Seismic Hazard Estimation in Canada and its Contribution to the Canadian Earthquake Loading Code - Implications for Code Development in Countries such as Australia

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Abstract

The history of national seismic hazard mapping in Canada is summarised together with comments on the most recent code cycle and how national anti-seismic building codes might best evolve in general. It is argued that an iterative process of continual code improvement occurring within an ongoing (permanent) national code committee is very important to the improvement of the earthquake provisions. While increases in code requirements may be resisted, these may be required to attain the expected performance (life-safety) or may be justified on economic grounds (present cost versus future loss).

INTRODUCTION

A national seismic hazard map forms the fundamental basis of the most effective way that we can reduce deaths and economic losses from future earthquakes. To be useful, a national map must estimate hazard fairly across the country, so future protection can be distributed equitably according to the hazard. This clearly requires a good assessment of the earthquake sources, but it also needs the selection of the probability level for the assessment and a wise choice of earthquake parameters.

The Government of Canada has been involved in earthquake monitoring since 1906 (Hodgson, 1989; Stevens 1980), with the work currently occurring in the Geological Survey of Canada (GSC). The results of this long-term commitment to basic data collection - including running seismographs and strong motion instruments, collecting felt information and assembling information about historical earthquakes, as well as basic research about the nature and origins of Canada’s earthquakes - have been the basis for all previous seismic hazard assessments. Since the late 1970s a major focus of the work (and external product for the Department) has been the preparation of seismic hazard maps for the National Building Code, an activity that has used a sustained commitment of 1-2 staff with additional personnel during the peak effort years. This work is coordinated with the main user, the committee in charge of the seismic provisions of the National Building Code of Canada (e.g. NBCC, 2005).

The goal of the seismic provisions is to ensure the life-safety of Canadians by preventing building collapse during damaging earthquakes and to ensure the continued use of emergency buildings like fire stations and hospitals (which are designed to 150% of the loads of common buildings). Those performance goals are intended to be the same for all regions (both high and low seismicity), so the code needs to be fair in distributing the cost in proportion to the benefits, cost-effective in achieving the performance goals, and the code requirements should be “as simple as possible, as complicated as necessary” (to aid in implementation and compliance). To assist in this the seismic hazard estimates need to evolve with time as scientific understanding grows, adjust in probability level as societal acceptance of risk levels changes, change in a steady fashion from code cycle to cycle (not be subject to wide swings in the estimates), and finally be reliable (an accurate estimate of the true hazard). These challenges can best be met by an iterative process of continual code improvement, of which Canada’s seismic code evolution is presented as an example that might encourage improvements to Australia’s code.

HISTORY OF SEISMIC HAZARD MAPS FOR CANADA

To date Canada has had four epochal seismic hazard maps, each of which were used in one or more editions of the NBCC (Figure 1). The national seismic hazard mapping efforts have moved from a qualitative assessment in 1953 (Hodgson, 1956), to a probabilistic assessment at 0.01 per annum (p.a.) using peak horizontal ground acceleration (PGA) in 1970, to a probabilistic assessment at 0.0021 p.a. using both PGA and peak horizontal ground velocity (PGV) in 1985, and to the recent (“4th Generation”) probabilistic assessment at 0.000404 p.a., which uses spectral acceleration parameters for the 2005 National Building Code of Canada (NBCC2005). The 2010 code will be based on a slight variation of the 2005 hazard results (the same 4th Generation model but with a tweaking of the ground motion relations). It is expected that the 2015 code will be based on a completely new hazard model (Canada's 5th Generation) which is being worked on at the moment, even in advance of the release of the 2010 code. Canada's 1985 maps (Basham et al., 1985) were an influence on the current Australian earthquake hazard map (McCue et al., 1993), and it is clear that many of the comments and insights mentioned below have already been raised in the Australian context (e.g. McCue, 2004).

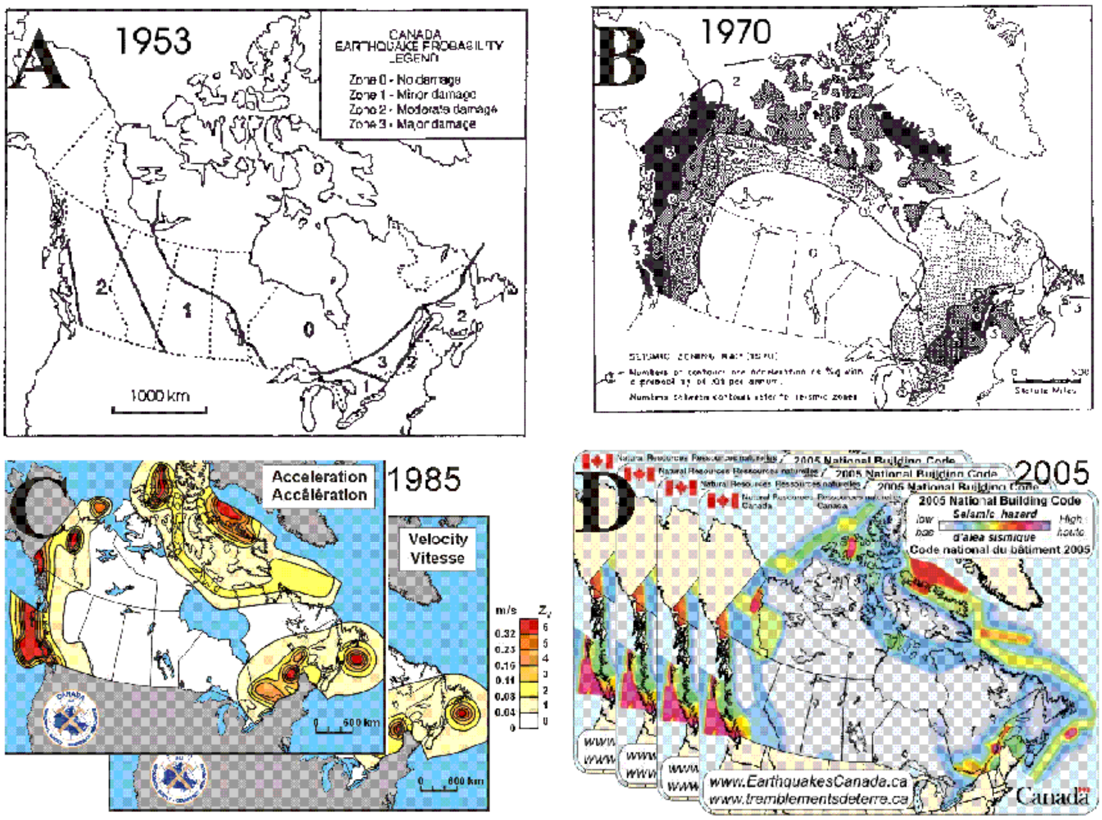

Figure 1. Past seismic hazard maps for Canada – A: 1953 (qualitative), B: 1970 (PGA at 0.01 p.a.), C: 1985 (2 maps: PGA and PGV at 0.0021 p.a.), and D: 2005 (4 maps: spectral acceleration at 0.000404 p.a.)

Figure 2 shows the 4th Generation hazard curves for representative Canadian cities together with the equivalent values for Sydney and Newcastle, Australia. The Sydney and Newcastle hazard values are about the same as Toronto's, and a clear step lower than Montreal's (Ottawa has a very similar hazard curve to Montreal). Note that the probability factors from AS1170.4 generate flatter curves than computed for the eastern Canadian cities and are more similar in shape to western Canadian cities (e.g. Vancouver).

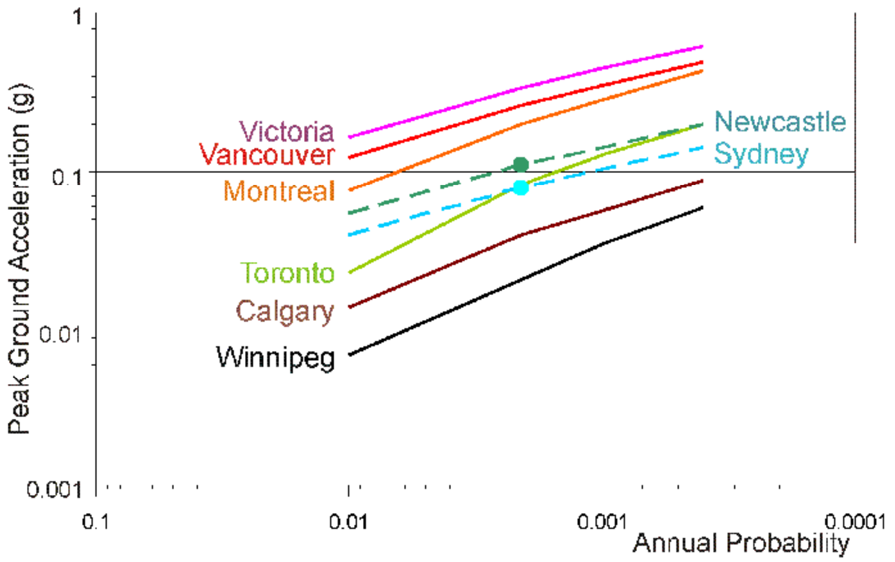

Figure 2. Seismic hazard curves for representative Canadian cities plus Newcastle and Sydney (dashed curves obtained using probability factors from AS1170.4)

MODELLING CANADA'S SEISMIC HAZARD ENVIRONMENT – THE CHALLENGES OF HIGH AND LOW SEISMICITY REGIONS

Canada's seismic hazard environment includes: a major subduction zone (Cascadia, which generated a magnitude 9+ interface earthquake in 1700), a patch of high-activity in-slab deep earthquakes in the subduction zone (Puget Sound, last major event a magnitude 6.8 in 2001), a major strike slip fault (Queen Charlotte, last ruptured in a magnitude 8.1 in 1949), crustal events in the western Cordillera (e.g. 1946 M7.3; 1985 M6.9), offshore events in the Canadian Arctic (1920 M6), offshore events in the eastern margin (1929 M7.2, 1933 M7.3), moderate-activity onshore earthquakes in southeastern Canada (1663 M~7, 1925 M6.2, 1935 M6.2, 1988 M5.9), and a large region in the centre of the country of very low seismicity (largest historical event M~5) (Lamontagne et al., 2008; Bent 2009). Useful summaries of the seismicity and its likely causes are given by Adams and Basham (1991) and Rogers and Horner (1991).

Each of these sources poses different challenges for seismic hazard assessment (a more complete discussion is given in Adams and Halchuk, 2003), two key ones being the handling of the Cascadia subduction zone and the estimation of seismic hazard for the low-seismicity areas.

For the Cascadia subduction zone it was decided for NBCC2005 that probabilistic modelling was not justified, given the state of knowledge in the early 1990s. Instead, a simple deterministic model was used, with the hazard being determined by placing a M8.2 event at the closest point on the inferred seismogenic rupture area to each site and then using the median ground motions as the 10%/50yr estimate and the median plus one sigma ground motions as the 2%/50yr estimate. These choices were made because the probability of the each of the deterministic estimates then approximates the probability used for the probabilistic estimate (for example the return period for the

Cascadia events is about 1/600 years, so the median deterministic values are appropriate for 10%/50 yr hazard). Details of the deterministic model ("C") are given in Adams and Halchuk (2003).

There are significant difficulties estimating seismic hazard for regions with few earthquakes like eastern Canada (or Australia). In some of the seismic source zones few earthquakes pass completeness, and hence the magnitude-recurrence parameter estimates (especially the b-value) are very uncertain. In Canadian zones where the b-value appeared unusual (very much larger or smaller than 0.9) we sometimes decided to fix the b-value to a regional value. In some regions there were too few earthquakes even to estimate a-values for intended sources, and these were combined into background zones.

For the central, very low seismicity part of Canada "stable Canada" local seismicity was deemed inadequate and a seismicity rate and b-value from global analog regions (such as the Australian continent, excluding its passive margins) was adopted (Fenton et al, 2006). This was implemented as a Floor ("F") model, which effectively specifies the minimum seismic design level (see below). An different hazard estimate for this region has since been made by Atkinson and Martens (2007).

Regionalization of Canada

Of necessity, eastern and western Canada must be treated slightly differently because of the different properties of the crust. Figure 3 shows the earthquakes and the regionalization used and identifies in a general way the "stable Canada" region. Seismic hazard to the west of the leftmost dashed line on Figure 3 was calculated using western strong ground motion relations; eastern relations were used for the remaining regions.

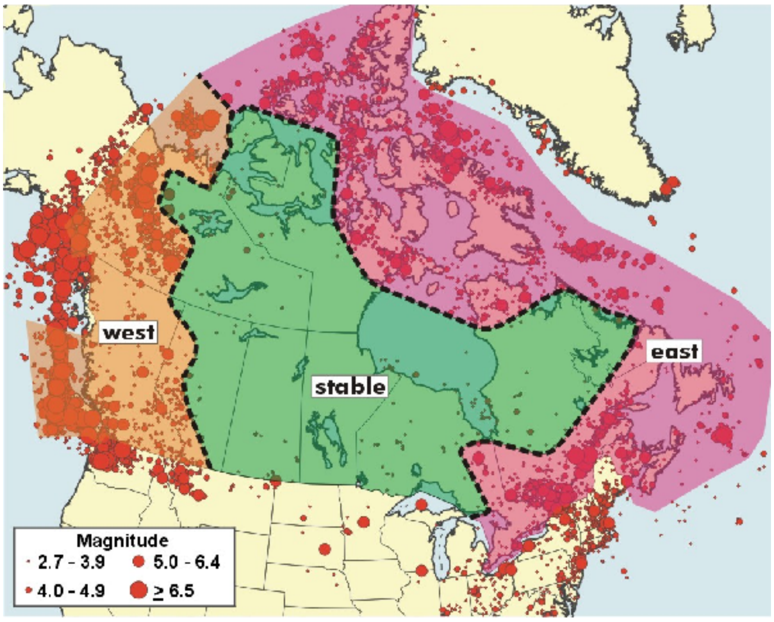

Figure 3. Map of Canada showing the earthquake catalog used for the 4th Generation model together with dashed lines delimiting the eastern and western seismic regions and the "stable Canada" central region.

INCORPORATION OF UNCERTAINTY INTO NBCC2005

The 4th Generation seismic hazard model for Canada considered two types of uncertainty, aleatory uncertainty due to randomness in process and epistemic uncertainty due to uncertainty in knowledge; the former cannot be reduced by collecting additional information, but the latter can be (Adams and Atkinson, 2003).

Aleatory uncertainty arises from physical variability that is inherent in the unpredictable nature of future events. For example there is a random component of earthquake source and propagation processes which will cause a scatter of amplitudes about the median values, even if the median were known with perfect accuracy. The Cornell-McGuire approach used in the 2005 hazard maps included the aleatory uncertainty by incorporating the "sigma" of the ground motion relations into the computation. The sigma is the standard deviation of the scatter of the data about the median ground motion relations, and its incorporation appropriately increases the median hazard (the aleatory uncertainty is also included in all the percentiles of hazard).

Epistemic uncertainty arises from the differences in expert specification of modelling assumptions, unknown or only partially known parameters, and extrapolation beyond observed range of data. The GSC uses a standard "logic tree" approach with the proprietary code FRISK88 (FRISK88 is a proprietary software product of Risk Engineering Inc.) to include easily-quantified epistemic uncertainty, and the uncertainty is incorporated through the weighting of upper and lower values to the “best” estimates of quantitative parameters for earthquake depth, upper-bound magnitude, a- and b-values, and Ground Motion Prediction Equations (GMPEs). The 3-branch representation was chosen so as to incorporate the uncertainty while keeping the computational requirements reasonable. (A 5-branch representation will probably be used in the next model). It is an irony that although considerable effort went into setting up the uncertainties in the model, the results have been poorly utilised. The Standing Committee on Earthquake Design (SCED) decided, based on GSC advice, that it preferred to use the median estimates of seismic hazard as the basis for the seismic designs, chiefly because it was felt that the mean (or 84th percentile) measures incorporated a large measure of uncertainty, and that those uncertainties were poorly understood and quantified. An over- or under-estimation of uncertainty can dramatically change the mean value but usually has little effect on the median.

Other sources of epistemic uncertainty are less easily quantified, such as: specification of seismic source zones; judgments on stochastic behaviour of historical seismicity; belief in future activity of seismic gaps; assumptions made in calculations of recurrence curves, such as their analytical form; and extrapolation beyond the observed data range or duration of historical record.

One major source of uncertainty that was addressed was due to the source zone models, but this was not included via a logic tree. Instead the hazard at each site was computed from two alternative probabilistic models (“H” - which used small seismic source zones around historical clusters and “R” – which grouped clusters into large-scale geological or regional sources) and the two additional models mentioned above (“C” and “F”), and the highest seismic hazard value of the four was used, a method termed "robust" in

Adams and Halchuk (2003). The chief advantage of the "robust" approach is that it preserves protection in areas of high seismicity but also provides increased protection in low-seismicity areas that are considered geologically likely to have future large earthquakes, such as the St. Lawrence valley near Trois-Rivières. Thus for certain low-seismicity regions a conservative bias was deliberately introduced. A further advantage is that the approach is computationally simple, and it is easy to explain what was done. Finally, the method allows a simple combination of deterministic and probabilistic hazard where this is desired.

It is interesting to see how the data has evolved to test the “R” hypothesis. Explicitly, if the R-type geological sources are a valid interpretation, then some new earthquakes will occur outside of the known active clusters on the suspect geological structures. Figure 4 shows contemporary small-magnitude seismicity in southeastern Canada with the active clusters outlined in purple. The symbol size has been chosen to emphasise the small magnitude activity, so the clusters are less distinct than as depicted on most maps. It is clear from the figure that there is a band of higher activity along the St. Lawrence valley, spatially associated with the 550-million-year-old rifted passive margin it overlies, and this lends weight to the geological hypothesis underlying the R-model (though it does not confirm that large earthquake will occur outside the clusters).

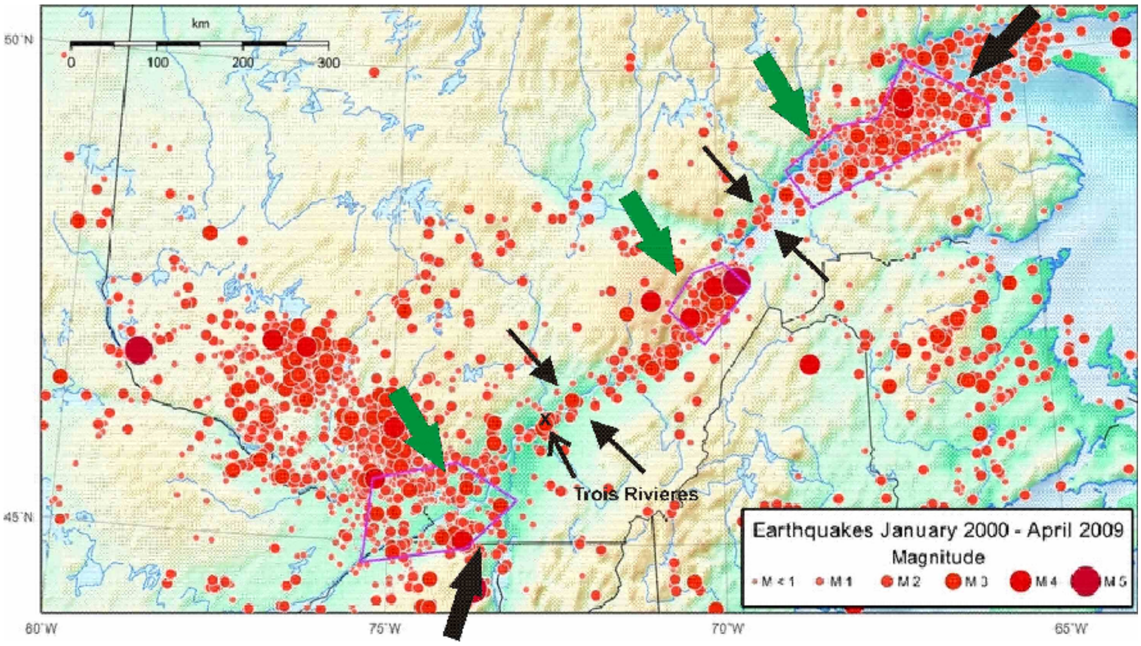

Figure 4. Contemporary small-magnitude seismicity in southeastern Canada. Seismicity between thick black arrows is associated with the rifted passive margin. Note the microseismicity of the rift faults (thin black arrows) between the active clusters (outlined in purple and indicated by green arrows).

COMMITTEE PROCESS FOR IMPLEMENTING THE GSC'S SEISMIC HAZARD MAPS INTO THE NATIONAL BUILDING CODE

The Standing Committee on Earthquake Design (SCED) has just replaced the Canadian National Committee for Earthquake Engineering (CANCEE). CANCEE was a committee of the National Research Council of Canada (NRC) and had been continually active since the early 1960s. In its reincarnation as SCED it has been elevated to "Standing Committee" status, which brings higher status, more access to funding but also enhanced bureaucracy. In the following 'SCED' is used to also refer to actions by its progenitor. SCED's committee's prime responsibility is to propose earthquake design provisions to the 'Part 4 Structural Design Committee', which in turn is represented on the main NBCC committee. Part 4 covers "large" buildings, whereas Part 9 covers "small" buildings such as houses and low-rise multi-unit apartments. The design provisions for Part 9 are relatively simple, as it is perceived that the inherent robustness of common small buildings means that they pose little threat to life safety (see also below).

SCED has a matrix membership, aiming to cover the necessary range of roles (research, design and regulation), expertise (seismology, foundations, etc), materials (wood, steel, concrete, masonry), as well as including representatives from key Canadian Standards committees and being geographically representative. It currently comprises about 21 engineers and 3 seismologists. Members are appointed for 5-year terms (ties to the code cycle) with a goal of 20-30% turn-over at the end of each term. However, there is a core of members with ~20 years' membership that provides corporate memory and continuity. The committee typically meets twice a year for 2-3 working days, with the interval between meetings and their duration being adjusted according the workload at that point in the code cycle. Such repeat assembly facilitates continuous improvement, and although there is usually a focus on the provisions for the next code committee members (particularly those at universities) may well be working or research or analytical studies intended for the next-following code. Members are not paid for their work, but the NRC covers meeting room costs, travel for non-government employees, and provides significant technical and administrative support. The meetings are open to the public, but in practice there are usually only a few visitors, and those usually relate to technical issues under discussion.

Proposed earthquake design provisions are developed as code clauses and advanced to the Part 4 Structural Design Committee which reviews the proposals for soundness and cost-effectiveness, may request additional considerations, but ultimately chooses whether to issue the proposed changes for public comment. Public comments are resolved, revised code changes are accepted, and the new edition of the building code is issued. However, the NBCC is a model code with no legal standing, because building regulations are a provincial responsibility. Each province needs to adopt the NBCC for it to become required practice, a process that can delay implementation by up to 2 years. In some cases the Province will adapt the NBCC, and in one Province, Manitoba, the 2005 seismic provisions were effectively removed. Manitoba is in a region of very low seismic hazard like much of Australia, and the provincial consensus was that the increase in design effort, and perhaps the increase in construction cost, of the Floor seismic hazard values were disproportionate to the risk.

The National Building Code is typically issued on a 5-year cycle, and the intent of SCED has been to alternate seismic hazard and engineering changes, thus issuing new seismic hazard maps every 10 years. The alternation was not possible for the 2005 Code, as both the seismic hazard and the engineering provisions needed to change together in order to accommodate the move from peak to spectral parameters. Although there is a planned 5-year cycle, emergency changes can, and have, been made, one of the most notable being the addition of an extra soft-soil class after the implications of the 1985 Mexico City damage were appreciated. Having a standing committee with common purpose and history facilitates such emergency changes.

LESSONS FROM THE 1985-2005 CYCLE

The interval between the 1985 and 2005 maps was unusually long. My own career with the GSC started in 1981, just before the 1985 maps were finalized in 1982. It was understood that I would be working towards the 1995 NBCC maps, for which a final draft would be required in ~1992. Considerable work was started including the contracting-out of newspaper searches to improve the historical catalogue and the incorporation of geological information as a way of moving beyond the historical pattern of activity. Test hazard maps were being computed at the time of the Mw 5.9 Saguenay earthquake (1988), Saguenay being the largest onshore event in southeastern Canada (or eastern US) since about 1935. It happened away from populated regions and caused damage in the tens-of-million dollars range (Mitchell et al 1990), very much lower than might have happened had it been close to an urban centre as was the Newcastle earthquake 13 months later. One engineering requirement of the engineering reconnaissance was rushed into the 1990 code – the anchoring of the top edge of long concrete block in-fill walls to the beam above to prevent the out-of-plane failures of the top few blocks – after the damage that these falling blocks caused in several buildings (no one was hurt). A more significant information increment was the unprecedented set of strong motion records obtained at 11 stations (Munro et al., 1989). These records were fortuitous, as the Saguenay earthquake was in an unexpected location but had occurred close to the Charlevoix region which had heavily-instrumented because it had been judged the most likely source of large earthquake records. The Saguenay records showed that prior GMPEs severely underestimated the observed ground shaking. Relative to their predictions, the Saguenay records represented +2.5 to +3 sigma ground motions. As a result of the discrepancy, the validity of prior and post GMPEs was in dispute and under vigorous debate for the next few years, and it was decided that it would be unwise to attempt new seismic hazard maps until the debate was resolved. The very strong ground motions were subsequently attributed to rupture directivity (Haddon 1995), although the degree to which the earthquake was normal (or abnormal) is still under debate and recent GMPEs still consider the Saguenay earthquake to simply be an unusual “high stress-drop” event. The proposed 1995 maps (which were substantially completed in 1993) were thus deferred by a cycle and were intended to become the year-2000 maps.

No NBCC was issued in 2000. From the point of view of CANCEE, the code work had been completed in 1998, but NRC had decided to cast the NBCC into performance-based code language, replacing the prescriptive code of 1995 and earlier codes. The bureaucracy involved in this process dragged on for a further 5 years, so that the 1993 model (slightly updated to take into account new GMPEs) became the basis for the 2005 code. With the additional delay in provincial enactment, the code was not actually in effect in some provinces until 2007.

Two lessons can be gleaned from this: it takes time for certain consequences such as information from important earthquakes to work their implications through the system; and the delays due to the code process itself should not be underestimated.

There were very significant changes from the 1985/1990/1995 seismic provisions and the proposed 2005 ones, including the change from peak to spectral parameters and changes to probability level and soil classes (see DeVall, 2003). During the delay from 2000 onwards there was a concerted attempt to educate the user community about these changes through regional seminars and publications including a special issue of the Canadian Journal of Civil Engineering (DeVall, 2003). Despite these attempts, very late in the process there were strong objections, based on analysis-effort (the expanded need for dynamic analysis) and cost, from one province; these were defused by a day-long seminar presented by SCED experts who pointed out that while the new code increased costs for some short-period structures the earthquake loads on tall buildings founded on rock dropped. Seismic provisions included the introduction of a floor level affecting the large stable-Canada region for buildings on NEHRP-class D or softer soil. The requirement involved seismic design for the first time (but static design was sufficient) and small amounts of lateral resistance for short heavy buildings (for which the lateral forces were not dominated by wind). The late objections of Manitoba, mentioned above, were apparently not assuaged, and the Province opted out.

GROWTH OF INDEPENDENT SEISMIC HAZARD ASSESSMENT CAPACITY IN CANADA

In the 1970s it was accepted that the Canadian expertise in seismic hazard resided entirely within the GSC. This went as far as to GSC scientists providing the seismic hazard values for provincial nuclear power plants. The situation has improved greatly since then, with a handful of practitioners in industry and at universities capable of performing seismic hazard assessments. Federal environmental protection legislation now requires the proponents of significant projects provide site-specific seismic hazard assessments (usually performed by their contractors) and show how their design and/or emergency plan will cope with strong earthquake shaking. Government scientists evaluate those assessments for completeness and accuracy and make recommendations for approval or revisions. The process can lead to situations where the proponent’s site-specific assessment produces values different from those in the NBCC.

Different hazard estimates may occur not due to differences in the methodology, but in the input (model) choices. *A priori* one cannot say whether a particular set of choices is "right". In each case seismic hazard is being estimated, and we do not know the true value. It is likely that some choices are unreasonable, based on past experience. An example would be choosing the upper-bound magnitude for a source zone as 6.0 and then a few years later having a magnitude 6.9 earthquake (this happened in the Nahanni region of northwestern Canada, for the source model used for NBCC1985). A smart community takes such experiences and generalizes them to all other sources. Thus we have come to a general community consensus on certain choices as being "reasonable". There are other parameters where there is less consensus, and indeed disagreement on the choices to be made. To some degree the range of choices can be captured by including them as weighted alternatives in a full logic tree approach. Doing so usually represents an honest recognition that the proponent's preferred choice may not be correct, and might differ from that of other practitioners. It also provides a certain amount of wiggle room if new data arrives. However the weights applied to the choices are subjective, and very much a matter of opinion. In evaluating a proponent's hazard results it has been important to determine if the range of choices included is reasonable, and if the weights applied appropriate. To date, most differences have been resolved by iteration between the proponent and regulator, and no impasse has developed. Should an impasse develop, is it envisaged that an independent assessment be performed, probably by a neutral party outside of Canada.

Such independent assessments suggest that the national seismic hazard map is likely inaccurate in places, simply because the detailed effort necessary to get a better answer was not practicable on the nation-wide scale. It is *likely* that the seismic hazard in many places is only approximately correct, and it is *possible* that the NBCC values may be conservative on average (on the high side; for example because of the robust combination used in 2005), in which case certain site–specific surveys might derive lower values. An overall slight over-estimate in a national hazard map is probably healthy, for reasons now described.

MODELS FOR THE EVOLUTION OF SEISMIC HAZARD LEVELS AND HENCE CODE PROTECTION

Consider the following schematic evolutions of seismic hazard values (Fig. 5). The ideal would be an unbiased estimation that is correct and does not change (curve 1). Two good alternatives are curve 2 (which is monotonically approaching the actual value) and

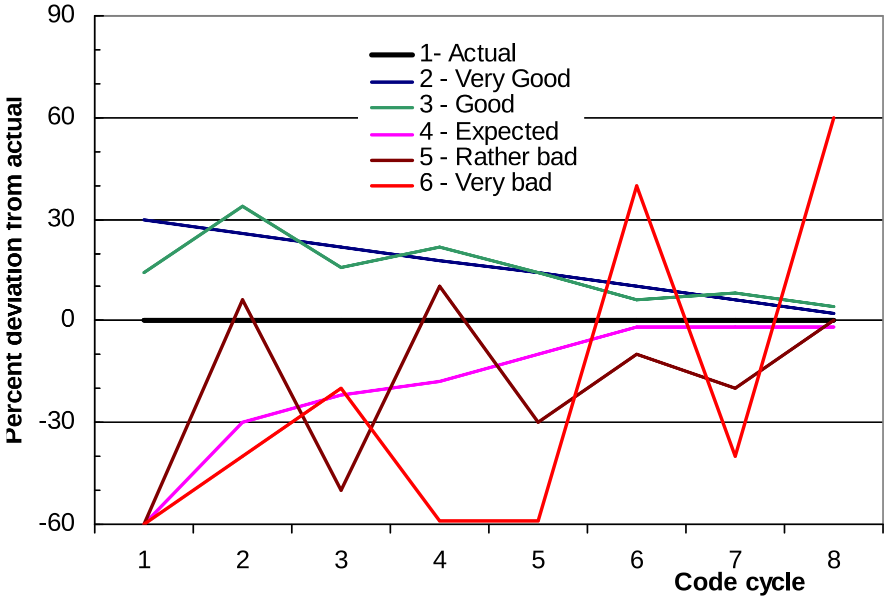

Figure 5. Schematic evolution paths for seismic hazard estimates and/or design values.

curve 3 (which approaches the actual value with cycle to cycle swings that get smaller as the code matures). Both of these approach the actual value from above. This is important, as when the actual value is “discovered”, there will be no part of the national building stock that has been under-designed and needs retrofit.

The remaining curves approach the actual value from below, meaning that certain cohorts of buildings have been under-designed and might need retrofit. Curve 4 represents a fairly typical case, probably representing the average state of code evolution in most developed countries – the design level has started low and increased as there was new appreciation of the largest likely earthquakes and of the very strong ground motions close to large earthquakes. Curves 5 and 6 represent possible paths which include cycle to cycle swings; the latter is extremely bad because the swings are getting larger with time, indicating that the state of knowledge is insufficient for stable hazard estimates.

How does Canada’s evolution of hazard values compare to the models? Because of our four cycles we have a history of estimated PGA at Montreal (Figure 6). While PGA is a very poor parameter to be comparing, we use it because we can track its change at a few probability levels. The longest history of change is for 0.01 p.a. because it was used in the 1970 model and we can calculate it from subsequent models. (One cannot assign a probability to the 1953-1969 code values because they were essentially deterministic estimates, but they might have been equivalent to 0.01 p.a.; the numerical value for Montreal appears to have been about 0.04 g). Figure 6 suggests that the 0.01 p.a. 2010 ground motions have returned to the pre-1985 level; they will stay there until the 2015 code is issued.

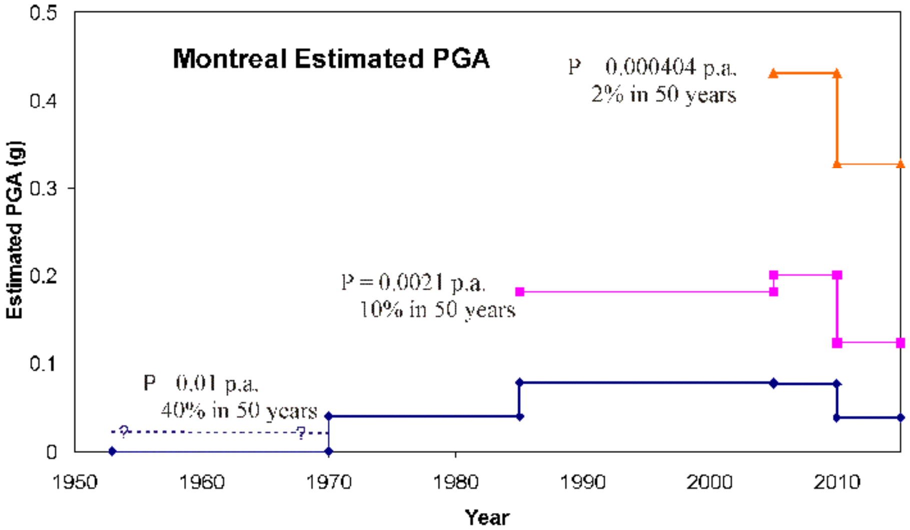

Figure 6. Evolution of estimates of Peak Ground Acceleration for Montreal, at various probability levels.

There have been criticisms of previous code cycles in that “fudge-factors” (e.g. 0.6 in NBCC1985) were incorporated so that although the numerical seismic hazard estimate changed greatly (in part due to a reassessment of hazard, but in part due to the change in probability level), the design loads did not. Mitchell et al. (in press) have assessed the changing seismic provisions in NBCC and estimated the design change (load to be resisted) with code cycle. Figure 7 is adapted from their figure 8 by normalizing past values to the current design level. This is the difference to be considered should an older building need to be retrofitted to the current code (retrofit is not normally a code requirement, since NBCC applies only to new construction, but an upgrade to 100% of the current code is required when there is substantial change of use, e.g. from a warehouse to apartments). Figure 7 suggests that for this particular building class the design values for the 1953-1969 period were actually higher than for the 1970-1984 period; perhaps this occurred as a consequence of a large degree of engineering conservatism in the early years of earthquake engineering. As a result, it is possible that different retrofit levels (or strategies) might be needed for the 1970-1984 buildings.

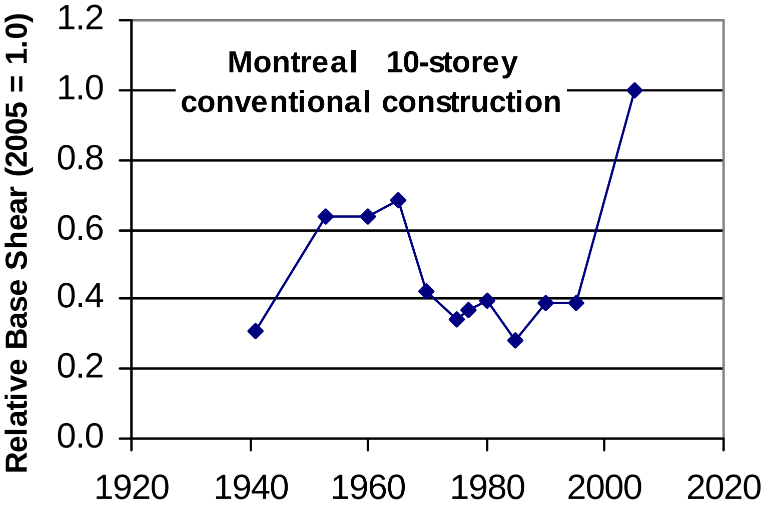

Figure 7. Design base shear for a conventional 10-storey concrete wall building in Montreal, showing relative design level through time (drawn from data in Mitchell et al., in press).

National building codes are only one part – albeit an extremely important part – of an earthquake-mitigation strategy. They have the advantage that they are relatively inexpensive (~2% of project value) and are passive, that is once the earthquake-resistant building is constructed it will protect the occupants even if they do nothing and do not even think about earthquakes. An analogy would the air-bag restraint system of a modern automobile – once it's part of the car, it sits ready to do its job without a thought from the driver. The other part of mitigation is more active, analogous to the seatbelt which needs to be buckled in order to work. Active mitigation includes public education, home emergency kits, community emergency plans, and rapid notification systems on the one hand and both home and commercial retrofit strategies on the other. If earthquake issues are not regularly aired, these strategies will probably not be implemented or only exist in stale versions. However, all mitigation strategies in addition to building codes have a role to play, and the relative importance of each may depend on the local circumstances.

SEISMIC RISK ACROSS CANADA

Most of this paper is concerned with seismic hazard. A full assessment of seismic risk in Canada involves much non-seismological data, knowledge and skills to translate the effects of seismic hazard shaking into likely losses. It is thus beyond the scope of this paper, and beyond the current mandate of the GSC. However, a first approximation is extremely useful for allocating resources and effort to those places where the benefits will be largest. The GSC's crude method assesses the distribution of urban seismic risk in Canada from the sum of city population times the probability of damaging ground motion (Adams et al., 2002). For the probability, we used the more-likely of two damage thresholds in PGA and PGV to capture the different hazard to short (1-2 storey) and tall (circa 10 storey) buildings. Choosing different thresholds or ground motion parameters would produce results that differ in detail, but substantially mimic the risk distribution shown in Figure 8. Between them, the greater Vancouver and Montreal account for more than half of the urban seismic risk. Canada's six largest cities at risk account for over three-quarters of the risk.

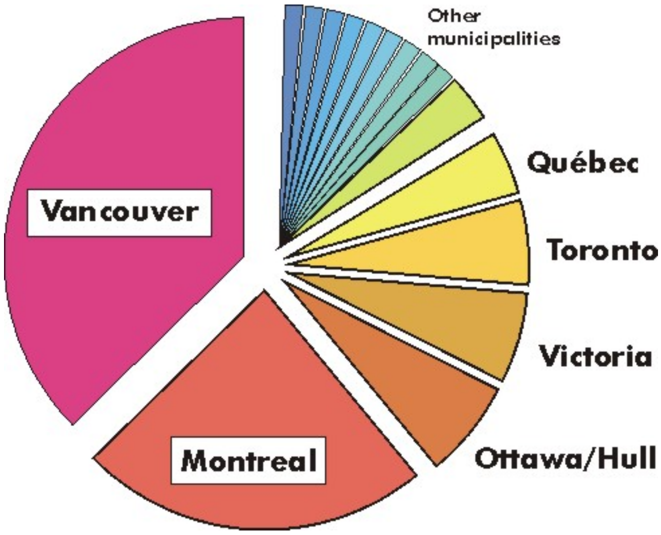

Figure 8. Relative distribution urban seismic risk in Canada.

THE COST-BENEFIT OF EARTHQUAKE MITIGATION WORK

Economist Neil Swan (1999) assessed the economic value of NRCan's earthquake hazard work as being the benefit from the reduction, due to NRCan's earthquake studies, in loss from a disastrous earthquake *less* the cost of complying with the earthquake provisions of the National Building Code. Swan started with the best loss estimation then available for Canada - Munich Reinsurance's assessment of a mean loss of $12 billion to buildings and contents in Greater Vancouver from a magnitude 6.5 earthquake under the Straits of Georgia (Munich Reinsurance, 1992). This is a credible disaster scenario, with an annual expectation of about 0.2% ("return period" of 500 years).

U.S. engineers have estimated the difference in construction standards between California and moderate-seismicity states where seismic codes are less stringent. They estimate that a given earthquake shaking would cause 30% (for wood frame buildings) to 90% (for other structures) greater damage than in California. Canada's earthquake code is approximately proportional to California's, so Dr. Swan took the avoidance of this extra damage to be the benefit from NRCan's earthquake activities (knowledge of earthquakes, estimation of earthquake shaking, and getting the results into the building code). The difference made by NRCan's influence is $6 billion for the $12 billion 1-in-500-year earthquake scenario, or $12 million per year.

Using a method we judge to be reasonable, Swan estimated additional loss reductions of $10 million per year from smaller (less damaging, more frequent) and $9 million/year from larger (more damaging, less frequent) scenario earthquakes, for a total of $32 million per year. Allowing for reduced fire damage and deaths and injuries associated with the earthquake increases the savings to $47 million.

Earthquake code compliance costs for Greater Vancouver were estimated at $680 million, and the corrected interest and depreciation on that sum was the annual cost of compliance, $38 million. The net annual benefit was $9 million for Greater Vancouver. This was increased by a factor of 5 (Greater Vancouver comprises about one fifth of the total Canadian seismic risk, a smaller fraction than the urban risk as shown on Figure 8), for a net annualized saving of $43 million.

NRCan was annually spending about $2.5 million on earthquake studies in 1998. Thus an average Canadian citizen (say in Manitoba, which has just opted out of the seismic provisions) paid 8 cents for the national earthquake program through taxes each year, but would receive $1.60 in time-averaged annual benefits. As Swan points out, this benefit accrues to all Canadians, even if they do not live in an earthquake zone, because damage in any Canadian urban centre would be paid for largely from federal taxes collected nationwide.

RETURN ON INVESTMENT: WHO WINS? WHO PAYS? – THE CASE FOR DESIGN EXCEEDING CODE LEVELS

There is a constant challenge in today’s society to ensure that money is spent wisely. Damaging earthquakes are relatively rare in Canada and Australia, so it may seem uneconomic to some to invest in earthquake resistance that will only pay off if a rare earthquake happens (indeed some owners and some provincial regulators question whether the current design levels are too high). Although the Swan report argues otherwise, today’s focus tends to be on the front-end cost and short-term return on investment and not on long-term cost reductions. It does not help that the front-end costs of earthquake-resistant design are borne entirely by individuals or companies but the long-term costs of earthquake disasters are usually co-shared or borne by society at large.

The global news is unfortunately full of earthquake disasters, and each resonates with the population of developed countries who say “it should not happen here”. Thus the societal life-safety issue is the one has most influenced on the national building code seismic provisions that we have today. It is a tribute to the professionalism of Canada’s engineers that the code is implemented almost universally with very little systemic avoidance in spite of a regulatory presence that has been greatly reduced over the last few decades.

It is possible that there is a good case to be made for investment in earthquake-resistant buildings that exceed the current code minimum. Such enhanced resistance of course delivers life-safety, but can also confer increased usability after smaller earthquakes, which are more common than the rare destructive earthquakes. The value of this increased usability is partly in the reduced repair costs and partly in the decrease in business interruption (disruption): a building that has been earthquake-damaged to the point of needing evacuation and repair (even if there were no injuries) places a high disruption cost on a company. Some of these costs are insured, and in an efficient market the insurance premiums should presumably be smaller for buildings designed to levels that exceed the code; at some point the present value of this on-going reduction in premiums would balance the initial cost of exceeding the code design.

This should be a fruitful field of optimization. Goda and Hong (2006) attempted to answer the question (for a very specific building type) "what is the optimal return period at which the rising cost of design balances the consequent cost of adverted damage (including non-structural) and injury plus fatality?" They concluded that design periods of ~3600 years (damage only) and ~5600 years (damage and injury plus fatality) gave optimal benefits. The results clearly show that: the *de facto* standard return periods used twenty years ago (ground motions at 1/500 p.a. or 10%/50 years) were too short; current design periods of 1/2500 p.a. are probably still a bit short (though perhaps not by much, as the optimal expected cost is fairly insensitive to return period); and that designs more stringent than current codes might perhaps be economic.

Another argument for earthquake-resistant buildings that exceed the current code is that the incremental cost of improved earthquake design (perhaps of the order of ½%, remembering that the total cost of earthquake-resistant design in a new building is ~2 – 4% of the total project value) might well be recovered in reduced retrofit costs (and occupancy down-time) over the building's life. This is an argument made by Robin McGuire for "over-designing" nuclear power plants (McGuire, 1987) – the initial cost of the higher design is much less than the plausible costs of retrofit plus the loss of revenue during shutdown. It echoes the cartoon cases made by Curves 1-3 of Figure 5, where retrofit is not required.

Costs of appropriate or over-design for critical projects may be quickly recovered should shaking near the design level occur. A recent success was the 1972 design of the Alaska oil pipeline at its crossing of the Denali Fault (USGS press release, 2002). The fault moved about 5 m during the 2002 earthquake, but the pipeline was built on sliders to accommodate 6 m of motion and was undamaged. The pipeline was shut down for just a few days for precautionary inspection. Had the pipeline ruptured, economic losses would have been considerable as the pipeline carries $US25M of oil per day. More importantly, such a catastrophic oil spill might have proved almost impossible to remediate, and environmental considerations might have prevented the re-opening of the pipeline.

A final argument is that earthquake-resistant design confers a considerable robustness on buildings that allows them to resist unexpected loads (sometimes termed accidental loads) that vastly exceed the expected loads. In particular robustness inherent in seismic detailing can reduce cascading failures, say of the type that exacerbated the structural failure following the Oklahoma City bombing in 1995, perhaps by 80% (Corley et al., 2001).

RISK MITIGATION OF “SMALL” EARTHQUAKES THROUGH BUILDING CODES

When considering seismic risk scenarios the earthquakes chosen from deaggregations of seismic hazard usually represent relatively large-magnitude earthquakes (M ~6½ and larger) that cause catastrophic losses. These scenarios often drive the risk assessments (and mitigation strategies) because they pose financial risks beyond the capacity of the insurance community, requiring re-insurance or governmental support. But such losses are rare during an individual’s period of property ownership. Instead one might focus on “Newcastle-sized” earthquakes (M ~5) that are more common, relevant to the current population, and indeed similar to events represented in the historical catalog (and therefore an easy risk to convey to the population). These “small” earthquakes usually do not threaten long-period “important” engineered buildings common in cities, or necessarily cause collapse in many buildings, but they radiate lots of short-period energy which makes them very damaging to short, rigid structures (like brick houses); they therefore threaten the majority of built infrastructure in suburbs and small towns.

Although the damage may be of low intensity and localized, it can accumulate to potentially large losses if the “small” earthquake is under a suburban/urban area. Examples include Newcastle, Australia (1989), Ste Agathe de Fossili, Italy (2003), Cornwall, Canada (1944), Cacoosing Valley, Pennsylvania (1994) and Folkestone, U.K. (2007). The damage levels may be severe enough to require building inspection before re-occupancy (delaying homeowner re-occupancy and requiring emergency housing), affect business continuity (low-rise retail), and so may involve a prolonged period of social disruption.

Given the suburban loss distribution described above, what is the correct mitigation strategy, considering that building codes are at their best in preventing collapse in “large” engineered buildings shaken to the design event?

While new houses can be made much more earthquake-resistant during construction, this probably only makes sense as part of a complete disaster mitigation strategy including enhanced resistance to other natural disasters, especially meteorological ones. Even with a complete strategy there would likely be considerable resistance because even a small incremental cost is considered a significant barrier to home ownership.

For existing buildings the option is retrofit. In places like California where strong shaking is relatively common the improved anchoring of a suburban bungalow – a Part 9 building in the NBCC – to its foundation is expected to greatly reduce the structural loss and is expected to be a cost-effective retrofit (i.e. a few thousand dollars can offset a few hundred thousand dollars in loss). Such mitigation is probably not cost-effective in most parts of eastern Canada or Australia, because during the lifetime of the house the probability of strong shaking is far lower than in California.

As it is not clear how even new (let alone the existing building stock) “conventional” construction can be made more resistant to the common short-period earthquakes, it may be that planning better for the post-disaster recovery phase, including rapid economic follow-through, is the most effective overall mitigation strategy for suburbs in low seismicity regions.

CONCLUSIONS

I summarise by giving a list of things that I believe have led to successful code development in Canada:

- A long-term government commitment to national earthquake monitoring
- A national strong motion network
- Detailed research to understand individual earthquakes and their ground motions
- Close dialog between seismologists and earthquake engineers
- A national earthquake engineering society (Canadian Association for Earthquake Engineering) organising national meetings
- Post-earthquake visits to learn lessons from significant earthquakes impacting building types used in contemporary construction
- University research to validate earthquake-resistant design and construction methods
- A national building code that that is committed to a periodic editions
- An ongoing (permanent) national code committee to ensure an iterative process of continual code improvement for the earthquake provisions

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REFERENCES

Adams J., Atkinson G.M. 2003. Development of Seismic Hazard Maps for the 2005 National Building Code of Canada. Canadian Journal of Civil Engineering Vol 30, p. 255-271.

Adams, J. and P.W. Basham, 1991. The seismicity and seismotectonics of eastern Canada. Chapter 14 *in* Neotectonics of North America, Decade of North American Geology, volume DMV-1, p. 261-276.

Adams, J. and 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.

Adams, J., Rogers, G., Halchuk, S., McCormack, D., and Cassidy, J. 2002. The case for an advanced national earthquake monitoring system for Canada’s cities at risk. 7th US Conference on Earthquake Engineering, Boston, USA, July 21-25, 2002. 10 pp.

Atkinson, G.M. and Martens, S. N., 2007**.** Seismic hazard estimates for sites in the stable Canadian craton. Canadian Journal of Civil Engineering, Vol 34, No. 10, p. 1299-1311.

Basham, P.W., D.H. Weichert, F.M. Anglin, and M.J. Berry, 1985. New probabilistic strong seismic ground motion maps of Canada. Bulletin of the Seismological Society of America, Vol.. 75, p. 563-595.

AS1170.4, 2007. Structural design actions, Part 4: Earthquake actions in Australia. Standards Australia, Sydney.

Bent, A. L., 2009. A Moment Magnitude Catalog for the 150 Largest Eastern Canadian Earthquakes. Geological Survey of Canada Open File 6080, 23 pp.

Corley, W.G., Smith, R.G., and Colarusso, L.J. 2001. Effects of structural integrity on damage from the Oklahoma City, USA bombing. Chapter 1 in “Forensic Engineering – the investigation of failures” B.S. Neale (ed.). Telford Publishing, London, 212 pp.

DeVall, R., 2003. Introduction, Proposed earthquake design requirements of the National Building Code of Canada, 2005 edition. Canadian Journal of Civil Engineering, Vol 30(2), p. v-xvii.

Fenton, C., Adams, J., and Halchuk, S. 2006. Seismic hazards assessment for radioactive waste disposal sites in regions of low seismic activity. Geotechnical and Geological Engineering, Vol 24, p. 579-592.

Goda, K. and Hong, H.P. 2006. Optimal seismic design for limited planning time horizon with detailed seismic hazard information J. Structural Safety Vol. 28, p. 247–260.

Haddon, R. A. W. 1995. Modelling of source rupture characteristics for the Saguenay earthquake of November 1988, Bulletin of the Seismological Society of America, Vol. 85, p. 525-551.

Hodgson, J. H. 1956. A seismic probability map for Canada, Canadian Underwriter, Vol 23, p. 3-6.

Hodgson, J. H. 1989. The heavens above and the Earth beneath – A history of the Dominion Observatories. Geological Survey of Canada, Open File 1945, 193 pp.

Lamontagne, M., Halchuk, S., Cassidy, J.F., and Rogers G.C. 2008. Significant Canadian earthquakes of the period 1600–2006. Seismological Research Letters Vol 79, p. 211–223.

McCue, K., 2004. From PSHA to Building Codes in Australia. Invited paper in Lam, Wilson and Butler Editors, Earthquake Engineering in Australia. Proceedings AEES Conference, 25 – 27 November 2004, Albury NSW, paper 27, 8 pp.

McCue, K., (Compiler), Gibson, G., Michael-Leiba, M., Love, D., Cuthbertson, R., & Horoschun, G., 1993. Earthquake hazard map of Australia, 1991.

McGuire R.K., 1987. Seismic hazard uncertainty and its effects on design decisions in F.H. Wittmann (ed) Transactions, 9th International Conference on Structural Mechanics in Reactor Technology, Lausanne, p. 3-12.

Mitchell, D.; Tinawi, R.; Law, K. T., 1990. Damage caused by the November 25, 1988 Saguenay Earthquake. Canadian Journal of Civil Engineering, Vol. 17, No. 3, p. 338-365.

Mitchell, D., Paultre, P., Tinawi, R., Saatcioglu, M., Tremblay, R., Elwood, K., Adams, J., and DeVall, R., (in press). Evolution of Seismic Design Codes in Canada. Canadian Journal of Civil Engineering.

Munich Reinsurance Company of Canada, 1992. A study of the economic impact of a severe earthquake in the lower mainland of British Columbia, Munich Reinsurance Company of Canada, 390 Bay Street, 22nd Floor, Toronto, Ontario, Canada, M5H 2Y2.

Munro, P S; North, R.G. 1989. The Saguenay Earthquake of November 25, 1988, Strong Motion Data/Le Tremblement De Terre Du Saguenay, Le 25 Novembre 1988, Enregistrements Des Secousses Fortes. Geological Survey of Canada, Open File 1976, 17 pp.

NBCC, 2005. National Building Code of Canada 2005. Document NRCC 47666. National Research Council of Canada, Ottawa, Ontario.

Rogers, G.C. and Horner R.B., 1991. An overview of western Canadian seismicity, Chapter 5 in Slemmons, D.B., E.R. Engdahl, M.D. Zoback and D.B. Blackwell, eds., Neotectonics of North America, GSA DNAG Vol. DMV-1, 69-76.

Stevens, A.E., 1980. History of some Canadian and adjacent American seismograph stations. Bulletin of the Seismological Society of America; vol. 70; No. 4; p. 1381-1393.

Swan, N., 1999. Benefits from Expenditures on Earthquake Research at Natural Resources Canada. Geological Survey of Canada, Open File 3764, 45 pp.