 2015). Boundaries of the individual areal source zones were revised to reflect new information, and their earthquake magnitude-frequency distributions were recalculated using the updated catalogue (Halchuk *et al.*, 2015b).

The 5th Generation model includes fault sources for three low-angle subduction thrusts in the Cascadia subduction zone (i.e., the Juan de Fuca, Explorer and Winona segments), an updated treatment of the faults offshore of Haida Gwaii (formally the Queen Charlotte Islands), and adds five onshore strike-slip and reverse faults in the Yukon-Alaska region (Allen *et al.*, 2015a). The modelled sources appropriately concentrate the hazard near the faults, instead of averaging it out over a wider area (as was done for 2010 4th Generation SHMC).

3.2 Ground-motion models (GMMs)

A major enhancement is the adoption of modern ground motion models (GMMs). The modern GMMs for North America have incorporated an improved understanding of the magnitude- and distance-scaling of earthquake ground motions, a wealth of new data, and the use of finite-fault stochastic

simulations to account for the absence of ground-motion data from large eastern North American earthquakes (e.g., Atkinson & Boore, 2006).

The different physical properties of the crust in eastern and western Canada and the different nature of the earthquake sources in southwestern Canada require the use of separate GMMs, as detailed by Atkinson & Adams (2013). Unlike the 4th Generation SHMC which used a single published relation (with rather arbitrary uncertainty bounds) for each region, the 5th Generation model uses representative suites of GMMs (Atkinson *et al.*, 2014). A suite of crustal relations based on the ground-motion values from five appropriate eastern GMMs was used for eastern Canada. For the western Canadian crustal source zones, as well as the crustal faults, a suite of models that use the Boore & Atkinson (2008) GMM as the backbone model was used. For subcrustal, chiefly normal-mechanism, earthquakes within the subducting slab under Puget Sound and west of Vancouver Island, the backbone GMM was centred on the Zhao *et al.* (2006) inslab relation with representative depths of 30 km and 50 km, respectively. For the Cascadia and Haida Gwaii subduction earthquakes, a 50/50 weight for simulation- and empirical-based interface GMMs was applied. Finally, the ground motions were adjusted so as hazard was calculated on "firm ground" site conditions, or Site Class C (Finn & Wightman, 2003), defined as $V_{S30} = 450$ m/s for 2015 NBCC.

3.3 2015 hazard values

Seismic hazard values were calculated for a grid extending over Canada and used to create nationalscale contour maps (Fig. 2). The spectral values are used to construct Uniform Hazard Spectra (UHS) on Site Class C for a few major cities to illustrate the range and period dependence of seismic hazard across Canada (Fig. 3). The UHS for Winnipeg, Manitoba, is representative of many localities in lowseismicity parts of Canada. In general, for locations in eastern Canada, the estimated seismic hazard at $T \ge 2.0$ s has increased while the seismic hazard at short periods has decreased – in some places significantly. For locations in western Canada, the seismic hazard at long periods has increased significantly for areas affected by great Cascadia interface earthquakes. In Haida Gwaii and the Yukon, the explicit inclusion of fault sources has also raised the estimated hazard at some localities. Unlike the U.S. national design maps (e.g., Leyendecker *et al.*, 2000), we did not employ the so-called deterministic cap to avoid potentially unrealistic probabilistic ground motions from crustal fault sources. See Adams *et al.* (2015) for further details on the rationale for changes to the seismic hazard estimates across Canada.

4 TOWARDS THE 2020 NBCC HAZARD MODELS

There are several research priorities that will be investigated prior to the development of the 6th Generation SHMC. Paramount among these priorities is the need to migrate the hazard computational platform to modern open source PSHA software (e.g., Pagani *et al.*, 2014). The GSC has used the same software (with minor modifications) since the late 1980's. This software has become inflexible and difficult to maintain, particularly with rapid scientific advances in seismic hazard modelling. The migration to new software will require extensive testing and validation to ensure continuity between the 5th and 6th Generation hazard models, in part to ensure that any potential variation in modelled hazard is due to genuine scientific advances rather than to model implementation. In addition to the migration to modern PSHA software, other research priorities (some briefly discussed below) may include: incorporation and identification of additional crustal faults in Canada and adjacent U.S.; an enhanced earthquake catalogue; evaluation of the hazard sensitivity to catalogue declustering; evaluation of smoothed seismicity models; assessment and/or development of new GMMs; assessment of passive margin hazard from global analogues; improved site classification schemes; evaluation of risk-targeted hazard and; inclusion of induced seismicity.

Comparisons between the Canadian and U.S. national seismic maps are often made for cross-border locations. Differences between the 2015 Canadian and the 2014 U.S. model (Petersen *et al.*, 2014) can largely be attributed to the definition of source zones, choice of ground motion prediction equations, the earthquake catalogue, and mode of incorporating Cascadia subduction earthquakes (Halchuk *et al.*, 2015a). While there is general agreement in the pattern and relative hazard levels, we intend to continue working with our U.S. counterparts to minimise differences between the two national models.



Figure 2: Sa(0.2) for Canada (mean values of 5% damped spectral acceleration for Site Class C (defined as $V_{S30} = 450$ m/s for 2015 NBCC) and a probability of 2% in 50 years) in g.



Figure 3: Uniform Hazard Spectra for mean 2% in 50-year ground motions on Site Class C for key cities.

4.1 Catalogue declustering

Previous sensitivity analyses of earthquake catalogue declustering for eastern Canada indicated little difference in hazard values when standard California algorithms were applied (e.g., Gardner & Knopoff, 1974). However, studies suggest that aftershock sequences for large intraplate earthquakes can continue for longer durations than in seismically active regions (Stein & Liu, 2009; Leonard *et al.*, 2014) rendering traditional declustering techniques unsuitable and providing non-Poissonian datasets

for earthquake occurrence. Consequently, declustering parameters and methods will be reviewed for both active tectonic and intraplate regions.

4.2 Evaluating smoothed seismicity

The basis of the 5th Generation SHMC relies on areal source zones that assume a uniform rate of earthquake occurrence within a spatial region. The hazard in some regions is highly sensitive to the placement of source zone boundaries (e.g. Richardson Mountains, Yukon Territory). While every effort has been made to respect the knowledge base of seismotectonic and geophysical characteristics of the crust and historical seismicity, the definition of areal source zones remains somewhat subjective in nature. However, these areal sources do allow hazard modellers to forecast hazard in regions where there may be little evidence of earthquakes in the historical record, but where large earthquakes might reasonably be expected based on seismotectonic analogues. Consequently, their use will be retained for the 6th Generation SHMC.

Adaptively smoothed seismicity models offer a more objective method determine seismicity distribution models based on historically-observed seismicity (e.g., Helmstetter *et al.*, 2007). Whilst the application of this technique might be better suited to active tectonic regions with shorter recurrence intervals, the method will be explored as an alternative earthquake spatial model for the 6^{th} Generation SHMC.

4.3 Evaluation of ground-motion models

Ground-motion models are often considered to contribute one of the largest sources of uncertainty in PSHA. The production of seismic hazard models requires assumptions on the selection and use of GMMs, often with little local empirical evidence. Preliminary assessment on the appropriateness of modern GMMs (including those used for the 2015 SHMC) for use in western Canada has begun using limited datasets from largely offshore earthquakes along the Pacific-North America tectonic plate boundary (Allen & Brillon, 2015; Brillon & Allen, 2015). While still preliminary, these assessments suggest that the use of modern GMMs tend to overestimate recorded ground motions from offshore earthquakes by factors of two or more. This work is ongoing for western Canada and efforts are underway to systematically process and evaluate ground-motion data for all earthquakes of $M_W \ge 4.0$ with moment tensor solutions, with an emphasis on crustal earthquakes *within* the North American plate.

A suite of GMMs has recently been completed for eastern North America through the Next Generation Attenuation-East project (Pacific Earthquake Engineering Research Center, 2015). The models developed through this research project have been extensively tested and validated. These models will likely be adopted in some fashion for the 6th Generation SHMC.

4.4 Risk-targeted hazard

Allen et al. (2015b) explored the utility of so-called "risk-targeted" ground motions for future editions of the NBCC. The risk-targeted approach described by Luco et al. (2007) was adopted into the 2012 International Building Code for the United States. The method provides a framework for assessing hazard based on a uniform probability of collapse rather than uniform ground-motion exceedance probabilities. The risk coefficients (i.e., the proposed adjustment factors from 2% in 50-year mean hazard) presented in the study of Allen et al. (2015b) are necessarily dependent on the level of "acceptable risk," or the collapse risk objective. This preliminary assessment indicates that there is moderate variability in the risk coefficient across Canadian localities, with all localities showing a slight reduction in design ground motions relative to the proposed 2015 NBCC 2% in 50-year hazard values. The largest potential changes in design ground motions are observed on the west coast of Vancouver Island near Tofino and Ucluelet, for example (Fig. 4). The adjustment factors observed in this region are commensurate with the changes seen in coastal regions in the US Pacific Northwest that are affected by hazard from the Cascadia subduction zone. Risk coefficients of around 0.85 suggest that structures in these localities may be overdesigned by 15%. However, recent research suggests that the current approach in the United States - as also used by Allen et al. (2015b) - may lead to unconservative design values in subduction environments (Liel et al., 2015). This is because

the median collapse capacity of buildings from subduction earthquakes is typically lower (because of longer duration shaking) than that assumed by the generic building collapse fragility curves used to determine the risk-targeted ground motions (Chandramohan *et al.*, 2015; Raghunandan *et al.*, 2015).

Because the localities on the west coast of Vancouver Island represent a minor contribution to the nation's building stock (i.e., they are sparsely populated regions), there may be small returns for adopting risk-targeted ground motions for future editions of the NBCC based solely on the numerical impacts to design values. This assumes that by not adopting the risk-targeted approach for the NBCC that there is little-to-no impact on life safety as a consequence of this decision. However, benefits for the adoption of risk-targeted ground motions for the NBCC include the explicit quantification of collapse prevention objectives in building design and mainstreaming the consideration of collapse risk into earthquake engineering practice. Ultimately, the decision to adopt risk-targeted ground motions, and at what collapse probability level, should be based on broad community consultation that involves structural engineers, hazard practitioners, sociologists and decision makers.



Figure 4: Calculated risk coefficients for Sa(1.0 s) at southwestern Canadian localities based on the hazard values proposed for the 2015 NBCC.

4.5 Induced seismicity

The integration of seismic hazard triggered by induced earthquakes – either through hydro-fracturing or wastewater injection – into building design maps has become the subject of much debate in recent times (Petersen *et al.*, 2015). Due to the transient and spatially variable nature of this hazard, its consideration presents a major challenge for typical exceedance probabilities of engineering interest (e.g., 2% in 50 years), which assume time-stationary earthquake behaviour. Furthermore, any potential changes in design requirements may result in potential economic impacts in regions affected by induced hazards.

There are now several documented cases of earthquakes potentially triggered by hydro-fracturing (*not* wastewater injection) in Canada (Atkinson *et al.*, 2015a; Farahbod *et al.*, 2015), the largest of these being a M_W 4.6 event in the Fox Creek, Alberta region (June 2015) and a M_W 4.6 event in northern British Columbia (August 2015). In a preliminary study for a typical site affected by induced earthquakes, Atkinson *et al.* (2015b) demonstrated that the hazard can greatly exceed the hazard from natural background seismicity at most probabilities of engineering interest; a finding that is supported by analogue studies in the United States (Petersen *et al.*, 2015). Should the 6th Generation SHMC integrate hazard from potentially induced earthquakes, there are several philosophical issues and

assumptions that need to be addressed. These include: 1) the appropriateness of the Poisson earthquake process; 2) catalogue declustering, earthquake rates, and *b*-value; 3) the maximum magnitude of induced events; 4) ground motions from shallow induced events; and 5) the frequency of hazard model updates in response to hydro-fracturing activities. As yet there is no consensus in how the hazard from induced earthquakes should be incorporated into design maps. Any move to do so in Canada will require broad stakeholder consultation in order to provide information and products that are useful for decision makers and users.

5 CONCLUDING REMARKS

The 2015 5th Generation SHMC yields many important advances on its predecessors, including: reconfigured seismic sources and special consideration of large rare eastern earthquakes; the use of a representative suite of ground-motion models; and explicit definition of crustal fault sources in the Yukon Territory and offshore western margin faults (north of Cascadia) based on GPS and paleoseismic slip rates. The reasons for the changes to modelled hazard are well-described by Adams *et al.* (2015). The GSC is now looking forward to the 2020 building code cycle with a view of rethinking the fundamental scientific questions and building on the advances made for the 2015 model. Primary fields of investigation for the future hazard model include: sensitivity of hazard to various declustering algorithms; exploring the use of smoothed seismicity as an alternative earthquake spatial model; the evaluation of modern GMMs; exploring risk-targeted hazard for the NBCC; and investigate the need to consider hazard from induced seismicity.

REFERENCES:

- Adams, J. 2011. Seismic hazard maps for the National Building Code of Canada. Canadian Society for Civil Engineering General Conference, Ottawa, Canada, Paper JHS-1-1.
- 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, 155 pp, doi:10.4095/214223.
- Adams, J., Halchuk, S., Allen, T. & Rogers, G. 2015. Canada's 5th Generation seismic hazard model, as prepared for the 2015 National Building Code of Canada. 11th Canadian Conference on Earthquake Engineering, Victoria, Canada, Paper 93775.
- Allen, T.I., Adams, J., Rogers, G.C. & Halchuk, S. 2015a. 5th generation seismic hazard model for north-western Canada. 11th Canadian Conference on Earthquake Engineering, Victoria, Canada, Paper 93782.
- Allen, T.I. & Brillon, C. 2015. Assessment of ground-motion attenuation in the British Columbia north coast region. *Bull. Seism. Soc. Am.*, 105(2B): 1193-1205, doi: 10.1785/0120140266.
- Allen, T.I., Luco, N. & Halchuk, S. 2015b. Exploring risk-targeted ground motions for the National Building Code of Canada. *11th Canadian Conference on Earthquake Engineering*, Victoria, Canada, Paper 93781.
- Atkinson, G.M. & Adams, J. 2013. Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps. *Can. J. Civ. Eng.*, 40: 988–998, doi: 10.1139/cjce-2012-0544.
- Atkinson, G.M., Assatourians, K., Cheadle, B. & Greig, W. 2015a. Ground motions from three recent earthquakes in western Alberta and northeastern British Columbia and their implications for induced-seismicity hazard in eastern regions. *Seism. Res. Lett.*, 86(3): 1022-1031, doi: 10.1785/0220140195.
- Atkinson, G.M., Bommer, J.J. & Abrahamson, N.A. 2014. Alternative approaches to modeling epistemic uncertainty in ground motions in probabilistic seismic-hazard analysis. *Seism. Res. Lett.*, 85(6): 1141-1144.
- Atkinson, G.M. & Boore, D.M. 2006. Earthquake ground-motion predictions for eastern North America. *Bull.* Seism. Soc. Am., 96: 2181-2205, doi: 10.1785/0120050245.
- Atkinson, G.M., Ghofrani, H. & Assatourians, K. 2015b. Impact of induced seismicity on the evaluation of seismic hazard: Some preliminary considerations. *Seism. Res. Lett.*, 86(4): 1009-1021, doi: 10.1785/0220140204
- Basham, P.W., Weichert, D.H., Anglin, F.M. & Berry, M.J. 1985. New probabilistic seismic ground motion maps of Canada. *Bull. Seism. Soc. Am.*, 75(2): 563–595.
- Boore, D.M. & Atkinson, G.M. 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthq. Spectra*, 24(1): 99–138, doi: 10.1193/1.2830434.

- Brillon, C. & Allen, T. 2015. Assessment of Ground Motion Models for use in South-Western British Columbia. 11th Canadian Conference on Earthquake Engineering, Victoria, Canada, Paper 93804.
- Chandramohan, R., Baker, J.W. & Deierlein, G.G. 2015. Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records. *Earthq. Spectra*, doi: 10.1193/122813EQS298MR2.
- Farahbod, A.M., Kao, H., Walker, D.M. & Cassidy, J.F. 2015. Investigation of regional seismicity before and after hydraulic fracturing in the Horn River Basin, northeast British Columbia. *Can. J. Earth Sci.*, 52(2): 112– 122, doi: 10.1139/cjes-2014-0162.
- Finn, W.D.L. & Wightman, A. 2003. Ground motion amplification factors for the proposed 2005 edition of the National Building Code of Canada. *Can. J. Civ. Eng.*, 30: 272–278, doi: 10.1139/L02-081.
- Gardner, J.K. & Knopoff, L. 1974. Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian? Bull. Seism. Soc. Am., 64: 1363-1367.
- Halchuk, S., Adams, J., Petersen, M., Rogers, G. & Allen, T. 2015a. Crossing the border again: Assessing the differences between Canada's 2015 and the United States' 2014 seismic hazard maps. 11th Canadian Conference on Earthquake Engineering, Victoria, Canada, Paper 93826.
- Halchuk, S., Allen, T.I., Rogers, G.C. & Adams, J. 2015b. Seismic Hazard Earthquake Epicentre File (SHEEF2010) used in the Fifth Generation Seismic Hazard Maps of Canada. Geological Survey of Canada Open File 7724, 16 pp.
- Helmstetter, A., Kagan, Y.Y. & Jackson, D.D. 2007. High-resolution time-independent grid-based forecast for $M \ge 5$ earthquakes in California. *Seism. Res. Lett.*, 78(1): 78-86, doi: 10.1785/gssrl.78.1.78
- Hodgson, J.H. 1956. A seismic probability map for Canada. Can. Underwriter, 23: 3-6.
- Leonard, M., Burbidge, D.R., Allen, T.I., Robinson, D.J., McPherson, A., Clark, D. & Collins, C.D.N. 2014. The challenges of probabilistic seismic-hazard assessment in stable continental interiors: An Australian example. *Bull. Seism. Soc. Am.*, 104(6): 3008-3028, doi: 10.1785/0120130248.
- Leyendecker, E.V., Hunt, R.J., Frankel, A.D. & Rukstales, K.S. 2000. Development of maximum considered earthquake ground motion maps. *Earthq. Spectra*, 16(1): 21-40, doi: 10.1193/1.1586081.
- Liel, A.B., Luco, N., Raghunandan, M. & Champion, C.P. 2015. Modifications to risk-targeted seismic design maps for subduction and near-fault hazards. 12th International Conference on Applications of Statistics and Probability in Civil Engineering, Vancouver, Canada.
- Luco, N., Ellingwood, B.R., Hamburger, R.O., Hooper, J.D., Kimball, J.K. & Kircher, C.A. 2007. Risk-targeted versus current seismic design maps for the conterminous United States. *SEAOC 2007*, Squaw Creek, CA.
- Milne, W.G. & Davenport, A.G. 1969. Distribution of earthquake risk in Canada. Bull. Seism. Soc. Am., 59(2): 729–754.
- Pacific Earthquake Engineering Research Center 2015. NGA-East: Median ground-motion models for the central and eastern North America region. PEER Report No. 2015/04, Berkeley, CA, 321 pp.
- Pagani, M., Monelli, D., Weatherill, G., Danciu, L., Crowley, H., Silva, V., Henshaw, P., Butler, R., Nastasi, M., Panzeri, L., Simionato, M. & Vigano, D. 2014. OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model. *Seism. Res. Lett.*, 85(3): 692–702, doi: 10.1785/0220130087.
- Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A. & Olsen, A.H. 2014. *Documentation for the 2014 update of the United States National Seismic Hazard Maps*. U.S. Geological Survey, 243 pp, http://dx.doi.org/10.333/ofr20141091.
- Petersen, M.D., Mueller, C.S., Moschetti, M.P., Hoover, S.M., Rubinstein, J.L., Llenos, A.L., Michael, A.J., Ellsworth, W.L., McGarr, A.F., Holland, A.A. & Anderson, J.G. 2015. *Incorporating induced seismicity in* the 2014 United States National Seismic Hazard Model—Results of 2014 workshop and sensitivity studies. U.S. Geological Survey, 69 pp, http://dx.doi.org/10.3133/ofr20151070.
- Raghunandan, M., Liel, A.B. & Luco, N. 2015. Collapse risk of buildings in the Pacific Northwest region due to subduction earthquakes. *Earthq. Spectra*, doi: 10.1193/122813EQS298MR2.
- Rogers, G., Adams, J., Halchuk, S. & Allen, T. 2015. 5th Generation (2015) seismic hazard model for southwest British Columbia. 11th Canadian Conference on Earthquake Engineering, Victoria, Canada, Paper 94198.
- Stein, S. & Liu, M. 2009. Long aftershock sequences within continents and implications for earthquake hazard assessment. *Nature*, 462(5 November 2009): 87-89, doi:10.1038/nature08502.
- Zhao, J.X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H.K., Somerville, P.G., Fukushima, Y. & Fukushima, Y. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bull. Seism. Soc. Am.*, 96(3): 898–913, doi: 10.1785/0120050122.