EXPLORING RISK-TARGETED GROUND MOTIONS FOR THE NATIONAL BUILDING CODE OF CANADA

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ABSTRACT: Since 2012, the *International Building Code (IBC)*, developed in the United States (US) has specified so-called Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motions for designing new buildings and other structures. The MCE_R ground motions were developed by the Building Seismic Safety Council (with funding from the Federal Emergency Management Agency; FEMA) and the U.S. Geological Survey for the *2009 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. In contrast to the uniform-hazard Maximum Considered Earthquake (MCE) ground motions specified in previous editions of the *IBC*, the MCE_R ground motions make use of all the probability levels on the underlying hazard curves that result from Probabilistic Seismic Hazard Analysis (PSHA). The MCE ground motions only considered values corresponding to a 2% probability of exceedance in 50 years, and in doing so, did not consider geographic differences in the ground motions at other probability levels (i.e., shapes of hazard curves). Perhaps more importantly, the MCE ground motions did not explicitly consider the risk of collapse of a building designed for such ground motions. Instead, they assumed that designing buildings against ground motions that have a uniform (2%-in-50-years) probability of being exceeded results in uniform collapse risk. As has since been shown for the US and other countries, however, the aforementioned geographic differences in shapes of hazard curves can result in inequitable risks of collapse. The MCE_R ground motions are calculated such that they result in a targeted level of collapse risk, and can be larger or smaller than corresponding uniform-hazard MCE ground motions.

Like pre-2012 editions of the *IBC*, the *National Building Code of Canada* (*NBCC*) specifies uniform-hazard ground motions with 2% probability of being exceeded in 50 years. This paper explores risk-targeted ground motions for Canada, using hazard curves proposed for the seismic provisions for the 2015 *NBCC*.

1. Introduction

Traditionally, seismic design codes rely on maps that provide a “constant hazard” assumption where the Maximum Considered Earthquake (MCE) ground motions (or accelerations) used for design are those that assume a uniform exceedance probability (e.g., 2% probability of exceedance in 50 years) that is constant across a spatial region (Adams and Halchuk, 2003; Douglas *et al.*, 2013). However, Luco *et al.* (2007) suggested it would be more consistent with the final use of seismic design maps to adopt a “constant risk” assumption in which the design ground motions are defined to provide to a certain level of risk, for example, annual probability of collapse, *P*[*Collapse*].

The *International Building Code (IBC)* developed in the United States (US) has specified so-called Risk-Targeted Maximum Considered Earthquake (MCE_R) ground motions for designing new buildings and other structures since 2012. If employed for design purposes, MCE_R ground motions lead to the same nominal probability of collapse, or a uniform level of risk, over the region of concern (Silva *et al.*, 2014). In this contribution, we summarise the risk-targeting methodology and discuss its utility for future editions of the *National Building Code of Canada* (*NBCC*).

2. Risk-Targeted Ground-Motions

Maps that indicate the spatial variability of MCE ground-motion hazard (or demand) at a uniform exceedance probability provide the basis for seismic design in most jurisdictions around the world. The decision to design structures to a uniform demand level assumes a structure would have the same collapse probability in any locality (Silva *et al.*, 2014). However, MCE ground-motion maps do not necessarily lead to uniform estimates of collapse probabilities due to differences in the shape of hazard curves at different exceedance probabilities and uncertainties in collapse capacity (e.g., the acceleration threshold at the structure's fundamental period) for different structures. The collapse capacity for any given structure will be sensitive to variability in: event-to-event ground motions (i.e., the acceleration time history), construction quality, material properties, building vintage and state of repair, structural irregularities, non-structural components, and other factors affecting the structural performance of the building (Luco *et al.*, 2007). Furthermore, the uniform hazard assumption can often lead to inequitable risks of collapse over a given time period at different localities.

Risk-targeted MCE_R ground motions are based on the "risk integral." The integral takes into account the whole hazard curve across a range of exceedance probabilities rather than simply basing the design ground motions on a single spectral acceleration for a pre-defined return period (Douglas *et al.*, 2013). Consequently, the relative slopes of the hazard curves for each site can have a significant impact on the MCE_R ground motions.

The key ingredients for risk-targeted calculations are:

- MCE ground motion hazard curves that cover a range of exceedance probabilities
- fragility (or capacity) curves
- a pre-defined uniform collapse risk objective, or the probability of collapse (e.g., 1% in 50 years)

As discussed previously, most seismic design codes around the world rely on maps that provide a "constant hazard" assumption where the MCE ground motions (or accelerations) used for design are those that assume a uniform exceedance probability (e.g., Stirling *et al.*, 2012; Leonard *et al.*, 2014; Adams *et al.*, 2015). These models are typically developed through consideration of the historical seismicity (e.g., earthquake magnitude-frequency distributions), fault deformation rates from GPS measurements and paleoseismic observations (e.g., Allen *et al.*, 2015), and the characteristics of earthquake ground motions (Atkinson and Adams, 2013). Hazard curves calculated over a range of exceedance probabilities from such models are required for the calculation of the risk integral.

Fragility curves express the conditional probability $f_{capacity}(a)$ of failure at a ground motion level a. Incorporating uncertainty into the fragility curve is necessary because of variability in the performance of structures due to differences in their aforementioned construction characteristics. Fragility curves commonly adopt a lognormal distribution, defined by the mean μ and standard deviation β:

$$f_{capacity}(a) = \Phi\{[\ln(a) - \ln(\mu)]/\beta\} \tag{1}$$

where Φ is the standard normal cumulative distribution function. For the 2012 *IBC*, β = 0.6 is assumed. In the absence of analogue studies in Canada, the present study also adopts this standard deviation for the fragility curves. Sensitivity testing using different values of β suggest that it has little bearing on the final MCE_R estimation. For the calculation of the risk integral, the mean of the fragility curve is adjusted such that the collapse risk objective is achieved for fragility having a 10% probability of collapse at the MCE_R design ground-motion (Luco *et al.*, 2007). That is, there is approximately a 10% chance that any structure (built to code) will experience partial or total collapse as a result of its $\mathrm{MCE_R}$ design ground-motion.

The final risk integral, or probability of collapse *P*[Collapse] is calculated by integrating the convolution of the structural capacity and the hazard curve (i.e., the risk integrand; Fig. 1):

$$P[Collapse] = \int_0^\infty P[Sa > a] \cdot f_{capacity}(a)\,\mathrm{d}a \tag{2}$$

where *P*[*Sa* > *a*] is the probability of ground-motion spectral accelerations *Sa* exceeding the ground motion level *a*.

The evaluation of this integral requires that the acceptable risk to the population be quantified. This is not solely a scientific question and it should be established through the involvement of not only structural engineers, but also politicians, sociologists and other decision makers (Douglas *et al.*, 2013; Silva *et al.*, 2014). The level of acceptable risk might also vary depending on the importance of the structure (Douglas *et al.*, 2013), such as nuclear power plants and other critical infrastructure (Kennedy, 2011). The average probability of collapse was estimated for typical structures in the western US region (FEMA, 2009). It was determined that a uniform national risk of 1% in 50 years (about 2×10^{-4} per annum) is an acceptable threshold for use in the *IBC*. We have adopted a collapse risk objective of 1% in 50 years as used in the *IBC* and make no attempt to justify the rationale for this decision. However, it seems sensible that US and Canadian construction practices would be comparable across most structural typologies and the risk tolerance is also expected to be similar.

The risk-targeted design ground motion is often represented in terms of the risk coefficient C_R, or the ratio of the $\mathrm{MCE_R}$ and the MCE ground-motion value, to express the relative adjustment to the design ground motions:

$$C_R = \mathrm{MCR_R}/\mathrm{MCE} \tag{3}$$

Figure 1 shows an example of the risk targeting approach for two Canadian localities with identical ground-motion hazard at the 2% in 50-year probability level, but with very different-shaped hazard curves. The figure shows the collapse risk for proposed 2015 *NBCC* ground motions as well as for $\mathrm{MCE_R}$ ground-motions that have a collapse risk objective of 1% in 50 years.

3. Hazard Values Proposed for the 2015 NBCC

The Geological Survey of Canada (GSC) has had the mandate to develop national-scale hazard models which underpin the seismic provisions of the *NBCC* (e.g., Adams, 2011). To explore the utility of the risk-targeted hazard method for Canadian localities, we use the proposed seismic hazard curves prepared for the 2015 *NBCC*, which have been calculated at 10 probability levels from 0.02 to 10^{-4} per annum. (Fig. 2). The basis of, and rationale for these hazard claculations is discussed in several manuscripts presented at the present meeting (Adams *et al.*, 2015; Allen *et al.*, 2015; Rogers *et al.*, 2015).

Mean hazard values are calculated for the horizontal component of ground-motion. Unlike the risk-targeted hazard assessments conducted in the United States, we do not convert MCE ground motions to the maximum horizontal component. We also do not impose a deterministic cap on fault sources for this preliminary assessment.

As suggested by Luco *et al*. (2007), differences in the uniform risk for a particular locality are most sensitive to the relative shape of the hazard curve. To explore this observation in more detail, the hazard curves in Figure 2 are normalised at a uniform probability of 2% chance of exceedance in 50 years (Fig. 2). This figure more clearly illustrates the relative differences in the shapes of the hazard curves. In particular, the eastern cities of Toronto and Montreal suggest a faster rate of increasing hazard at decreasing probabilities than the western cities of Victoria and Vancouver. The calculated hazard tends to converge very slowly at low probability levels, particularly for shorter spectral periods.

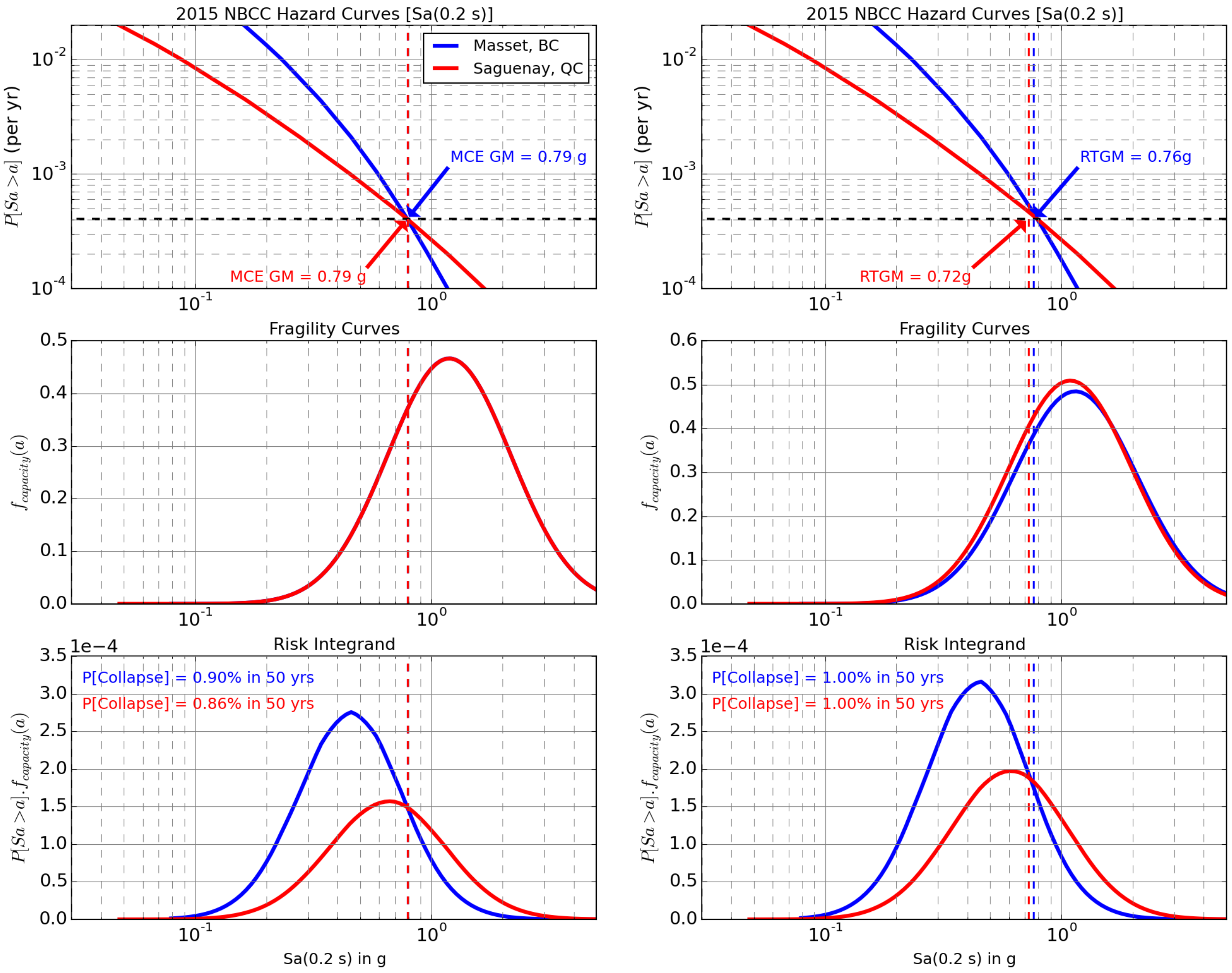

Figure 1 – Examples of the risk integral calculation for two Canadian localities with identical design ground motions for *Sa*(0.2 s) at the 1 in 2,475-year level: Masset, BC and Saguenay, QC. The example assesses the probability of collapse in 50 years of a structure designed for the ground motions proposed for the 2015 NBCC. For the two localities, left panels show (top-to-bottom) the 2015 NBCC proposed hazard curves, fragility curves assuming a 10% probability of collapse under the MCE ground motions, and the resulting risk integrand over which the integral is calculated. Right panels are analogous to the left-hand panels, but use risk-targeted MCE$_R$ ground motions to achieve a 1.0% probability of collapse in 50 years. Both localities experience a moderate drop in hazard through the application of the risk-targeted procedure.

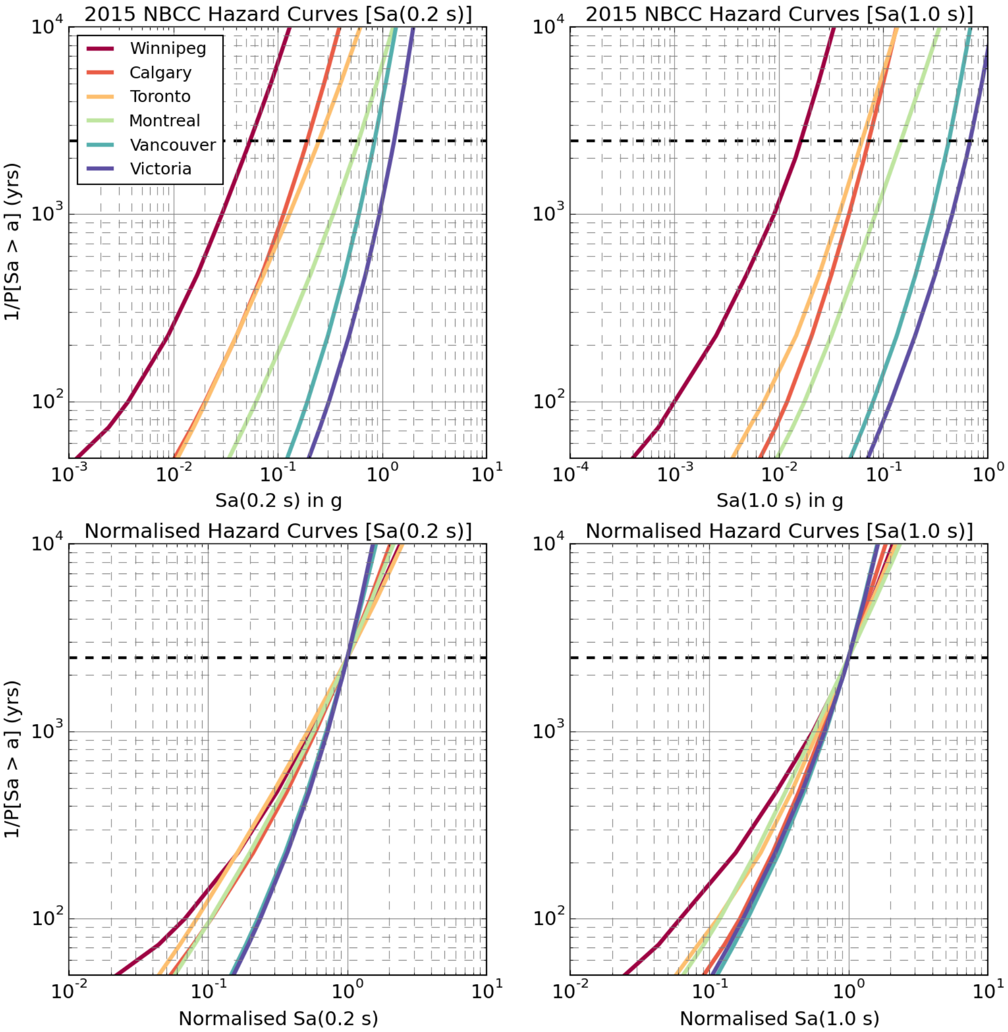

Figure 2 – Top panels show hazard values proposed for the 2015 NBCC for major Canadian cities for *Sa*(0.2 s) and *Sa*(1.0 s). Horizontal dashed line indicates the uniform-hazard at a level of 2% probability of being exceeded in 50 years (i.e., 1 in 2,475 years). Bottom panels are same hazard curves normalised at the 1 in 2,475 year level to emphasise different shapes of hazard curves.

4. Preliminary Risk-Targeted Hazard for Canadian Localities

Preliminary risk-targeted hazard values were calculated for Canadian localities using the method of Luco *et al.* (2007). Figures 3 and 4 show the national pattern of $\mathrm{MCE_R}$ adjustment factors, C_R, based on the proposed hazard curves calculated for the 2015 NBCC for *Sa*(0.2 s) and *Sa*(1.0 s). Overall, most of the proposed adjustments, or risk coefficients, are relatively modest, ranging from factors of 0.84 to just below 1.0 (i.e. no adjustment). The largest adjustments (reductions) tend to occur in the regions nearest to the Cascadia subduction zone (e.g., Rogers *et al.*, 2015) on the west coast of Vancouver Island (Fig. 5). The risk coefficients for the west coast of Vancouver Island are commensurate with the adjustment factors given in the *IBC* for US Pacific Northwest coastal localities (see Figures 22-3 and 22-4 in; BSSC, 2009). On a national scale, the average risk coefficients for the 680 localities for the *NBCC* are 0.93 and 0.92 for *Sa*(0.2 s) and *Sa*(1.0 s), respectively.

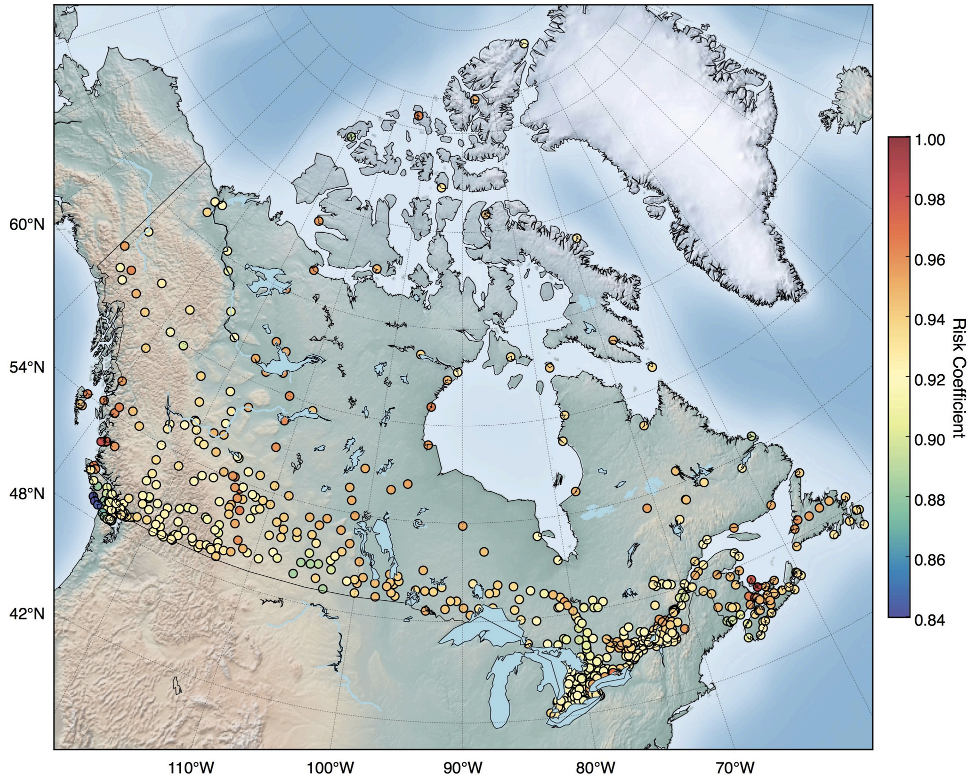

Figure 3 – Calculated risk coefficient for *Sa*(0.2 s) at Canadian localities based on the hazard values proposed of the 2015 NBCC.

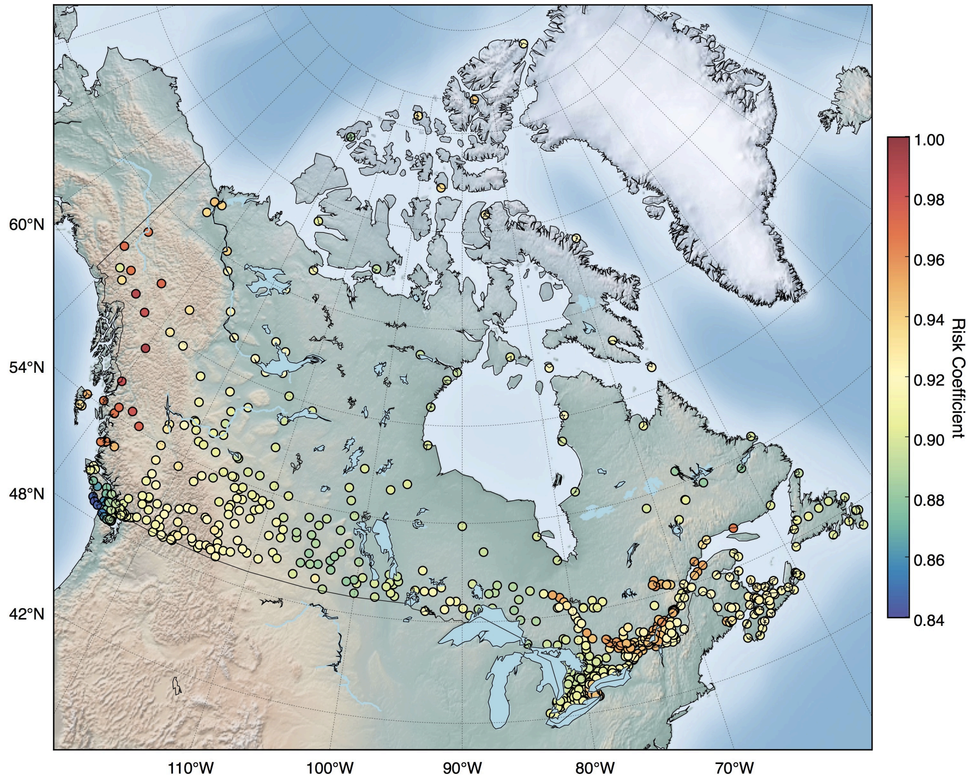

Figure 4 – Calculated risk coefficients for *Sa*(1.0 s) at Canadian localities based on the hazard values proposed of the 2015 NBCC.

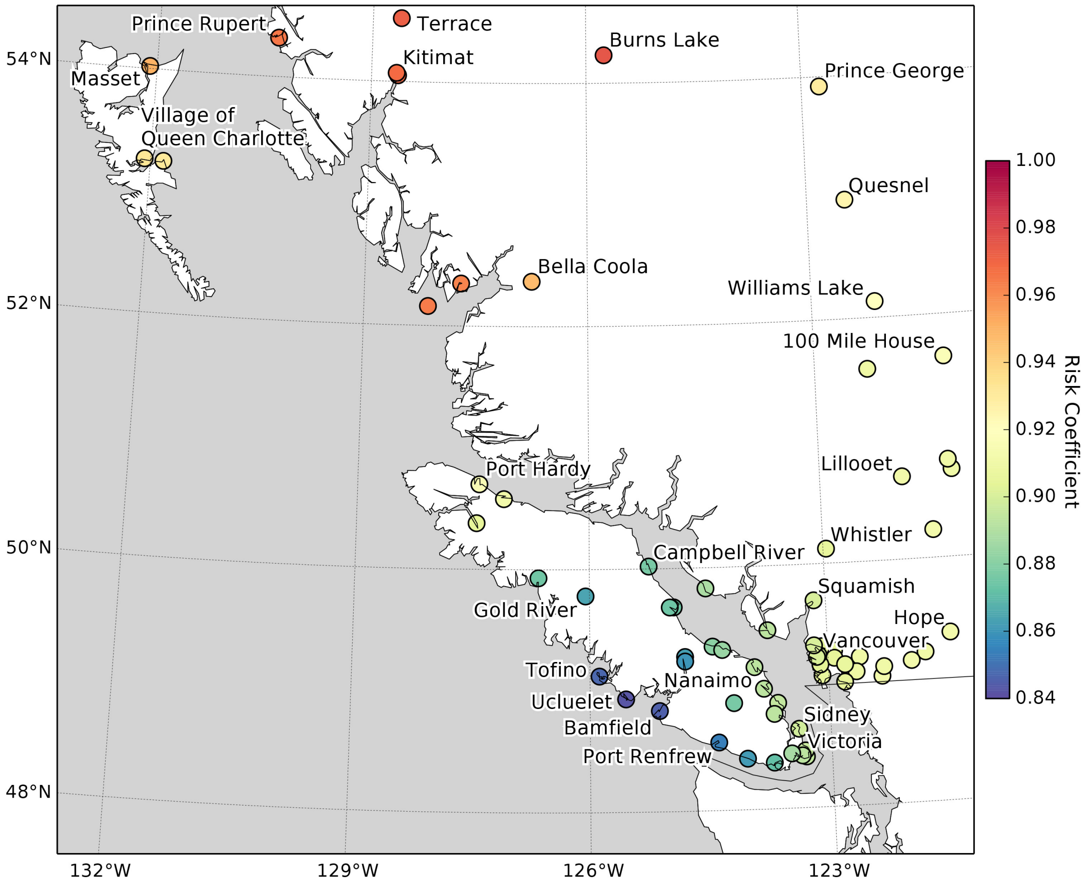

Figure 5 – Calculated risk coefficients for *Sa*(1.0 s) at southwestern Canadian localities based on the hazard values proposed of the 2015 NBCC.

5. Considerations for the 2020 NBCC

Besides the numerical impacts of risk-targeted ground motions explored in the preceding section, in the US their adoption has had other, perhaps more important, impacts. First and foremost, they brought about explicit quantification of the collapse prevention objective of US building codes (i.e., 1% probability of collapse in 50 years), in terms of seismic risk that can be better compared with other hazards and types of structures (see Chapter 1 Commentary of ASCE, 2013). Analogous quantifications of the functionality and economic-protection objectives have since been recommended for future US building codes (NEHRP Consultants Joint Venture, 2012), and now there is a launching point for explicitly quantifying life-safety risk. US design standards for retrofitting existing buildings have begun to consider such quantifications of seismic risk (e.g., Luco and Pekelnicky, 2012), which have the potential to improve upon the current performance objectives matrix of paired performance and hazard levels (ASCE, 2014).

In turn, the risk-based quantification of building performance objectives brought about by risk-targeted ground motions has led to some changes to otherwise prescriptive US design provisions. For example, seismic response history procedures have been changed such that they explicitly or implicitly test whether a building design meets the targeted collapse risk (Chapter 16 of BSSC, 2015). Previously, without an explicitly quantified performance objective, improvements to these procedures were relatively subjective in nature.

6. Conclusions

The study presented herein was intended to explore the utility of risk-targeted ground motions for future editions of the *NBCC*. This approach provides a framework for assessing hazard based on a uniform collapse probability rather than uniform ground-motion exceedance probabilities. The risk coefficients presented in this study are necessarily dependent on the level of "acceptable risk" or the collapse risk objective. Through this preliminary assessment, we have shown that there is moderate variability in the risk coefficient across Canadian localities, with all localities showing a slight reduction in MCE_R ground motions relative to the proposed 2015 *NBCC* 2% in 50-year hazard values. The largest changes in potential design ground motions are observed on the west coast of Vancouver Island near Tofino and Ucluelet, for example (Fig. 5). The adjustment factors observed in this region are commensurate with the changes seen in coastal regions in the US Pacific Northwest (BSSC, 2009). Risk coefficients of around 0.85 suggest that structures in these localities may be overdesigned by 15%. Because these localities represent a minor contribution to the nation's building stock (i.e., they are sparsely populated regions), there may be diminishing returns in adopting risk-targeted ground motions for future additions of the *NBCC* based solely on the numerical impacts to design values. However, as discussed above, other benefits include the explicit quantification of collapse prevention objectives and mainstreaming the consideration of collapse risk into earthquake engineering practice. Ultimately, the decision to adopt MCE_R ground motions for future editions of the *NBCC*, and at what probability level, should be based on broad community consultation that involves structural engineers, hazard practitioners, sociologists and decision makers.

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