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Towards Fourth Generation Seismic Hazard Maps for Canada

J. Adams[1], D.H. Weichert[2], S. Halchuk[1] and P.W. Basham[1]

ABSTRACT

We summarize the methodology being used for new seismic hazard maps of Canada and tabulate for major cities the 50th and 84th percentile ground motions for a 10% probability of exceedence in 50 years. The availability of strong ground motion relations for spectral parameters allows the computation of spectral value maps and uniform hazard spectra, which are being recommended as input to the seismic provisions of the National Building Code.

INTRODUCTION

The Geological Survey of Canada is producing a suite of new seismic hazard maps for Canada. These maps, to be released for trial use in 1995, are intended to be revised as appropriate in about 1997 as the basis for seismic design provisions in the year-2000 edition of the National Building Code of Canada (NBCC). 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 in view of considerable new information available to improve the hazard estimates (Basham, 1995).

This paper is a summary, with key results, of a suite of GSC Open Files which will be issued in mid-1995 to document the 1995 "Trial Seismic Hazard Maps of Canada" (e.g. Adams et al., 1995b). Basham (1995) gives a discussion of the background and philosophy. The new hazard maps incorporate an extra 13 years of earthquake data, the most recent research on source zones and earthquake occurrence, together with complementary research on strong ground motion relations. In contrast to the 1985 maps, which gave peak ground velocity (PGV) and peak ground acceleration (PGA) values, we now provide spectral acceleration values ("PSA"; 5% damped) for several periods. In addition to tabular data for most of the larger population centres exposed to seismic hazards, we present sample hazard maps computed for a 10% probability of exceedence in 50 years (0.0021 per annum).

METHOD

The present method for calculating seismic hazard 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 (e.g., McGuire, 1993) using the hazard code FRISK88 (a proprietary software product of Risk Engineering Inc.). This code allows inclusion of both aleatoric (randomness) and epistemic (model or professional) uncertainty (a brief treatment of uncertainty is given by Basham, 1995). The 1985 NBCC hazard maps allowed for the irreducible scatter about the ground motion relations (the "sigma" or 1 standard deviation), a measure of aleatoric uncertainty that increases the median hazard. FRISK88 does the same, (our 50th percentiles include the aleatory uncertainty) but it

[1]Geological Survey of Canada, Ottawa K1A 0Y3
[2]Geological Survey of Canada, Sidney V8L 4B2

also uses a standard "logic tree" approach to include the epistemic uncertainty. Our 84th percentile values include the epistemic uncertainty from all the explicit parameters (strong ground motion relations, focal depth, earthquake recurrence parameters, upper bound magnitude); a further parameter — earthquake source zone configuration — is treated separately, as discussed below.

SEISMICITY PARAMETERS

Earthquake Catalogue

We are currently using the Canadian earthquake catalogue up to 1990 for the east and up to 1991 for the west. Relative to the catalog used for the 1985 maps, this adds 13-14 years of new data. We have also made a significant number of revisions to older earthquake locations and magnitudes, and have supplemented the Canadian catalogue by recent U. S. catalogues. The eastern earthquake catalogue is standardized on m(bLg) magnitudes; these are converted to moment magnitudes in order to use the Atkinson (1995) ground motion relations. The western earthquakes have a mix of magnitudes, depending on availability and quality, and are assigned in order of preference; thus, we demonstrate they are equivalent to moment magnitudes in order to apply the Boore et al. (1993, 1994) relations.

Earthquake Source Zones

While the 1985 maps used a single earthquake source model, we now use two (Fig. 1), each with a full suite of earthquake source zones and magnitude recurrence curves, upper-bound magnitudes and earthquake depth information, to represent the uncertainty in location (and cause) of future earthquakes. To capture the lack of knowledge in the east, one model (**H**) assumes that the historical earthquake clusters will continue their activity, while the other (**R**) groups a number of seismicity clusters that are inferred to have a common cause into large source zones such the Arctic Continental Margin (ACM), the Eastern Continental Margin (ECM), and the Iapetan Rifted Margin (IRM) (compare the two parts of Fig. 1). The geological basis for such zones is discussed by Adams et al. (1995a) and summarized by Basham (1995). Model **R** implies that currently aseismic regions between adjacent seismicity clusters are capable of large earthquakes (e.g. the St. Lawrence valley near Trois Rivières).

In western Canada earthquake tectonics are better understood, and the models are not as different. For example, model **R** collects crustal earthquakes around Vancouver and Seattle together with the central Vancouver Island earthquakes into one zone (CAS) 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.

The Cascadia subduction zone has generated prehistorical great earthquakes off Vancouver Island; from their geological record, the average recurrence interval is about 600 years, and the last happened about 300 years ago (Adams, 1990). The probability of the next great earthquake is similar to that used for seismic zoning maps, and new U.S. and Canadian hazard mapping projects will need to accommodate its expected ground motions. We have chosen a deterministic, rather than probabilistic, estimate of Cascadia earthquake ground motions, and tabulate the hazard separately.

Magnitude Recurrence Parameters

We use the maximum likelihood method of Weichert (1980) to compute the magnitude recurrence parameters. To provide an estimate of epistemic uncertainty we have taken the standard errors for the calculation and combined them to give an upper and lower curve which correspond to one sigma

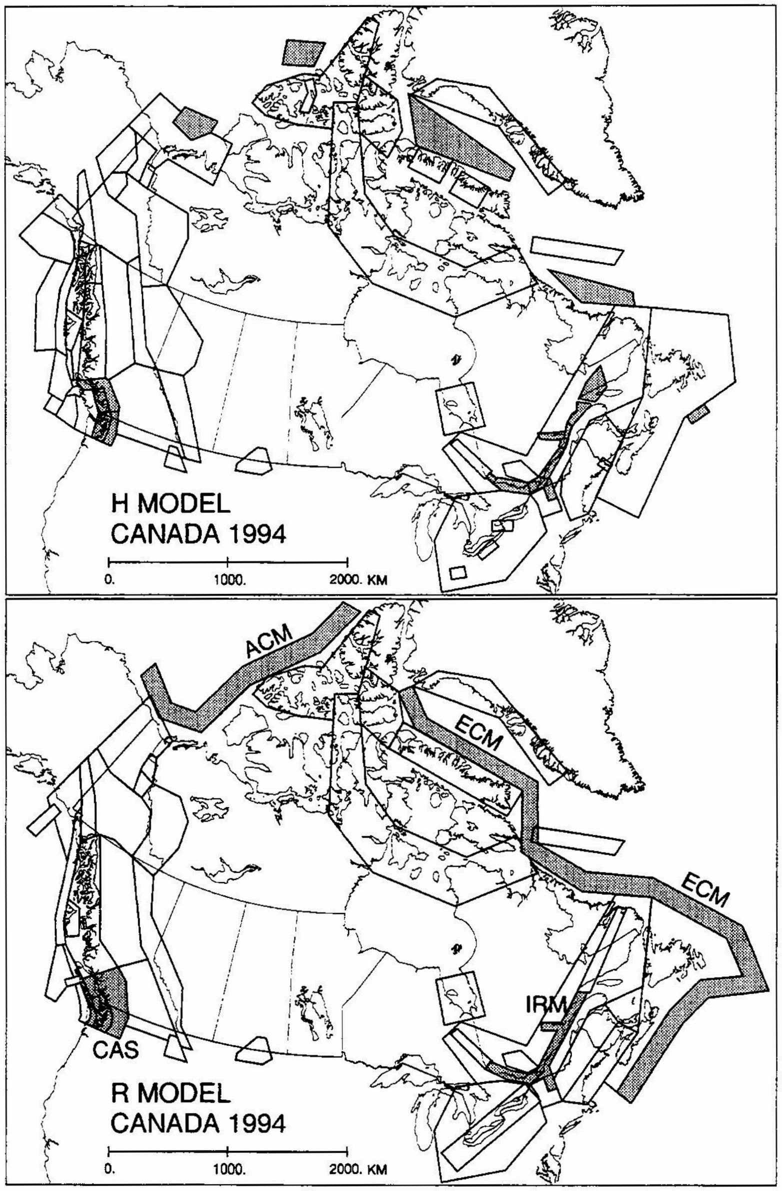

Figure 1. Earthquake source zone maps of Canada showing the zones that form the H (top) and R (bottom) models for earthquake distribution. Zones referred to in the text are shaded and labelled on the bottom map; corresponding H-model zones are shaded on the top map.

(standard deviation) error bounds. The curves are asymptotic to an assumed upper bound magnitude, and again we have used our judgement to associate the three curves with three possible upper bound values. Examples for two source zones are shown in Fig. 2.

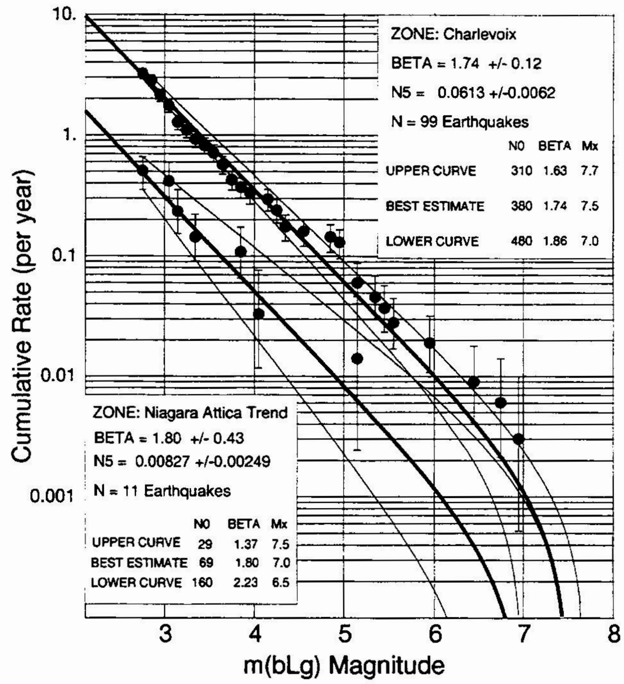

Figure 2. Sample magnitude-recurrence data and curves for Charlevoix and the Niagara-Attica Trend (NAT) zones. The cumulative rates of earthquakes are represented by solid circles with stochastic error bounds and the best-fit curves (bold) are each flanked by upper and lower "error" curves that are more widely separated for the poorly-constrained NAT dataset. All curves are asymptotic to the assumed upper bound magnitudes.

STRONG GROUND MOTION RELATIONS

For eastern Canada, a source of great uncertainty in hazard estimation at the moment is the correct ground-motion relations to be used. In particular, the recordings of the 1988 Saguenay earthquake have caused the ground motion modellers to revise their prior relationships to account for its unexpectedly-large low-period motions. Because there appears to be a consensus emerging, we have adopted the best available suite of relationships, their aleatory uncertainty (sigma), and their epistemic uncertainty consistent with that consensus (as proposed by Atkinson, 1995), though recent modelling of the Saguenay ground motions at the GSC gives us reservations about the absolute values the consensus has produced.

For the western Canadian shallow source zones, including the subcrustal transition zones west of Vancouver Island and the Queen Charlotte Fault, we have adapted the ground motion relations from Boore et al. (1993, 1994). Our adaptation involved the addition of a period-dependent anelastic attenuation term (values from G. Atkinson, pers. comm, 1994) applied to distances larger than 100 km. For subcrustal source zones deeper under Puget Sound and for the Cascadia subduction zone we used Crouse's (1991) relations that were specifically developed for these areas. As representative depths we adopted 50 km for the normal-mechanism events within the subducting slab, and 25 km for the centre of energy release of the Cascadia thrust earthquake. For aleatory uncertainty we have used the "sigma"s listed by the cited authors. We estimate the epistemic uncertainty (comparable to that used for the east) on each relationship 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.

Reference Ground Conditions

For western Canada we have used the Boore et al. "firm soil" (class B) relations. For eastern Canada, the Atkinson (1995) relations were derived from ground motions recorded at hard-rock sites, and require a soil parameter to adjust their ground motions to our reference ground condition (RGC) of class B soil. Such a ground condition was implicit in the 1985 hazard maps, because in the absence of hard-rock recordings, the eastern relations used in 1985 relied on western near-source levels on soil and felt-intensity information (isoseismal maps) reported by Canadians living on average eastern site conditions. Preliminary period-dependent RGC factors (given by Adams et al., 1995b) are applied to Table 1 as noted below the table. These RGC factors make the eastern hazard values both backward comparable to the 1985 maps and directly comparable to the "soil class B" western values we tabulate.

RESULTS

Table 1 gives separate hazard values for the H and R models, and the Cascadia deterministic ground motions, for selected Canadian cities. Contour maps of hazard computed using the **R** model have long 'ridges' of moderate hazard and lack the 'bulls-eyes' of high hazard produced by the **H** model. As a consequence, using the **R** model in a building code would reduce the protection significantly in regions of high historical seismicity while increasing protection only slightly in other places. This poses a dilemma to engineers concerned with safety. A 'robust' or 'quasi-probabilistic' method is suggested to combine the probabilistic estimates from each model into design value maps by using the higher value in each place (Adams et al. 1995b; Basham 1995). Figure 3 shows examples of such contour maps of 'robust' hazard, for spectral acceleration (5% damped at 0.0021 p.a.) at 0.1 and 1 second periods.

The values for the seismic hazard from the Cascadia subduction zone in Table 1 are intended to be incorporated into the national hazard maps by the 'robust' approach; that is, where the Cascadia ground motions are larger than the probabilistic calculation, the Cascadia values would be adopted; they are not included on the map in Figure 3.

Uniform Hazard Spectra result in non-Newmark-Hall amplification

The previous code used scaled Newmark-Hall spectra (Newmark and Hall, 1969). These spectra were derived by averaging (or enveloping) the few then available spectra from magnitude 6-7 earthquakes in the 20-50 km range. The spectral shape was specified by certain corner frequencies and fixed amplification factors relative to peak ground motion. If the dominant hazard at the desired probability level comes from such earthquakes and distances in similar tectonic environment, this spectrum is appropriate. For many sites in Canada, short period hazard comes from smaller magnitude events at near distances; longer period hazard from larger earthquakes at greater distances. This was recognized by the last code edition by giving PGA and PGV values at the same hazard level, necessarily resulting in a variable corner period, i.e. variable spectral shape. Similarly, the spectral acceleration relations now allow construction of uniform hazard spectra for given sites (e.g. Fig. 4) which have variable shapes and amplification factors different from the deterministically-derived Newmark-Hall spectrum.

ACKNOWLEDGEMENTS

The creation of a new suite of national hazard maps is a complex undertaking, and we thank all of our colleagues, who will be acknowledged fully in the appropriate sections of the forthcoming reports.

TABLE 1. Seismic hazard values at 0.0021 per annum for "Firm Soil"

City	Coordinates °North	Coordinates °West	PGV (m/s) 50% H	PGA (%g) 50% H	Samax (%g) 50% H	Samax (%g) 50% R	Samax (%g) 84% H	Samax (%g) 84% R	0.5 s PSA (%g) 50% H	0.5 s PSA (%g) 50% R	0.5 s PSA (%g) 84% H	0.5 s PSA (%g) 84% R	0.5 s PSA (%g) 50% Cascadia	0.5 s PSA (%g) 84% Cascadia
St. John's	47.6	52.7	0.019	2.9	11[d]	9.2[c]	20[d]	19[e]	7.3	6.1	18	15	see note	
Halifax	44.6	63.6	0.027	3.1	7.0[c]	10[c]	13[e]	19[d]	3.6	6.5	9.4	16		
Moncton	46.1	64.8	0.041	8.7	14[c]	13[c]	24[c]	23[d]	4.7	7.3	12	18		
Fredericton	45.9	66.6	0.046	9.7	16[c]	17[c]	28[c]	29[c]	8.5	8.8	22	23		
La Malbaie	47.6	70.1	0.27	57	100[c]	27[b]	170[c]	44[c]	46	11	120	29		
Quebec	46.8	71.2	0.061	14	24[c]	23[b]	40[c]	38[c]	12	10	32	27		
Trois-Rivieres	46.3	72.5	0.046	8.1	16[c]	29[b]	28[d]	47[c]	8.8	12	23	31		
Montreal	45.5	73.6	0.066	16	24[c]	31[a]	42[c]	50[c]	11	13	28	33		
Ottawa	45.4	75.7	0.053	12	21[c]	28[b]	36[c]	46[c]	9.3	12	24	31		
Niagara Falls	43.1	79.1	0.044	13	17[a]	9.6[c]	30[c]	17[c]	6.5	4.9	17	12		
Toronto	43.7	79.4	0.032	6.8	10[c]	8.7[c]	20[c]	15[c]	4.9	4.6	13	12		
Windsor	42.3	83.0	0.015	2.5	5.8[c]	7.3[c]	9.8[c]	12[c]	2.8	3.4	7.4	8.9		
Calgary	51.0	114.0	see note	2.4	6.7	9.1	12	17	2.8	3.4	5.0	6.6	3.4	6.4
Kelowna	49.9	119.4		5.7	19	14	37	28	8.2	6.6	16	13	8.4	16
Kamloops	50.7	120.3		5.8	19	15	37	31	8.0	6.9	16	14	8.4	16
Prince George	53.9	122.7		3.0	7.7	8.5	15	16	3.1	3.4	5.8	6.6	5.8	11
Vancouver	49.2	123.2		17	58	59	120	120	28	27	52	51	19	37
Victoria	48.5	123.3		23	78	65	160	140	35	31	67	57	27	53
Tofino	49.1	125.9		8.8	29	42	56	87	13	17	25	34	40	77
Prince Rupert	54.3	130.4		5.5	17	30	34	56	8.8	12	17	24	see note	
Queen Charlotte	53.3	132.0		19	58	64	130	140	32	34	59	65		
Inuvik	68.4	133.6		3.5	10	10	20	19	4.3	4.5	8.7	9.2		

Abbreviations: PGV - peak ground velocity; PGA - peak ground acceleration; Samax - largest value of spectral acceleration in the period range 0.1 to 0.5 s; 0.5 s PSA - pseudo-spectral acceleration at 0.5 seconds; RGC - reference ground condition.

This table is a summary of values in Adams et al. 1995b. Superscripts on eastern Samax values indicate their corresponding periods (with eastern RGC multiplicative factors in brackets) as follows — a: 0.1 s (RGC=1.39); b: 0.15 s (1.73); c: 0.2 s (1.94); d: 0.3 s (2.17); e: 0.4 s (2.30). For PGV, PGA, and 0.5 s PSA RGC's of 2.38, 1.39, and 2.38 were used. Eastern hard rock values can be found by dividing by the appropriate RGC factor. All western Samax values occur at 0.2 s period, so they are not superscripted; RGC factors are not applicable.

The columns labelled "50%" are the medians, which are exceeded half of the time. The columns labelled "84%" are the 84th percentiles, which are exceeded only 16% of the time.

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

note: PGV values are not available for the west; Cascadia values are given only where relevant.

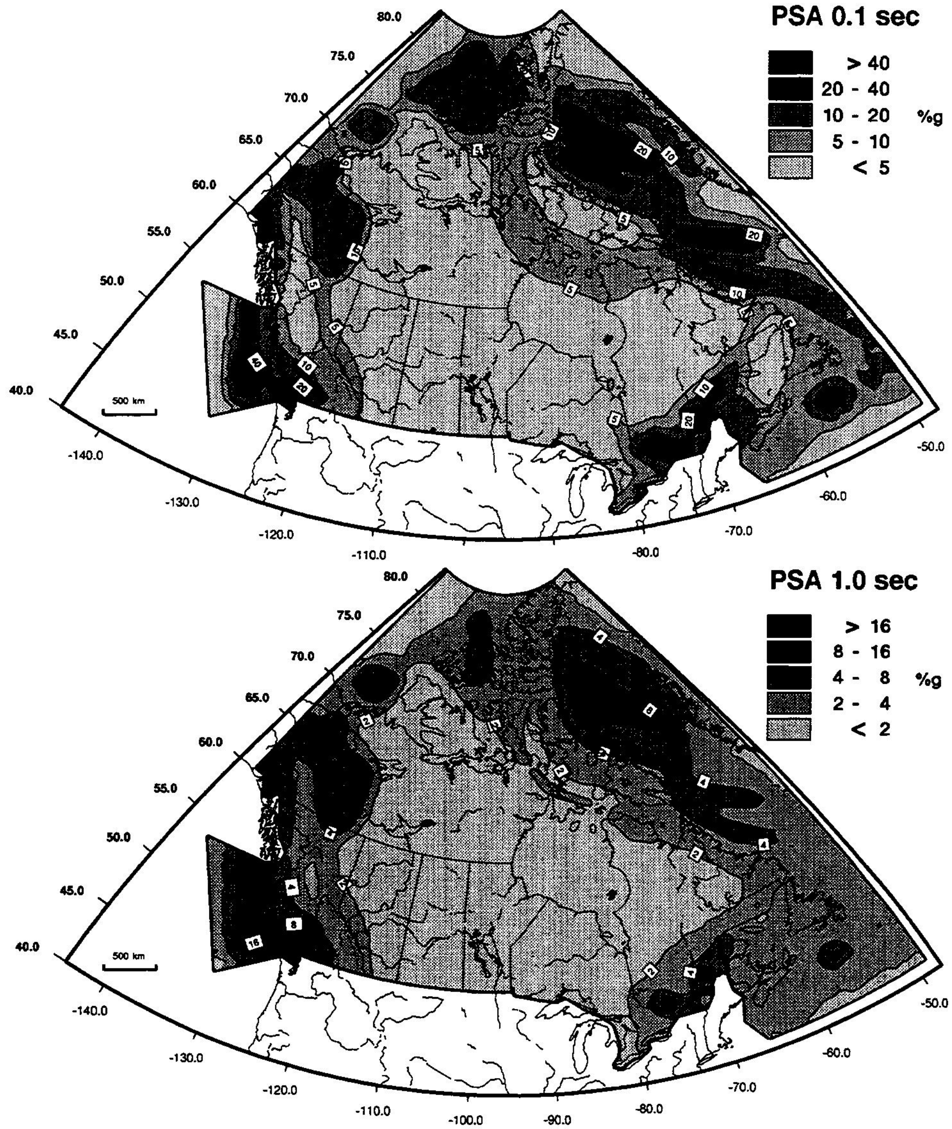

Figure 3. Contour maps of hazard prepared under the 'robust' method for 0.1 second PSA (top) and 1 second PSA (bottom) (5% damped at 0.0021 p.a.). The Cascadia deterministic hazard is not included. For illustration purposes, five arbitary levels were used to identify the hazard.

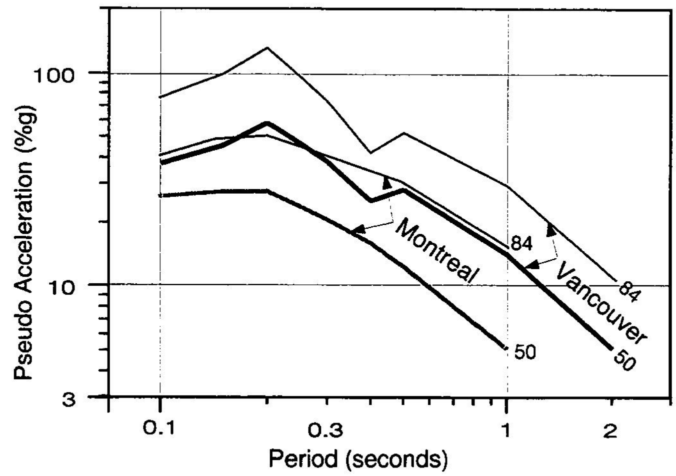

Figure 4. Uniform hazard spectra for Montreal and Vancouver showing the 50th (median; thick line) and 84th percentile hazard at 0.0021 per annum, as derived for firm soil from the H model.

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