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Seismic Hazard Maps for the National Building Code of Canada

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Abstract: Canada has had four epochal seismic hazard maps. The 2005 (“4th Generation”) probabilistic assessment was made at 0.000404 p.a., and provided spectral acceleration parameters allowing site-specific uniform hazard spectra for the first time. The 2010 code, just released, was based on a slight variation of the 2005 hazard results (the same 4th Generation model but with a small refinement of the eastern ground motion relations) resulting in generally-lower short-period shaking in low-seismicity eastern regions. The 4th Generation model which was derived in the mid-1990s needs to be replaced, and the GSC is now working to create a new model for the 2015 code. Although some of the decisions like computing at the 2%/50 year (0.000404 p.a.) level are relatively uncontroversial, others like whether the median or the mean ground motions should provide the design value are less obvious.

1. Introduction

Canada has had four epochal seismic hazard maps (1953, 1970 1985 and 2005), each of which were used in one or more editions of the National Building Code of Canada (NBCC; Figure 1). The 1953 map was a qualitative assessment (Hodgson, 1956), and was primarily a zoning map rather than a map of seismic hazard. The 1970 map (Milne and Davenport, 1969) was a true probabilistic seismic hazard map, one of the earliest such national maps. It depicted the Peak horizontal Ground Acceleration (PGA) to be expected at 0.01 per annum (p.a.). The 1985 maps by Basham et al. (1985) were probabilistic at 0.0021 p.a. and were given for both PGA and Peak horizontal Ground Velocity (PGV), the pair of ground motion measures being used to give more appropriate zonal spectra than a standard shape anchored to PGA. The 2005 (“4th Generation”) probabilistic assessment was made at 0.000404 p.a., 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. In the following I discuss the 2005 assessment, the variation that forms the basis for the 2010 code, and the direction being followed to derive a 5th Generation model for the 2015 Code.

2. 2005 Model

The 2005 model had an unusually long genesis, being started when the 1985 model was being finalized (in 1981 when the author joined the Geological Survey of Canada, GSC) and being intended for the 1995 code. One of the recognized weaknesses of the 1985 maps is that they were dominated by the occurrence of a few large events (the three bulls-eyes in eastern Canada are centred on the 1925, 1929

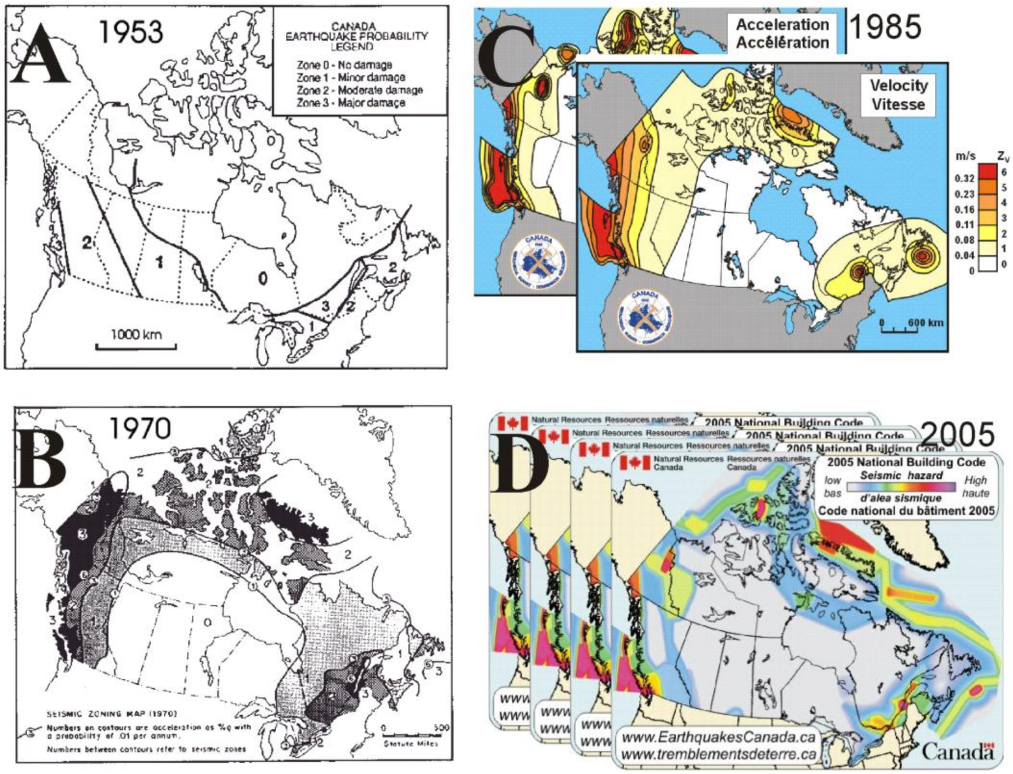

Figure 1: Four generations of Seismic hazard maps for Canada. A: 1953 (qualitative), B: 1970 (PGA at 0.01 p.a.), C: 1985 (2 maps: PGA and PGV at 0.0021 p.a.), and D: 2005 (5 maps: PGA plus spectral acceleration for 0.2, 0.5, 1.0 and 2.0 sec at 0.000404 p.a.).

and 1933 earthquakes). It was hoped to incorporate more geological information into the seismic source able to incorporate the likely occurrences of future earthquakes. As the model evolved, the 1982-1989 active period of seismicity in eastern Canada provided some important lessons including:

- The Saguenay earthquake (Mw 5.9) which occurred in an area that had had only rare small earthquakes, but is now associated with the Saguenay Graben, an arm of the Iapetan rift along the St Lawrence River that has associated earthquake clusters at Charlevoix and the Lower St. Lawrence.
- The Nahanni earthquakes (Mw 6.6 and 6.9) which greatly exceeded the size of the largest earthquake (Mmax) considered in the 1985 model.
- Surface faulting from the 1989 Mw 6.1 Ungava earthquake, indicating the chance of large earthquakes in the Canadian Shield.
- Increased attention on the Cascadia subduction zone arising from the 1985 Mexico earthquake
- Ground motions from certain eastern earthquakes (including Saguenay) which greatly exceeded the motions predicted from prior ground motion prediction equations (GMPEs).

To address these lessons the 4th Generation model incorporated seismic source zones that took into account the geological controls on earthquake distribution, earthquake recurrence models that included the contributions from earthquakes larger than had occurred historically (using continental and global geological analogs for guidance), and new GMPEs. Estimated shaking from the Cascadia subduction zone and from the low-seismicity centre of Canada was included for the first time. Furthermore, a pair of source models (H and R) was included to sample the range of possible source zone sizes, and epistemic uncertainty was incorporated through estimating the ranges of the key input parameters (Adams and Halchuk, 2003). The ground motions to be used in the NBCC2005 were the median values for the four spectral parameters, for a “firm ground” site condition analogous to that used in 1985. Hazard values were computed at 0.000404 p.a. (2%/50 years) because this probability better captured the relative seismic hazard across Canada for design against collapse (NRCC 2006, p. J-6).

Although the model was in draft form at the time of the Saguenay earthquake in 1988, ready for the 1992 deadline for NBCC1995, the discrepancy between the recorded Saguenay ground motions and those from the existent GMPEs became a matter for vigorous debate, and it was decided that it would be unwise to attempt new maps until the debate was resolved. Therefore the planned 1995 maps were deferred by a cycle and intended to become the year-2000 maps. However the planned NBCC2000 was progressively delayed until it was issued in 2005. During this time the 1993 model was slightly updated to use mid-1990s GMPEs, but otherwise represented a 10-15 year old model.

The change to the use of spectral values represented a major seismological and engineering change, so that NBCC2005 differed greatly from NBCC1995 (DeVall, 2003). Mapped seismic hazard values increased because the probability level was dropped, but also increased for short-periods because the UHS spectral shape was not artificially capped as were the NBCC1985 spectra. Offsetting the design level increases were the introduction of the "overstrength factor", Ro, and a relatively large reduction for structures built on "Rock" relative to those on "Firm Ground" (NRCC, 2006 pages J-5 and J-19). More on the seismological history of NBCC2005 is given in Adams and Atkinson (2003) and Adams (2011).

3. Changes from 2005 to 2010

The 2010 seismic hazard values were based on the same 4th Generation seismic hazard model as the 2005 values, but with seismic hazard values updated by replacing the quadratic fit to the ground motion relations used in NBCC2005 for earthquakes in eastern, central and north-eastern Canada by an 8-parameter fit. For NBCC2005, it was recognized that, while the quadratic fit provided a good approximation in the high-hazard zones, it was rather conservative at short periods for the low-hazard zones; however, because the design values are small in the low-hazard zones, the approximation had been accepted. The 8-parameter fit gave a good fit across all zones. The changes from 2005 had a complex, but understandable, pattern. In general, PGA and short-period spectral values were reduced in most regions, while long-period values slightly increased (Humar et al., 2010). This is illustrated by the spectral shape changes shown in Figure 2 for four cities.

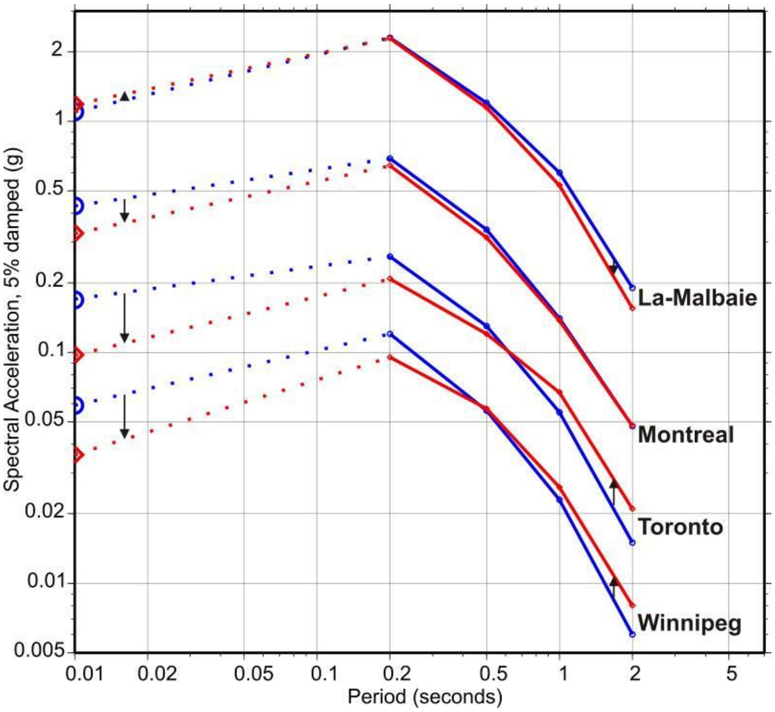

Figure 2: Uniform Hazard Spectra changes from 2005 (blue lines) to 2010 (red lines) for four localities which are representative of the range in hazard values for eastern Canada. Note log-log plot. Peak ground acceleration is plotted at a period of 0.01 seconds (from Humar et al., 2010).

4. Possible Model Changes for 2015

4.1 Improved Earthquake Catalog

Because of the long delay between creating the 4th Generation model and its adoption as the basis for NBCC2005, the earthquake catalog used for NBCC2005 only included earthquakes up to 1990 in the east and 1991 in the west. The magnitudes in this catalog were of mixed type, and the predominant type differed between west and east. In the west, a hierarchal preference was imposed so that the magnitudes (of varying type) were then considered to be equivalent to moment magnitude for the application of the GMPEs. Most of the magnitudes for the onshore events were "ML", and the assumption then made that the ML=Mw has since been shown to be generally correct (Ristau et al., 2005). For the offshore earthquakes (high seismicity regions off southwestern BC) the ML underestimates the true Mw, but this underestimate is acceptable because the ground shaking is much less from these earthquakes than for equivalent-ML onshore events. In effect the underestimate of magnitude balances an overestimate of the onshore shaking from the (inappropriate) GMPEs. In the east the most common magnitude for onshore events is mN, and to the degree possible all events were represented by their mN magnitude. These magnitudes were used to generate the magnitude–frequency curves (in mN), and the magnitudes of the rate equations derived from these were converted to Mw before application of the eastern GMPE (see Adams and Halchuk, 2003).

The GSC is currently working on a definitive catalog which converts the individual earthquake magnitudes to the Mw scale. This is being done in three ways: 1) modern large earthquakes for which the Mw has been derived from waveform modelling are having that Mw assigned; 2) older large events on an event-by-event basis use either Mw derived from special waveform studies, converted from teleseismic magnitude types, or Mw estimated by alternative methods such as felt-area estimates of Mw tempered by judgement for the older, poorly known events; and 3) the instrumental magnitudes of many smaller earthquakes are converted using empirical relations calibrated from recent Mw 4.5-5.5 events. For example, for eastern earthquake Bent (2009) individually estimated Mw for the largest 150 events; the remaining mN events (all Mw ≤4.5) were converted using one equation for pre-1995 events and another for subsequent events (Bent, pers. comm., 2011).

The conversions together with an additional two decades of earthquakes (1990-2010) will allow improved magnitude-frequency curves to be computed for Mw, and these can then be used directly with new GMPEs (see below).

4.2 New Representations for the Activity of Eastern Crustal Earthquake Source Zones

For NBCC2005 complete probabilistic calculations of seismic hazard were made for each of two source models – **H** representing historical clusters, and **R** representing large seismotectonic structures. The proposal for 2015 is as follows. There was irrationality that in the **R** model the activity of clusters of earthquakes was spread out along the long seismotectonic zones. Our current expectation is that the active clusters will continue to produce earthquakes, and so that part of the **H** model correctly captures the hazard, while spreading out the activity does not necessarily indicate the hazard of future large earthquakes in the lower seismicity parts of "**R**" zones (e.g., near Trois Rivières). Current thinking on the clusters is that they represent activity consequent on a large initiating event, and are in a fashion "aftershocks" albeit with a very long time horizon. For example the activity in Charlevoix, the best known and most active cluster, contains 4 M>6 events since 1663, and it is hypothesized these earthquakes are consequences of the large initiating earthquake in 1663 (of magnitude ~7)[1]. Under this hypothesis, a continuation of Mw~6 and smaller earthquakes ("aftershocks") seems likely, but a repeat of a M~7 ("mainshock" or initiator) at Charlevoix seems unlikely. The seismic hazard could then be estimated as being made up of two contributions. The contribution up to some threshold (the GSC is currently using

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[1] Several authors have proposed this, including John Ebel, but in publication it goes back to at least to Basham et al. (1983), if not before. Recent probabilistic models by Gail Atkinson and Lan Lin have incorporated similar ideas.

6.75), would be based on the local activity rate. The hazard computed like this will be high at Charlevoix, but low at Trois Rivières. What about the hazard contribution from the larger events we consider initiated the clusters' activity? We consider the larger events to occur anywhere along the seismotectonic structure, and to have magnitudes only between 6.8 and Mmax. This is tantamount to saying that a large earthquake could happen even in an area of low seismicity of a seismotectonic structure, and it therefore covers off the most important hazard contribution of the R model not captured by the **H** model. The combination of the two contributions – local rates for M<6.75 and regional rates for M>6.75 – we term "hybrid". Note that for low-seismicity segments of a long seismogenetic structure the rate of earthquakes of M6.8 might well be higher than for M6.7, which is a non-intuitive result.

Support for the hybrid model comes from a number of sources. Firstly, we can see from the low level seismicity that although the rate of M≥4 earthquakes around Trois Rivières is very low, the smaller earthquakes (magnitude 1-2) outline the seismogenic structure that the large events are attributed to (Figure 3). Secondly, we have examples of large events (disproportionate in size to the preceding activity) occurring in low-seismicity regions. For example, as mentioned above, the Saguenay earthquake Mw 5.9 occurred in the Saguenay graben, an area that had been monitored for over five decades before 1988 without detecting any event larger than magnitude 3.

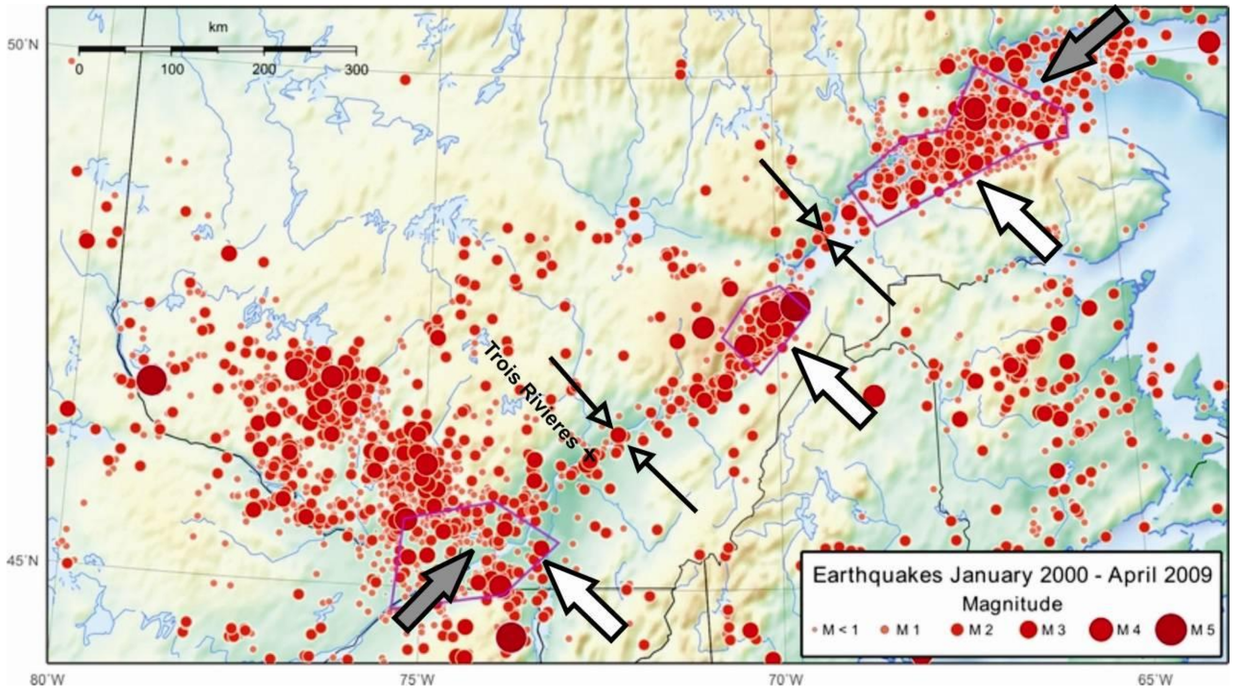

Figure 3: Contemporary small-magnitude seismicity in southeastern Canada. The microseismicity (between pairs of thin black arrows) indicates the activity of the implicated St. Lawrence valley rift faults in between the active clusters (white arrows) along the Iapetan passive margin (between grey arrows).

Determining the rate for the initiators is a challenge, because they are by definition rare. Since they do however carry the largest part of the tectonic deformation it is possible to attempt to estimate their rate from the observed rate of geodetic strain. Such geodetic observations are in their infancy, however, and have extremely large uncertainties (Mazzotti et al., 2005). Another constraint comes from nascent paleoseismic studies: if we expect initiators to occur in the future, past such events should have left a paleoseismic signature in the geological record. There are two types of signature: an active fault with an offset at the surface that can be dated and interpreted in terms of magnitude (none are yet known in southeastern Canada); or a signature of seismic shaking, which is an indirect record of large earthquakes. At least two large (M>6.5?) paleoearthquakes are interpreted for the Ottawa valley in the past 10,000 years (Aylsworth et al., 2000), and pending evidence suggests there have been others. A careful search for paleoseismic indicators near Charlevoix and upstream to Trois Rivières (Tuttle and Atkinson, 2010) suggested that there had been previous events near Charlevoix but not (over the past ~12,000 years) near Trois Rivières. Studies like these could place an upper limit on the rate of initiator events.

An alternative is to ask which of the larger southeastern Canadian earthquakes could be considered an initiator-type earthquake, at least to the degree that we know their preceding and subsequent earthquake history. We do this by winnowing out nearby earthquakes that are smaller than an earlier one. This is an extreme form of "declustering" and is routinely applied in the U.S. and elsewhere to remove aftershocks from the catalog, so as to leave a catalog for which the event occurrences are independent and Poissonian distributed. However a typical declustering considers periods of months after a mainshock, whereas the eastern Canadian situation under our hypothesis requires centuries. For the demonstration below we applied a 400-year time window (sufficiently long to span back to the 1663 earthquake) and a 50-km distance window.

As an illustration of the approach, Figure 4 shows "independent" events for eastern Canada. Once the dataset is corrected for catalog completeness, the magnitude-recurrence relation (Figure 4) gives an estimate of 0.01 p.a for Mw>6.7 as the total rate for all of the seismotectonic sources on the map. Most of the events are smaller than Mw6.7 and contribute to the rate of Mw>6.7 events through defining the magnitude-recurrence relation. As an alternative approach, all these events could be used to generate the seismic hazard from the seismotectonic sources, as long as the events were also removed from the clusters so that there was no double-counting.

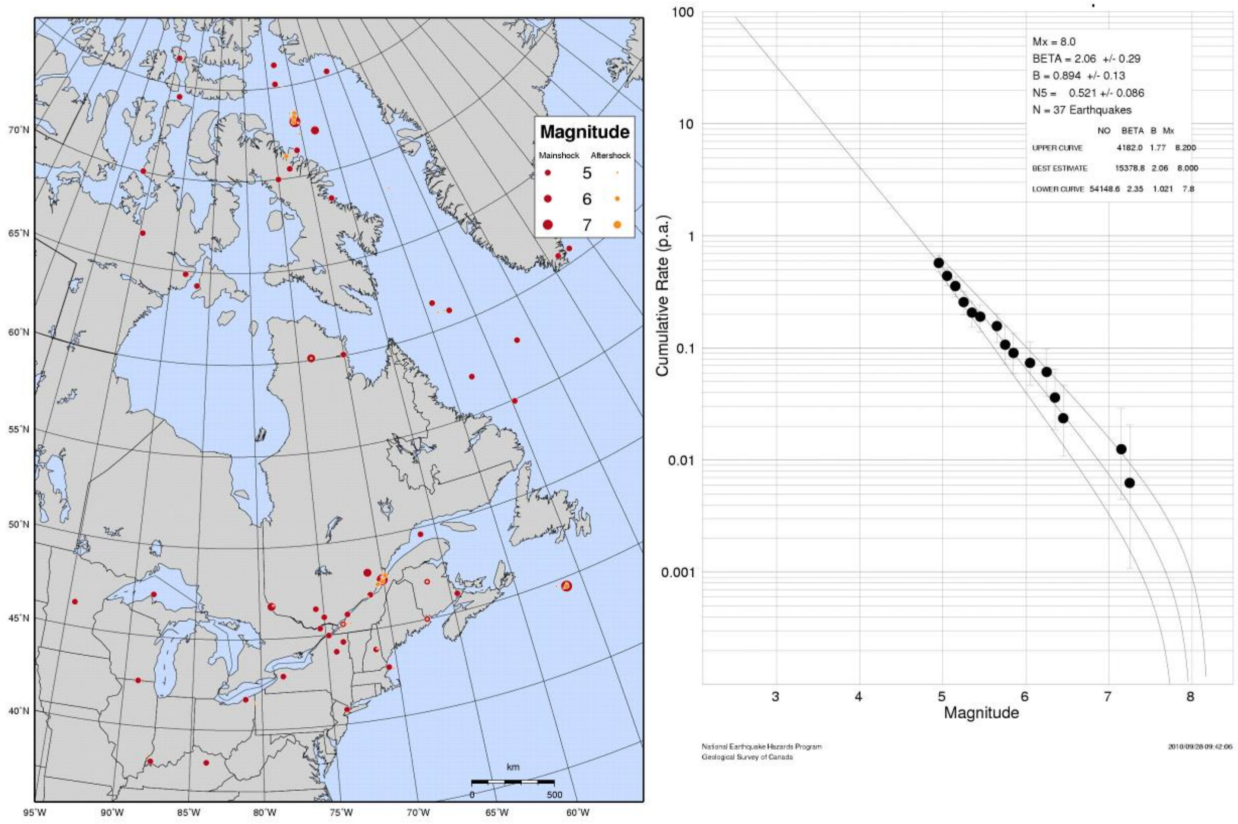

Figure 4: Left: Map of eastern Canada showing earthquakes larger than magnitude 5 that pass the declustering rule in the text (red) and their M>5 "aftershocks" (orange). Right: Magnitude-recurrence curve for the earthquakes on the map, after removing events that do not pass completeness (source S. Halchuk, pers. com, 2011).

The above leads to a range of rates, with large uncertainty, that can feed into the model. The hybrid model then comprises two parts: for magnitudes less than 6.75, a set of source zone models similar to those in the **H** model, but with their magnitude-recurrence curve capped at 6.75, plus for magnitudes between 6.75 and Mmax a large source along the seismotectonic sources such as the Iapetan Rift margin faults (i.e. with a spatial extent like the zone IRM of the R model). In a similar way hybrid sources will need to be defined for the Appalachians, the eastern margin, southern Ontario, and equivalent regions in the eastern Arctic. This completes a reconciliation of the eastern **H** and **R** models, the hybrid model capturing the most important features of each. Of course, the hazard model will need to consider uncertainties in the geometric extent of the new sources (both for the clusters and the broader seismotectonic sources), and the considerable uncertainty in the rate of the initiator events. Still to be investigated is whether the M<6.75 source zones need to be defined for the clusters, or whether their rate information can be carried by a smoothed-seismicity model (Frankel, 1995), which is fully objective (if lacking in geological insights).

4.3 New Models for the Cascadia and Explorer Subduction Zone Earthquakes

The Cascadia subduction zone was treated deterministically in NBCC2005, this simple treatment being justified by the fact that it was being introduced for the first time. Shaking from the Explorer subduction zone was ignored, though a sensitivity analysis in the early 2000's by the GSC suggested that including it would not significantly increase the hazard levels on the adjacent west coast of Vancouver Island. A preliminary probabilistic model was developed for the Cascadia subduction zone by Adams et al. (2000), but was not incorporated into the NBCC2005 model because some of the inputs were rather uncertain and in any event the hazard results were not very different from the deterministic model that had been proposed as the **C** model. For 2015 it is intended to update that Cascadia probabilistic model and add a model for the Explorer plate.

4.4 Probabilistic Treatment to Replace the "Robust" Combination of Model Hazard Values

For NBCC2005, at each location considered, the higher of the **H** and the **R** spectral values at any period was used to specify the design ground motion – a method termed "robust" (Adams and Halchuk, 2003 p. 16). The mapped design values were probabilistic for a particular period at any one location, in that they are derived from an identifiable probabilistic hazard calculation based on a particular source model. However, the overall map of design values was "quasi-probabilistic" in that the model that produced the maximum value varied from location to location, and even from period to period at a particular location. The robust method was extended to include results from the Cascadia deterministic model ("**C**") and the floor model ("**F**"). The robust method was adopted at the time because there was no *a priori* reason for preferring either the **H** or the **R** model, and it was felt that an arbitrary weighting of the models (which would have generated a probabilistic map) would preserve neither the level of protection in areas that are historically highly-active nor provide increased protection in areas that have been less seismically active in recent times but that are deemed likely to have large earthquakes in the future (Adams and Halchuk, 2003). This was an acceptable degree of conservatism in the 1990s.

Although not much has changed in terms of deciding which of **H** or **R** is the more correct description, the GSC has decided that it is time to place the hazard model on a probabilistic footing, largely because of its increased use for non-building-design applications such as estimating earthquake losses.

Once the **H**+**R** models have been reconciled in the above hybrid fashion, it becomes simple to add the **F** model as a background source with an activity rate appropriate to the stable craton core and add Cascadia and Explorer sources as a probabilistic fault models. Doing so will correct the underestimation that occurred where the robust method was used to join the **H**+**R** with the **F** model, and the **H**+**R** with the **C** model, since at the join the correct hazard now comes from both models, and the total is about 40% higher than either (instead of 0% when the Robust method was used).

4.6 Ground Motion Prediction Equations

A major change will be the adoption of new Ground Motion Prediction Equations (GMPEs). In the three decades since the publication of the first national Canadian relations (Hasegawa et al. 1981) new GMPEs for North America have incorporated a better understanding of the underlying functional form of the relationship, a wealth of new data, and the use of fault simulations to generate synthetic time histories to fill in for the absence of data from large, eastern North American earthquakes. The choices are still under review, but they will certainly include GMPEs derived by the NGA project for western North American crustal earthquakes. All the new ground motion relations compute shaking for the B/C boundary site condition, and it is likely that this will be adopted as the reference soil condition, replacing Site Class C in NBCC 2010.

Although we will use a catalog homogenous in Mw, there is still the issue of regionalization of the GMPEs (which relations apply to which terrane). The 2005 and 2010 NBCC model used just 4 relations – for eastern crustal earthquakes, for western crustal earthquakes, and for the subduction zone interface and inslab earthquakes. It is apparent that a finer regionalization will be required for 2015. Explicitly, the path from the high-seismicity regions offshore of southwestern British Columia is strongly attenuating, so that using western crustal earthquake GMPEs with the catalog Mw would overestimate the onshore shaking hazard from these earthquakes. It is likely that a downward adjustment of the NGA-west relations (probably by simply reducing the magnitude by a constant) can be made to bring the predicted ground motions closer in line with the observations. A different, but similar type of adjustment is probably needed for eastern offshore earthquakes. It should be noted that neither of these reductions in of themselves are likely to reduce the hazard below 2005/10 levels. This is because of the way the mixed magnitude types were used in the earlier composite-magnitude catalog more-or-less compensated for the inappropriate use of an onshore GMPE.

4.7 Other Changes to be Considered

An additional change that will be implemented is the incorporation of finite fault effects. For the 4th Generation computations all earthquakes (except those on the Queen Charlotte fault) were modelled as point sources. This is acceptable simplification for small earthquakes, as for magnitudes below about 5½ the fault dimensions are less than a few kilometres, and are essentially negligible relative to the hypocentral distance. However, larger earthquakes may have fault lengths of tens to hundreds of kilometres, and a site say 40 km from the hypocentre might be right above the fault rupture. Correcting for the proper distance metric increases the hazard by 15-50% over the point source approximation, with the larger increases happening in high-seismic regions dominated by large earthquakes.

NBCC2010, like NBCC2005 was based on the median hazard, i.e. there is a 50/50 chance of the value being exceeded. However there are also arguments for using the mean hazard, i.e. the mathematically expected value. As the mean hazard is invariably larger than the median hazard, any future use of the mean would tend to increase the hazard values.

Although no decision has been made, it seems likely that the probability level will remain at 2%/50 years. The change from 10%/50 years in the 1985 maps was clearly justified by the need to provide a more uniform margin against collapse (NRCC2006, p J-4), but it is not yet clear whether an even lower probability would provide additional benefits.

5. Impact of Model Changes and Conclusions

It is premature to comment on the amount or even direction of the model changes. Preliminary results have been made for Toronto as a sensitivity analysis to decide the degree of refinement of the changes needed for each input. For Toronto, some of the changes have very little effect (e.g., moment magnitude catalog), others decrease the estimates hazard (e.g., new GMPEs), and still others increase it (e.g., finite fault; mean instead of median). It is therefore to be expected that there will be changes in estimated hazard from the NBCC2010, but the degree of change across the nation and by spectral period will have to wait until the full model is assembled, run and iterated.

Any seismic hazard model produces an *estimate* of the (unknown) true hazard values. Model deficiencies (for example the choice of 0.01 p.a. in 1970, the too-low values of Mmax in 1985) have been progressively identified, often using lessons from "unexpected" Canadian and foreign earthquakes or simply through the adoption of international norms. We believe that the seismic hazard estimates are improving and that as a consequence the structures we design and build today and tomorrow will be better able to resist the effects of future earthquake shaking.

6. Acknowledgements

Hazard map developments like these are a team effort, and I thank my colleagues, especially Stephen Halchuk and recently Lan Lin for their criticism and assistance over the years. The improvement of the last hazard model and its adoption into the 2005 and 2010 NBCC has been the result of many concerned engineers who have taken the time to learn about the issues, and being very intelligent have asked penetrating questions that have improved the seismologist's product. They will do so for the 5th Generation model. Among these concerned engineers is Jag Humar, and I thank him for his support over the years.

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