Development of seismic hazard maps for the proposed 2005 edition of the National Building Code of Canada[1,2]

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Abstract: A new seismic hazard model, the fourth national model for Canada, has been devised by the Geological Survey of Canada to update Canada's current (1985) seismic hazard maps. The model incorporates new knowledge from recent earthquakes (both Canadian and foreign), new strong ground motion relations to describe how shaking varies with magnitude and distance, the newly recognized hazard from Cascadia subduction earthquakes, and a more systematic approach to reference site conditions. Other new innovations are hazard computation at the 2% in 50 year probability level, the use of the median ground motions, the presentation of results as uniform hazard spectra, and the explicit incorporation of uncertainty via a logic-tree approach. These new results provide a more reliable basis for characterizing seismic hazard across Canada and have been approved by the Canadian National Committee on Earthquake Engineering (CANCEE) as the basis of the seismic loads in the proposed 2005 edition of the National Building Code of Canada.

Key words: seismic hazard, earthquake, probability, uniform hazard spectrum, maps, Cascadia subduction, strong ground motions, uncertainty, CANCEE, National Building Code of Canada.

Résumé : Un nouveau modèle du risque sismique, le quatrième modèle national au Canada, a été mis au point par la Commission Géologique du Canada (« Geological Survey of Canada : GSC ») dans le but de mettre à jour les cartes actuelles (1985) du risque sismique. Le modèle incorpore les nouvelles connaissances tirées des récents tremblements de terre (à la fois canadiens et étrangers), les nouvelles relations de mouvements forts du sol décrivant comment les secousses varient en fonction de l'amplitude et de la distance, le risque nouvellement reconnu provenant des tremblements de terre dans la zone de subduction des Cascades, ainsi qu'une approche plus systématique pour référencer les conditions du site. D'autres innovations ont été incorporées, soit le calcul du risque au niveau de probabilité sur 50 ans de 2 %, l'utilisation des mouvements médians du sol, la présentation des résultats sous forme d'un spectre de risque uniforme, et l'incorporation explicite de l'incertitude au moyen d'une approche logique de type arbre. Ces nouveaux résultats fournissent une base plus sûre pour la caractérisation du risque sismique à travers le Canada et ont été approuvés par le Comité National Canadien en Ingénierie Sismique (« Canadian National Committee on Earthquake Engineering : CANCEE ») en tant que base pour les chargements sismiques du Code National du Bâtiment du Canada de 2005.

Mots clés : risque sismique, tremblement de terre, probabilité, spectre de risque uniforme, cartes, subduction des Cascades, mouvement de terrain forts, incertitude, CANCEE, Code National du Bâtiment du Canada.

[Traduit par la Rédaction]

Introduction

Seismic hazard maps are an integral part of the seismic provisions of the National Building Code of Canada (NBCC), providing the underlying parameters that are used to calculate seismic loads. The seismic hazard maps in the current NBCC (1995) were developed in the early 1980s. Since that time, there have been significant advances in our understanding of seismicity (Fig. 1) and ground motions in Canada and corresponding advances in methodologies to as-

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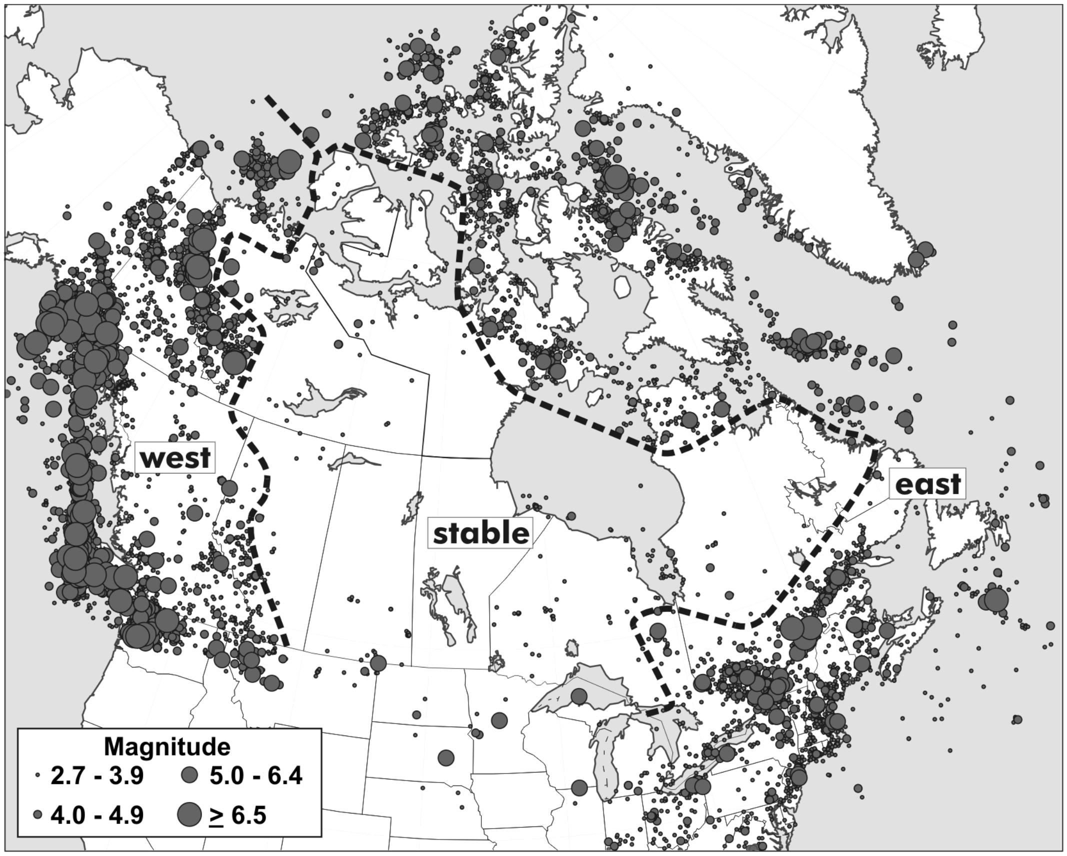
Fig. 1. Seismicity of Canada to 2001. The two broken lines delimit the west, stable, and east earthquake regions referred to in the text.



sess seismic hazard. In this paper, we overview those advances and describe how they have shaped the new seismic hazard maps intended for use in the proposed 2005 edition of the NBCC.

Seismic hazard analysis has been an element of good engineering design practice through the NBCC for many decades. Since 1970, seismic hazard maps have been developed for building code applications based on a probabilistic approach. The current code maps were developed using the well-known Cornell–McGuire probabilistic approach (Cornell 1968; McGuire 1976; Basham et al. 1982, 1985). In this method, the spatial distribution of earthquakes is described by seismic source zones, which may be either areas or faults; the source zones are defined based on seismotectonic information. The spatial distribution of earthquakes within each source is assumed to be random (i.e., uniformly distributed), and the temporal distribution of events as a function of magnitude is specified from historical seismicity supplemented by geologic or geodesic data where practicable. The exponential relation of Gutenberg and Richter (Richter 1958), asymptotic to an upper bound magnitude (M_x), is used to describe the magnitude–recurrence statistics. Magnitude (M) in this work is intended to be equivalent to moment magnitude, the standard measure of earthquake size and the magnitude type used in most strong ground motion relations. An alternative magnitude scale, m_{bLg}, is used for eastern earthquakes and then converted to moment magnitude using an empirical relationship (Atkinson and Boore 1995). The link between earthquake occurrence within a zone and ground motions experienced at a site is provided by ground motion relations. These are equations specifying the median (50th percentile) amplitude of a ground motion parameter, such as peak ground acceleration (PGA) or spectral acceleration ($S_a(T)$, where T is the period in seconds), as a function of earthquake magnitude and distance, and the distribution of ground motion amplitudes about the median value (i.e., variability). To compute the probability of exceeding a specified ground motion amplitude at a site, hazard contributions are integrated over all magnitudes and distances, for all source zones, according to the total probability theorem (in practice, sensible limits are placed on the integration range for computational efficiency). Calculations are performed for a number of ground motion amplitudes, and interpolation is used to find the ground motions associated with the chosen probability levels. The basic procedures are described by the EERI Committee on Seismic Risk (1989) and the NRC Committee on Seismology (1988). Because of its ability to incorporate both seismicity and geologic information, the Cornell–McGuire method is the most widely used seismic hazard evaluation technique in North America and perhaps the world.

There are two common misconceptions about probabilistic hazard analysis, both of which are relevant to the new seismic maps for Canada. The first is that low-probability hazard estimates are an extrapolation of a short historical record (100 years of data are extrapolated to return periods of thousands of years). In fact, the low probability of the calculated ground motions results from breaking the problem into its

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component parts, where the result is the product of the components (NRC Committee on Seismology 1988). It is the ground motion at a site that has a low probability, not the event itself. For example, suppose we have a region that has experienced 10 potentially damaging ($M > 5$) earthquakes in the last 100 years. Then the probability (per annum) of occurrence of an event of $M > 5$ is 0.1. If an $M > 5$ event occurs, we know from both regional and global recurrence models that the conditional probability of its magnitude being 6 or larger is about 0.1. Based on the total area of the subject region, the probability of the event being within 50 km of the site of interest is, say, 0.02. Lastly, the probability of ground motions exceeding a certain target, given all of the above, is 0.5. The total probability of exceeding the ground motion target is thus the product $(0.1)(0.1)(0.02)(0.5) = 10^{-4}$, or a "return period" of 10 000 years. The dominant factor that lowers the probability of damaging ground motions is the sparse spatial distribution of events; in this sense, the low probability is more nearly an interpolation in space than an extrapolation in time.

Another misconception is that probabilistic analyses are of suspect reliability because of limited knowledge of the component processes and large uncertainties in their interpretation, and that these uncertainties become particularly pronounced at low probabilities. The important role of uncertainty is a valid issue, and one that has been carefully addressed in the new seismic hazard maps. Each of the input components of the problem is indeed subject to considerable uncertainty, as described in the sections that follow. It should be understood, however, that uncertainty is inherent, and not specific to probabilistic analysis.

The proper treatment of uncertainty in hazard analysis is a field where significant advances have been made over the last decade. It has been recognized that it is important to distinguish between randomness in process and uncertainty in knowledge. Randomness is physical variability that is inherent to the unpredictable nature of future events, an example being the scatter of ground motion values about a median regression line; this is often referred to as aleatory uncertainty. Aleatory uncertainty cannot be reduced by collecting additional information. Uncertainty in process, referred to as epistemic uncertainty, arises from our incomplete knowledge of the physical mechanisms that control the random phenomenon; epistemic uncertainty can be reduced by collecting additional information.

The seismic hazard maps developed for previous building codes (Basham et al. 1982) incorporated aleatory uncertainty (the uncertainty in the ground motion relations, sigma) but were known to be sensitive to epistemic uncertainty. In recent years, a formal method of handling the epistemic uncertainty has been developed (McGuire and Toro 1986; Toro and McGuire 1987) using a logic-tree approach. Each input variable to the analysis, as described in more detail later in the paper, is represented by a discrete distribution of values, with subjective probabilities being used to describe the credibility of each possible assumption. Each possible combination of inputs produces a different output, so a typical application of the process would produce thousands of possible results. The epistemic uncertainty in results can then be expressed by displaying a mean or median curve, together with fractiles that show the confidence with which the estimates can be made (EPRI 1986; Toro and McGuire 1987; Bernreuter et al. 1985; McGuire 1995). The use of a logic-tree approach to investigate and quantify epistemic uncertainty in seismic hazard estimates is a major advance in methodology that is implemented in the new seismic zoning maps for Canada.

Another major change in the methodology of specifying ground motions in the maps involves the use of the "uniform hazard spectrum" or UHS. The UHS is a representation that plots, for each spectral period, the spectral amplitude that has a specified probability of exceedance. Thus the probability of exceeding a UHS is constant (or uniform) as a function of period. This differs from the previous code maps, for which the hazard analysis was used to estimate expected levels of PGA and peak ground velocity (PGV) for the specified probability level. The response spectrum used for engineering design was then constructed by scaling a standard spectral shape (Newmark and Hall 1982) to the site-specific PGA and PGV. The resulting spectrum did not necessarily have a uniform probability of exceedance at all periods. In the last 10–15 years, it has become standard seismological practice to instead develop a UHS. The underlying probabilistic seismic hazard calculation is the same. In the UHS methodology, however, the hazard analysis computes expected response-spectral ordinates for a number of given periods (McGuire 1977). This eliminates the need to use standard spectral shapes scaled to an index parameter such as PGA, thus providing a more site-specific description of the earthquake spectrum and ensuring a uniform hazard level is achieved for all spectral periods. This has been a natural evolution of the Cornell–McGuire methodology, made possible by improved ground motion relations for spectral parameters. (The primary motivation for the development of standard spectral shapes, in the 1960s and 1970s, was to overcome the lack of such relations.) It is important to recognize that the UHS represents a composite of all earthquakes that contribute to the hazard. Typically, the short-period end of the UHS is attributable to moderate nearby earthquakes, while the long-period end reflects the hazard from larger, more distant events. Thus the UHS may not resemble the response spectrum from any specific earthquake magnitude and distance.

UHS computations, and more recent ground motion data, have revealed that the scaled-spectrum approach overestimated response spectra for intermediate periods for some types of earthquakes by a very significant margin (Atkinson 1982, 1991). This is because the standard spectral shape was a description of ground motions for earthquakes in California, within a limited magnitude and distance range. It is now well known that the shape of earthquake spectra is actually a function of magnitude and distance, and so varies regionally (e.g., Atkinson and Boore 1997). In the new seismic hazard maps of Canada, a UHS approach is used to overcome previous shortcomings of the scaled-spectrum approach and more accurately describe the site-specific frequency content of the expected ground motions. A similar change has been made in the approach to seismic hazard mapping in the U.S. (Frankel et al. 1996, 1999; Building Seismic Safety Council 2000).

Another important change in the new maps is the lowering of the probability level from 10% in 50 years (0.002 per an-

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num) to 2% in 50 years (0.000404 per annum) (Adams et al. 1999). This change was motivated by studies over the last 10–20 years that have shown that the best way to achieve uniform reliability across the country is by basing the seismic design on amplitudes that have a probability close to the target reliability level (Whitman 1990). The reason is that the slope of the hazard curve, the rate at which ground motion amplitudes increase as probability decreases, varies regionally. In active regions like California, ground motion amplitudes may grow only a little as probability is lowered from 1/100 to 1/1000 (this is because the 1/100 motion is already coming from nearby earthquakes close to the maximum magnitude in many areas). In inactive regions, 1/100 motions are small but grow steadily as the probability level is lowered. Thus there is no single "factor of safety" that could be applied to motions calculated at, say, 1/100 per annum, which would provide design motions for a desired reliability of, say, 1/1000 per annum in both regions. For uniform reliability across regions with differing seismic environments, the seismic hazard parameters on which the design is based should be calculated somewhere near the target reliability level. As discussed in a companion paper by Heidebrecht (2003), it is believed that this target reliability level for seismic design of common structures in Canada is about 2% in 50 years. The new ground motion spectra are therefore calculated for an exceedance probability of 2% in 50 years. This is also consistent with recent parallel developments in the U.S. (Building Seismic Safety Council 1997, 2000; Frankel et al. 1996, 1999), though the way that the spectra are used for Canadian design will differ from the approach in the U.S., which is to design to two thirds of the 2% in 50 year values.

Lastly, there have been significant advancements in our understanding of the physical processes that control seismic hazards in Canada, as described in the following sections, where we briefly discuss the choice of input parameters, their uncertainties, and the resultant hazard. The hazard model was described more fully by Adams and Halchuk (2003), which also contains the full model parameters. The Canadian National Committee on Earthquake Engineering (CANCEE) has been closely involved in the development of the model.

Seismic source parameters

Source models for Canada

The 1985 hazard maps described the distribution of seismicity using a single set of seismic source zones. Since then, two decades of additional knowledge about earthquakes have revealed clearer epicentre patterns in some places but "unexpected" events in others. This has led to a better understanding of the seismotectonics behind the seismicity, but also an appreciation that much is unknown about how the future pattern of seismicity will resemble or differ from the historical pattern.

In some places, the Queen Charlotte Fault being an example, the seismotectonics are relatively well understood, and a single model would suffice. In most other places, the range of opinions as to the cause and distribution of the earthquakes make a single model subject to much arbitrariness, so the hazard results would reflect the current opinion of the compiler. The resultant hazard maps might change drastically if there were a change of compiler, an unexpected earthquake, or a shift in the paradigm of earthquake occurrence. For these reasons, it is prudent to consider a range of models to represent the diversity of opinion as to the causes and future locations of earthquakes.

For eastern Canada, the credible range of models was represented by two philosophically distinct probabilistic models: the H (historical seismicity) model uses relatively small source zones drawn around historical seismicity clusters, whereas the R (regional) model establishes larger, regional zones (Fig. 2). Although some of the same philosophy is applicable in the eastern Rockies, the differences between the H and R models in western Canada are not generally interpretable in this manner, as neither model compiler in the west supported a strongly historical model. (Note that the H and R models in the west actually refer to their authors, R. Horner and G. Rogers.)

The U.S. Geological Survey (USGS) currently estimates northeastern U.S. seismic hazard based chiefly on the spatial occurrence rate of small and moderate historical earthquakes (Frankel et al. 1996). The smoothing of seismicity rates that is applied in the USGS approach is analogous to the use of source zones, which also smooth seismicity. The Geological Survey of Canada (GSC) applied Frankel's computer code to the eastern Canadian earthquake catalogue and found this alternative approach replicated the hazard from the H model very closely (the H model in the east was designed to estimate hazard from the historical earthquake clusters). It is reassuring that the assumptions made for the H model, and the simplifications adopted in the Frankel method, resulted in similar hazard. CANCEE had reservations about basing seismic hazard so heavily on contemporary seismicity rates, however, especially for regions of low or negligible seismicity.

In eastern Canada, the R model often combines a number of seismicity clusters that are inferred to have a common cause into large source zones, the larger of which are the Arctic Continental Margin (ACM), the Eastern Continental Margin (ECM), and the Iapetan Rifted Margin (IRM), shown in Fig. 2*b*. For each, the R model zone implies that currently aseismic regions between adjacent seismicity clusters (e.g., the St. Lawrence valley near Trois-Rivières) are capable of large earthquakes. Over the long run, the rate of activity along these extensive tectonic zones (e.g., at any place along the continental margin) may be constant; the current seismicity "hot spots" may be just a temporary clustering, speculatively representing prolonged aftershock sequences. Contour maps of hazard computed using the R model have long "ridges" of moderate hazard and lack the "bull's eyes" of high hazard produced by the H model (and that exist in the 1985 maps). As a consequence, if only the R model hazard were implemented in a building code, it would reduce the seismic protection significantly in regions of high historical seismicity while increasing protection only slightly in other places. A probabilistic combination of the two models would involve their weighted sum, but any weight given to the R model would reduce the protection in regions of high historical seismicity. This dilemma is addressed by performing calculations for both models, then adopting the more conservative result, the so-called "robust" approach, as described in more detail later in the paper.

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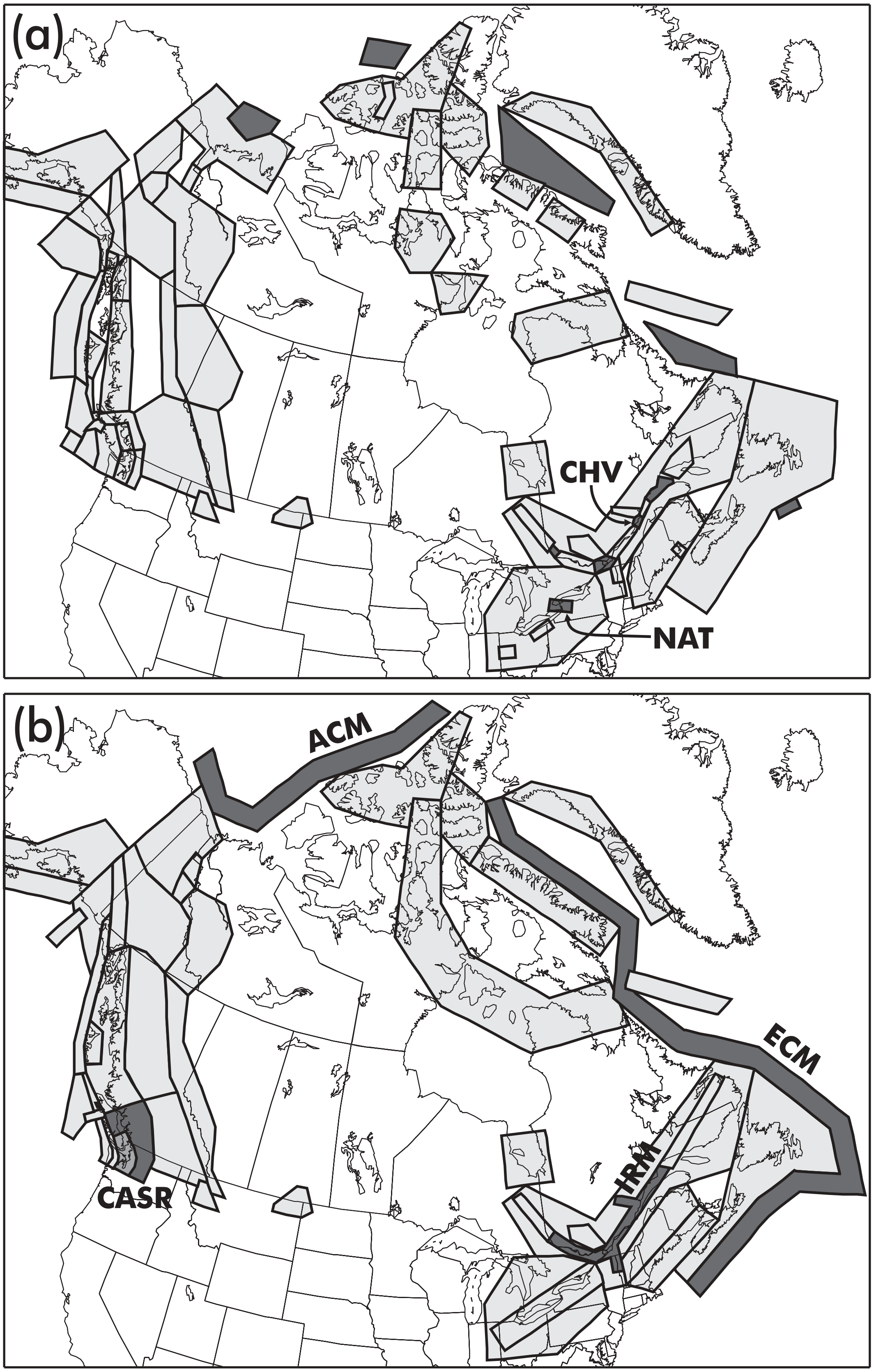
Fig. 2. Source zones used in the H and R models. Certain shaded zones show how small clusters of seismicity in the H model are combined into large zones in the R model. Seismicity for relatively aseismic regions outside of zones is accounted for by the stable Canada model: (*a*) H model; (*b*) R model. ACM, Arctic Continental Margin; CASR, Cascade Mountains; CHV, Charlevoix; ECM, Eastern Continental Margin; IRM, Iapetan Rifted Margin; NAT, Niagara–Attica.



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In western Canada, although the tectonics are better understood and the models are not as different, there are still differences of opinion. For example, model R collects crustal earthquakes around Vancouver and Seattle together with the central Vancouver Island earthquakes into one zone (CASR) to represent shallow seismicity in this region of the North American Plate above the Cascadia subduction zone; model H uses two smaller zones. The Queen Charlotte Fault is the only earthquake source treated as a fault; all others are area sources.

Source model for "stable" Canada

About half of the Canadian landmass has too few earthquakes to define reliable seismic source zones. On previous maps the hazard computed for these regions came only from distant external sources. International examples, however, suggest that large ($M > 6$) earthquakes might occur anywhere in Canada, albeit rarely (Johnston et al. 1994). To improve the reliability of the estimate of seismic hazard for the stable part of Canada, the global earthquake activity of continental shields tectonically comparable to the Canadian Shield was used to estimate a magnitude–recurrence curve for such stable regions (Fenton and Adams 1997). Observed North American shield activity rates are lower than the global average, and rates in the part of central Canada not included in a source zone (Fig. 2) are lower still. To capture the uncertainty in seismicity rate, all three rates were normalized by area and used with weights of 0.4 for the global average rate, 0.4 for the North American rate, and 0.2 for the central Canada rate, the lower weight for the latter reflecting the belief that the process of defining source zones has produced a residual area ("background zone") artificially depleted in earthquakes. The hazard, using eastern strong ground motion relations, was then computed at the centre of a large octagonal source zone using these activity levels. Although the hazard values have quite a large uncertainty, the median values are expected to characterize the lowest likely hazard for any part of Canada, and so form an appropriate "floor" for Canadian seismic design. These floor values are also used for some low-hazard sites in western Canada, where the activity rates are likely to be higher, but the attenuation is stronger.

Deterministic model for Cascadia subduction earthquake

The Cascadia subduction zone has generated prehistorical great earthquakes off Vancouver Island. From the geological record, the mean recurrence interval of great Cascadia earthquakes is about 600 ± 170 years (Adams 1990); the last great event happened 300 years ago, in 1700 A.D. (Satake et al. 1996). As the long-term probability of the next great earthquake is about 10% in 50 years (Adams 1990), seismic hazard maps need to accommodate the expected ground motions. The GSC has chosen to provide a deterministic, rather than probabilistic, estimate of Cascadia earthquake ground motions.

Present evidence suggests that the next great Cascadia subduction earthquake may have a moment magnitude as large as 9, with a rupture length of up to 900 km (Hyndman and Wang 1995). For any site of interest, only part of the rupture will be close enough to contribute to the ground motion hazard. Thus the hazard will not be overly sensitive to the choice of magnitude (at least within the range from $M8$ to $M9$). With this in mind, a moment magnitude of 8.2 was adopted for the Cascadia scenario; this is also a practical choice, as there are no empirical ground motion relations that are valid for magnitudes greater than 8.5. The Cascadia event is modelled as an offshore line source set one third of the way into the transition zone below the locked zone (Hyndman and Wang 1995; Dragert et al. 1994). The line is taken to represent the closest point of energy release and is used for computing distances to the various sites.

The occurrence of the deterministic scenario has a probability of about 10% in 50 years (-600 year recurrence interval), so its median values have a probability of exceedance of about 5% in 50 years. The 84% ground motions for the scenario will have a probability of exceedance of 16% of 10% in 50 years, or about 2% in 50 years, which makes them appropriate for combination with the 2% in 50 year probabilistic maps. In a similar manner, for the 84th percentile measures of the 2% in 50 year values in Table 1 we have used the median plus two sigma ground motions of the Cascadia deterministic scenario.

Seismicity parameters

Earthquake catalogue

The fourth-generation maps use the Canadian earthquake catalogue up to 1990 for the east and up to 1991 for the west. Relative to the pre-1977 catalogue used for the 1985 maps, this adds a significant amount of data, particularly in the Arctic. The location and magnitude parameters of older earthquakes have been revised, and the Canadian catalogue has been supplemented by recent U.S. catalogues. The eastern earthquakes (eastern Canada is taken as that part east of the Rocky Mountains on the basis of crustal properties) chiefly have m_{bLg} magnitudes. Eastern recurrence relations are calculated in terms of m_{bLg} and converted to moment magnitudes within the hazard program using the empirical relation of Atkinson and Boore (1995). The western earthquakes have a mix of magnitudes, depending on availability and quality, and are assigned in order of preference, moment magnitude for the largest, surface-wave magnitude for the next, and so on; since the definition (or calibration) of these different scales is generally perceived to blend the scales smoothly into one another, the GSC considered them equivalent to moment magnitudes to apply the relevant strong ground motion relations.

Magnitude–recurrence parameters

The maximum likelihood method of Weichert (1980) was used to compute the magnitude–recurrence parameters. To provide an estimate of epistemic uncertainty, the standard errors for the calculation were taken and combined to give upper and lower curves that approximate one standard deviation error bounds. The curves are asymptotic to an assumed upper bound magnitude, and again the GSC used judgment to associate the three curves with three possible upper bound values. Examples for two eastern source zones are shown in Fig. 3. For some zones, the number of earthquakes was small and the statistics poor, so a regional value of the slope parameter was imposed. The level of the recurrence curves

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Fig. 3. Magnitude–recurrence curves for Charlevoix (top; a zone with many earthquakes and hence relatively small error bands) and Niagara-Attica (bottom; a zone with large uncertainty in the rate of large earthquakes).

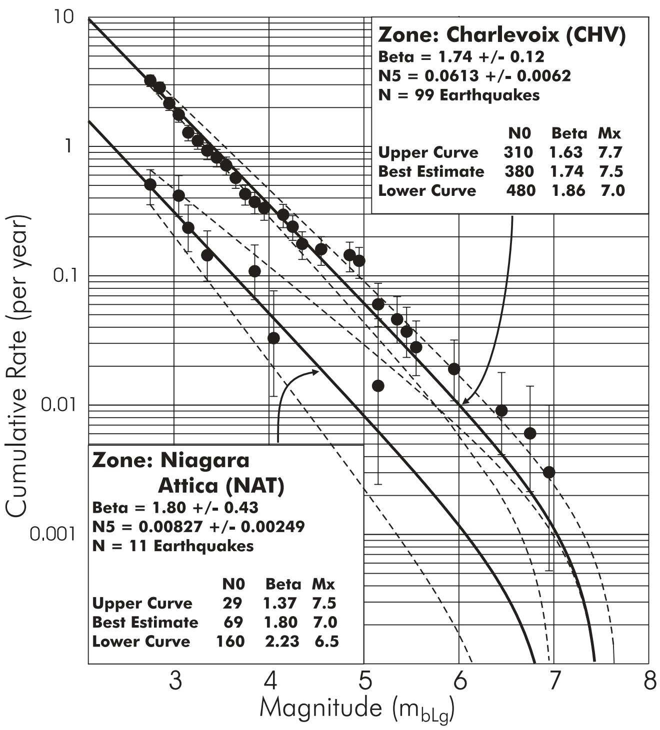
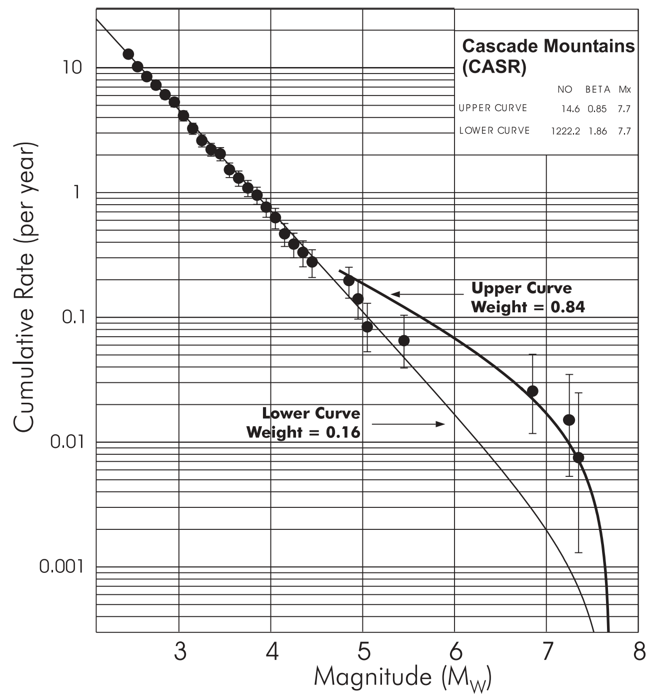


Fig. 4. Magnitude–recurrence curves for crustal earthquakes near Vancouver, showing how the rate of larger earthquakes greatly exceeds the rate predicted by extrapolating the excellent fit to the rate of small earthquakes. The upper curve, fitted to only the larger earthquakes, is a better representation of the historical hazard (see text). M_w, moment magnitude.



is dominated by the number of small earthquakes, but for the hazard integration a lower magnitude cutoff of 4.75, near the smallest magnitude of engineering interest, was used.

For a few zones the GSC tempered the mathematical fit by judgement. The only case where this had a dramatic effect on major urban areas was in the Strait of Georgia region. Figure 4 shows the magnitude–recurrence curves adopted for zone CASR, which surrounds Vancouver. The lower curve, representing a maximum likelihood fit to the earthquakes larger than magnitude 2.5, underestimates the rate of $M > 6.7$ crustal earthquakes from the past hundred years by an order of magnitude. It is not known whether the large historical earthquakes are a statistical anomaly or whether the fitted model for the rates is incorrect. Therefore, to better match the historical rate of large earthquakes, a second maximum likelihood fit, neglecting all earthquakes smaller than the hazard cutoff ($M4.75$), was made; the result is the upper curve. This curve, if extrapolated to smaller magnitudes, would badly underestimate the rates of small earthquakes. These earthquakes do not contribute to the hazard, however, whereas the upper curve, by matching the observed rate of larger earthquakes, better represents the historical hazard and so is given the most weight.

Maximum magnitude

Estimates of upper bound magnitude (M_x) were made for each source zone by considering the largest earthquakes observed in similar tectonic regions around the world (Johnston et al. 1994). This is a more conservative view of maximum possible events than has been applied in the past. Previously, the maximum observed historical event within the zone played a large role in estimating M_x, even if the expected recurrence intervals of larger events were longer than the period of historic record. The imprudence of the previous approach was highlighted by the occurrence of the 1985 Nahanni and 1988 Saguenay earthquakes, both of which exceeded the maximum earthquake specified for their respective source regions within 10 years of preparation of the 1985 maps. For each source zone in the new model, three estimates were used to represent the epistemic uncertainty, a "best" estimate together with upper and lower bound values, as detailed by Adams and Halchuk (2003). Some regions have a quite well established M_x because of high historical activity with a sharp cutoff, supported by a knowledge of maximum fault areas in the source zone; for these cases the best and upper bound magnitude estimates were set close together. Best M_x estimates range to moment magnitude 7.5 for the eastern and Arctic continental margins, 7.0–7.8 for zones of weakness within the continent, 7.0 for the stable shield of Canada, 7.0–7.7 for the Cordillera and western crustal zones, 7.0–7.3 for in-slab earthquakes under Puget Sound, and 8.5 for the Queen Charlotte Fault and plate margin. Typical upper bound and lower bound values are 0.3 units higher and lower (Adams and Halchuk 2003).

Depth

Although local damage from particular earthquakes can be strongly related to earthquake depth, the probabilistic hazard for most of Canada is relatively insensitive to the exact depths used. For eastern Canada, earthquake depths were represented by best estimates together with upper and lower

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bounds (note that the terms upper and lower refer merely to alternative values, not relative depths). For western crustal zones, the "depth" value is a predetermined parameter in the Boore et al. (1993, 1994) equations that are adopted and depends on the period for which ground motions are being estimated. For the subcrustal in-slab zones, a single depth of 50 km was used; this is about the depth of the large earthquakes that occur at or near the change of dip of the subducting Juan de Fuca plate. For the Cascadia subduction scenario a depth of 25 km was used.

Strong ground motion relations

Ground motion relations are a key component of any seismic hazard model, as they govern the amplitudes of motion predicted for any magnitude and distance. No matter how good our seismotectonic source models, the reliability of the final hazard values is highly dependent on the reliability of the strong motion relations and on the extrapolations within them, as observational data from large earthquakes in Canada are sparse. The different physical properties of the crust in eastern and western Canada require the use of separate strong ground motion relations for different regions, as was the case for the 1985 maps, which used the eastern and western relations of Hasegawa et al. (1981). Their relations were based on very sparse data, and in the west did not provide separate relations for the different types of western earthquake. Consequently, new relations have been adopted.

Eastern Canada

For eastern Canada, ground motion relations are a major source of uncertainty in seismic hazard estimation because of the paucity of observations in the magnitude–distance range of engineering interest. Consequently, eastern ground motion relations may change significantly as new events are recorded. For example, the recordings of the 1988 Saguenay earthquake caused ground motion modellers to revise their prior relationships to account for its unexpectedly large short-period motions. Deliberations of the Senior Seismic Hazard Analysis Committee (SSHAC) suggested an emerging consensus. On that basis the GSC adopted a suite of relationships with their aleatory uncertainty (the base relations of Atkinson and Boore 1995), and their epistemic uncertainty (Atkinson 1995*a*), consistent with that consensus. These represent the available published ground motion relationships, but there is considerable controversy in this field (Atkinson and Boore 1997, 2000*a*). The Atkinson–Boore suite of relationships was derived to fit observational data on hard-rock seismometer sites and so needs adjustment to represent the ground motions on the "firm ground" reference ground condition chosen for Canada (see the section Reference ground condition (RGC)).

Western Canada

For the western Canadian shallow source zones, including the subcrustal transition zones west of Vancouver Island and the Queen Charlotte Fault, the GSC adapted the ground motion relations from Boore et al. (1993, 1994; the same authors have published more recently, i.e., Boore et al. 1997) for National Earthquake Hazard Reduction Program (NEHRP) class C "firm soil" (360–750 m/s average shear wave velocity in the uppermost 30 m). The adaptation included the addition of a period-dependent anelastic attenuation term (using values from Atkinson 1997) applied to distances larger than 100 km. The Youngs et al. (1997) "intra-slab" relations adjusted to firm soil were adopted for subcrustal source zones deeper under Puget Sound, using depths of 50 km for the normal-mechanism events within the subducting slab. The Youngs et al. "interface" relations adjusted to firm soil were adopted for the deterministic Cascadia subduction earthquake, using a magnitude of 8.2 (for reasons detailed earlier in the paper), a depth of 25 km, and the line source for computing distances.

For aleatory uncertainty for the relations of Boore et al. (1993, 1994), the GSC used the smoothed standard deviations (sigmas) about the fitted relationships, as listed by the cited authors. The epistemic uncertainty (comparable to that used for the east) on each relationship was estimated by generating a pair of parallel alternative relations, factors of two higher and lower, and having weights of 0.3 each, leaving weight 0.4 for the median relation. This represents a small conservative bias in the computation of the expected ground motions. The measure of epistemic uncertainty is intended to capture (*i*) the range of opinion on western ground motions (for example, the upper curve envelopes the recent relations of Idriss), and (*ii*) the possibility that there may be systematic biases in the Boore et al. (1993, 1994) relations. For example, the stress drops of the larger western Canadian earthquakes might differ from those used in defining the Boore et al. (1993, 1994) relations; analysis of seismographic records suggests lower stress drops than those typically found for Californian events (Atkinson 1995*b*; Dewberry and Crosson 1995). The GSC recognized that the assigned epistemic uncertainties represent an arbitrary and slightly conservative choice in treating this uncertainty.

Epistemic uncertainties in western ground motion relations are of a different nature from those in the east but are potentially just as large. For crustal events in British Columbia, we have assumed that empirical relations from California are appropriate; there is some limited evidence that this may be a conservative assumption (Atkinson and Boore 1997). For subduction events, we adopted the Youngs et al. (1997) relations, although new subduction databases, including the recent 2001 Nisqually, Washington, event, may suggest significant revision to these relations (Atkinson and Boore 2000*b*, 2003). The large uncertainties in ground motion relations highlight the need to consider a range of models to capture uncertainty in the final results.

Reference ground condition (RGC)

For the preparation of national hazard maps it is essential to present seismic hazard information for the same ground condition for all of Canada. The "reference ground condition" (RGC) is intended to make the 2005 hazard values (*i*) numerically comparable between east and west, and (*ii*) roughly comparable in intent to the 1985 hazard maps. CANCEE's choice for the Canada-wide RGC is NEHRP site class C (also termed site class C in the 2005 NBCC), with a 360–750 m/s average shear wave velocity in the uppermost 30 m (Finn and Wightman 2003). NEHRP site class C is chosen because it appears to be the closest to the soil conditions implied in the 1995 NBCC and referred to as rock or

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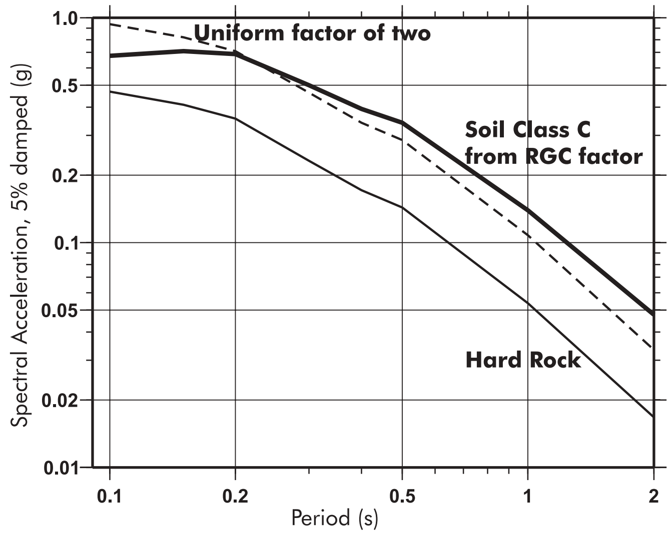
firm soil. This class also contains the largest number of strong motion recordings used by Boore et al. (1993). (Note that Boore et al. (1993) originally referred to this as class B, and it was their work that formed the seismological basis of the choice.) A choice near the midrange between very hard and very soft ground is also preferred because it minimizes the effects of uncertainty in the amplification or deamplification factors for the extreme sites. The hard-rock strong ground motion equation of Atkinson and Boore (1995) must be modified to firm ground by a series of frequency-specific multiplicative factors. These factors are as follows: 1.94 for $S_a(0.2)$, 2.38 for $S_a(0.5)$, 2.58 for $S_a(1.0)$, 2.86 for $S_a(2.0)$, 1.39 for PGA, and 2.38 for PGV (Table 2 of Adams and Halchuk (2003)).

The RGC factors have been used to amplify seismic hazard *spectral* values calculated from the hard-rock Atkinson–Boore relations to those to be expected for the RGC. Hard-rock hazard values for eastern sites can be extracted from the published results by dividing by these factors. The effect of applying the RGC factors is to flatten the spectra of eastern sites, most particularly by the small amplification at periods less than 0.2 s. This is evident in Fig. 5. As discussed by Finn and Wightman (2003), the RGC factor is only one aspect of the adjustments that need to be made for soil conditions, some of which reduce the severity of very strong ground motions at high frequencies, possibly even below those on a hard-rock site.

Fig. 5. Uniform hazard spectrum for Montréal for the probability level 2% in 50 years for sites on hard rock (thin line) and NBCC site class C (bold line) as amplified from the hard-rock values by the reference ground condition (RGC) factors discussed in the text. For reference, the broken line shows the hard-rock spectrum simply amplified by a period-independent factor of 2.



Representation of seismic hazard

Ground motion parameters

In contrast to the 1985 maps, which gave values for PGV and PGA, the 2005 NBCC will use spectral acceleration values for periods of 0.2, 0.5, 1.0, and 2.0 s (denoted $S_a(0.2)$, $S_a(0.5)$, etc.). These four parameters are deemed sufficient to construct spectra closely matching the shape of the UHS. PGA values will also be provided. Certain other spectral parameters, not referenced by the NBCC, will be available from the GSC.

Choice of probability and confidence levels

Hazard values for a specified probability are given for two confidence levels, the 50th percentile and the 84th percentile; the former is the median, and the latter includes a measure of epistemic uncertainty arising from the incorporation of uncertainty into the model. For typical seismic hazard computations in Canada the mean hazard value typically lies between the 65th and 75th percentiles of the hazard distribution. Either the median, mean, or 84th percentile might be used as the basis for engineering design, but the median was chosen. Statistically speaking, the mean is the best single representatation of the hazard, as it is the expected value. The mean is affected by the amount of epistemic uncertainty incorporated into the analysis, however, and the view of the GSC, supported by CANCEE, was that the estimation of the epistemic uncertainty was still too incomplete to adopt into the code. As a certain conservative bias has been included in the hazard model, particularly through the definition of upper and lower bound values, it is anticipated that the estimated median values presented here may actually lie between the true median and the true mean hazard values. Thus, as improved knowledge about epistemic uncertainty is incorporated into the analysis, a future change to using mean values may not be a large one. Current USGS practice (Frankel et al. 1999) is to compute the mean hazard value at 2% in 50 years, thus including directly a measure of the perceived uncertainty; however, in U.S. building code applications the design motions adopted are two thirds of the mean values.

Choice of confidence level (50th, 84th, 95th percentile) and choice of probability level (10% in 50 years, 2% in 50 years, etc.) of ground motions are linked. One might determine seismic loading based on the 84th percentile ground motions at the 10% in 50 year probability level, because this ensures that there is little likelihood the design value will be exceeded, and so provides an appropriate degree of engineering conservatism consistent with general engineering practice (Naumoski and Heidebrecht 1995). One might also choose a lower probability level and base the seismic loading on the 50th percentile ground motions. Although either might result in satisfactory design, the choice of median values at lower probability is preferred as providing a more consistent basis across the country, as discussed previously. It should be noted that the 84th percentile of the 10% in 50 year uniform hazard spectra is, coincidentally, very similar to the median (50th percentile) of the 2% in 50 year results (see, e.g., Figs. 23–45 in Adams and Halchuk (2003)). Thus designs based on the median 2% in 50 year seismic hazard values for the new NBCC effectively accommodate the proposal of Naumoski and Heidebrecht (1995). For backward comparison with the 1985 maps, 10% in 50 year values are given in Adams and Halchuk (2003).

Computational aspects

The GSC modified a commercial software program (FRISK88, a proprietary product of Risk Engineering, Inc.)

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to compute hazard and its uncertainty for the fourth-generation maps. As discussed previously, three values were usually used to represent the epistemic uncertainty in each input parameter (alpha and beta of the magnitude–recurrence parameter, upper bound magnitude, depth, strong motion relations), this being deemed sufficient to capture the range of uncertainty in each parameter. For computational efficiency, however, these values were set to be dependent between the sources. That is, instead of a fully independent logic computation where each parameter choice for one source is combined with each choice for every other source, a "trimmed-tree" approach was used that included only those branches with the same (high, medium, or low) value of the parameter. This still captures the range of uncertainty acceptably well and has lower computational requirements. Although the full calculation requires the integration over all magnitudes and distances, in practice sensible limits were placed on the integration range. For example, the contributions of earthquakes smaller than magnitude 4.75 are excluded because they are not of engineering concern. Also, contributions from more distant source zones (more than 600 km in the east and 400 km in the west) are excluded because their hazard contributions are negligible.

Combining diverse hazard estimates using the robust approach

It is important to realize that each of the outputs from the H and R seismotectonic source models represents the result of a complete probabilistic hazard calculation. For the 2005 NBCC the complete probabilistic hazard results from each of the two models (H and R), together with the probabilistic floor level for the stable part of Canada and the deterministic hazard from the Cascadia model, were combined in the fashion termed robust by Adams et al. (1995*a*) and Adams and Halchuk (2003). The robust model is just choosing the highest value from the four sources for each grid point across Canada.

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 geologically likely to have future large earthquakes, such as the St. Lawrence valley near Trois-Rivières. In this way the approach deliberately introduces a conservative bias to certain low-seismicity sites. A further advantage is that the approach is computationally simple, and it is easy to explain what was done. Lastly, the method allows a simple combination of deterministic and probabilistic hazard where this is desired.

It is recognized that the GSC robust combination of the deterministic Cascadia results with probabilistic crustal plus subcrustal hazard underestimates the total hazard at sites that could be strongly shaken by both sources. In effect, the design is for either the Cascadia earthquake or the expected crustal (or subcrustal) earthquake that will cause the design ground motions, whichever is larger, but not their probabilistic combination. At places where the two contributions are equal, the underestimate is the largest and is likely of the order of 40%. On the other hand, there is the possibility that new knowledge may find that the time-varying current hazard from the subduction zone is below the Poissonian rate assumed for a probabilistic combination, or that ground motions for this particular subduction zone have been overestimated. Rather than raise the designs immediately to the full probabilistic level (as should probably be the goal in the future), this either–or approach was adopted as a first step towards incorporating the hazard from megathrust earthquakes in Cascadia.

With the exception of places dominated by the Cascadia deterministic hazard, the mapped robust estimates are probabilistic at any one place, in that for each site and every ground motion parameter computed there is an identifiable probabilistic hazard calculation made using a particular source-zone model. Hence for design purposes (for a building or a city) the map provides a suitable probabilistic hazard value, though from a regional perspective the map as a whole is not probabilistic because the model used may differ from site to site, or indeed from ground motion period to period at a particular site. Estimates for southeastern Canada suggest that adopting the robust method is equivalent to a 30% increase in seismic energy release over the historical rate, an amount equivalent to the addition of one *M*6.6 earthquake in the near future or one *M*7 earthquake just before the historical period began (Adams et al. 1995).

Results

Figure 6 shows the Canada-wide distribution of robust $S_a(0.2)$ hazard. Hazard maps for longer periods are similar but have lower amplitudes and are more dominated by the sources of larger earthquakes. The floor hazard for the stable part of Canada is given as the Winnipeg entry in Table 1. The inclusion of these floor values eliminates the lowest contours from many of the trial hazard maps the GSC has recently produced, but the 10% in 50 year floor value is still below the lowest contour of the 1985 PGA map.

An indication of the seismic hazard contributed by the Cascadia deterministic model is shown in Fig. 7, which also indicates the places that it exceeds the probabilistic hazard estimates.

Table 1 gives the 2% in 50 year robust hazard values for selected Canadian cities, noting which source zone model controls the hazard. The median (50th percentile) values are the intended design values, and the 84th percentile values indicate the amount of uncertainty in the hazard estimate. Space precludes the presentation of all but a few median UHS (Fig. 8), but others, together with their 84th percentile UHS, are given in Adams and Halchuk (2003). PGA values are not displayed in these plots because the associated period differs from place to place and is generally not known. The increase in shaking level with decreasing probability is illustrated in Fig. 9, which shows the complete hazard curves for $S_a(0.5)$ for selected cities.

Discussion

Greater understanding of seismicity patterns, their cause and recurrence rates, and increased knowledge of strong ground motion has led to significant changes in hazard estimates relative to those of the 1985 maps. The changes are period dependent. The 2005 spectral values cannot be compared directly with the 1985 peak ground acceleration and velocity measures because they differ in parameter type and probability level. One comparison that reveals some of the

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Table 1. Summary of NBCC 2005 design values (median values) and uncertainty (84th percentile) for selected Canadian cities.

	Median (50th percentile) robust values						84th percentile robust values					
City	$S_a(0.2)$	$S_a(0.5)$	$S_a(1.0)$	$S_a(2.0)$	PGA	PGV	$S_a(0.2)$	$S_a(0.5)$	$S_a(1.0)$	$S_a(2.0)$	PGA	PGV
St. John's	0.18 R	0.11 R	0.060 R	0.016 R	0.090 R	0.057 R	0.31 R	0.29 R	0.16 R		0.14 F	0.14 R
Halifax	0.23 R	0.13 R	0.070 R	0.019 R	0.12 R	0.071 R	0.41 R	0.34 R	0.18 R		0.19 R	0.18 R
Moncton	0.30 H	0.16 H	0.068 H	0.021 H	0.21 H	0.095 H	0.52 H	0.42 H	0.22 H		0.30 H	0.23 H
Fredericton	0.39 R	0.20 R	0.086 H	0.027 H	0.27 R	0.12 R	0.69 R	0.52 R	0.27 R		0.38 R	0.29 R
La Malbaie	2.3 H	1.2 H	0.60 H	0.19 H	1.1 H	0.62 H	3.8 H	3.1 H	1.8 H		2.0 H	1.5 H
Québec	0.59 R	0.29 H	0.14 H	0.048 H	0.37 R	0.16 R	1.0 R	0.75 H	0.44 H		0.57 R	0.41 R
Trois-Rivières	0.64 R	0.31 R	0.12 R	0.043 R	0.40 R	0.17 R	1.1 R	0.77 R	0.40 R		0.62 R	0.44 R
Montréal	0.69 R	0.34 R	0.14 R	0.048 R	0.43 R	0.18 R	1.2 R	0.83 R	0.44 R		0.63 R	0.48 R
Ottawa	0.67 R	0.32 R	0.14 R	0.045 R	0.42 R	0.18 R	1.1 R	0.80 R	0.42 R		0.63 R	0.46 R
Niagara Falls	0.41 H	0.20 H	0.073 H	0.021 H	0.30 H	0.13 H	0.93 H	0.52 H	0.25 H		0.48 H	0.35 H
Toronto	0.28 H	0.14 H	0.055 R	0.016 H	0.20 H	0.083 H	0.56 H	0.35 H	0.17 H		0.28 H	0.22 H
Windsor	0.18 R	0.087 R	0.040 R	0.011 R	0.12 R	0.055 R	0.32 R	0.22 R	0.11 R		0.19 R	0.14 R
Winnipeg	0.12 F	0.056 F	0.023 F	0.006 F	0.059 F	0.040 F	0.21 F	0.17 F	0.079 F		0.14 F	0.11 F
Calgary	0.15 H	0.084 H	0.041 H	0.023 H	0.088 H		0.29 H	0.17 H	0.080 H	0.045 H	0.18 H	
Kelowna	0.28 H	0.17 H	0.089 R	0.053 R	0.14 H		0.55 H	0.34 H	0.18 R	0.11 R	0.27 H	
Kamloops	0.28 H	0.17 H	0.10 R	0.060 R	0.14 H		0.55 H	0.34 H	0.20 R	0.12 R	0.27 H	
Prince George	0.13 H	0.080 H	0.041 R	0.026 R	0.071 H		0.26 H	0.17 F	0.080 H	0.052 R	0.14 H	
Vancouver	0.96 H	0.66 R	0.34 R	0.18 R	0.48 H		1.9 H	1.3 R	0.68 R	0.35 R	0.96 H	
Victoria	1.2 H	0.83 H	0.38 H	0.19 R	0.62 H		2.5 H	1.7 H	0.77 H	0.37 R	1.2 H	
Tofino	1.2 C	0.93 C	0.47 C	0.21 C	0.52 C		2.3 C	1.8 C	0.90 C	0.44 C	1.0 C	
Prince Rupert	0.38 R	0.25 R	0.17 R	0.096 R	0.18 R		0.75 R	0.50 R	0.33 R	0.19 R	0.36 R	
Queen Charlotte City	0.66 R	0.63 R	0.50 R	0.26 R	0.36 R		1.3 R	1.2 R	1.0 R	0.53 R	0.71 R	
Inuvik	0.12 F	0.067 H	0.039 R	0.025 R	0.060 H		0.21 F	0.17 F	0.079 F	0.050 R	0.14 F	

Note: The second column for each parameter indicates which of the four models provides the "robust" or largest values: C, deterministic Cascadia scenario; F, floor level probabilistic; H, H model probabilistic; R, R model probabilistic. Peak and spectral acceleration values are in *g*, and peak velocity in m/s. All values are reported to two significant figures. Peak velocity values are not available for the west, and 84th percentile values for $S_a(2.0)$ are not available for the east.

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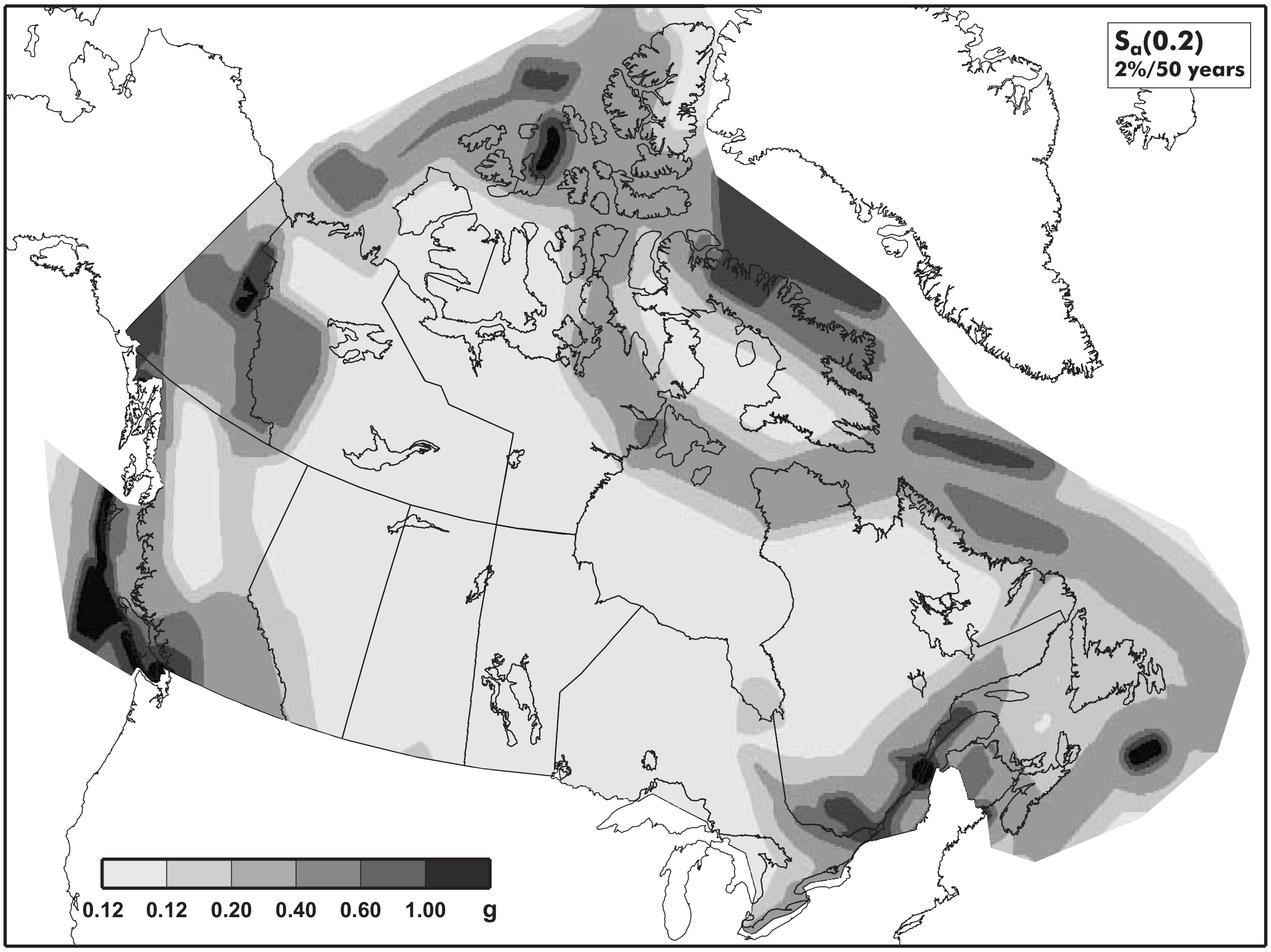
Fig. 6. Representative contour map of seismic hazard forming the basis for the 2005 NBCC. This map shows $S_a(0.2)$ spectral hazard for a probability level of 2% in 50 years on a firm ground site and hence hazard levels relevant to short-period structures. Maps for longer periods are similar but have lower amplitudes and are more strongly dominated by the sources of larger earthquakes.



hazard model changes is the comparison of 1985 PGA values with PGA values computed from the fourth-generation map for the same 10% in 50 year probability (Table 2). The comparisons are not ideal because PGA is a short-period measure that captures the damage potential of ground motions much more poorly than spectral acceleration at short or long periods. Brief reasons for the changes in our estimate of hazard are summarized in the last column of Table 2. The stated reasons necessarily oversimplify the effect of many changes, some acting to increase and some to decrease the estimated hazard.

The GSC fourth-generation hazard model is the first Canadian national model to include an explicit assessment of uncertainty. The uncertainty (e.g., measured by the ratio of 84th to 50th percentile values in Table 1) varies across the country, generally being higher for long periods in the east and lower near high-activity zones in the west. Experiments with varying the uncertainty of various parameters suggest that the hierarchy of importance shown in Fig. 10 applies to many sites, with the uncertainty in the strong ground motion relations dominating the total uncertainty. The chief exceptions are sites above high-activity zones where earthquake depth can become important and low-seismicity sites where the difference in source models can be large.

Fig. 7. Map of southwestern British Columbia showing the offshore locus of closest energy release for the deterministic Cascadia model (bold broken line) and contours of 2% in 50 year hazard for $S_a(0.2)$ seismic hazard from the deterministic model (solid lines) and from the higher of the H and R probabilistic model results (light broken lines). Cascadia deterministic hazard exceeds the probabilistic model hazard at places where the Cascadia hazard contours are highlighted by bold broken lines. Contours are not extended into the offshore.

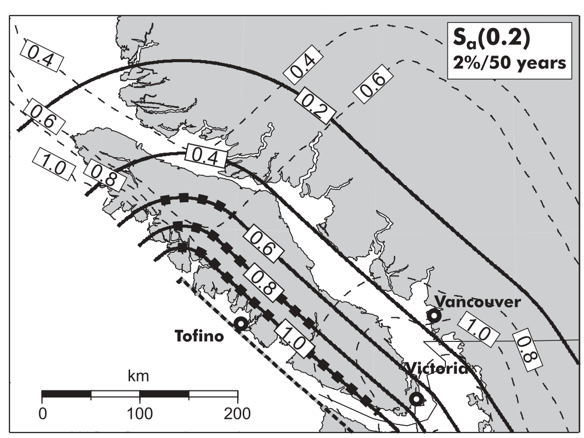


Fig. 8. Uniform hazard spectra for selected Canadian cities for a probability level of 2% in 50 years on firm ground. Note the logarithmic vertical scale: the expected shaking in Victoria is eight times stronger than that in Calgary or Winnipeg. The UHS for Winnipeg is also the stable Canada UHS and represents the floor spectrum for sites in the lowest seismicity parts of Canada.

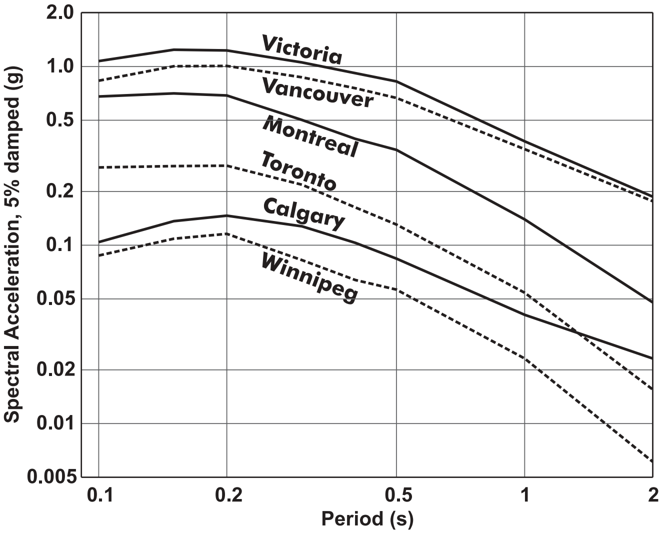
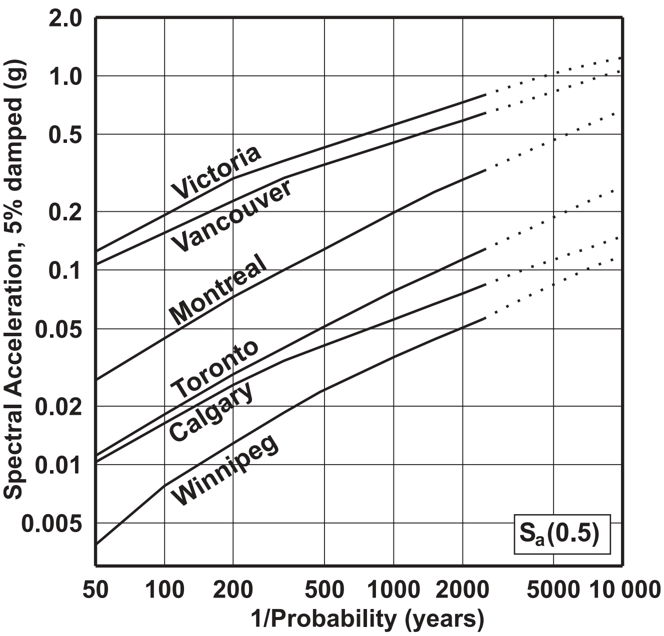


Fig. 9. Hazard curves (here $S_a(0.5)$ ground motions as a function of probability level) for selected Canadian cities. Note different slopes of the various curves. Curves are dotted for the extrapolation beyond 2% in 50 years because in many places the model may not be adequate for such low-probability hazard.



The 1997 NEHRP hazard maps, prepared by the USGS in 1996 (Frankel et al. 1996), are now being updated and may be included in the 2003 NEHRP. Although the USGS maps computed spectral parameters for the same 2% in 50 year probability level, they used a different way of defining source zones, a different choice of ground motion relations, and a different way of incorporating Cascadia subduction

Table 2. Peak ground acceleration (in *g*) 10% in 50 year values from the 1985 NBCC compared with median 10% in 50 year firm-ground values from the hazard model used for the 2005 NBCC.

City	1985[a]	2005	Change	Chief reasons[b]
St. John's	0.054	0.036	Down	1 and 2
Halifax	0.056	0.057	Slight	—
Moncton	0.085	0.072	Down	2
Fredericton	0.096	0.094	Slight	—
La Malbaie	0.70	0.59	Down	2
Québec	0.19	0.16	Down	2
Trois Rivières	0.12	0.18	Up	3
Montréal	0.18	0.20	Slight	—
Ottawa	0.20	0.20	Slight	—
Niagara Falls	0.084	0.12	Up	4 and 5
Toronto	0.056	0.080	Up	4 and 5
Windsor	0.029	0.040	Up	3 and 5
Winnipeg	0	0.021	Up	6
Calgary	0.019	0.040	Up	5
Kelowna	0.054	0.071	Up	5
Kamloops	0.056	0.071	Up	5
Prince George	0.034	0.033	Slight	—
Vancouver	0.21	0.26	Up	4
Victoria	0.28	0.34	Up	7
Tofino	0.35	0.27	Down	4 and 8
Prince Rupert	0.13	0.095	Down	2
Queen Charlotte City	0.57	0.22	Down	2
Inuvik	0.060	0.032	Down	2

[a]1985 values were taken from the 1985 NBCC Commentary where possible. Values not in the commentary were computed using the 1985 seismic hazard model.

[b]1, less impact of 1929 earthquake; 2, new strong ground motion relations used; 3, effect of R model; 4, change in source zone boundary position; 5, larger upper bound magnitudes used; 6, effect of stable Canada model; 7, corrected coordinates to downtown; 8, less impact of 1946-type earthquakes.

earthquakes. Furthermore, they computed hazard for the mean, not the median. All of these factors contribute to cross-border differences, so although there is general agreement in relative hazard levels, as shown by comparing hazard between Canadian and appropriate U.S. cities (Halchuk and Adams 1999), hazard contours do not necessarily match across the border. In any event, given the way in which engineering design differs between the NBCC and U.S. codes, it is the way in which final building safety (Heidebrecht 2003) compares that matters, not hazard per se. It is expected that as the level of knowledge improves and a consensus evolves on the best approach there will be a convergence between Canadian and U.S. hazard estimates.

Although the UHS will be used directly in design (Heidebrecht 2003) and takes into account more characteristics of earthquake ground motions than peak measures, an alternative method is the use of time histories. Indeed, the 2005 NBCC provisions will require dynamic analysis in a number of situations, and time history methods may be chosen. Appropriate time histories that match the UHS can be scaled from selected strong ground motion records (where these exist) or from synthetic time histories generated to have the appropriate characteristics (Atkinson and Beresnev

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Fig. 10. Diagram showing schematically the contribution of various input parameters to uncertainties in the final hazard. a-value and b-value, standard parameters for the magnitude–recurrence curves; SGM, strong ground motion relations; UBM, upper bound magnitude.

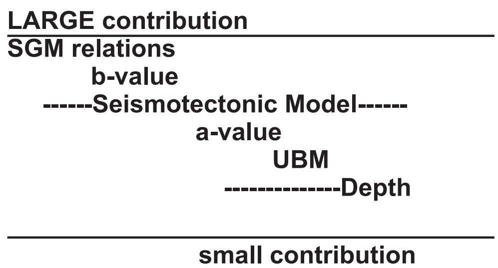


Fig. 11. Trial deaggregations of 2% in 50 year median seismic hazard for $S_a(0.2)$ in Montréal and Vancouver. These deaggregations were produced by the commercial program EZ-Frisk, not FRISK88.

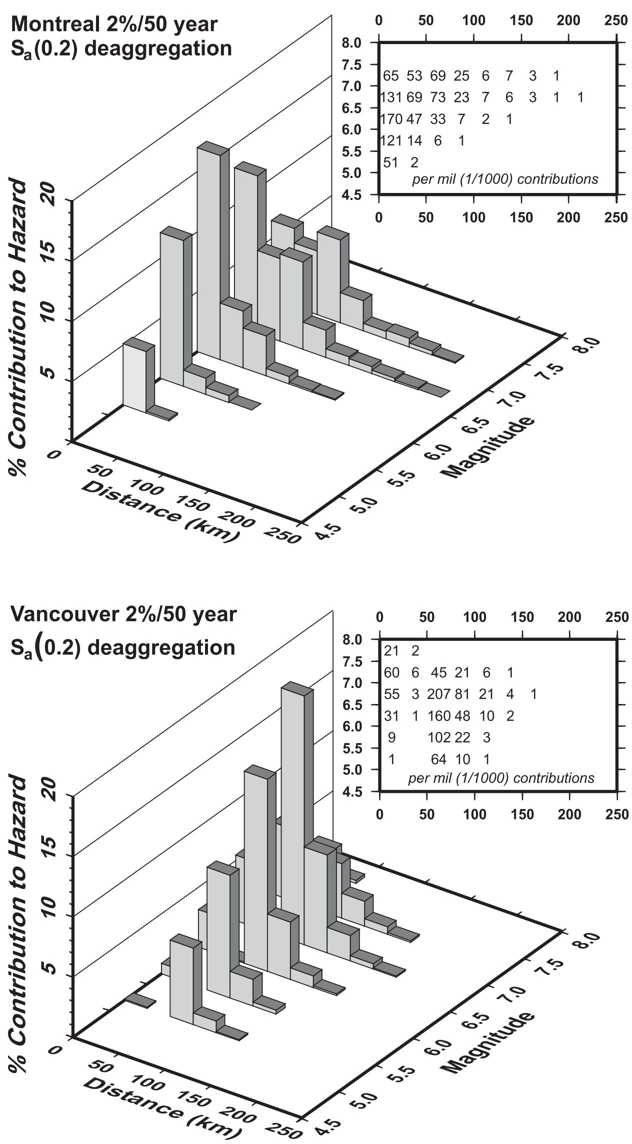
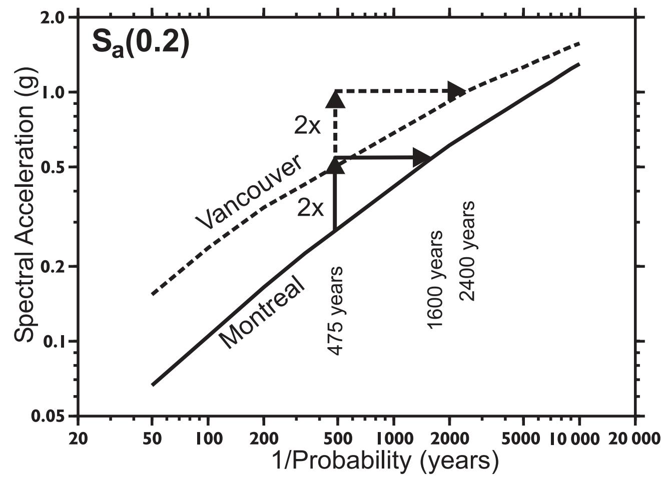


Fig. 12. $S_a(0.2)$ hazard curves for Vancouver and Montréal, showing how increasing the 10% in 50 year median hazard by a factor of two (2×) produces different increases in safety.



1998). Such records have been generated for selected Canadian cities, for compatibility with the 2% in 50 year and 10% in 50 year UHS. (Note that Atkinson and Beresnev (1998) provide records matching the 10% in 50 year UHS, and corresponding 2% in 50 year records are available via e-mail request to the second author at gma@ccs.carleton.ca.)

The seismic hazard value at each site represents the integrated effect of a range of earthquake magnitudes and distances, so different parts of the UHS may need to be matched by different types of time histories (typically from small, close earthquakes for shorter periods and large, distant earthquakes for longer periods). The choice of magnitude and distance is aided by deaggregation (McGuire 1995; Bazzurro and Cornell 1999; Harmsen et al. 1999), a process that breaks out the hazard contributions into selected magnitude–distance bins (Fig. 11). Such plots reveal the earthquake–distance combinations that make the largest contribution to the total hazard. For example, the deaggregation for Vancouver at $S_a(0.2)$ indicates that most of the hazard comes from magnitude 6–7 earthquakes at a distance of 50–75 km (these are the subcrustal earthquakes within the subducting Juan de Fuca plate, nearly underneath the city). Deaggregations like these allow the sensible choice of scenario events or time histories to check engineering design.

The slope of the hazard curve varies regionally. For example, the hazard curve for Montréal is steeper than that for Vancouver (Fig. 12). The slopes are a function of the size and distance distribution of the earthquakes that contribute hazard to each city and the strong ground motion relations applied to them. In general, where sites are dominated by distant, high-activity zones (in which earthquakes near the upper bound are relatively common), the hazard curve is less steep than for sites that lie within moderate-seismicity zones. The average values for the ratio of the 2% in 50 year $S_a(0.2)$ value to the corresponding 10% in 50 year value are approximately 2.34 and 1.91 for eastern and western Canadian cities, respectively (specifically, 2.35 for Montréal and 1.94 for Vancouver). These ratios vary considerably, however, even within southwestern British Columbia (Adams et al. 2000; see also Fig. 47 of Adams and Halchuk 2003).

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The variability in hazard ratio means that applying a national or even regional multiplicative factor to the 10% in 50 year values will not reproduce lower probability hazard values reliably. The very different average slopes between east and west have important consequences for safe design. For example, the annotations in Fig. 12 show the effect of applying a constant factor of two (say an "experiential factor of safety" term) to both the Vancouver and Montréal 10% in 50 year values. For Vancouver this would give ground motions with a 1/2400 per annum exceedance probability, but for Montréal the ground motions would have a 1/1600 per annum exceedance probability. Clearly the same level of safety would not be achieved. Even if different constants were used for east and west, the geographical variation present across Canada would preclude achieving a constant level of safety. CANCEE concluded that the direct calculation of seismic hazard at the probability level most appropriate for design is necessary. As suggested by Heidebrecht (1999), the 2% in 50 year probability level represents the approximate structural failure rate deemed acceptable, and so the 2% in 50 year seismic hazard values recommended by CANCEE can help to achieve a uniform level of safety.

Conclusions

The seismic hazard results generated from the new national model will provide a more reliable basis for seismic design of new buildings across Canada. They provide an updated depiction of hazard across Canada, including its variability with spectral period. The spectral parameters used will describe the expected shaking better than the peak motion parameters used in the 1995 NBCC. Understanding of the new results will be aided by new ways of presenting the information, such as deaggregation. Lastly, the explicit measures of uncertainty incorporated into the model represent the next frontier of research. More reliable hazard values for future building codes will arise from reducing the epistemic uncertainty wherever possible, with the greatest gains likely to come from the parameters to the left in Fig. 10.

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