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Lowering the Probability Level - Fourth Generation Seismic Hazard Results for Canada at the 2% in 50 year probability level

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ABSTRACT

The Geological Survey of Canada's new hazard model for Canada, released for public comment in 1996, is intended to form the basis for seismic design codes in the next edition of the National Building Code of Canada. As such it will produce Canada's fourth generation of official seismic hazard maps. The three probabilistic parts of the model use two complete earthquake source models and a separate estimate for the stable part of Canada to represent the uncertainty in where (and why) earthquakes will happen in the future. A deterministic estimate is made for the Cascadia subduction earthquake. A "robust" method is used to combine these probabilistic and deterministic estimates: the mapped value for spectral parameters is the largest of the values determined from these four sources. The previous code was based on median (50th percentile) ground motions for a 10% probability of exceedence in 50 years. We present the 2% in 50 year (equivalent return period of approximately 2500 years) results for major cities, compare them to the 10%/50 year values, and demonstrate that they provide a better basis for achieving a uniform level of building safety across Canada.

INTRODUCTION

Three generations of seismic hazard maps for Canada have been produced at roughly 15-year intervals (1953, 1970, 1985), and a fourth generation is now justified because there is sufficient new information available to improve the hazard estimates (Basham, 1995). As described by Adams et al. (1995), the new hazard maps incorporate a significant increment of earthquake data, recent research on source zones and earthquake occurrence, together with recently-published research on strong ground motion relations. Spectral acceleration values ("PSA"; all 5% damped) are computed for the range of periods important for common engineered structures, together with the peak ground velocity (PGV) and peak ground acceleration (PGA) parameters of the current (1985) maps. Our previous publications on the 4^{th} generation maps provided 10%/50 year values directly comparable to the 1985 maps. However, we now present 2%/50 year (0.000404 per annum) values, and show why they should form the basis of the revised building code (Heidebrecht, 1999).

METHOD

The present method builds upon the work of Basham et al. (1985) which established the third generation of seismic hazard maps for Canada. We apply the same Cornell-McGuire methodology using a customized version of the FRISK88 hazard code (FRISK88 is a proprietary software product of Risk Engineering Inc.), which includes epistemic uncertainty into the computation. Details of the seismicity model are contained in Adams et al. (1999). The two probabilistic source zone models, intended to span the range of likely models, are substantially unchanged from Adams et al. (1996), but we highlight the following two changes.

<u>Seismic Hazard for the "Stable" Part of Canada.</u> About half of the Canadian landmass has too few earthquakes to define reliable seismic source zones, and on prior maps the hazard computed for these regions came only from distant external sources. However, international examples suggest that large earthquakes might occur *anywhere* in Canada (albeit rarely). To improve the reliability of the estimate of seismic hazard for the stable part of Canada we combine the earthquake activity of those stable continental shields of the globe comparable to the Canadian shield (Fenton and Adams, 1997) and then compute the hazard, using eastern strong ground motion relations, at the centre of a large octagonal source zone with this per-area activity level. As our selection of comparable shield areas was conservative, these values are expected to be the lowest likely for any part of Canada not included in a source zone, and so form an appropriate "floor". This floor is also used for sites west of the Rockies, where the activity rates are likely to be higher, but the attenuation is stronger.

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Deterministic Subduction Earthquake Ground Motions. Great earthquakes happen on the Cascadia subduction zone on the average about every 500-600 years, so the median values from our deterministic scenario have an annual probability about the same as for the 10%/50 year probabilistic values. However, those median values are not appropriate for the 2%/50 year hazard, since in circa 2500 years (i.e., approx 0.0004 p.a. or 2%/50 years) we can expect to have 4-5 Cascadia subduction earthquakes with a suite of shaking levels. Hence, there is an even chance one of the five will exceed the 75-80th percentile ground motions of the suite. This percentile is very close to the 84th, so we have used the median plus one sigma ground motions from our 10%/50 year calculations for the 2%/50 year deterministic hazard.

Strong Ground Motion Relations

For eastern Canada we continue to use the Atkinson and Boore (1995) relations, with the same adjustment to take them from "hard rock" to "firm ground". While these relations are fairly consistent with the majority consensus in the field, the excellent Saguenay data and contrary opinions (e.g., Haddon, 1997) give us strong reservations about the shaking predicted for the larger (magnitude about 6½) earthquakes critical for hazard estimation. We hope that this contentious issue will be resolved before the preparation of final maps for the National Building Code. We would emphasize that no matter how good our source models, the reliability of the final hazard values is highly dependent on the reliability of the extrapolations within the attenuation relations used, as observational data from large eastern earthquakes is sparse. For the western Canadian shallow source zones, including the subcrustal transition zones west of Vancouver Island as well as the Queen Charlotte Fault, we continue to use our adaptation of the ground motion relations of Boore et al. (e.g., 1997). For subcrustal source zones deeper under Puget Sound and for the Cascadia subduction zone we have chosen to use the Youngs et al. (1997) relations, adjusted to "firm soil", as we judge they are based on a larger and better-selected data set than the Crouse relationship we previously used.

Ground Motion Parameters and Choice of Confidence Level

While the 1985 maps gave PGV and PGA values, we present spectral acceleration values for 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 1.0, and 2.0 second periods (denoted PSA0.1 etc) for both east and west (note epistemic uncertainty is not available for PSA2 in the east). We also give PGA values for both east and west, but PGV values for just the east (a PGV ground motion relation is not available for the west). We provide values 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 in the model. Either might be used for engineering design. The median is often chosen because it is a robust parameter and can be expected to remain stable as the range of scientific opinion changes, while the 84th percentile must be expected to fluctuate in future (hopefully decreasing over the long term) as improved knowledge about epistemic uncertainty is incorporated into the analysis.

Combining Hazard Estimates Using the "Robust" Approach

We combine the complete probabilistic hazard calculation from each of the two models, together with the probabilistic "floor" level for the "stable" part of Canada and the deterministic Cascadia model, in the fashion we term "robust" (Adams et al., 1995, 1999), i.e. by choosing the highest value of the four sources for each grid point. 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.

RESULTS

Table 1 gives the 2% in 50 year probabilistic hazard values for selected Canadian cities, itemizing separately the values for the two source zone models and their 50th and 84th percentiles, together with the appropriate Cascadia values. Space precludes the presentation of individual uniform hazard spectra, but these are given in Adams et al. (1999). The "floor" hazard for the "stable" part of Canada, for firm-ground at the 2% in 50 year probability level, is: PSA0.1=11%g; PSA0.2 =10.6%g; PSA0.3=8.3%g; PSA0.4=6.3%g; PSA0.5=5.0%g; PSA1.0=1.8%g; PSA2%=0.6%g; PGA=7.4%g; PGV=0.033 m/s. Figure 1 shows the Canada-wide distribution of PSA0.2 hazard. Note that the inclusion of the floor value (11%g for this map) eliminates the lowest contour of prior (10%/50 year) maps. Table 2 compares the 2% and 10% values, including their ratios. As it happens, median values for the 2%/50 year probability level are larger than, or nearly the same as, 84th percentiles for the 10%/50 year level. The reason for the different ratios in the east and west is illustrated on Figure 2, which shows the complete hazard curves for PSA0.2 for the important (and fairly typical of western and eastern) cities of Vancouver and Montreal.

Table 1. Selected seismic hazard values at 0.000404 per annum for "Firm Ground"

City	Coordinates °North	Coordinates °West	PGV (m/s) 50% H	PGA (%g) 50% H	0.2 s PSA (%g) 50% H	0.2 s PSA (%g) 50% R	0.2 s PSA (%g) 84% H	0.2 s PSA (%g) 84% R	1.0 s PSA (%g) 50% H	1.0 s PSA (%g) 50% R	1.0 s PSA (%g) 84% H	1.0 s PSA (%g) 84% R	1.0 s PSA (%g) 50% Cascadia
St. John's	47.6	52.7	0.048	7.5	15	18	27	30	4.2	6.1	12	16	**see**
Halifax	44.6	63.6	0.052	7.6	16	20	29	34	4.9	6.3	14	17	**note**
Moncton	46.1	64.8	0.093	19	31	28	51	50	7.1	6.7	22	20	
Fredericton	45.9	66.6	0.10	21	35	38	61	66	8.6	8.3	27	26	
La Malbaie	47.6	70.1	0.62	110	230	61	380	100	57	12	160	41	
Quebec	46.8	71.2	0.14	28	51	56	84	90	14	11	42	36	
Trois-Rivieres	46.3	72.5	0.11	20	34	68	61	110	10	13	29	44	
Montreal	45.5	73.6	0.17	38	58	68	100	110	13	14	37	46	
Ottawa	45.4	75.7	0.13	26	45	62	85	99	11	13	31	42	
Niagara Falls	43.1	79.1	0.13	30	40	22	90	39	7.2	5.5	25	15	
Toronto	43.7	79.4	0.081	18	28	20	55	34	4.8	5.3	17	14	
Windsor	42.3	83.0	0.038	6.1	12	18	21	31	2.4	3.8	8.4	11	
Calgary	51.0	114.0	**see**	9.1	15	9.5	30	18	3.9	3.3	8.1	6.2	1.2
Kelowna	49.9	119.4	**note**	13	27	19	50	38	8.4	8.8	16	17	4.1
Kamloops	50.7	120.3		12	26	20	48	40	8.2	10	16	19	4.1
Prince George	53.9	122.7		6.5	12	9.7	25	18	3.9	3.8	7.7	7.4	2.5
Vancouver	49.2	123.2		45	95	97	190	190	30	34	56	66	14
Victoria	48.5	123.3		58	120	110	240	220	37	36	74	71	26
Tofino	49.1	125.9		16	33	49	65	110	12	22	24	43	37
Prince Rupert	54.3	130.4		11	20	33	39	61	13	15	25	31	**see**
Queen Charlotte	53.3	132.0		33	59	63	120	130	42	45	87	99	**note**
Inuvik	68.4	133.6		5.7	10	8.5	20	17	3.7	3.8	7.2	7.6	

Notes: PGV is not available for the west; Cascadia values are give only where relevant.

Abbreviations: PGV - peak ground velocity; PGA - peak ground acceleration; 0.2 s PSA - pseudo-spectral acceleration at 0.2 seconds; 1.0 s PSA - pseudo-spectral acceleration at 1.0 seconds; RGC - reference ground condition.

Eastern RGC multiplicative factors (in brackets) as follows: PGV (2.38), PGA (1.39), 0.2 s (1.94), 1.0 s (2.58). Eastern hard rock values can be found by dividing by the appropriate RGC factor; RGC factors are not applicable for the west.

Columns labelled "50%" are the medians, which are exceeded half of the time.

Columns labelled "84%" are the 84th percentiles, which are exceeded only 16% of the time.

Columns labelled 'H' and 'R' are the hazard values for the probabilistic models discussed in the text.

'Cascadia' is the Cascadia scenario event.

DISCUSSION AND CONCLUSIONS

The hazard curve for Montreal is steeper than for Vancouver (Fig. 2), with the 2%/10% ratio being 1.94 for Vancouver but 2.35 for Montreal. Thus the different ratios in Table 2 reflect the slopes of each city's hazard curve. These in turn are a function of the size and distance distribution of earthquakes contributing hazard to each city. 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 (= low ratio) than for sites that lie within moderate seismicity zones. While average values for the ratios for east and west cities are approximately 2.34 and 1.91 (Table 2), they vary considerably, as shown also by the spatial variation for southwestern B.C. (Fig. 3).

The variation means that applying a national, or even regional multiplicative factor to the 10%/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 on Figure 2 show the effect of applying a constant factor of two (say a "experiential factor of safety" term) to both the Vancouver and Montreal 10%/50 values. For Vancouver this would give a design appropriate to 1/2400 year shaking, but for Montreal appropriate to 1/1600 year shaking. Clearly the same level of safety has not been achieved. Even if different constants were used for east and west, the geographical variation shown in Figure 3 (and present across all of Canada) would preclude achieving a constant level of safety. Similar points are made by Heidebrecht (1999). A related suggestion by Naumoski and Heidebrecht (1995), to use the 84th percentile values of the 10%/50 year probability so as to ensure an appropriate degree of engineering conservatism consistent with general engineering practice by incorporating the epistemic uncertainty, leads to similar inconsistencies (though the median 2%/50 year results are coincidentally similar to the 84th percentile of the 10%/50 year results, so they accommodate the intent of Naumoski and Heidebrecht's proposal).

We conclude that the direct calculation of seismic hazard at the probability level most appropriate for design is necessary. As suggested by Heidebrecht (1999), the 2%/50 year probability level represents the approximate structural failure rate deemed acceptable, and so the 2%/50 year seismic hazard values we present can help to achieve a uniform level of safety.

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Table 2. Comparison of PSA0.2 hazard values for probabilities of 10% and 2% per 50 years. Average values for eastern and western cities are 2.34 and 1.91

City	10%/50 yr		2%/50 yr		Ratio of median
PSA0.2 (%g)	50%	84%	50%	84%	2%/10%
St. John's	8.9	15	18	30	1.99
Halifax	9.7	17	20	34	2.10
Moncton	14	23	31	51	2.28
Fredericton	17	28	38	66	2.27
La Malbaie	99	170	230	380	2.28
Quebec	24	40	56	90	2.32
TroisRivieres	27	48	68	110	2.48
Montreal	29	50	68	110	2.32
Ottawa	27	46	62	99	2.34
Niagara Falls	15	31	40	90	2.57
Toronto	11	21	28	55	2.55
Windsor	6.8	12	18	31	2.64
Calgary	6.7	14	15	30	2.20
Kelowna	14	28	27	50	1.99
Kamloops	13	28	26	48	1.92
Prince George	5.7	12	12	25	2.16
Vancouver	50	110	97	190	1.96
Victoria	64	130	120	240	1.91
Tofino	29	55	49	110	1.66
Prince Rupert	18	35	33	61	1.86
Queen Charlotte	41	82	63	130	1.54
Inuvik	5.4	11	10	20	1.91

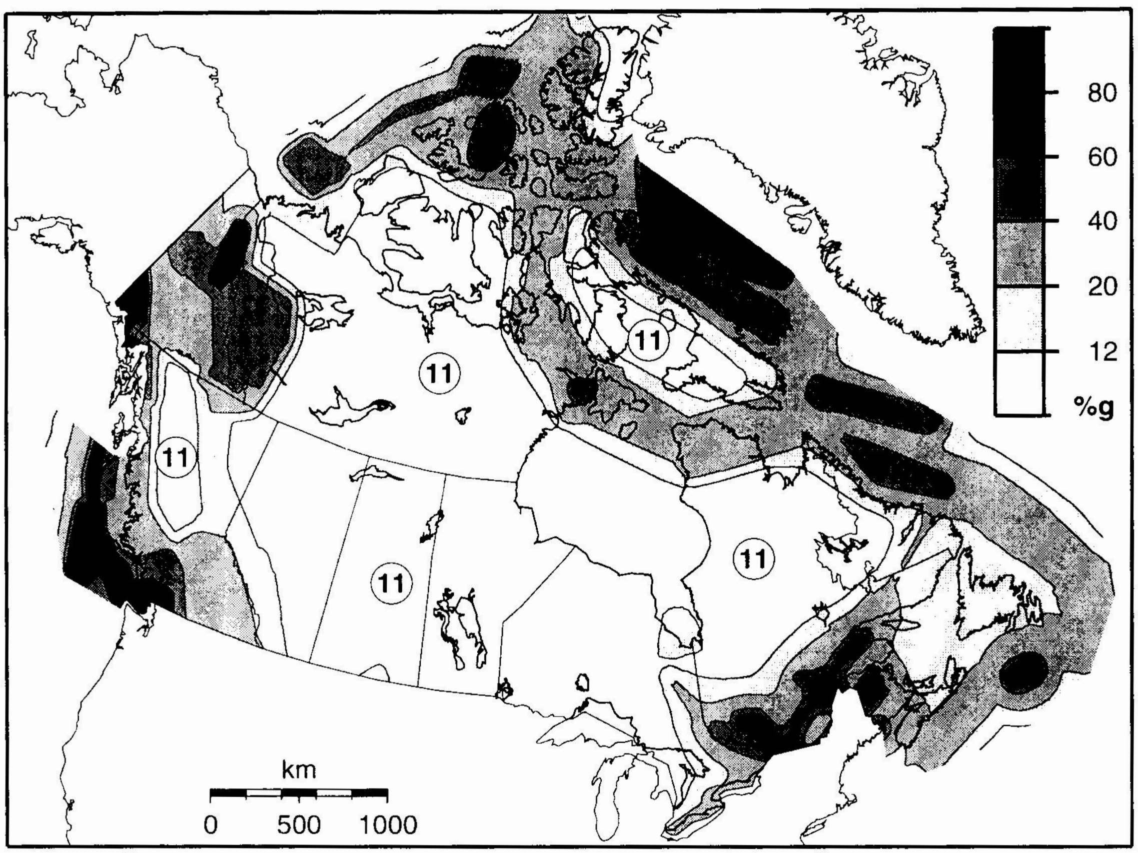

Figure 1. Contour map of 2%/50 year seismic hazard prepared under the "robust" method for 5% damped PSA0.2, on firm ground.

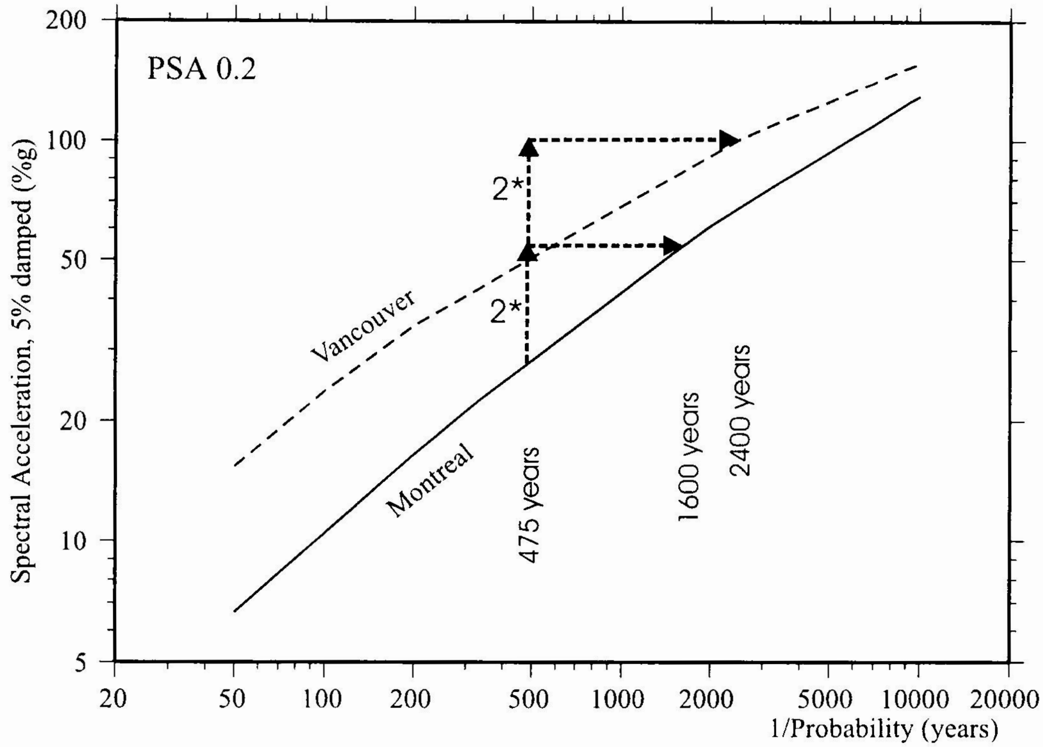

Figure 2. PSA0.2 hazard curves for Vancouver and Montreal, showing how increasing the 10%/50 year hazard by a factor of two produces different increases in safety.

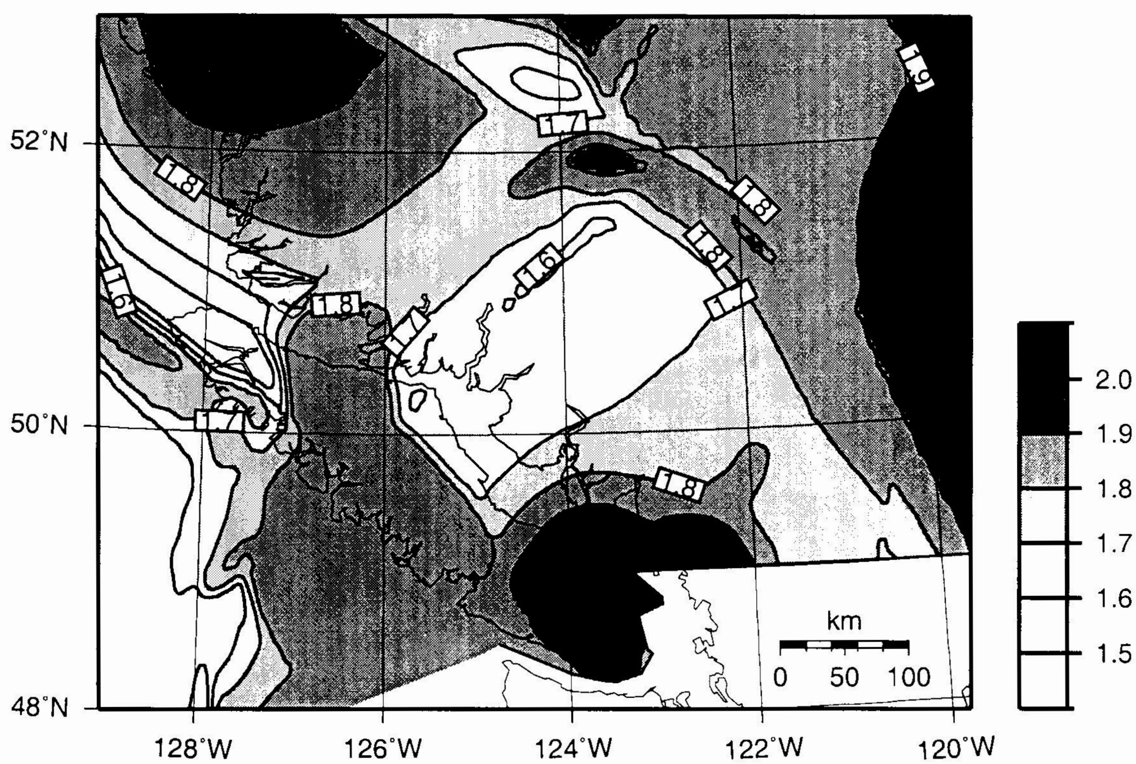

Figure 3. Ratio of 2%/50 year to 10%/50 year PSA0.2 hazard for southwestern B.C.