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Trial seismic hazard maps of Canada – 1995: preliminary values for selected Canadian cities

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Trial Seismic Hazard Maps of Canada - 1995: Preliminary Values for Selected Canadian Cities

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ABSTRACT

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

RÉSUMÉ

Nous résumons les méthodes utilisées pour les nouvelles cartes de péril séismique du Canada, donnons les mouvements du sol du 50^{e} et 80^{e} centile pour les villes importantes et donnons les spectres de péril uniforme, tout cela pour des sites sur sol dur et une probabilité de dépassement de 10% en 50 ans. Les relations de mouvements forts du sol pour les paramètres de spectre ainsi obtenus permettent de calculer des cartes d'accélération spectrale qui sont recommandées comme base des dispositions séismiques du Code National du Bâtiment.

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 and public comment in 1995, are intended to be revised as appropriate and reissued in about 1997 as the basis for seismic design provisions in the year-2000 edition of the National Building Code of Canada. 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).

The present open file is being issued in preliminary form to release key seismic hazard values computed using the methods that will form the basis of the 1995 "Trial Seismic Hazard Maps of Canada". A suite of Open Files will be issued in mid-1995, to be entitled:

"Trial Seismic Hazard Maps of Canada - 1995: Overview of the Method"
"Trial Seismic Hazard Maps of Canada - 1995: Eastern Earthquake Source Zones"
"Trial Seismic Hazard Maps of Canada - 1995: Western Earthquake Source Zones"
"Trial Seismic Hazard Maps of Canada - 1995: Choice of Strong Ground Motion Relations"
"Trial Seismic Hazard Maps of Canada - 1995: Computational Aspects"
"Trial Seismic Hazard Maps of Canada - 1995: Results and Maps"

For convenience, the above Open Files will be referred to as: 95-Overview, 95-East, 95-West, 95-SGM, 95-Comp, and 95-Results. The current open file ("95-Cities") will be superceded by the 95-Results Open File, when issued. Around 1997, the hazard model and open files will be revised and will probably be re-issued as a series: New Seismic Hazard Maps of Canada - 1997: ABCDE.

The new hazard maps will 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 national values for peak ground velocity (PGV) and peak ground acceleration (PGA), we can now provide spectral acceleration values ("PSA"; 5% damped) for the range of periods important for common engineered structures. We present tables of hazard values for most of the larger population centres exposed to seismic hazards, as well as Uniform Hazard Spectra (UHS), all computed for sites on firm soil at a 10% probability of exceedence in 50 years (0.0021 per annum).

METHOD

Because this Open File is being issued in advance of the Open Files containing the full documentation, a brief overview is given below.

The present method for calculating seismic hazard builds upon the work of Basham et al. (1982; 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, and other new-generation codes, allow explicit inclusion, for the first time for a national hazard map of Canada, of both aleatory (randomness) and epistemic (model or professional) uncertainty (a brief account of uncertainty is given below).

Of necessity, eastern and western Canada must be treated slightly differently. In the following, the boundary between east and west is taken to slice diagonally across Canada from southeastern Alberta to the eastern Beaufort Sea.

Probability level

The probability level is 0.0021 per annum, or a 10% chance of exceedence in 50 years. This is the same as in the 1985 maps.

Cities

The "cities" in the list include most of the larger population centres exposed to seismic hazards, together with a few select localities to round-out the geographical distribution. Coordinates for the cities are given only to 0.1 degree. Final values in the 95-Results open file will be given to 0.01 degree and will represent the town hall, chief post office, or downtown core, and not the airport or weather station, as is often the case in the current NBCC.

Uncertainty

A full treatment of uncertainty will be given in 95-Overview. Suffice it to say here that the new seismic hazard maps of Canada under preparation at GSC consider both types of uncertainty:

Aleatory uncertainty arises from physical variability that is inherent in the unpredictable nature of future events. For example there is a random component of earthquake source and propagation processes which will cause a scatter of amplitudes about the median values, even if the median were known with perfect accuracy. The Cornell-McGuire approach, as implemented in the 1985 NBCC hazard maps included the aleatory uncertainty by incorporating the "sigma" of the ground motion relations into the computation. The sigma is the standard deviation of the irreducible scatter of the data about the median ground motion relations, and is a measure of aleatory uncertainty that increases the median hazard. FRISK88 incorporates the aleatory uncertainty into all the percentiles.

Epistemic uncertainty arises from the differences in expert specification of modelling assumptions, unknown or only partially known parameters, and extrapolation beyond observed range of data. Examples are: specification of seismic source zones, including judgments on stochastic behaviour of historical seismicity, or belief in future activity of seismic gaps; assumptions made in calculations of recurrence curves, such as their analytical form, and extrapolation beyond the observed data range or duration of historical record; and choice of maximum magnitude. FRISK88 uses a standard "logic tree" approach to include the epistemic uncertainty. Our 84th percentile values include the contribution of the epistemic uncertainty from all the explicitly-included 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 have used 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 a further 13-14 years of data. We have also made a significant number of revisions to older earthquake parameters of location and magnitude, and have supplemented the Canadian catalogue by recent U. S. catalogues. The eastern earthquakes chiefly have m_{bLg} magnitudes, so within the hazard program we converted them to moment magnitudes in order to use the Atkinson (1995) relations. 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; thus, we consider them equivalent to moment magnitudes in order to apply the Boore et al. (1993; 1994) relations.

Earthquake Source Zones

The last hazard maps were computed in 1982, using seismicity up to 1977. They represented the distribution of seismicity by a single set of seismicity source zones. Since the 1982 maps, we have accumulated an additional 14 years of earthquakes, and discovered clearer epicentre patterns in some places but been surprised by ‘unexpected’ events in others. We have developed a better understanding of the seismotectonics behind the seismicity, but also an appreciation that much is not known about how the future pattern of seismicity will resemble or differ from the historical pattern.

In some places, southwestern B.C. and the Queen Charlotte Fault being examples, the level of knowledge is quite high, and sufficient that we could still be satisfied with a single model. 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 that the hazard results would reflect the current opinion of the compiler(s) and hence add a deterministic flavour to the maps. 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 we think a pair of models provides the minimal representation of the diversity of opinion as to the causes and future locations of earthquakes.

To apply the Cornell-McGuire method we purchased a license for a large commercial program (FRISK88) in 1990 that allows us to use a number of source zone models and weight them by our (subjective) assessment that they are the correct model. For eastern Canada, our philosophy over the past 6 years has been shaped by the belief that while the scale of source zones could vary from the continent-scale to very small zones around single earthquakes, there are practical reasons for being in the mid-range. Hence we have two models, a **H** model that in general uses small source zones drawn around historical seismicity clusters, and a **R** model that establishes larger, regional zones (Fig. 1). The **H** and **R** models for the east were constructed by Adams and Halchuk (see 95-East), those for the west by Rogers and Horner (see 95-West). While 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 expert in the west adopted a strongly historical model.

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 on Figure 1. 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, and that the rate of activity at any place along the margin is constant, and not higher in the vicinity of the historical activity. 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 (and exist in the current code maps). As a consequence, if the **R** model were implemented in a building code, it 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 probabilistic combination of the two models (as is possible with FRISK88) would involve their weighted-sum, but any weight given to the **R** model would reduce the protection in regions of high historical seismicity. A possible non-probabilistic solution is discussed below under "Combining diverse hazard estimates using the 'robust' approach".

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 (see Fig. 1). The Queen Charlotte Fault is the only earthquake source treated as a fault; all others are area sources.

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 a lower curve which approximate one sigma (standard deviation) error bounds. The curves are asymptotic to an assumed upper bound magnitude, and again we have used our judgment to associate the three curves with three possible upper bound values. Examples for two eastern source zones are shown in Figure 2.

Seismic Hazard from the Cascadia Subduction Zone

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 long-term probability[1] 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 to adopt a deterministic, rather than probabilistic, estimate of Cascadia earthquake ground motions, and tabulate the hazard separately.

For the purpose of this report, we have chosen as distances to the various cities, the centre of energy release at about one-third the way down from the locked zone into the transition zone (e.g., Hyndman and Wang, 1993; Dragert et al. 1994); this is thought to be conservative, but an even more conservative choice would use the distance to the closest point on the transition zone. A combination of these and other opinions via a dendrogram (decision tree) will be used for the final maps.

STRONG GROUND MOTION RELATIONS

The different physical properties of the crust in eastern and western Canada require the use of separate strong ground motion relations.

Eastern Canada.

For eastern Canada, a source of great uncertainty in seismic 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 short-period motions. Because there appears to be a consensus emerging, we have adopted the best available suite of relationships (the base relations of Atkinson and Boore (1995), which were derived for hard rock sites), their aleatory uncertainty (sigma), and their epistemic uncertainty consistent with that consensus (as proposed by Atkinson, 1995). However, recent modelling of the Saguenay ground motions at the GSC (e.g. Haddon, 1992; 1995) gives us reservations about the absolute values the consensus has produced. Because this suite of relationships were derived to fit observational data on hard-rock seismometer sites, they need adjustment to represent the ground motions on the reference ground condition chosen for Canada (see below under "Reference ground condition for Canada").

Western Canada.

For the western Canadian shallow source zones, including the subcrustal transition zones west of Vancouver Island as well as the Queen Charlotte Fault, we have adapted the ground motion relations from Boore et al. (1993, 1994 - hereafter termed 'BJF'). Our adaptation included the addition of a period-dependent anelastic attenuation term (values from G. Atkinson, in prep. 1995) 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. Crouse excluded data from hard rock and soft soil sites,

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[1] The short-term probability is considerably lower, since we seem to be only at about the mid-point of its occurrence interval.

and specifies "firm soil" for his relations. Boore et al. (1993) differentiates between four soil classes, with most data in Class B, designated firm soil and specified as having 360 to 750 m/s average velocity in the uppermost 30 m. Our results are therefore consistent with "firm soil". 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 the Cascadia subduction zone hazard calculation we used Crouse (1991) with a magnitude of 8.2 and with the centre of energy release at about one-third the way down from the locked zone into the transition zone to establish distances to the various cities.

For aleatory uncertainty we have used the 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 we estimate 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 epistemic uncertainty is intended to capture firstly the range of opinion on western ground motions (the upper curve envelopes the Idriss (1991, 1993) relations), and secondly the possibility that there may be systematic biases in the BJF relations. For example, the stress drops of the larger western Canadian earthquakes might be either higher or lower than those used in defining the BJF relations. We recognize that the assigned epistemic uncertainties represent an arbitrary and possibly conservative choice, but prefer to err on the conservative side.

Ground Motion Parameters

In contrast to the 1985 maps, which gave national values for peak ground velocity (PGV) and peak ground acceleration (PGA), we present spectral acceleration values for 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, and 1.0 second periods for both east and west (denoted PSA0.1, PSA0.5, PSA2, etc), and spectral acceleration for 2.0 second period for west only (a 2.0 second PSA ground motion relation is not available for the east). We also give PGA values for both east and west and PGV values for the east (a PGV ground motion relation is not available for the west).

Units.

We have decided to express the PGA and PSA values as (unitless) percentages of g. This avoids many entries of the form "0.072", with consequent duplicate characters "0." and "0.0", and also corresponds to the appropriate level of precision for the PSA and PGA values. However, this would lead to unacceptable rounding for some low values. Therefore we have kept 2 significant figures, with a maximum of one decimal digit. For PGV we have kept 2 significant figures but expressed the result in m/s, as for the 1985 maps, to reduce he chance of confusion with the PSA and PGA values.

REFERENCE GROUND CONDITION FOR CANADA

For the preparation of national hazard maps it is essential to present seismic hazard levels on the same ground condition for all of Canada. Such a "reference" ground condition ("RGC") is needed in order to make the 1995 hazard values firstly, numerically comparable between east and west, and secondly, roughly comparable in intent to the current (1985) hazard maps.

The hard-rock equation of Atkinson and Boore (1995) has been modified by Atkinson (1995) to represent motions on the chosen reference ground condition in a way similar to that of BJF's equation for the western U.S. — by the addition of a soil response parameter, c_5S, (S=0 for hard rock and S=1 for soil sites) whose coefficients, c_5, are usually a function of period.

The BJF "Soil Class B" is our choice for a Canada-wide condition, because:

a) it appears to be the closest to the soil conditions implied in 1985 NBCC and referred as 'rock or firm soil'. Class B is the softer part of Joyner and Boore's (1981, 1988) 'rock' classification, with the larger number of strong motion recordings.

b) "Soil Class B" is the reference ground condition for the strong motion relationships we use in western Canada.

c) the Hasegawa et al. (1981) relations used in eastern Canada for the 1985 maps were established by setting their near-source levels equal to those for western Canada (i.e. on "firm soil") and using isoseismal (felt intensity) maps to constrain the distance dependence of the relations. The isoseismal maps relied on felt-intensities reported by Canadians living on average eastern site conditions that were certainly not "hard rock". Thus the Class B "firm soil" condition is in our view close to the ground conditions that were implied by the 1985 eastern relationships.

Atkinson (1995) does not recommend values for her c_5 coefficients, but notes that for 'deep soil' the values in Atkinson and Boore (1995) adopted directly from Boore and Joyner (1981) might be applicable. For our Class B reference ground condition we propose to use BJF's "B6" coefficients (as smoothed by period, see Boore et al., (1993) Table 7b and Fig. 3a, which are reproduced in the Appendix) as the seismological basis of our period-dependent values. The B6 coefficients relate BJF's California Soil Class B to the California Soil Class A, which is rock/soil with average velocity >750 m/s. Only one of the sites that contributed data to BJF's 1993 analysis is shown to be on rock with average velocity >1500 m/s. Hence the California Soil class A is distinct from eastern Canadian hard rock seismometer sites which were the observational basis for the Atkinson/Boore eastern relations, and which have velocities of >2,500 m/s.

A new "Hard Rock" class (termed 'Ao' by Martin and Dobry (1994) and, we believe, adopted into the 1994 NEHRP), has been defined to have average velocity >1500 m/s, and is appropriate for eastern hard-rock sites. Martin and Dobry (1994) reported the conclusions of a 1992 workshop on earthquake site response which represented the consensus of Borcherdt, Dobry and Seed. Their Tables 2 and 3 (reproduced in our Appendix) show that for both 0.3 s and 1 s periods, and for all shaking intensities, motions on Class A sites are 25% higher than on Class Ao sites. Although they specifically note that their analysis of Fa and Fv factors "does not address the period range between 0 and about 0.2 seconds, and thus cannot be used to amplify peak accelaration or other high frequency spectral values" we consider this caution does not apply to the A to Ao relation. Hence, we increase the B6 coefficients by the 25% factor (0.097 log units), and consider these new RGC factors to represent the difference in amplification between the hard-rock sites for which the Atkinson-Boore relations were derived and our reference "Class B" ground condition.

The Reference Ground Condition (RGC) factors in Table 1 have been used to amplify seismic hazard *spectral* values calculated for the hard-rock Atkinson-Boore relations to those to be expected for the reference ground condition. This is mathematically identical to introducing the appropriate log factors into the Atkinson-Boore strong ground motion relations (e.g. through Atkinson's 1995 soil-response parameter, S) before the hazard calculation. For consistency, a similar factor must be applied to the PGA and PGV values, but for those parameters it is necessary to assign an average period for the motions; we have chosen 0.1 s for PGA and 0.5 s for PGV, but recognize that these periods may be a function of earthquake magnitude and distance. It is important to realize that hard-rock hazard values for eastern sites can be extracted from Tables 3-12 by dividing the tabulated values by the appropriate RGC value from Table 1; these values are also given in footnotes to the tables.

Not too much should be read into the 3-figure precision for the RGC factors supplied in Table 1. We considered multiplying all periods by a simple factor of two, being a crude approximation with no pretensions to either accuracy or precision, however, on balance we feel that the tabulated RGC values better represent the period dependence. If new information on the reference ground condition arises, it can be incorporated by the revision of the "RGC" factor. (We note, for example, that some theoretical considerations based on seismic velocity impedance contrasts might suggest a factor of two between classes A and Ao).

The effect of the RGC approach is to flatten the spectra of eastern sites, most particularly by the decrease in amplification at 0.1 s. This is evident in Table 2 and Figure 3 which compare the 84th percentile hazard values for Montreal for hard-rock and RGC scenarios.

Discussion regarding the Reference Ground Condition for Canada

The proposed scheme allows the uniform representation of seismic hazard across Canada. The choice of Class B soil as the reference is appropriate, because this is the ground condition with the best observational data set (from California) and is the basis for the BJF relations we are using for western Canada. However, we emphasize we are not making any judgment as to whether Class B is a typical or even a common condition in either western or eastern Canada. Adjustments will need to be made to compensate for ground conditions different from Class B, most probably through a redefined Foundation factor, F. It is entirely possible that most sites will not have F = 1.0.

The choice of Class B soil (and hence the RGC factors in Table 1) places some constraints on the Foundation factors that must be used with the hazard results. In the current (1990) National Building Code of Canada, Foundation factors (F) of 1.0, 1.3, 1.5, and 2.0 are applied to the zonal hazard values, both east and west, dependent on the type and depth of soil as described in Table 4.1.9.C. The current code considers only amplifications of the computed hazard, and gives no credit for sites on hard rock. We accept that a consistent set of foundation factors should adjust the ground motion levels on the reference soil (irrespective of whether it is sited in the east or the west) to the various different ground conditions that are typical. For some conditions, e.g., long period motion on thick soft soils, this will be an amplification from the computed hazard (like the current code), for short period motion the amplification may be traded off against anelastic attenuation, reducing the motions.

Hence, our choice of Soil Class B requires that considerable deamplification also be allowed (i.e., $F < 1$) to give credit for better ground conditions than Class B. To be explicit, a period-dependent F factor which is the exact inverse of the RGC values in Table 1, would be required in order to recover the "hard-rock" ground motions, which should be the basis for design levels if a building's foundation is set on, or blasted into, hard rock. Although these "exact" foundation factors are correct, a simplified set may be more appropriate for the code. The same deamplification may occur in both eastern and western Canada, because some west coast rock sites have just as high a rock velocity as many eastern hard rock site; though others may be equivalent to California class A rock.

A further complication is that actual soil sites differ in both thickness and average velocity from the reference Class B condition. Class B was established for California, where most soils would be considered "deep", say 60 m thick, in contrast to much of eastern Canada where many firm soils are "thin". A soil column that is similar to the Class B soil, but only half as thick, will give both a different amount of amplification, but also a different distribution of amplification with period. Another issue not fully addressed by the movement in the U.S. to use average velocity of the soil/rock column in the top 30 m is the treatment of thin, very low velocity sediment over rock, which could have the same average 30-m velocity as a 30-m firm soil but very different amplifications.

It has been suggested that the typical eastern site has thinner and firmer soil than Class B; this will tend to cause less amplification at long periods, but more at short periods (because of competing effects involving thickness and the Kappa factor, i.e. anelastic attenuation). Hard data is sparse for eastern Canada, but five seismometer sites in southern Ontario (founded on firm till, but underlain by an unknown thickness of sediment of unknown properties) have considerable short-period amplifications (G. Atkinson, pers. comm., 1995), exceeding a factor of 5 at 0.1 s for station WEO (Atkinson, 1989).

These are factors that need to be considered jointly between seismologists and foundation engineers. It may be that the simple $F = 1, 1.3...$ factors of the existing code need to recognize the different period effects of thin and deep soils; one satisfactory way of doing this might be to make the F factors dependent on building height (1-2 storeys, 3-7 storeys, etc), since a continuous distribution of frequency-dependent F's, is clearly inappropriate.

RESULTS

Tables 3-12 give hazard values for selected Canadian cities, itemizing separately the values for the H and R models and the Cascadia results, and the 50th and 84th percentiles. (Note that some parts of the tables are blank when that parameter is not computed for either east or west.). Table 13 is taken from Adams et al. (1995b) and represents the summary of the values in Tables 3-12 provided to engineers for the purposes of proposing changes to the National Building Code.

Combining diverse hazard estimates using the 'robust' approach

It is important to realize that each of the entries labelled 'H' or 'R' in the tables represents the result of a complete probabilistic hazard calculation. Combining such diverse models within a probabilistic framework inevitably requires that one or other alternative models be down-weighted, thus reducing the protection it would otherwise provide.

Adams et al. (1994; 1995a) suggest a 'quasi-probabilistic' alternative method that they term "robust". We first compute the probabilistic hazard for a 100% **H** and for a 100% **R** model using the same grid of points, and then choose the higher value for each grid point to be contoured for the "robust" map. The mapped "robust" estimates are "probabilistic" at any one place, in that for each site and every ground motion parameter being 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 period to period at a particular site.

The chief advantage of the "robust" approach is that it preserves protection in areas of high seismicity but also provides increased protection in currently-aseismic areas that are geologically-likely to have future large earthquakes. A further advantage is that the approach is computationally simple, and it is easy to explain what was done. Finally the method allows a simple combination of deterministic and probabilistic hazard where this is desired. For example, the values for the seismic hazard from the Cascadia subduction zone in the Tables 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.

Choice of Confidence Level

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[2]. 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.

The forthcoming paper by Naumoski and Heidebrecht (1995) proposes that the 84th percentile values be used to determine seismic loading because it ensures that there is little likelihood the design value will be exceeded, so providing an appropriate degree of engineering conservatism

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[2] The 84th percentile is often chosen, because for a normal (or lognormal) distribution it corresponds the median plus one standard deviation. The standard deviation is less meaningful in our case, since the distributions of ground motions can be quite asymmetrical, due to the fact that the epistemic distribution is or can be quite asymmetric, and may be far from lognormal. Nevertheless, the use of the 84th percentile does include a measure of the epistemic uncertainty which we wish to include.

consistent with general engineering practice. Explicitly, that proposal is saying that instead of accepting a 50% chance that the 0.0021 p.a. ground motion *will* be exceeded, it would be better to choose a higher ground motion level and then be 84% sure that this higher value *will not* be exceeded.

Uniform Hazard Spectra

Spectral plots (Figures 4-25) show the results from Tables 3-10 as Uniform Hazard Spectra (UHS). Each figure shows the median (50th percentile) and 84th percentile UHS determined by the robust approach, ie., the values plotted for each period are the higher of the H or R model values. Hence adjacent values may be taken from different models. Note that it is inappropriate to display PGA values on these plots (even though PGA is sometimes plotted at 0.03 s or 0.01 s), because its associated period differs from place to place and is generally not known.

Non-Newmark-Hall amplification

The previous code used scaled Newmark-Hall spectra (Newmark and Hall, 1969; 1982). 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 a 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., Figs 4-25) which have variable shapes and amplification factors different from the deterministically-derived Newmark-Hall spectrum.

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TABLES

FIGURE CAPTIONS

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.

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 curve (bold) are flanked by upper and lower "error" curves that are more widely separated for the poorly-constrained NAT dataset. All curves are asymptotic to assumed upper bound magnitudes.

Figure 3. Seismic hazard for Montreal depicted as Uniform Hazard Spectra on various ground conditions. These 84th percentile UHS from the **R** model are derived from values given in Tables 3-9 for hard-rock and soil Class B using the RGC factors; a baseline derived from the hard-rock values using a uniform amplification of a factor of two is shown for comparison.

Figures 4-25 show the 0.0021 per annum ground motion results as Uniform Hazard Spectra for the named city. The 50th percentile (thick solid line) and 84th percentile (thick dashed line) UHS are derived by the robust method from the **H** and **R** model values given in Tables 3-10. For southwestern Canadian cities, two additional curves (light lines) are shown. These are the 50th and 84th percentile spectra for the deterministic values from a M8.2 Cascadia event, as given in Tables 3-10.

Figure 4. St. John's
Figure 5 Halifax
Figure 6. Moncton
Figure 7. Fredericton
Figure 8. La Malbaie
Figure 9. Quebec
Figure 10. Trois-Rivieres
Figure 11. Montreal
Figure 12. Ottawa
Figure 13. Niagara Falls
Figure 14. Toronto
Figure 15. Windsor
Figure 16. Calgary
Figure 17. Kelowna
Figure 18. Kamloops
Figure 19. Prince George
Figure 20. Vancouver
Figure 21. Victoria
Figure 22. Tofino
Figure 23. Prince Rupert
Figure 24. Queen Charlotte
Figure 25. Inuvik

TABLE 1

Reference Ground Condition factors

Period (s)	B6	A-to-Ao	C_5	RGC multiplicative
	.........log$_{10}$ units.........			
0.1	0.046	0.097	0.143	1.39
0.15	0.140	0.097	0.237	1.73
0.2	0.190	0.097	0.287	1.94
0.3	0.239	0.097	0.336	2.17
0.4	0.264	0.097	0.361	2.30
0.5	0.279	0.097	0.376	2.38
1.0	0.314	0.097	0.411	2.58
PGA	0.046	0.097	0.143	1.39
PGV	0.279	0.097	0.376	2.38

Notes:

1. column B6 is taken from Boore-Joyner-Fumal (1993) Table 7b.
2. the A-to-Ao conversion is +25% from Martin and Dobry (1994) Tables 2 and 3 (site class A = 1.0, site class Ao = 0.8 for all shaking intensities and both Fa and Fv periods (which are about 0.3 s and 1.0 s)).
3. column C_5 contains the proposed coefficients (in $\log_{10}$ units) to be used for Class B soil with Atkinson's (1995) S parameter.
4. the RGC (Reference Ground Condition) factor represents the C_5 values as a multiplicative factor, and is intended to modify eastern hard rock hazard values to those expected on the reference ground condition of "Class B" soil.
5. RGC factors for PGA and PGV were assigned by associating them with periods of 0.1 s and 0.5 s., respectively.

TABLE 2

Effects of new ground condition factors for a sample eastern site (Montreal)

Period (s)	Hard rock	Soil B
0.1	30	42
0.15	28	48
0.2	26	50
0.3	20	43
0.4	16	38
0.5	14	33
1.0	6.5	17

Notes:

1. Entries in the table represent the 84 percentile values of the 0.0021 p.a. seismic hazard (5% damped PSA values in %g) for the R model.
2. The "Hard rock" values are those computed using the Atkinson (1995) hard-rock ground motion relations; "Soil B" is the amplification of the hard rock values by the RGC factors given in Table 1).

Table 3. Pseudo-Spectral Acceleration for firm soil at 0.1 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	4.4	6.4	6.0	9.3		
Halifax	44.6	63.6	4.5	8.3	6.1	12		
Moncton	46.1	64.8	13	11	18	16		
Fredericton	45.9	66.6	14	15	20	22		
La Malbaie	47.6	70.1	93	27	150	37		
Quebec	46.8	71.2	21	23	29	32		
Trois-Rivieres	46.3	72.5	12	29	18	41		
Montreal	45.5	73.6	23	31	35	42		
Ottawa	45.4	75.7	18	27	27	37		
Niagara Falls	43.1	79.1	17	8.5	25	14		
Toronto	43.7	79.4	9.6	7.2	15	11		
Windsor	42.3	83.0	4.0	6.4	5.8	10		
Calgary	51.0	114.0	2.4	3.4	4.5	6.4	2.3	5.0
Kelowna	49.9	119.4	10	8.1	20	16	6.3	13
Kamloops	50.7	120.3	9.9	8.2	19	16	6.3	13
Prince George	53.9	122.7	3.0	3.2	5.5	6.0	4.4	9.1
Vancouver	49.2	123.2	37	41	77	87	15	32
Victoria	48.5	123.3	47	47	100	110	23	47
Tofino	49.1	125.9	14	20	30	41	34	71
Prince Rupert	54.3	130.4	6.2	12	12	23		
Queen Charlotte	53.3	132.0	24	27	47	52		
Inuvik	68.4	133.6	3.5	3.4	6.8	6.4		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 1.39 (see text).
Cascadia values are given only where relevant.

Table 4. Pseudo-Spectral Acceleration for firm soil at 0.15 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	4.8	8.0	8.7	13		
Halifax	44.6	63.6	5.3	9.3	10	16		
Moncton	46.1	64.8	12	11	22	20		
Fredericton	45.9	66.6	14	14	26	27		
La Malbaie	47.6	70.1	100	27	170	42		
Quebec	46.8	71.2	22	23	35	36		
Trois-Rivieres	46.3	72.5	13	29	24	45		
Montreal	45.5	73.6	24	30	40	48		
Ottawa	45.4	75.7	18	28	34	44		
Niagara Falls	43.1	79.1	15	8.7	30	16		
Toronto	43.7	79.4	8.8	7.5	19	14		
Windsor	42.3	83.0	4.8	6.6	8.7	12		
Calgary	51.0	114.0	3.4	4.7	7.4	10	2.6	5.3
Kelowna	49.9	119.4	12	9.7	25	19	6.9	14
Kamloops	50.7	120.3	12	10	25	20	6.9	14
Prince George	53.9	122.7	4.3	4.5	9.0	9.7	4.7	9.6
Vancouver	49.2	123.2	45	44	97	95	16	33
Victoria	48.5	123.3	57	50	120	110	24	49
Tofino	49.1	125.9	18	27	37	51	36	74
Prince Rupert	54.3	130.4	9.5	16	18	33		
Queen Charlotte	53.3	132.0	34	37	65	72		
Inuvik	68.4	133.6	5.3	5.0	11	11		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 1.73 (see text).
Cascadia values are given only where relevant.

Table 5. Pseudo-Spectral Acceleration for firm soil at 0.2 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	6.2	9.2	11	16		
Halifax	44.6	63.6	7.0	11	12	19		
Moncton	46.1	64.8	14	13	24	22		
Fredericton	45.9	66.6	16	17	27	29		
La Malbaie	47.6	70.1	100	25	170	44		
Quebec	46.8	71.2	24	22	40	38		
Trois-Rivieres	46.3	72.5	16	27	27	47		
Montreal	45.5	73.6	24	29	42	50		
Ottawa	45.4	75.7	21	27	36	46		
Niagara Falls	43.1	79.1	15	9.6	30	17		
Toronto	43.7	79.4	10	8.7	20	15		
Windsor	42.3	83.0	5.8	7.3	9.8	12		
Calgary	51.0	114.0	6.7	9.1	12	17	3.3	6.3
Kelowna	49.9	119.4	19	14	37	28	8.6	17
Kamloops	50.7	120.3	19	15	37	31	8.6	17
Prince George	53.9	122.7	7.7	8.5	15	16	5.8	12
Vancouver	49.2	123.2	58	59	120	120	20	40
Victoria	48.5	123.3	78	65	160	140	30	59
Tofino	49.1	125.9	29	42	56	87	45	88
Prince Rupert	54.3	130.4	17	30	34	56		
Queen Charlotte	53.3	132.0	58	64	130	140		
Inuvik	68.4	133.6	10	10	20	19		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 1.94 (see text).
Cascadia values are given only where relevant.

Table 6. Pseudo-Spectral Acceleration for firm soil at 0.3 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	11	8.5	20	18		
Halifax	44.6	63.6	5.5	9.2	11	19		
Moncton	46.1	64.8	6.8	10	13	23		
Fredericton	45.9	66.6	12	13	25	26		
La Malbaie	47.6	70.1	70	18	150	38		
Quebec	46.8	71.2	19	16	38	34		
Trois-Rivieres	46.3	72.5	13	20	28	40		
Montreal	45.5	73.6	18	20	35	43		
Ottawa	45.4	75.7	15	19	31	40		
Niagara Falls	43.1	79.1	10	7.5	25	15		
Toronto	43.7	79.4	8.0	7.3	18	15		
Windsor	42.3	83.0	4.5	5.5	9.2	11		
Calgary	51.0	114.0	3.5	4.7	7.6	10	3.2	6.1
Kelowna	49.9	119.4	12	9.1	22	17	8.0	15
Kamloops	50.7	120.3	11	9.7	22	18	8.0	15
Prince George	53.9	122.7	4.2	4.5	8.7	9.6	5.6	11
Vancouver	49.2	123.2	38	38	74	73	18	35
Victoria	48.5	123.3	48	42	99	83	26	51
Tofino	49.1	125.9	17	24	34	47	39	75
Prince Rupert	54.3	130.4	10	16	20	32		
Queen Charlotte	53.3	132.0	36	39	70	78		
Inuvik	68.4	133.6	5.7	5.6	12	12		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 2.17 (see text).
Cascadia values are given only where relevant.

Table 7. Pseudo-Spectral Acceleration for firm soil at 0.4 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	4.0	7.9	9.8	19		
Halifax	44.6	63.6	5.3	8.1	13	20		
Moncton	46.1	64.8	8.7	8.7	21	21		
Fredericton	45.9	66.6	10	11	25	26		
La Malbaie	47.6	70.1	55	14	130	34		
Quebec	46.8	71.2	14	12	35	31		
Trois-Rivieres	46.3	72.5	10	15	25	36		
Montreal	45.5	73.6	13	16	32	38		
Ottawa	45.4	75.7	11	15	27	35		
Niagara Falls	43.1	79.1	8.3	6.0	20	14		
Toronto	43.7	79.4	6.1	5.6	15	13		
Windsor	42.3	83.0	3.4	4.1	8.4	9.9		
Calgary	51.0	114.0	3.0	4.0	6.2	8.1	4.0	7.5
Kelowna	49.9	119.4	8.7	6.8	16	13	9.4	18
Kamloops	50.7	120.3	8.6	7.4	16	14	9.4	18
Prince George	53.9	122.7	3.6	3.9	6.9	7.9	6.7	13
Vancouver	49.2	123.2	25	25	42	44	20	38
Victoria	48.5	123.3	33	27	56	46	28	54
Tofino	49.1	125.9	14	19	25	37	40	77
Prince Rupert	54.3	130.4	9.5	14	18	28		
Queen Charlotte	53.3	132.0	34	36	64	71		
Inuvik	68.4	133.6	4.9	5.0	10	11		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 2.30 (see text).
Cascadia values are given only where relevant.

Table 8. Pseudo-Spectral Acceleration for firm soil at 0.5 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	7.3	6.1	18	15		
Halifax	44.6	63.6	3.6	6.5	9.4	16		
Moncton	46.1	64.8	4.7	7.3	12	18		
Fredericton	45.9	66.6	8.5	8.8	22	23		
La Malbaie	47.6	70.1	46	11	120	29		
Quebec	46.8	71.2	12	10	32	27		
Trois-Rivieres	46.3	72.5	8.8	12	23	31		
Montreal	45.5	73.6	11	13	28	33		
Ottawa	45.4	75.7	9.3	12	24	31		
Niagara Falls	43.1	79.1	6.5	4.9	17	12		
Toronto	43.7	79.4	4.9	4.6	13	12		
Windsor	42.3	83.0	2.8	3.4	7.4	8.9		
Calgary	51.0	114.0	2.8	3.4	5.0	6.6	3.4	6.4
Kelowna	49.9	119.4	8.2	6.6	16	13	8.4	16
Kamloops	50.7	120.3	8.0	6.9	16	14	8.4	16
Prince George	53.9	122.7	3.1	3.4	5.8	6.6	5.8	11
Vancouver	49.2	123.2	28	27	52	51	19	37
Victoria	48.5	123.3	35	31	67	57	27	53
Tofino	49.1	125.9	13	17	25	34	40	77
Prince Rupert	54.3	130.4	8.8	12	17	24		
Queen Charlotte	53.3	132.0	32	34	59	65		
Inuvik	68.4	133.6	4.3	4.5	8.7	9.2		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 2.38 (see text).
Cascadia values are given only where relevant.

Table 9. Pseudo-Spectral Acceleration for firm soil at 1.0 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	1.7	3.2	4.8	8.7		
Halifax	44.6	63.6	2.3	3.2	6.8	8.9		
Moncton	46.1	64.8	2.9	3.3	9.5	9.7		
Fredericton	45.9	66.6	3.5	3.7	11	11		
La Malbaie	47.6	70.1	19	4.4	58	14		
Quebec	46.8	71.2	5.3	4.1	17	13		
Trois-Rivieres	46.3	72.5	3.9	4.8	12	16		
Montreal	45.5	73.6	4.6	5.2	14	17		
Ottawa	45.4	75.7	4.1	5.0	12	16		
Niagara Falls	43.1	79.1	2.7	2.2	8.0	6.4		
Toronto	43.7	79.4	1.8	2.2	6.1	6.2		
Windsor	42.3	83.0	0.9	1.4	3.4	4.3		
Calgary	51.0	114.0	1.3	1.7	2.6	3.5	2.5	5.4
Kelowna	49.9	119.4	4.3	3.8	9.1	7.6	6.4	14
Kamloops	50.7	120.3	4.3	4.0	8.9	8.0	6.4	14
Prince George	53.9	122.7	1.6	1.9	3.2	3.8	4.5	9.5
Vancouver	49.2	123.2	14	14	31	29	15	31
Victoria	48.5	123.3	18	16	38	33	21	45
Tofino	49.1	125.9	7.2	9.0	15	18	31	66
Prince Rupert	54.3	130.4	6.4	8.2	13	16		
Queen Charlotte	53.3	132.0	20	23	41	44		
Inuvik	68.4	133.6	2.5	2.9	4.9	5.5		

Notes:

Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 2.58 (see text).
Cascadia values are given only where relevant.

Table 10. Pseudo-Spectral Acceleration for firm soil at 2.0 s (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7						
Halifax	44.6	63.6						
Moncton	46.1	64.8						
Fredericton	45.9	66.6						
La Malbaie	47.6	70.1						
Quebec	46.8	71.2						
Trois-Rivieres	46.3	72.5						
Montreal	45.5	73.6						
Ottawa	45.4	75.7						
Niagara Falls	43.1	79.1						
Toronto	43.7	79.4						
Windsor	42.3	83.0						
Calgary	51.0	114.0	0.8	1.0	1.6	2.0	1.5	3.2
Kelowna	49.9	119.4	2.1	1.9	4.2	3.9	3.1	6.2
Kamloops	50.7	120.3	2.1	2.1	4.1	4.2	3.1	6.2
Prince George	53.9	122.7	1.0	1.3	1.9	2.5	2.3	4.8
Vancouver	49.2	123.2	5.1	5.2	11	11	5.7	12
Victoria	48.5	123.3	6.5	5.4	13	11	7.5	15
Tofino	49.1	125.9	3.9	4.8	7.7	9.6	10	21
Prince Rupert	54.3	130.4	3.8	4.7	7.5	9.7		
Queen Charlotte	53.3	132.0	12	12	22	24		
Inuvik	68.4	133.6	1.6	1.8	3.2	3.6		

Notes: Seismic hazard levels (%g) for 5% damped spectral values for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Cascadia values are given only where relevant.
Spectral values for 2.0 s are not available for the east.

Table 11. Peak Ground Acceleration for firm soil (%g)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	2.9	4.2	4.1	6.1		
Halifax	44.6	63.6	3.1	5.2	4.3	7.6		
Moncton	46.1	64.8	8.7	7.6	13	12		
Fredericton	45.9	66.6	9.7	11	14	16		
La Malbaie	47.6	70.1	57	18	95	24		
Quebec	46.8	71.2	14	17	19	22		
Trois-Rivieres	46.3	72.5	8.1	20	12	27		
Montreal	45.5	73.6	16	21	24	27		
Ottawa	45.4	75.7	12	18	19	24		
Niagara Falls	43.1	79.1	13	5.9	18	10		
Toronto	43.7	79.4	6.8	5.0	10	8.0		
Windsor	42.3	83.0	2.5	4.7	3.7	7.5		
Calgary	51.0	114.0	2.4	3.3	4.6	5.9	0.6	1.3
Kelowna	49.9	119.4	5.7	4.0	12	8.0	2.5	5.5
Kamloops	50.7	120.3	5.8	4.4	12	9.2	2.5	5.5
Prince George	53.9	122.7	3.0	3.2	5.3	5.7	1.4	3.2
Vancouver	49.2	123.2	17	15	36	32	8.8	19
Victoria	48.5	123.3	23	17	48	36	15	33
Tofino	49.1	125.9	8.8	11	17	21	27	58
Prince Rupert	54.3	130.4	5.5	9.3	12	18		
Queen Charlotte	53.3	132.0	19	21	38	41		
Inuvik	68.4	133.6	3.5	3.3	6.9	6.4		

Notes: Seismic hazard levels (%g) for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 1.39 (see text).
Cascadia values are given only where relevant.

Table 12. Peak Ground Velocity for firm soil (m/s)

City	Coordinates		50%		84%		50%	84%
	°North	°West	H	R	H	R	Cascadia	
St. John's	47.6	52.7	0.019	0.032	0.049	0.073		
Halifax	44.6	63.6	0.027	0.034	0.061	0.080		
Moncton	46.1	64.8	0.041	0.039	0.10	0.097		
Fredericton	45.9	66.6	0.046	0.049	0.12	0.13		
La Malbaie	47.6	70.1	0.27	0.066	0.70	0.18		
Quebec	46.8	71.2	0.061	0.061	0.17	0.16		
Trois-Rivieres	46.3	72.5	0.046	0.073	0.12	0.19		
Montreal	45.5	73.6	0.066	0.075	0.17	0.21		
Ottawa	45.4	75.7	0.053	0.068	0.14	0.19		
Niagara Falls	43.1	79.1	0.044	0.032	0.12	0.075		
Toronto	43.7	79.4	0.032	0.029	0.080	0.068		
Windsor	42.3	83.0	0.015	0.024	0.041	0.056		

Notes: Seismic hazard levels (m/s) for a probability of 0.0021 p.a.
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', 'R', and 'Cascadia' are the models discussed in the text.
Eastern hard-rock values can be derived from the tabulated values by dividing by the RGC factor of 2.38 (see text).
PGV values are not available for the west

TABLE 13. 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) Cascadia 50%	0.5 s PSA (%g) Cascadia 84%
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	130	130	28	27	52	51	19	37
Victoria	48.5	123.3		23	78	65	200	160	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	140	160	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 reproduced from 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.

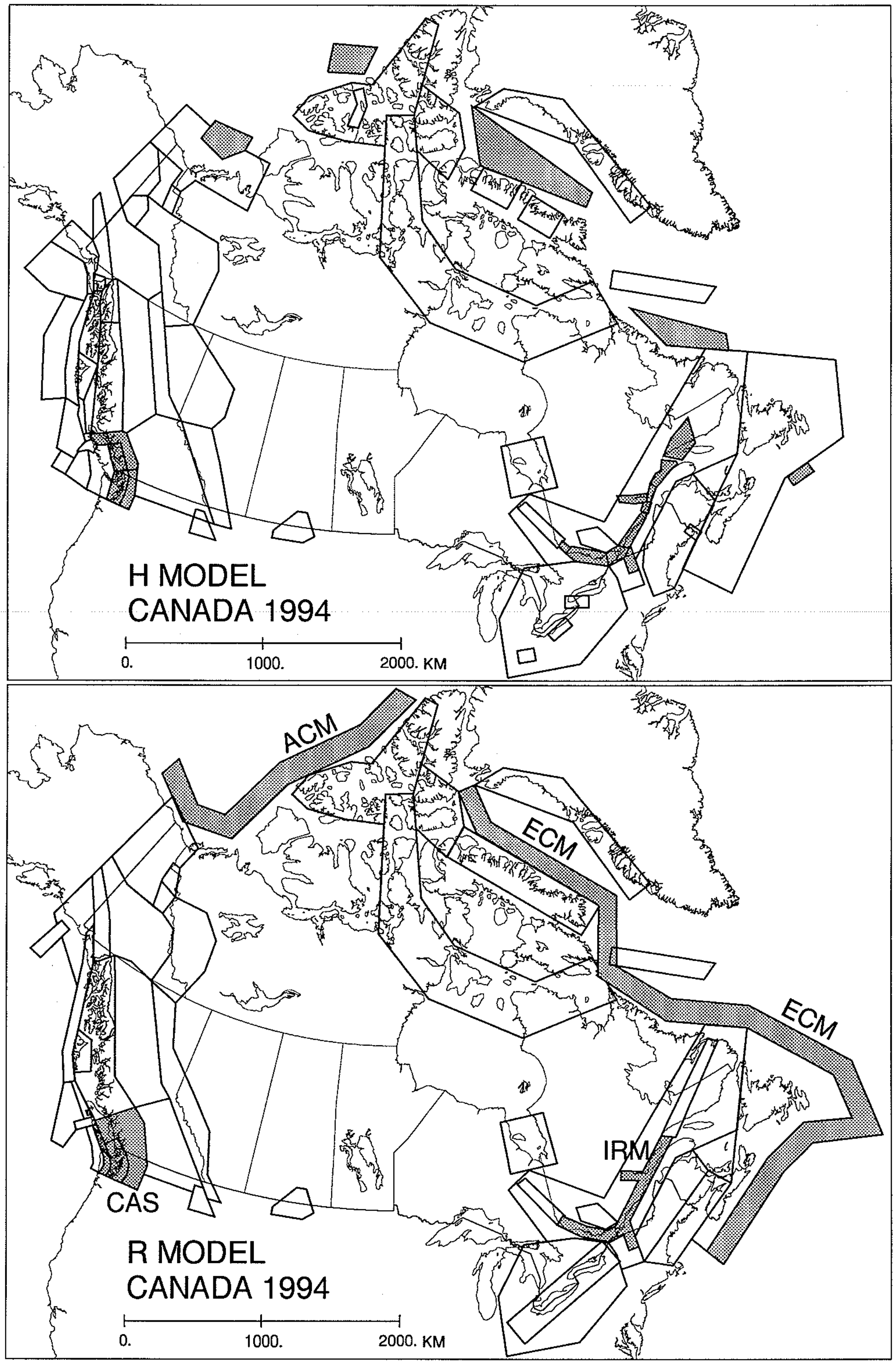

Figure 1. Earthquake source zone maps of Canada showing the zones that form the H (top) and R (bottom) models for earthquake distribution. Zones referred to in the text are shaded and labelled on the bottom map; corresponding H-model zones are shaded on the top map.

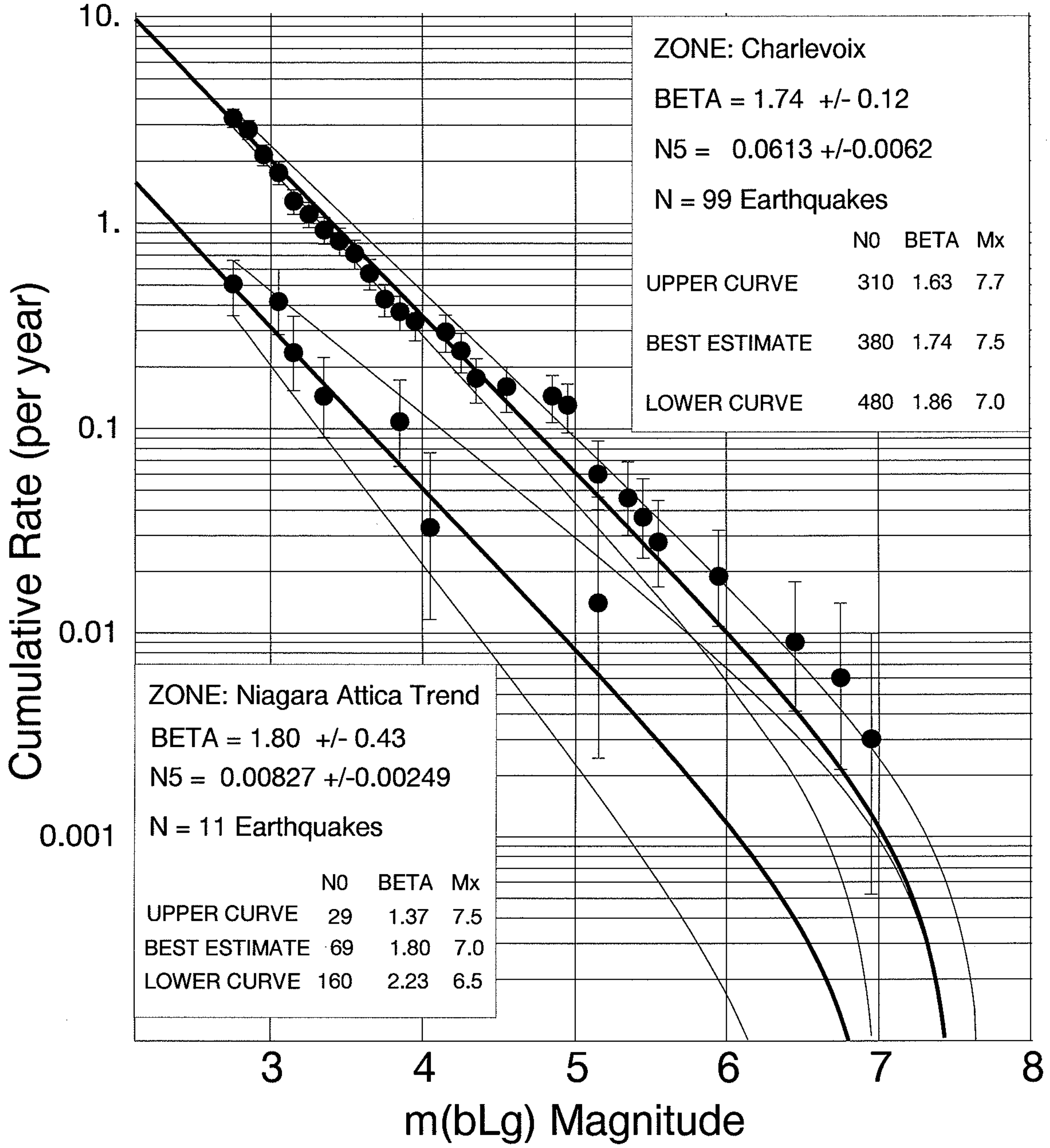

Figure 2. Sample magnitude-recurrence data and curves for Charlevoix and the Niagara-Attica Trend (NAT) zones. The cumulative rates of earthquakes are represented by solid circles with stochastic error bounds and the best-fit curve (bold) are flanked by upper and lower "error" curves that are more widely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

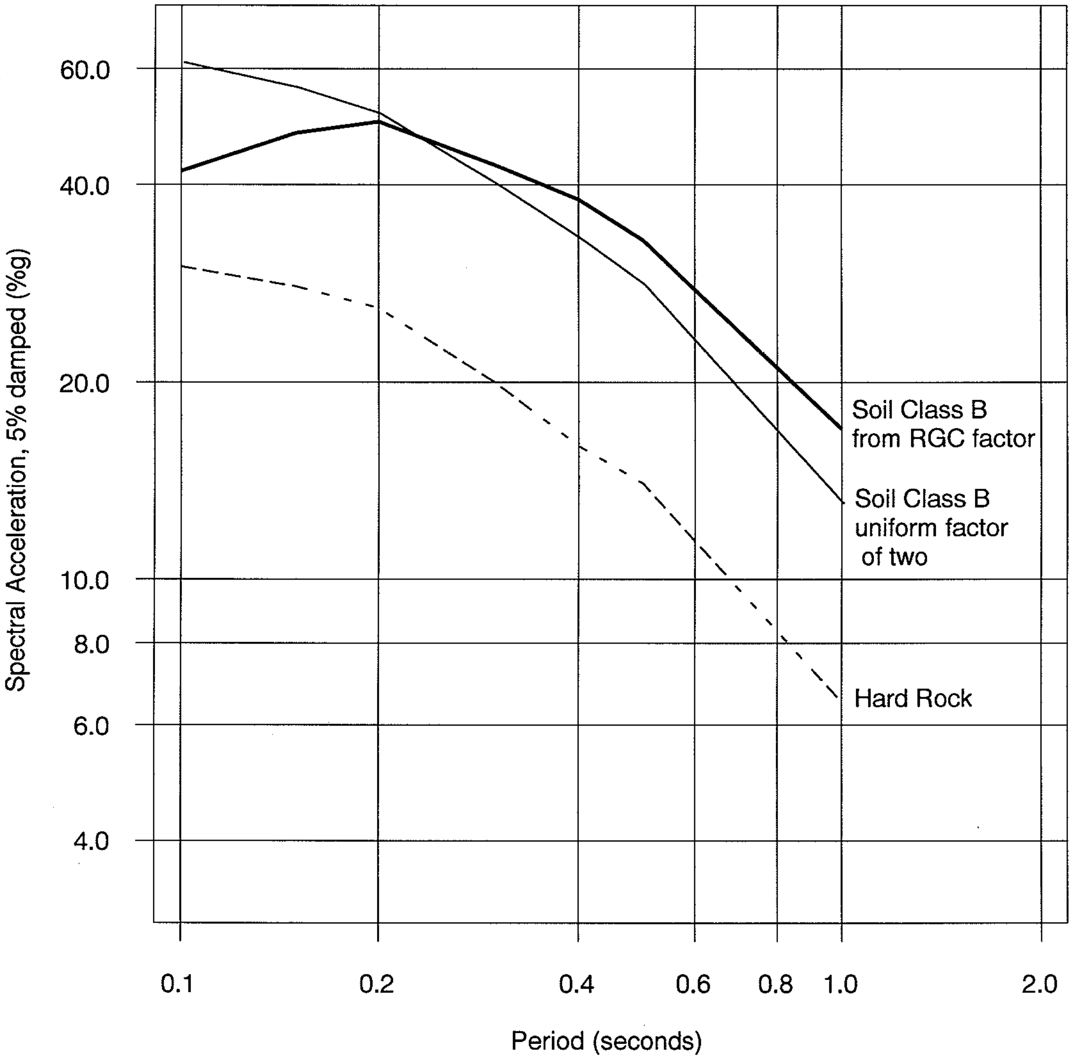

Figure 3. Seismic hazard for Montreal depicted as Uniform Hazard Spectra on various ground conditions. These 84th percentile UHS from the R model are derived from values given in Tables 3-9 for hard-rock and soil Class B using the RGC factors; a baseline derived from the hard-rock values using a uniform amplification of a factor of two is shown for comparison.

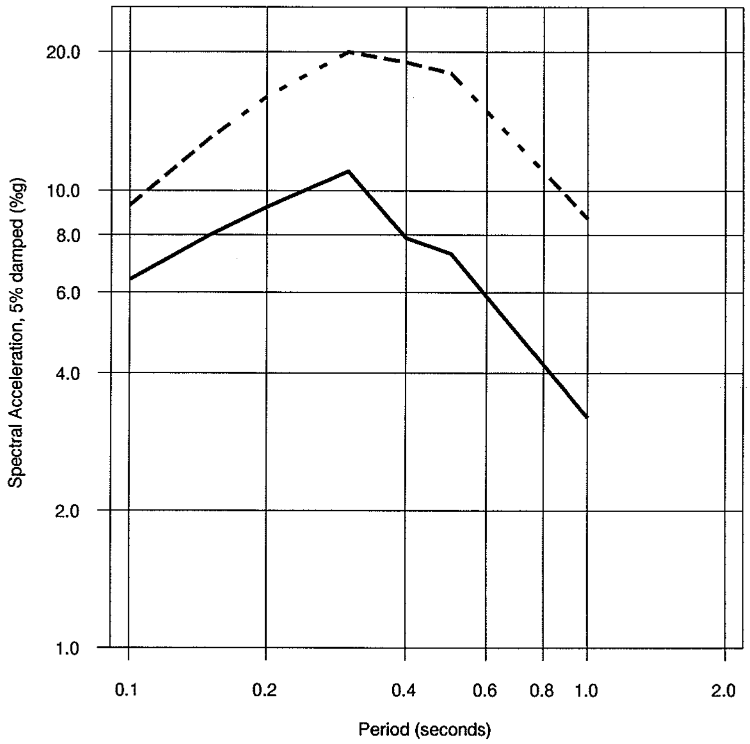

Figure 4. St. John's "Robust" Uniform Hazard Spectra

Figures 4-25 show the 0.0021 per annum ground motion results as Uniform Hazard Spectra for the named city. The 50th percentile (thick solid line) and 84th percentile (thick dashed line) UHS are derived by the robust method from the H and R model values given in Tables 1-8. For southwestern Canadian cities, two additional curves (light lines) are shown. These are the 50th and 84th percentile spectra for the deterministic values from a M8.2 Cascadia event, as given in Tables 1-8.

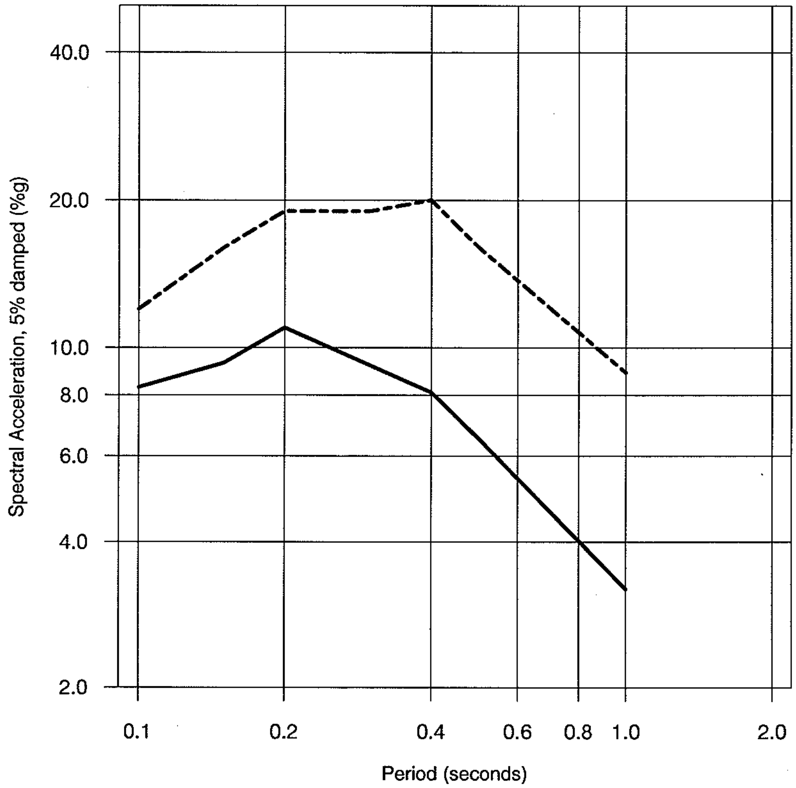

Figure 5. Halifax "Robust" Uniform Hazard Spectra

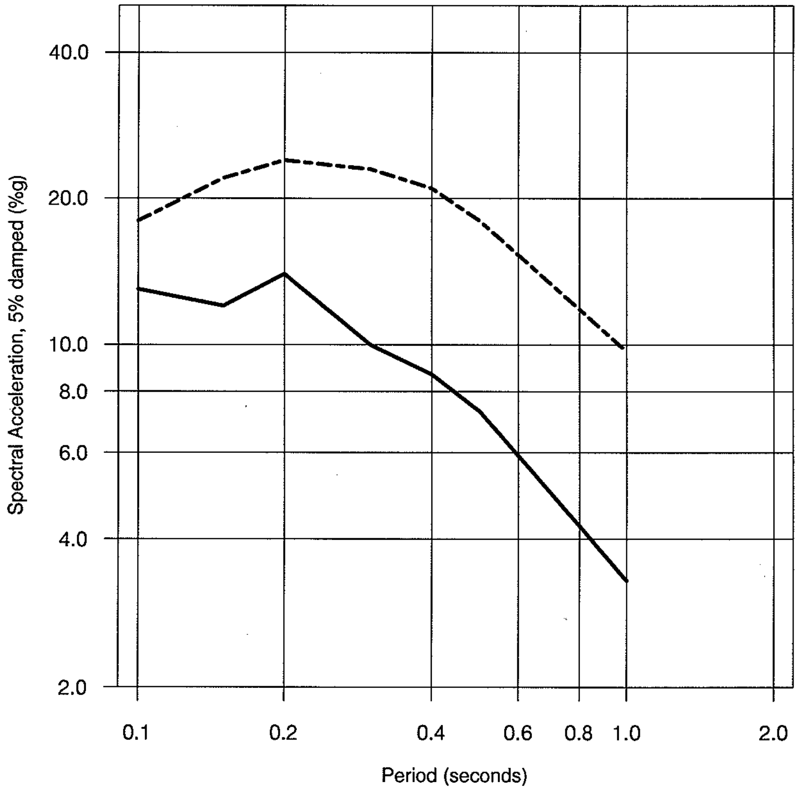

Figure 6. Moncton "Robust" Uniform Hazard Spectra

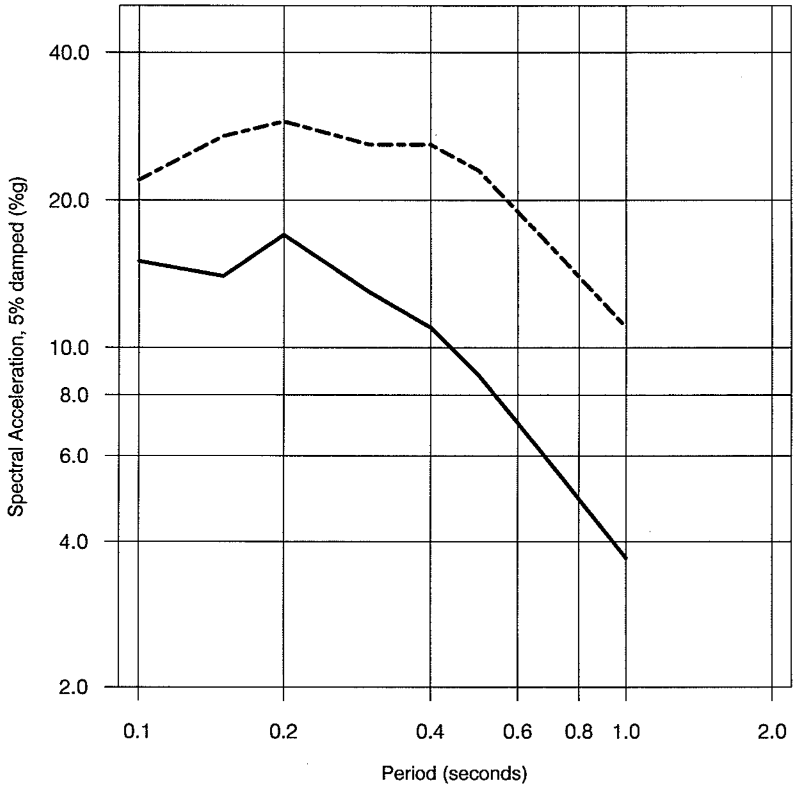

Figure 7. Fredericton "Robust" Uniform Hazard Spectra

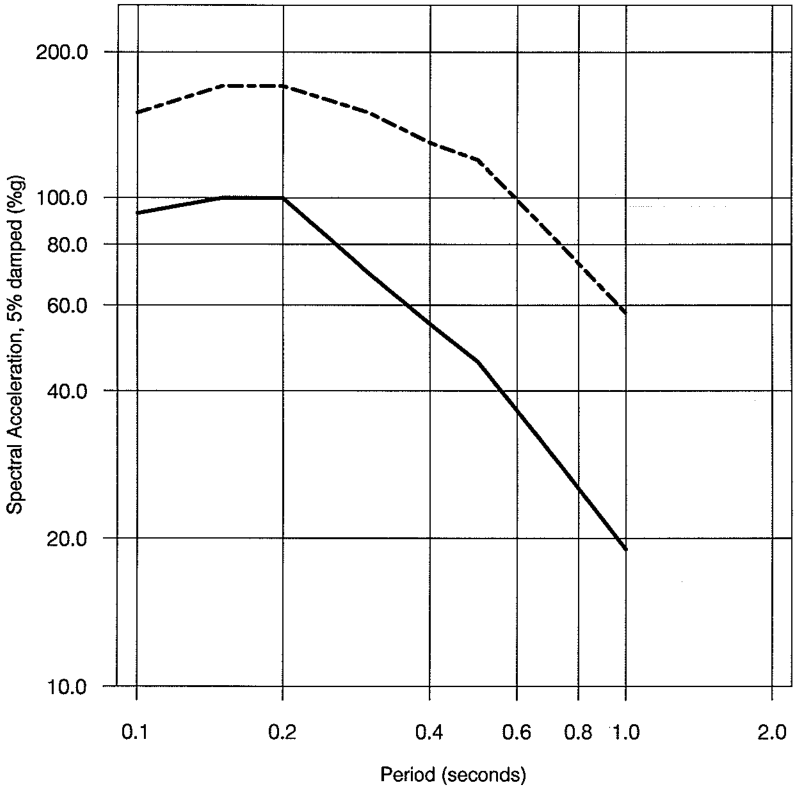

Figure 8. La Malbaie "Robust" Uniform Hazard Spectra

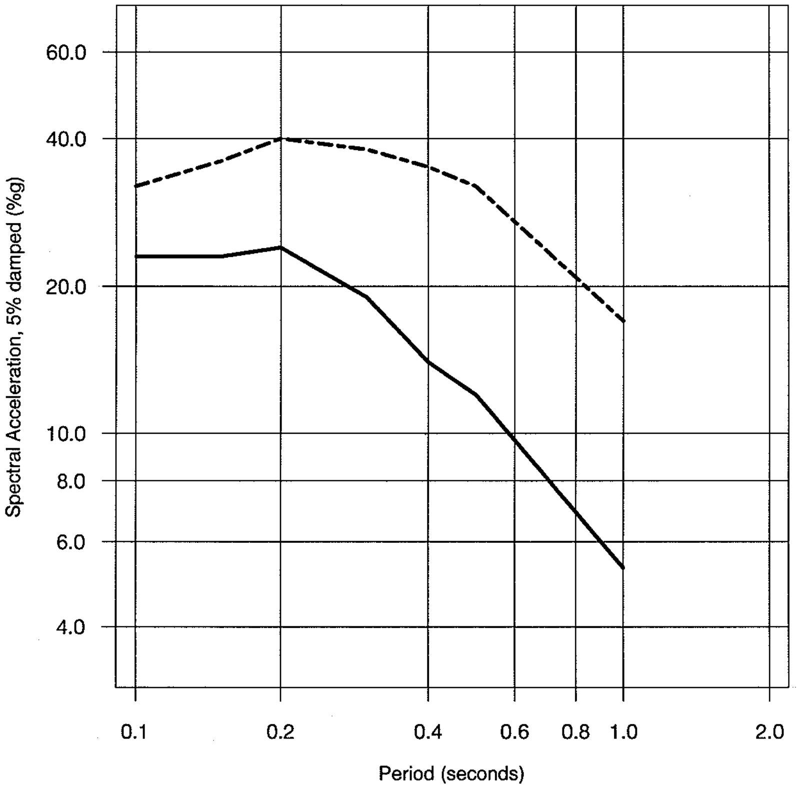

Figure 9. Quebec "Robust" Uniform Hazard Spectra

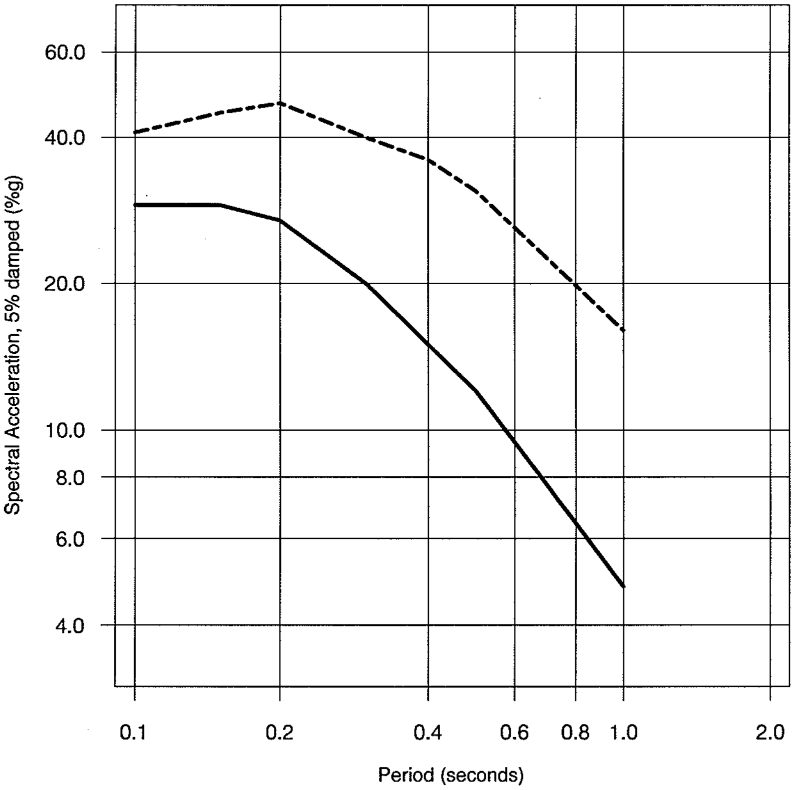

Figure 10. Trois-Rivieres "Robust" Uniform Hazard Spectra

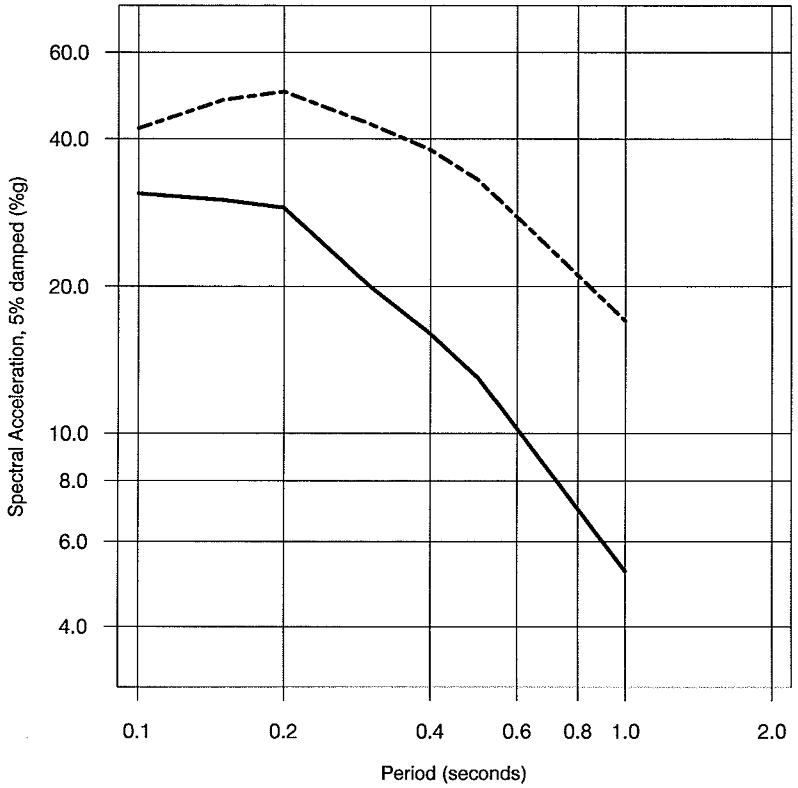

Figure 11. Montreal "Robust" Uniform Hazard Spectra

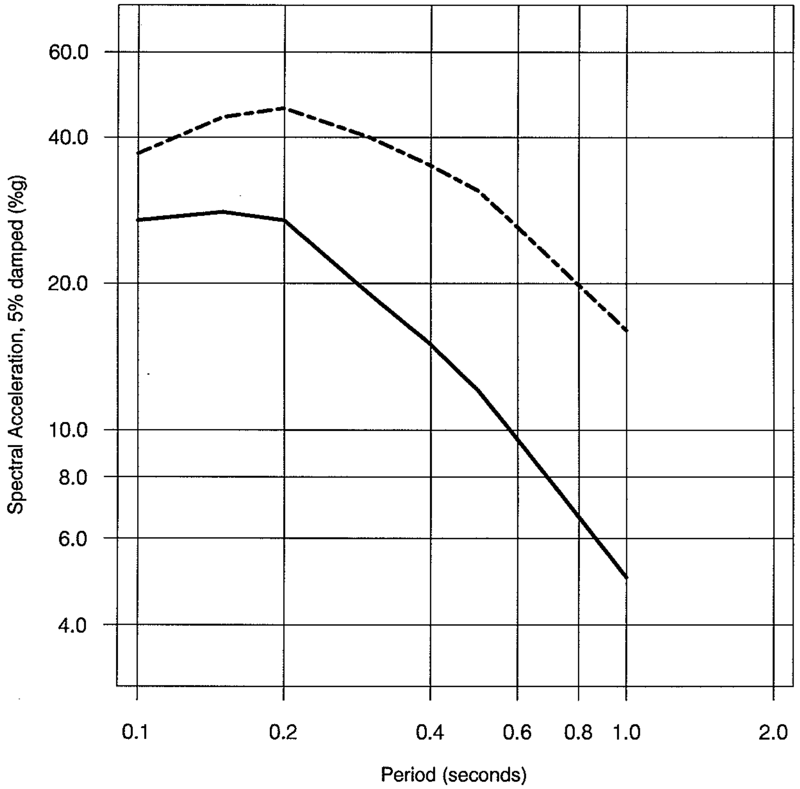

Figure 12. Ottawa "Robust" Uniform Hazard Spectra

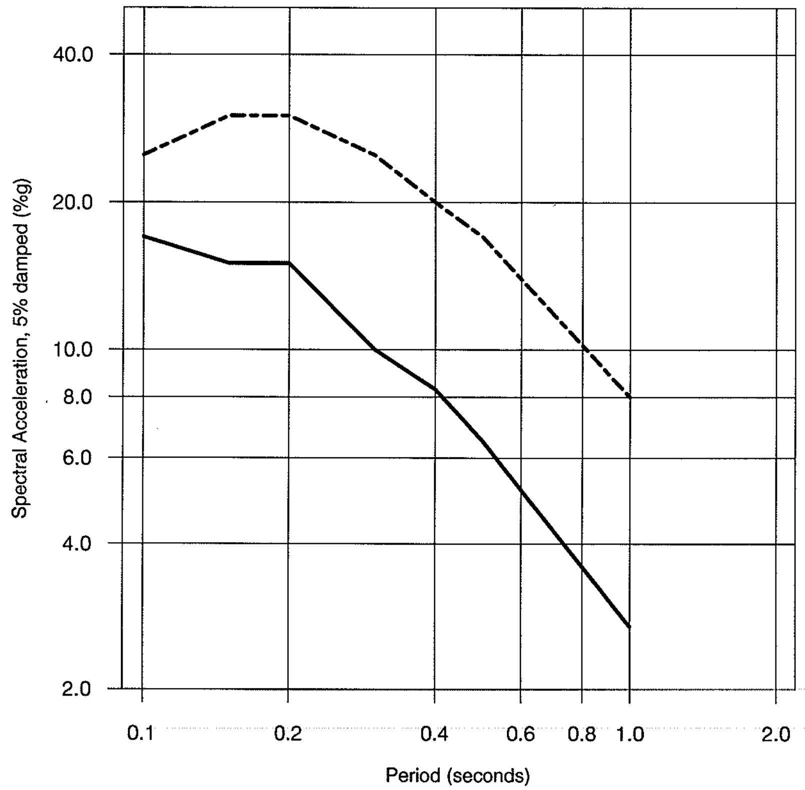

Figure 13. Niagara Falls "Robust" Uniform Hazard Spectra

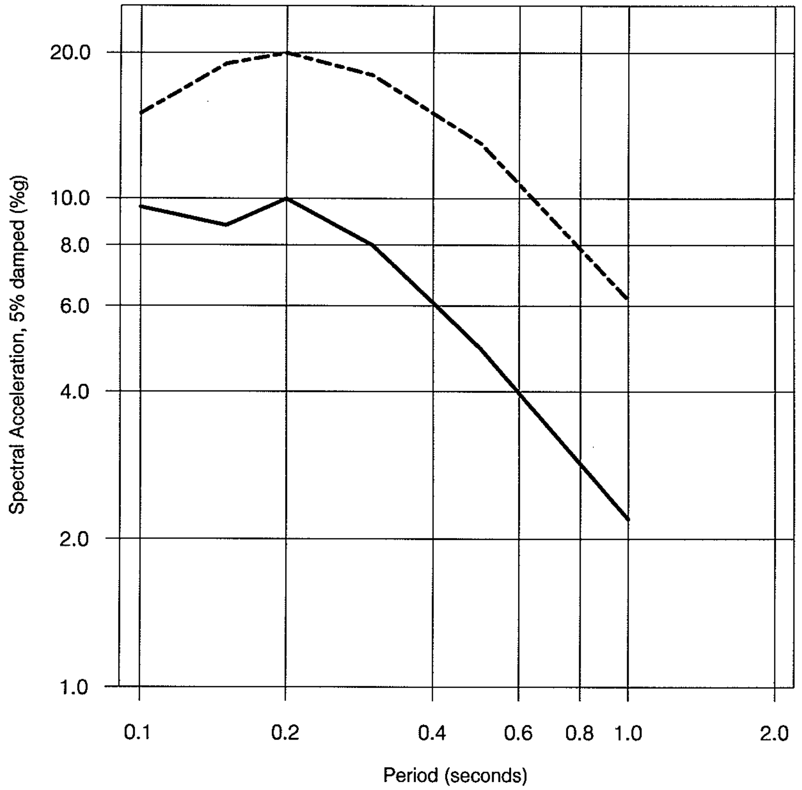

Figure 14. Toronto "Robust" Uniform Hazard Spectra

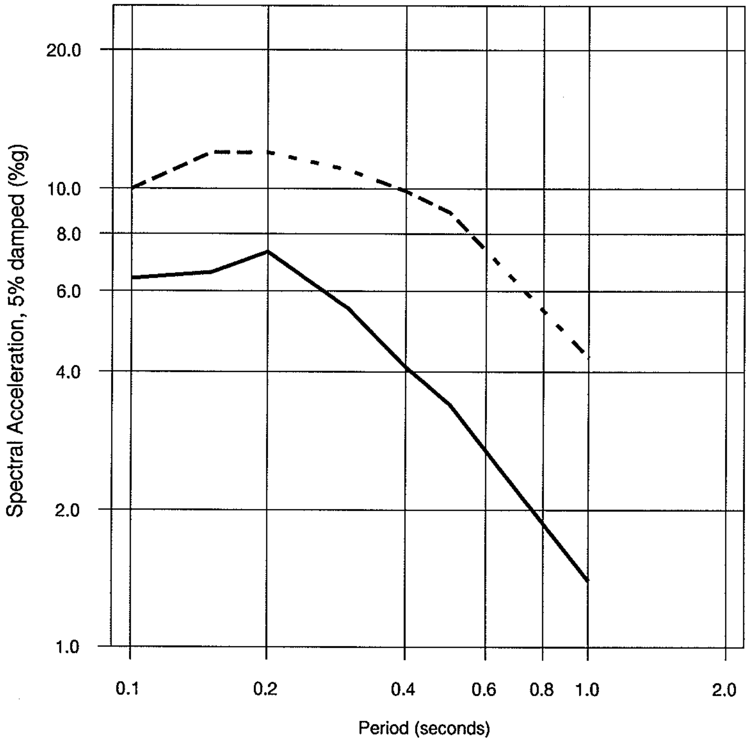

Figure 15. Windsor "Robust" Uniform Hazard Spectra

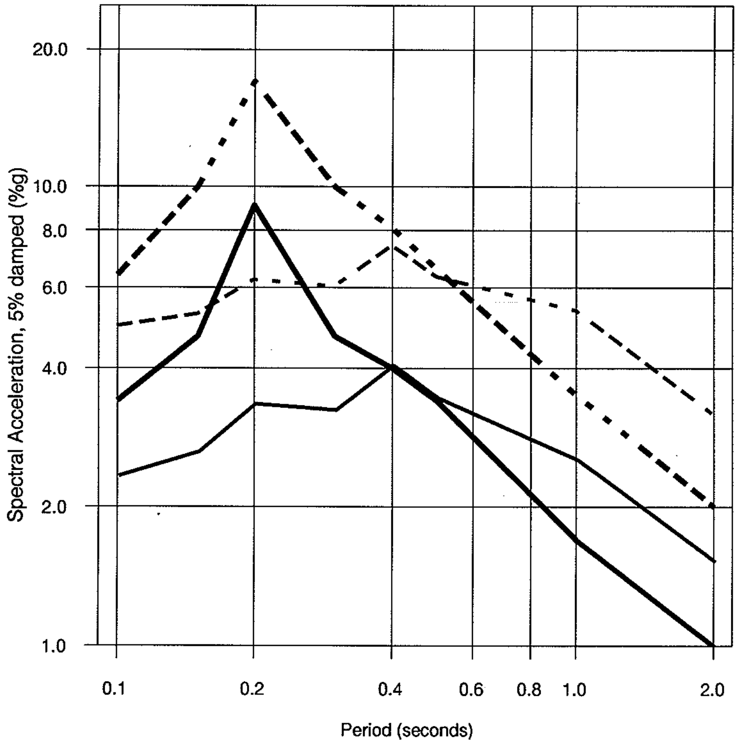

Figure 16. Calgary "Robust" Uniform Hazard Spectra

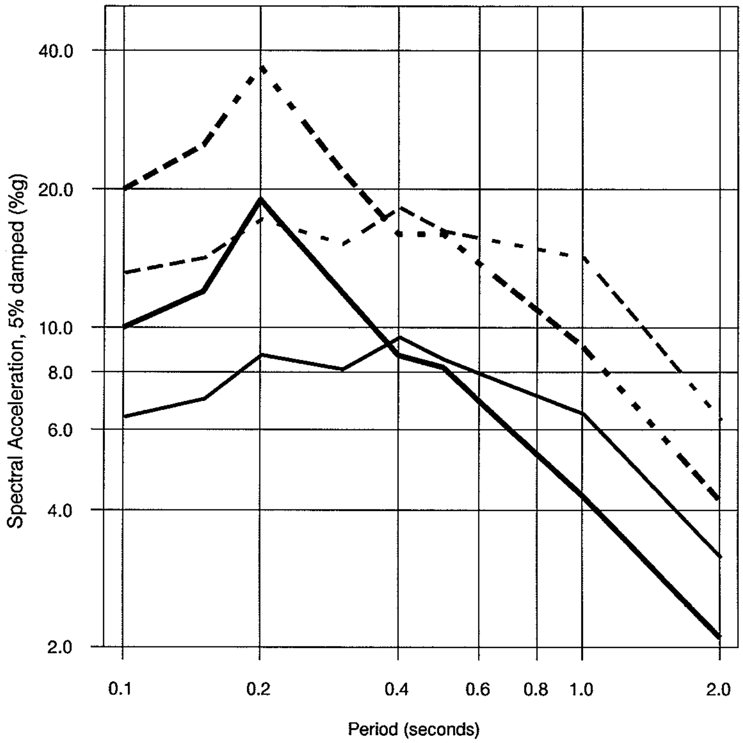

Figure 17. Kelowna "Robust" Uniform Hazard Spectra

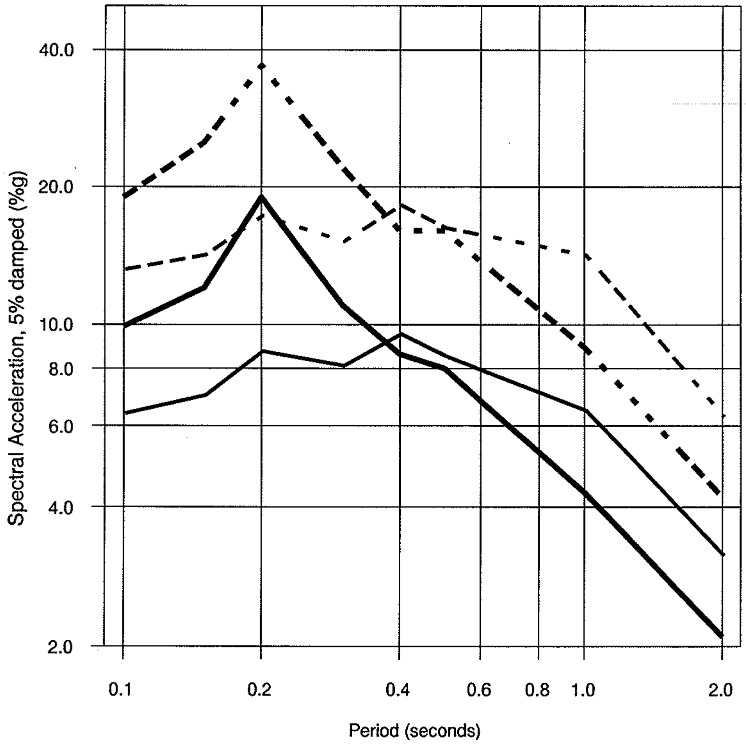

Figure 18. Kamloops "Robust" Uniform Hazard Spectra

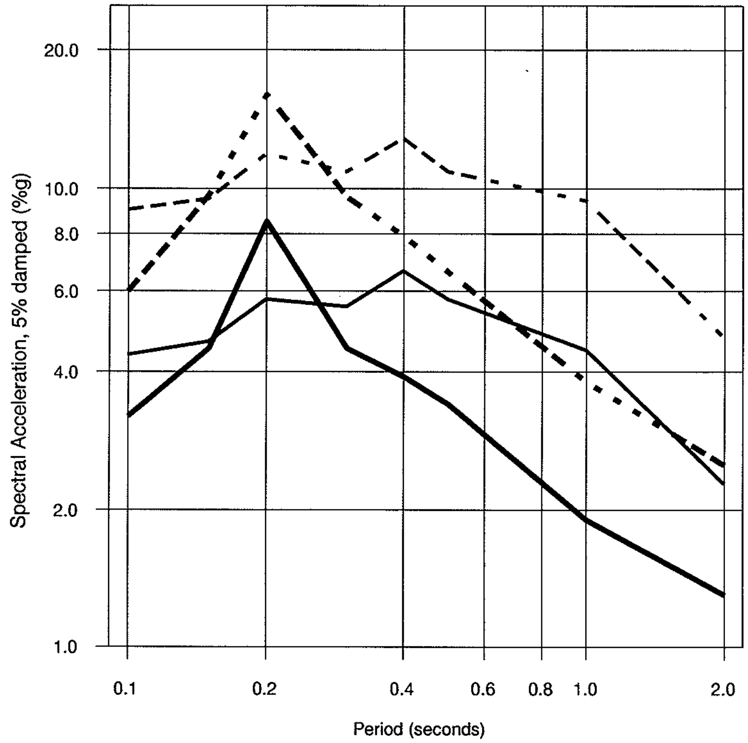

Figure 19. Prince George "Robust" Uniform Hazard Spectra

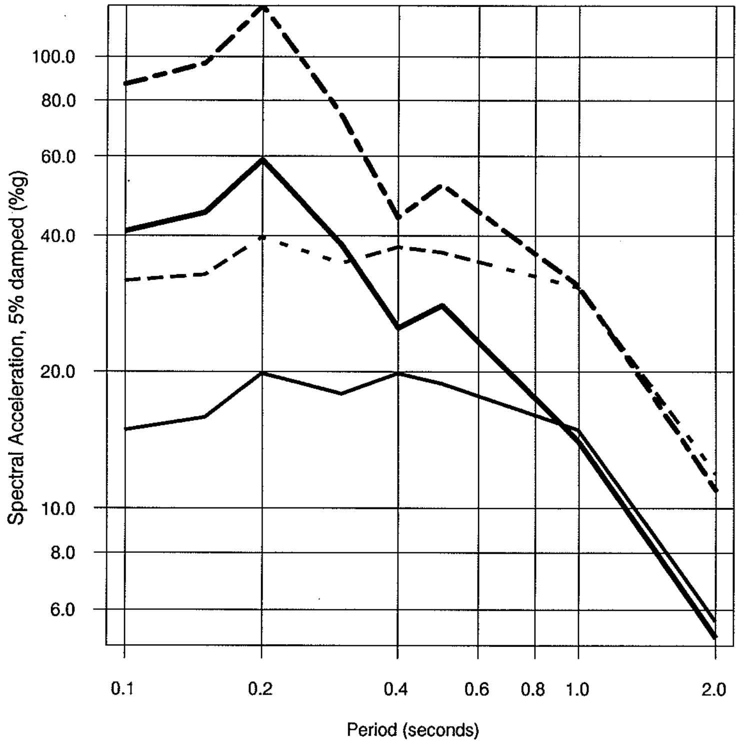

Figure 20. Vancouver "Robust" Uniform Hazard Spectra

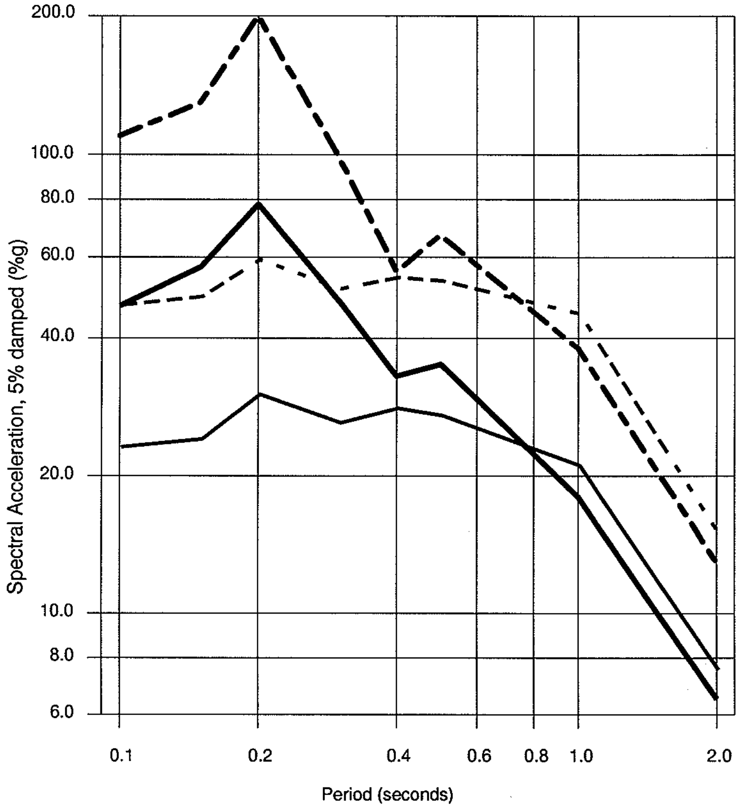

Figure 21. Victoria "Robust" Uniform Hazard Spectra

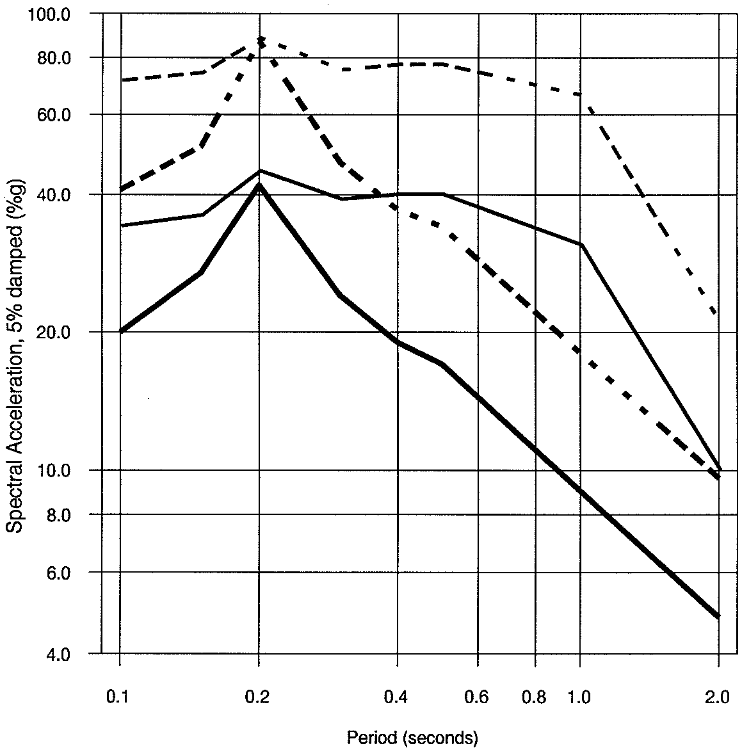

Figure 22. Tofino "Robust" Uniform Hazard Spectra

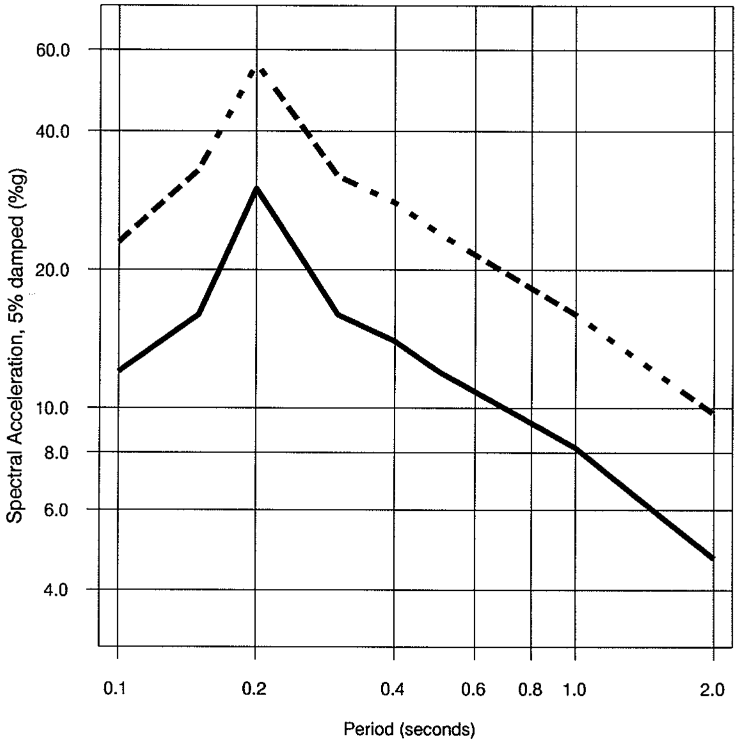

Figure 23. Prince Rupert "Robust" Uniform Hazard Spectra

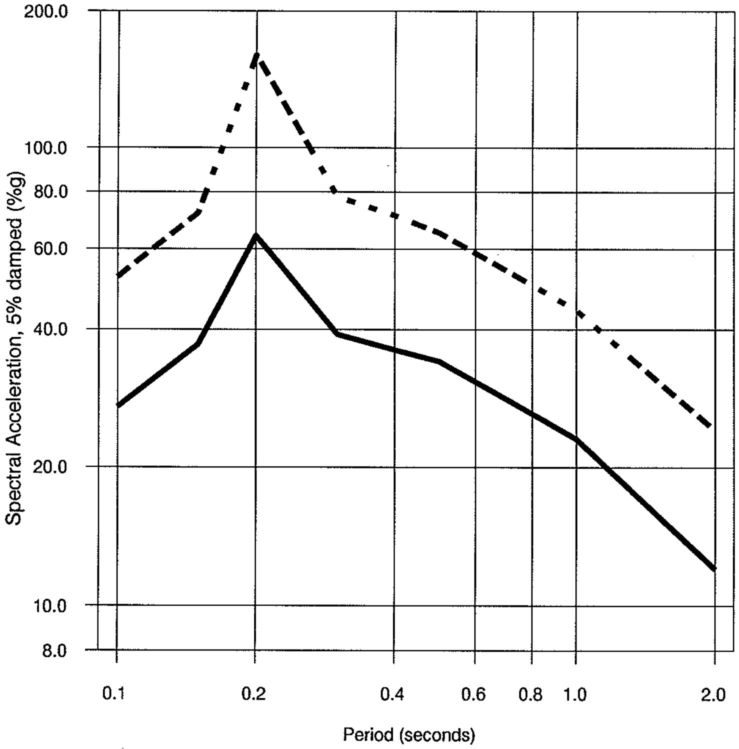

Figure 24. Queen Charlotte "Robust" Uniform Hazard Spectra

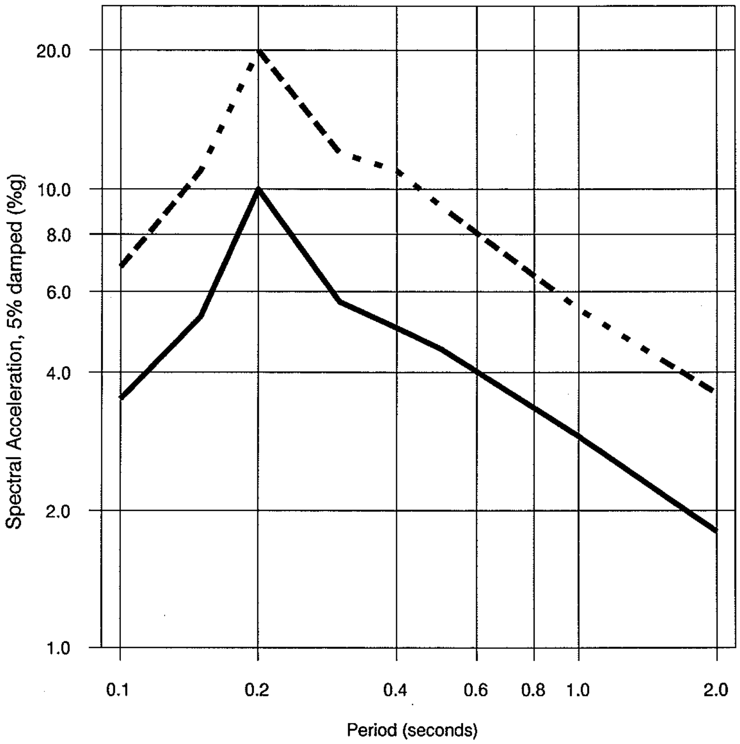

Figure 25. Inuvik "Robust" Uniform Hazard Spectra

APPENDIX

This appendix includes Figure 3a and Table 7b from Boore et al., (1993) and Tables 2 and 3 from Martin and Dobry (1994) referenced in the section on "Reference Ground Condition for Canada".

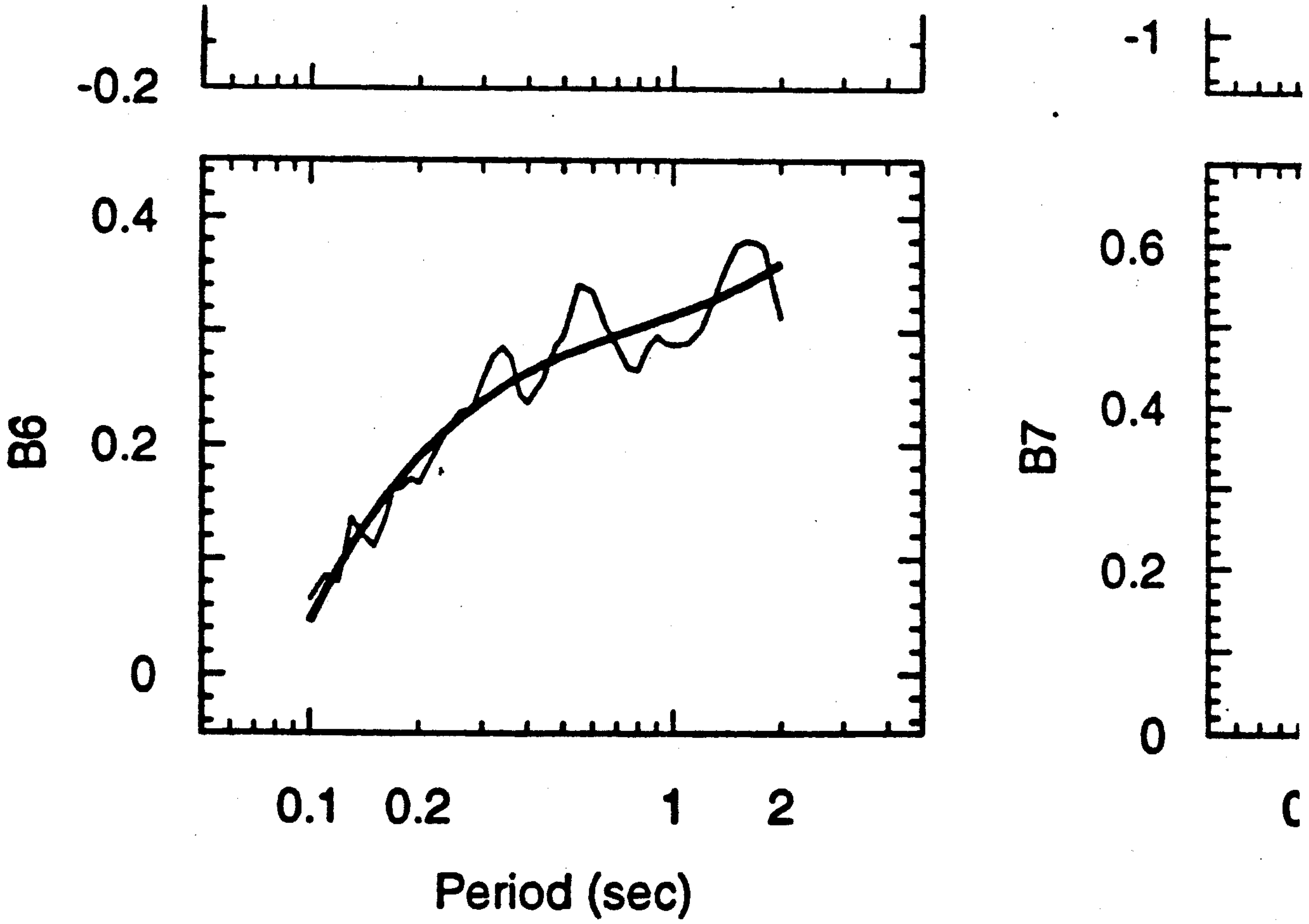

Figure 3a. The unsmoothed and smoothed coefficients (light and heavy lines, respectively) for the 5 percent damped response spectra of the random horizontal component.

Table 7b. Smoothed coefficients of equations for the random horizontal component of 5 percent damped PSV (cm/s; distance in km).

T(s)	B1	B2	B3	B4	B5	B6	B7	M	S1	SC	SR	SE	SLOGY
.10	1.653	.327	-.098	.00000	-.934	.046	.136	6.27	.191	.083	.208	.003	.208
.11	1.725	.318	-.100	.00000	-.937	.071	.156	6.65	.189	.087	.208	.005	.208
.12	1.782	.313	-.101	.00000	-.939	.093	.174	6.91	.187	.091	.208	.008	.208
.13	1.828	.309	-.101	.00000	-.939	.111	.191	7.08	.186	.094	.208	.010	.209
.14	1.864	.307	-.100	.00000	-.938	.127	.206	7.18	.185	.097	.209	.012	.209
.15	1.892	.305	-.099	.00000	-.937	.140	.221	7.23	.185	.100	.210	.015	.211
.16	1.915	.305	-.098	.00000	-.935	.153	.234	7.24	.184	.102	.210	.017	.211
.17	1.933	.305	-.096	.00000	-.933	.163	.246	7.21	.184	.104	.211	.019	.212
.18	1.948	.306	-.094	.00000	-.930	.173	.258	7.16	.184	.106	.212	.021	.213
.19	1.959	.308	-.092	.00000	-.927	.182	.269	7.10	.184	.108	.213	.023	.215
.20	1.967	.309	-.090	.00000	-.924	.190	.279	7.02	.184	.109	.214	.025	.215
.22	1.978	.313	-.086	.00000	-.918	.203	.297	6.83	.185	.112	.216	.029	.218
.24	1.982	.318	-.082	.00000	-.912	.214	.314	6.62	.185	.114	.217	.033	.220
.26	1.982	.323	-.078	.00000	-.906	.224	.329	6.39	.186	.116	.219	.036	.222
.28	1.979	.329	-.073	.00000	-.899	.232	.343	6.17	.187	.118	.221	.040	.225
.30	1.974	.334	-.070	.00000	-.893	.239	.356	5.94	.187	.120	.222	.043	.226
.32	1.967	.340	-.066	.00000	-.888	.245	.367	5.72	.188	.121	.224	.046	.228
.34	1.959	.345	-.062	.00000	-.882	.251	.378	5.50	.189	.122	.225	.048	.230
.36	1.950	.350	-.059	.00000	-.877	.256	.387	5.30	.190	.123	.226	.051	.232
.38	1.940	.356	-.055	.00000	-.872	.260	.396	5.10	.191	.125	.228	.054	.235
.40	1.930	.361	-.052	.00000	-.867	.264	.405	4.91	.192	.125	.229	.056	.236
.42	1.920	.365	-.049	.00000	-.862	.267	.413	4.74	.193	.126	.230	.058	.238
.44	1.910	.370	-.047	.00000	-.858	.271	.420	4.57	.193	.127	.231	.061	.239
.46	1.900	.375	-.044	.00000	-.854	.273	.427	4.41	.194	.128	.232	.063	.241
.48	1.890	.379	-.042	.00000	-.850	.276	.433	4.26	.195	.129	.234	.065	.243
.50	1.881	.384	-.039	.00000	-.846	.279	.439	4.13	.196	.129	.235	.067	.244
.55	1.857	.394	-.034	.00000	-.837	.284	.452	3.82	.198	.131	.237	.071	.248
.60	1.835	.403	-.030	.00000	-.830	.289	.464	3.57	.199	.133	.239	.076	.251
.65	1.815	.411	-.026	.00000	-.823	.293	.474	3.36	.201	.134	.242	.079	.254
.70	1.797	.418	-.023	.00000	-.818	.297	.483	3.20	.202	.135	.243	.083	.257
.75	1.781	.425	-.020	.00000	-.813	.300	.490	3.07	.203	.136	.244	.086	.259
.80	1.766	.431	-.018	.00000	-.809	.303	.497	2.98	.204	.137	.246	.089	.261
.85	1.753	.437	-.016	.00000	-.805	.306	.503	2.92	.205	.138	.247	.092	.264
.90	1.742	.442	-.015	.00000	-.802	.309	.508	2.89	.206	.139	.249	.095	.266
.95	1.732	.446	-.014	.00000	-.800	.312	.513	2.88	.207	.140	.250	.097	.268
1.00	1.724	.450	-.014	.00000	-.798	.314	.517	2.90	.208	.141	.251	.100	.270
1.10	1.710	.457	-.013	.00000	-.795	.319	.523	2.99	.209	.143	.253	.104	.274
1.20	1.701	.462	-.014	.00000	-.794	.324	.528	3.14	.210	.145	.255	.108	.277
1.30	1.696	.466	-.015	.00000	-.793	.328	.532	3.36	.211	.146	.257	.111	.280
1.40	1.695	.469	-.017	.00000	-.794	.333	.535	3.62	.212	.148	.259	.114	.283
1.50	1.696	.471	-.019	.00000	-.796	.338	.537	3.92	.212	.150	.260	.117	.285
1.60	1.700	.472	-.022	.00000	-.798	.342	.538	4.26	.212	.151	.260	.119	.286
1.70	1.706	.473	-.025	.00000	-.801	.347	.539	4.62	.212	.153	.261	.122	.289
1.80	1.715	.472	-.029	.00000	-.804	.351	.539	5.01	.212	.154	.262	.124	.290
1.90	1.725	.472	-.032	.00000	-.808	.356	.538	5.42	.212	.156	.263	.126	.292
2.00	1.737	.471	-.037	.00000	-.812	.360	.537	5.85	.212	.157	.264	.128	.293

The equations are to be used for 5.0 <= M <= 7.7 and d <= 100.0 km.

Table 2: Values of F_a as a function of site conditions and shaking intensity.

Shaking Intensity ⇒ **Site Class ⇓**	**A_a = 0.1 g**	**A_a = 0.2 g**	**A_a = 0.3 g**	**A_a = 0.4 g**	**A_a = 0.5 g**
(A_0)	0.8	0.8	0.8	0.8	0.8
A	1.0	1.0	1.0	1.0	1.0
B	1.2	1.2	1.1	1.0	1.0
C	1.6	1.4	1.2	1.1	1.0
D_1	2.5	1.7	1.2	0.9	(–)[1]
D_2	2.0	1.6	1.2	0.9	(–)[1]
(E)	(–)[1]	(–)[1]	(–)[1]	(–)[1]	(–)[1]

[1] Site-specific geotechnical investigations and dynamic site response analyses should be performed.

Table 3: Values of F_v as a function of site conditions and shaking intensity.

Shaking Intensity ⇒ **Site Class ⇓**	**A_v = 0.1 g**	**A_v = 0.2 g**	**A_v = 0.3 g**	**A_v = 0.4 g**	**A_v = 0.5 g**
(A_0)	0.8	0.8	0.8	0.8	0.8
A	1.0	1.0	1.0	1.0	1.0
B	1.7	1.6	1.5	1.4	1.3
C	2.4	2.0	1.8	1.6	1.5
D_1	3.5	3.2	2.8	2.4	(–)[2]
D_2	3.5	3.2	2.8	2.4	(–)[2]
(E)	(–)[2]	(–)[2]	(–)[2]	(–)[2]	(–)[2]

[illegible] Site-specific geotechnical investigations and dynamic site response analyses should be performed.

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