A 65-year history of seismic hazard estimates in Canada

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ABSTRACT

Natural Resources Canada (and its predecessors) has been responsible for six generations of seismic hazard maps for Canada, starting in 1953. These have formed the basis for the seismic design provisions of the National Building Code of Canada, and thus contribute to the seismic resistance of Canada's building stock. This paper indicates how the hazard estimates have changed since 1953. A simple model for possible change suggests that some countries start high and in successive hazard estimates approach the target ("true") value from above, but most countries start low and approach the value from below. In either case the hazard estimate seldom moves monotonically towards the target level, but oscillates above and below the trend. This paper gives a 65-year history of 5% damped spectral acceleration at 0.2 s estimate for the 2%/50yr probability level for Montreal, Vancouver and Victoria. Site Class C was used for the comparison. The Sa(0.2) parameter was not available until 2005 and neither were 2%/50yr probability estimates. Therefore, the earlier short-period hazard estimates were adjusted to be equivalent to Sa(0.2) at the 2%/50yr probability level by using ratios of results from the 4th Generation model. Hazard estimated for Montreal and Vancouver have trended up reasonably steadily at about 0.6% per year while for Victoria the increase has been faster and chiefly occurred in 1985 and 2020. While changes in the seismic hazard estimate reflect evolution of the seismic hazard models, they are only one component controlling changes in the base shear. Also, introduction of other code restrictions, application of better analysis methods, and improvements in associated standards mean that today's buildings are more earthquake resistant than those built 65 years ago.

Keywords: seismic hazard, history, Canada, short-period, Sa(0.2)

INTRODUCTION

Seismic hazard maps have formed the basis for the seismic design provisions of the National Building Code of Canada (NBCC) since 1953. Natural Resources Canada (and its predecessors) has been responsible for six generations of these maps, with the most recent of these being prepared for NBCC2020 (Fig. 1). There was also a minor tweak in 2010 that affected only eastern ground motions. In this paper I discuss how Canadian hazard estimates have changed since 1953 and discuss the main reasons for the changes. The goal is to give a longer perspective than comes from comparing Sa(T) values available just since 2005.

To the best of my knowledge no such longitudinal study has been published for Canada, though there have been papers that comment on the similarity of contours on successive seismic hazard maps (e.g., figure 1 in [1]). From a literature search and collegial enquiry it also appears that comparable long-term longitudinal studies are rare (or absent) from the international literature (though see [2] for an evaluation of PGA-deficit in Italy since 1909). Therefore there is no international context in which to place the evolution of Canadian seismic hazard estimates, and so a conceptual model will prove useful.

Conceptual model

The seismic hazard for a given place is an unknown that needs to be estimated. To a first approximation it is time independent, though more advanced estimations give time-dependent hazard for places where the earthquake history is known and the position in the earthquake cycle can be estimated. In this paper I shall assume that the seismic hazard that needs to be estimated is time independent, even though for places like Victoria and Vancouver it is slowly increasing as the time since the last great Cascadia earthquake increases.

A conceptual model for possible change in estimates with time (Fig. 2) suggests that for some countries the estimates started high and in successive hazard estimates approach the target ("true") value from above (curves 2 & 3). Such places are typically those with an earthquake disaster in the prior decades where current estimates are colored by that event, even though the probability of similar events repeating in future decades may be actually low. In such places buildings will be designed to a too-high shaking level, protecting against a repeat of the disaster-causing earthquake. If so, then the need for building seismic retrofit to achieve safety levels may be minimal, though there may always be a need to retrofit if the anti-seismic engineering measures used to resist the design shaking later prove to be inadequate.

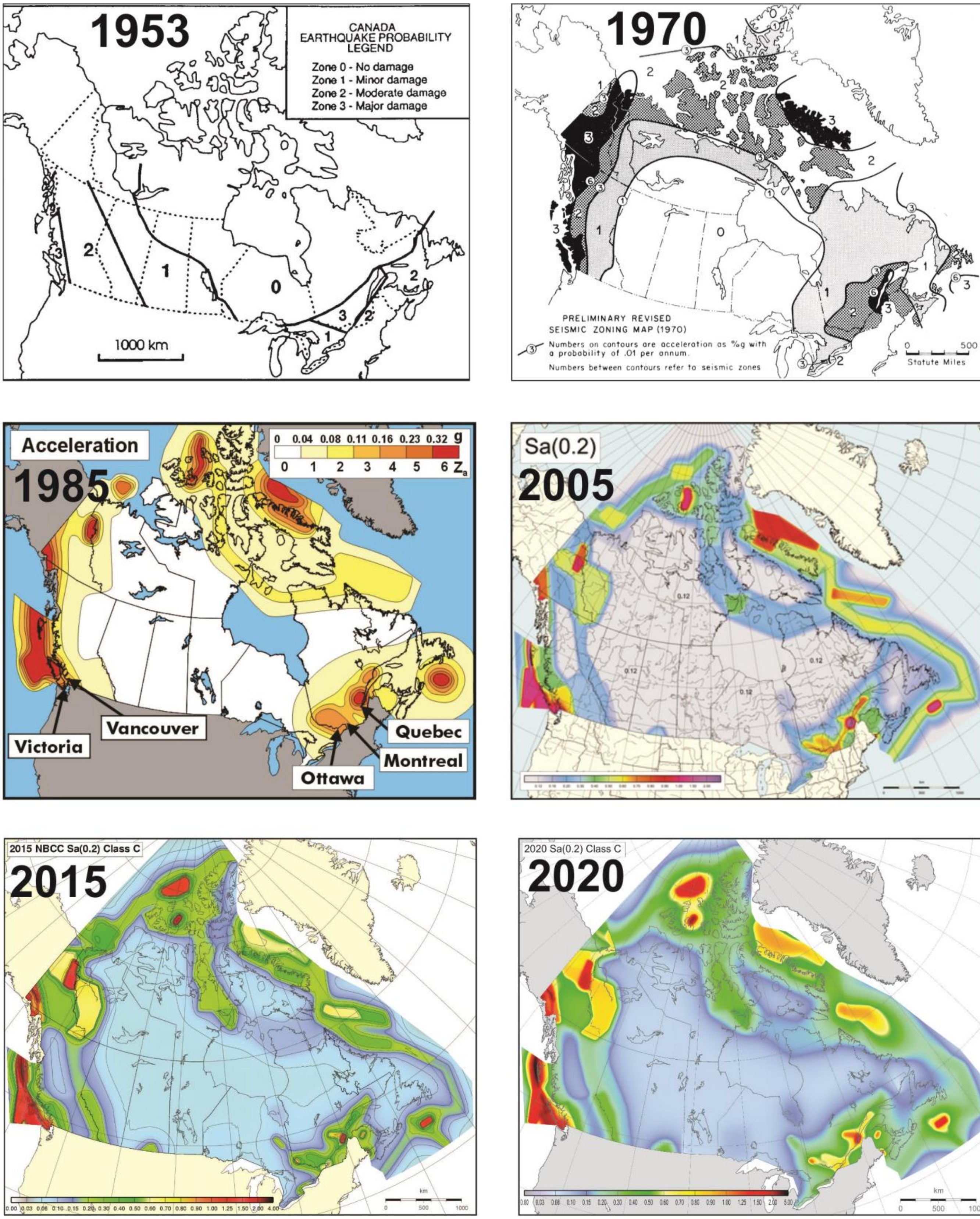

Figure 1. Representative seismic hazard maps for Canada. PGA for 1953 [3], 1970 [4], and 1985 [5], and Sa(0.2) for 2005 [6], 2015 [7], and proposed-2020 [8]. Note that the colour scales for 2005, 2015 and 2020 are not the same. For higher quality maps, see the referenced papers.

The seismic hazard estimates in most countries probably started low and approach the target value from below (curves 4-6; Fig. 2). Typically the climb towards the target level reflects greater understanding of rare shaking (see below) and has evolved as knowledge, methods and community consensus has accumulated. In such places existing-building retrofit will probably be desirable.

In either case the hazard value seldom moves monotonically towards the target level, but oscillates above and below their trends (Fig. 2). Small oscillations (curve 2 & 4) are preferred to large ones (curves 5 & 6), because large oscillations can reverse the trend towards appropriate protection. For a similar reason, oscillations of reducing amplitude with time are preferred to the opposite. Especially, the reversal of a large change as in curve 6, cycle 6-to-7 - even if scientifically based – can call into question the judgement of the engineers and their seismology advisors by users of the seismic hazard results.

The conceptual model indicates that eight code cycles are sufficient to approach the true value (recognizing that not every code edition represents a code cycle for seismic hazard estimation), but this is an arbitrary number, and not an indication that Canada will have reached the true value after just two more cycles.

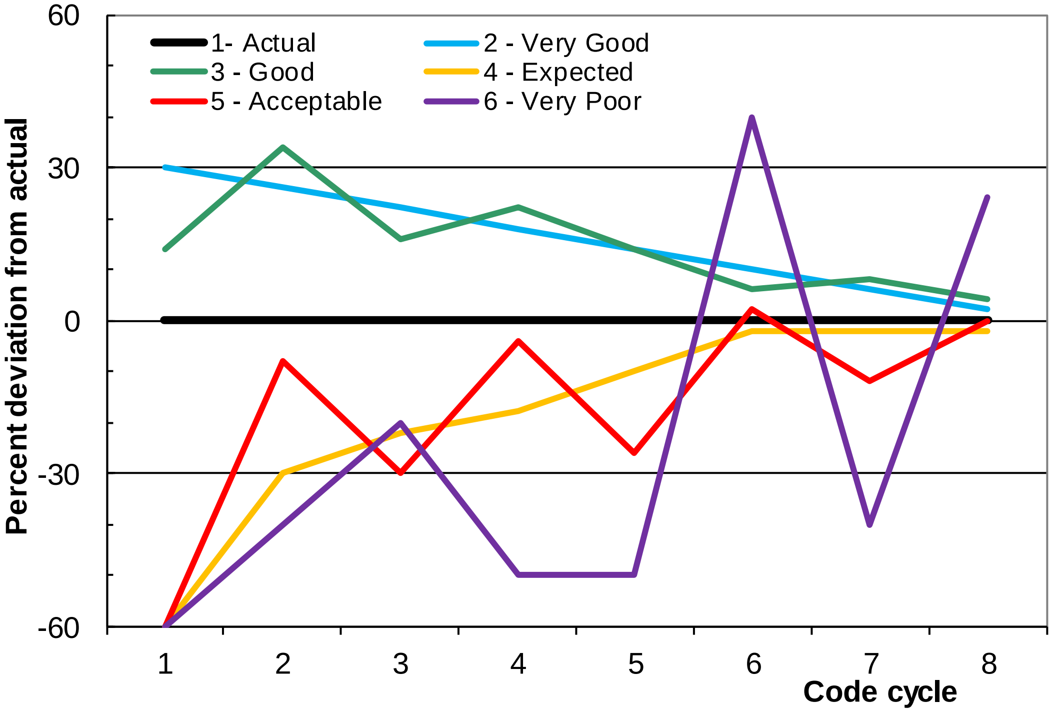

Figure 2. Cartoon of the evolution of seismic hazard estimates through successive code cycles (modified from [9]).

Two related issues are the reported precision of seismic hazard estimates and the uncertainty in the estimates. The first is clearly tied into the second. As is remarked by all practitioners, the uncertainty in current seismic hazard estimates is large, as documented for NBCC2015 in a companion paper [10]. With such a large uncertainty, the appropriate precision is at best 2 significant digits; certainly 3 digits is too many. The problem with reporting 1 digit is that the subtle changes that exist between sites (0.11 g, 0.16 g, 0.19 g) are reduced to changes between 0.1 g or 0.2 g, with implied design level differences of 30-50%. While such large step changes were considered acceptable in the times of seismic zones (e.g. 1970 maps) and the steps in NBCC1985 were reduced to a factor of $\sqrt{2}$ [5], the irrationality of large steps from one side of "Main Street" to the other moved Canadian practice to use site-specific values from NBCC2005 onwards. Computer programs and spreadsheets make it convenient to report the computed values to a larger number of digits, but these are provided on the understanding that only 2 digits are significant.

A related issue is that the building code uses threshold values to limit certain structural methods or heights. Ignoring for the moment the uncertainty in the seismic hazard estimates (see companion paper, [10]), consider successive code cycle estimates of Sa(0.2): 0.889 g, 0.911g, and 0.883 g. These three estimates would represent a remarkably stable history (within +/-5%), although the change has not been monotonic. Sensibly these would be used as 0.89 g, 0.91g, and 0.88 g, although a case could be made for considering them all 0.9 g. Consider though the difficulty for a designer, because the threshold to require a change from waferboard to plywood sheathing occurs at 0.9 g (NBCC2015 section 9.23.13.6). The requirement would go from waferboard-acceptable to plywood-required back to waferboard-acceptable – an undesirable change in practice resulting from marginal changes in the seismic hazard estimates.

As background to the following results and discussion, consider how Probabilistic Seismic Hazard Assessment (PSHA) has evolved as knowledge, methods and community consensus has accumulated:

- Increased rigor in the way that seismic hazard is calculated. These improvements in computation/methodology have been accompanied by an evolution of standards, so that today the consensus is that PSHA for building safety is best represented by 5%-damped mean values of spectral parameters (not PGA) at probabilities of 10%/50 yr or 2%/50 yr, with an increasing tendency to use the latter probability.
- Increased rigor in the treatment of uncertainty, replacing "best-estimate" values as were used in NBCC1985.
- Inclusion of the aleatory uncertainty "sigma" of the Ground Motion Models (GMMs) in the calculations (this was included since the 3rd Generation, but not for 1970 as its GMMs did not include a measure of uncertainty). Failure to do so gives estimates that are too low.
- Improvement in the GMMs that represent the shaking at a given distance from an earthquake of a given magnitude. Those improvements have come from a) the increasing database of observed ground motions which was very scant until the 1990s, b) the generation of synthetic earthquake records, and c) better modelling methods to identify the required parameters. Hazard estimate changes can arise from different median estimates, different epistemic spread among alternative median estimates, and different sigma estimates.
- Changes in the estimation of earthquake rates, including improved completeness from network observations, better estimation of the magnitudes of pre-instrumental earthquakes, and incorporation of the constraints provided by GPS deformation rates and (to a lesser extent) constraints from paleoseismic histories.
- Recognition that the largest considered magnitude "Mmax" is better constrained by considering the largest earthquakes in global analogous regions than by adding a constant to the largest historical earthquake's magnitude.
- Choice of Mmin, which affects the numerical values of short-period spectra in low-seismicity regions.
- Refinement of known seismic sources (often representing tighter bounds on their geographic extent, as deduced from the distribution of small earthquakes located by modern dense seismic networks or variations in crustal deformation from analysis of precise GPS measurements).
- The progressive inclusion of newly-recognized hazard sources (e.g., Cascadia great subduction earthquakes which were unexpected and not included before 1985; Leech River Valley Fault which is only included in the 6th Generation model).

While evolution of the six generations of Canadian seismic hazard maps involved most of the above, some of the largest estimate changes have come from the evolving GMMs; indeed as shown by a companion paper [8] just changing the eastern GMMs changes the hazard by 40%.

METHOD

For PSHA computed from the probability of exceeding fixed ground motions, the mean hazard values are always higher than the median (50th percentile) values, typically the mean is between the 60th and 85th percentiles of the distribution [10]. The 1985 hazard model did not included any measures of epistemic uncertainty, so the hazard estimates are "best estimate" values, where the mean equals the median. The 1970 and 1953 estimates can also be taken as mean values for the same reason. Note that the 2005 and 2010 values were "robust" median results, as they were computed to be the highest of 2 or 3 median values that each came from competing probabilistic seismic source models and a deterministic Cascadia scenario. As such, the robust medians were higher than a probabilistic median, but not necessarily as high as the mean from a probabilistic combination of the competing models would have been. Nevertheless, in this paper I take the 2005 and 2010 results to be equivalent to the probabilistic mean values of 2015.

The choice of the reference site condition is also important. Site Class C was adopted in 2005, replacing the "rock and firm soil" condition used in previous editions. I have argued in the past that, to be conservative, engineers would have wanted to design for the firm soil shaking (and not the rock shaking of "rock and firm soil"), i.e. Class C. The exception was Hodgson [3] who, working from a loss perspective, wished to include the greater damage in the St Lawrence valley because of soils softer than Class C (see notes below on 1953 Montreal results).

High-probability PGA has been the only consistent factor that can be compared since 1953, and this is probably the worst single ground motion measure to use. Therefore I chose to express the comparative results in terms of Sa(0.2) at 2%/50 yr, which is an engineering-relevant short-period spectral parameter with seismological behavior similar to PGA. Modern hazard results (I used the 2005 code values) can be used to estimate the relation between PGA and Sa(0.2) hazard at a given probability, and also to estimate the relation between hazard measures at different probability levels.

Proposed-2020 values came from spreadsheets distributed to the Standing Committee on Earthquake Design (SCED) in November 2018.

Spectral values for 2005, 2010, and 2015 were taken from NRCan's online calculator [11].

For 1985 (as used in 1985, 1990 and 1995 codes) estimates were taken from NRCan's online calculator, but only PGA and PGV at 10%/50 yr were used in NBCC1985. The 2%/50 yr values of Sa(0.2) were estimated by multiplying the 1985 10%/50 yr PGA by the ratio [2005 Sa(0.2) at 2%/50yr] / [2005 PGA at 10%/50yr] at each city. The computed values were used instead of the zonal value specified by the code.

For 1970 (as used in 1975, 1977, 1980 codes) estimates are only available for PGA at P=0.01 p.a. I chose to use the numerical values from [12]; their detailed contour maps were smoothed by [4] to get the zone contours on the 1970 map. The 2%/50 yr values of Sa(0.2) were estimated by multiplying the 1970 PGA by the ratio [2005 Sa(0.2) at 2%/50yr] / [2005 PGA at 40%/50yr].

For 1953 there was a qualitative "seismic probability map" comprising zones of expected equal probability of damage [3]. There is considerable uncertainty about the 1953 map in terms of the implied shaking parameter, soil condition, and probability level, and a close reading did not provide much clarity. I assumed the 1953 map represented P=0.01 p.a. PGA hazard, partly because the zone numbers used in NBCC did not change from 1953-1970 (though Montreal and Ottawa did change zones). If the zone number is the same as in 1970, the 1970 value is used (e.g. Victoria, Vancouver). In 1953 Montreal was in Zone 3 (R=4, as used in NBCC1970), but dropped to Zone 2 (R=2) in 1970, so 1953 was taken as twice the 1970 value. In part, the 1970 zone reduction may have corrected Hodgson's attempt to represent the extra damage on soft soils in the St Lawrence valley, and it represents a transition from risk map to a hazard map in terms of the way the two terms are currently used.

RESULTS

The derived Sa(0.2) 2%/50 yr hazard results on Class C are given in Table 1.

Table 1. Change of Sa(0.2) 2%/50 yr hazard estimates (in g) on Class C.

Code year	1953	1970	1985	2005	2010	2015	2020
Montreal	0.56	0.28	0.59	0.69	0.64	0.60	0.84
Vancouver	0.74	0.74	0.79	0.93	0.93	0.85	1.15
Victoria	0.80	0.80	1.26	1.22	1.22	1.30	2.00

DISCUSSION

Montreal: Figure 3 displays the history of seismic hazard estimates for Montreal. The main features of the history are:

- a drop in 1970 that reflected the change from zone 3 to zone 2. As discussed above this may have partly corrected an implicit soft-soil condition of the 1953 map, though estimates of the amplification between Class D and Class C used in NBCC2015 are less than 25%, not the 50% shown
- an increase in 1985 likely due to the new GMMs and new methodology replacing extreme-value extrapolation
- a period of fairly stable estimates from 1985 to 2020 – although there were many changes during this period, their effects have mostly cancelled out
- a large increase for the proposed-2020 estimate that arises entirely from the adoption of NGA-East GMMs - see companion paper [13]

Vancouver: Figure 4 displays the history of seismic hazard estimates for Vancouver. The main features of the history are:

- Stable estimates from 1953 to 1985
- Fluctuating estimates (<10%) for 2005 and 2015. There is no large increase in Sa(0.2) despite the robust and then probabilistic inclusion of great Cascadia earthquakes (because at Vancouver's distance those great earthquakes chiefly affect long-period motions)
- A 35% increase in proposed-2020 that arises chiefly from the increased epistemic uncertainty in the median GMMs and increased aleatory uncertainty (sigma) - see companion paper [13]

Victoria: Figure 5 displays the history of seismic hazard estimates for Victoria. The main features of the history are:

- A large increase in estimated hazard in Victoria in 1985 code. Victoria was assessed as similar in hazard to Vancouver in 1970 [4,12]. This appears to have arisen from Milne's PhD work being performed before the 1965 Seattle earthquake and from a lack of appreciation that the deep earthquakes extended farther north; the deficiency was corrected for the 1985 maps [5]
- Stable estimates for 2005 and 2015
- A 50% increase in proposed-2020 estimate that arises for similar GMM reasons to Vancouver, but is larger because of changes in the geometry of the underlying inslab source and the addition of the Leech River Valley Fault – see companion papers [8,14]

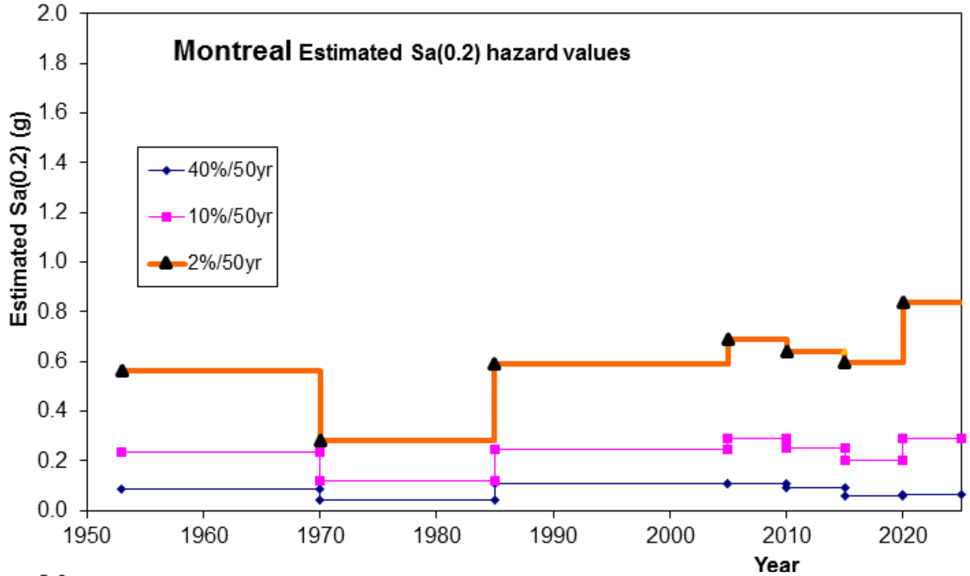

Figure 3. Evolution of seismic hazard estimates for Montreal. Black symbols represent hazard levels that last until the next code is released. Magenta and blue lines represent the history of higher probability estimates. 1953, 1970 and 1985 values converted from PGA. Pre-2005 lower probability values estimated from 2005's hazard probability ratios.

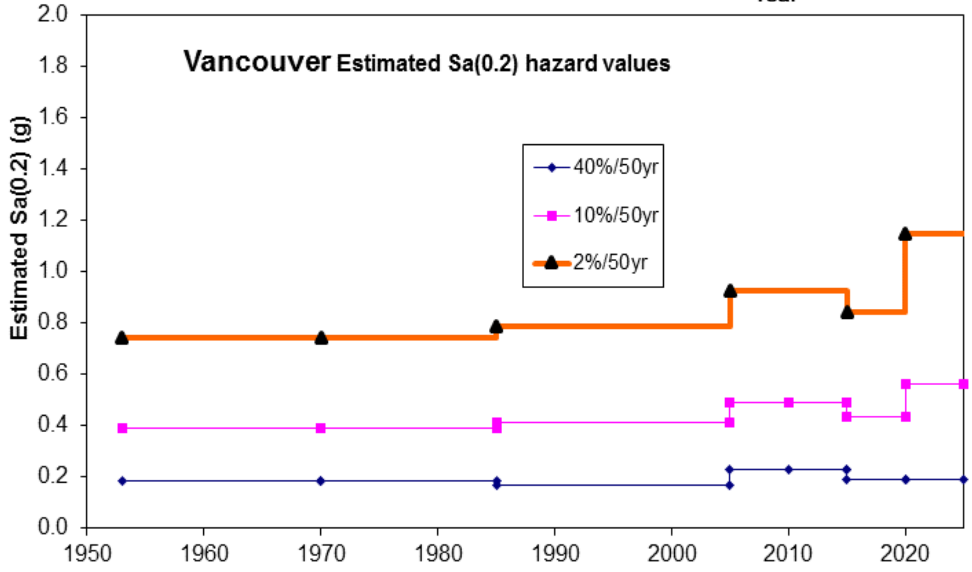

Figure 4. Evolution of seismic hazard estimates for Vancouver. Legend as for Fig. 3.

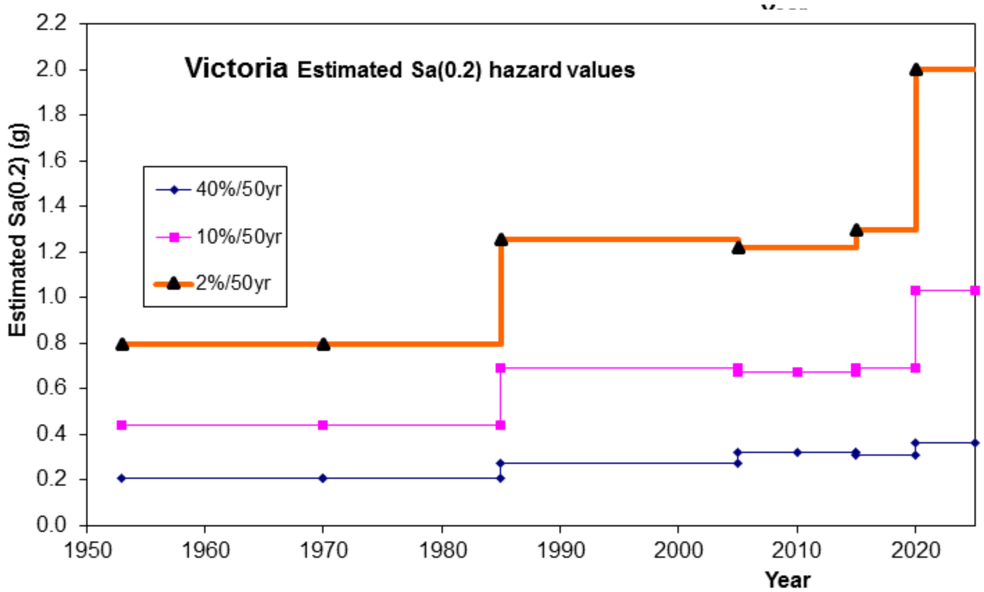

Figure 5. Evolution of seismic hazard estimates for Victoria. Legend as for Fig. 3.

Overall trends

The 1953-2020 trends indicate an overall increase in estimated hazard for Montreal and Vancouver of about 150%, that is about a 0.6% compounding increase per year on average, or about 3% over a 5-year code edition or 8% between seismic hazard generations. Victoria has increased by 250% overall, its larger increase representing progressively improving knowledge that it sits close to an active plate boundary. In all three cities a large fraction of the increase happens with the proposed-2020 values; it is possible that the 6th Generation hazard estimates have "over-shot" the true value, but this will not be known for a few more cycles.

The 1953-2020 estimates indicate a fairly steady trend in estimated hazard for Montreal and Vancouver with oscillations of about their upward trends of ±10-15%, the chief exceptions being a) the 1970 drop and its 1985 reversal for Montreal, b) the 1985 increase for Victoria, and c) the 30-50% increases for the proposed-2020 values relative to 2015 for all 3 cities.

Engineering implications

I have estimated seismic hazard changes in terms of Sa(0.2). Seismologists are normally implicated for the hazard estimate changes that cascade into new engineering design requirements, because seismic hazard is always the first part of the process and one of the easiest for which to quantify the change. However, engineering design spectra since 1940 have progressively included additional adjustments to the seismological input (PGA or UHS). An example is not allowing a rise in the design spectrum from 0.2 to 0.5 seconds (introduced explicitly in NBCC2005); such an adjustment may increase the base shear even if the Sa(0.2) values drop. A history of engineering code changes is beyond the scope of this paper, but a good review to 2005 is given by [15]. Figure 6 shows the evolution of "factored" design base shear for a 10-storey conventional reinforced concrete construction in Montreal, as compared to that of the Sa(0.2) seismic hazard estimates. The comparison of the 10-storey building's design to Sa(0.2), a shorter period hazard than the building's period, is actually inappropriate for 1985 onwards when Sa(1.0) would have been available. The step drop at the introduction of the 1970 seismic hazard map can be seen, but the 1985 Sa(0.2) increase is not seen in the base shear, because a) a calibration factor was introduced to keep the base shear similar to NBCC1980 and b) at T=1 s the base shear was proportional to 1/1.4 times the short-period hazard for cities like Montreal where Za>Zv (the dashed orange line on Figure 6 shows the level for Za=Zv that determines the level at 1 s). Quantifying the change in base shear is not the full story either, since other restrictions, analysis methods, and standards improvement mean that today's buildings are (probably) more earthquake resistant (for the same base shear) than those of 20, 40 or 60 years ago.

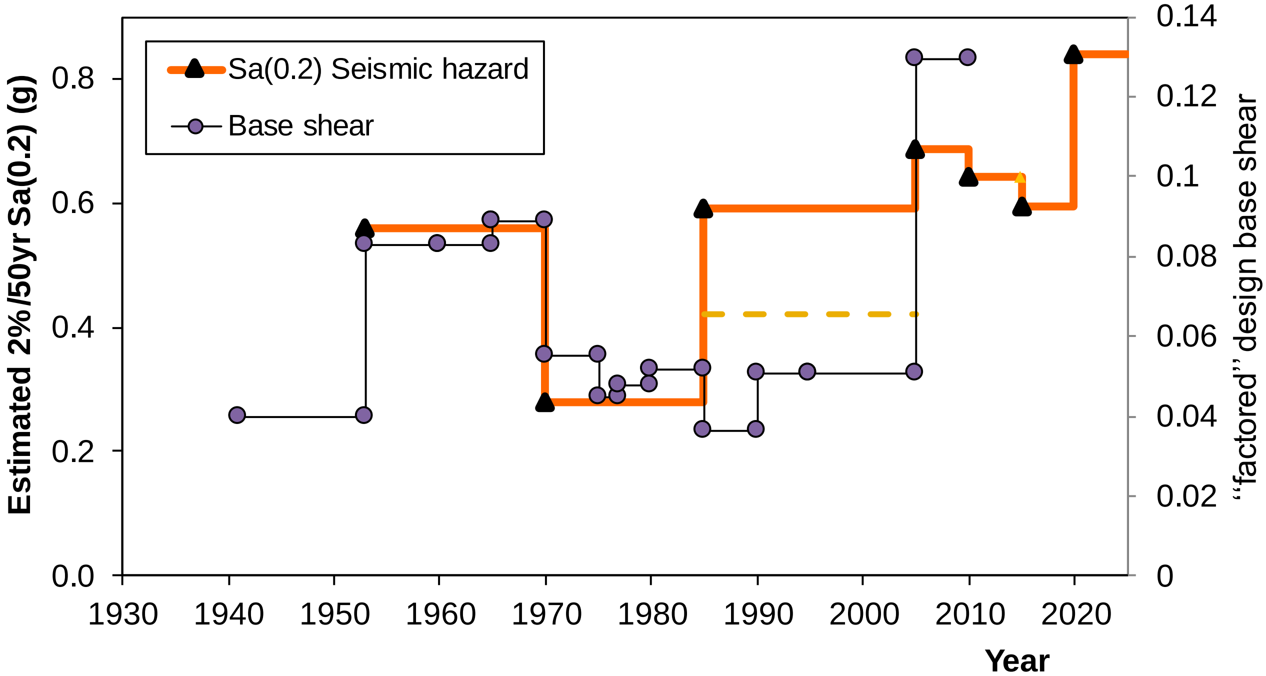

Figure 6. Curve for the evolution of Sa(0.2) seismic hazard for Montreal (taken from Fig. 3) compared to the factored design base shear for a conventional 10-storey concrete wall building in Montreal (thin line with dots, drawn from Figure 8 data in [15]). See text for discussion.

CONCLUSIONS

A 65-year history of 5% damped spectral acceleration at 0.2 s estimates for the 2%/50 yr probability level is given for Montreal, Vancouver and Victoria. Site Class C was chosen for the comparison. Pre-2005 short-period hazard estimates were adjusted to be equivalent to Sa(0.2) at the 2%/50yr by using ratios from the 4th Generation model. While there remains some potential for comparing the pre-2005 evolution of Sa(1.0) by estimating it from the 1985 PGV values, this would provide a shorter history than is available for Sa(0.2). Short-period hazard estimated for Montreal dropped abruptly in 1970 but has since increased to a level a little above that in 1969. Since 1985 it shows relatively small oscillations about an upward trend. Hazard estimated for Vancouver has increased steadily, with only one reversal in 2015. Overall, estimated hazard in both Montreal and Vancouver has increased at about 0.6% per year. Hazard estimated for Victoria has increased faster, with step jumps in 1985 and proposed-2020.

The changes reflect improved knowledge gained through time, reflected in the evolution of the seismic hazard models, as has been discussed in a general way. While changes in the seismic hazard estimate are important to understand, they are only one component controlling changes in the base shear, and changes in the base shear are not a full accounting of the history of seismic resistance. Introduction of other code restrictions, application of better analysis methods, and improvements in associated standards mean that today's buildings are more earthquake resistant than those built 65 years ago.

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