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A review of NBCC 2005 seismic hazard results for Canada - the interface to the ground and prognosis for urban risk mitigation

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A review of NBCC 2005 Seismic Hazard Results for Canada - the interface to the ground and prognosis for urban risk mitigation

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ABSTRACT
We summarize the methods being used for the new seismic hazard maps of Canada and estimate median ground motion on firm soil sites for a probability of exceedence of 2% in 50 years. Spectral acceleration at 0.2, 0.5, 1.0 and 2.0 second periods and peak acceleration will form the basis of the seismic provisions of the 2005 National Building Code of Canada. New soil factors will convert these firm soil values to other foundation conditions. The factors act to reduce design ground motions on rock and increase them on soft soils, and account for non-linear behaviour of soils under strong shaking. We discuss implications for geotechnical design, microzonation, and urban risk.

RÉSUMÉ
Nous résumons les méthodes utilisées pour les nouvelles cartes d'aléa séismique du Canada et nous estimons le mouvement moyen du sol sur sol ferme pour une probabilité d'excédence de 2% en 50 ans. L'accélération spectrale de 0,2, 0,5, 1,0 et 2,0 secondes et l'accélération maximale seront la base des dispositions séismiques du Code National du Bâtiment du Canada de 2005. Des nouveaux facteurs de sol convertiront ces valeurs de sol ferme aux autres conditions de fondation. Les facteurs agissent à réduire les mouvements de sol de conception sur du roc et à les augmenter sur des sols meubles, et les facteurs expliquent le comportement non linéaire des sols en cas d'ébranlement fort. On discute les conséquences pour la conception géotechnique, le microzonage et le risque urbain.

1. INTRODUCTION

A national seismic hazard map forms the fundamental basis of the most effective way that we can reduce deaths and economic losses from future earthquakes. To be useful, a national map must estimate hazard fairly across the country, so future protection can be distributed equitably according to the hazard. This clearly requires a good assessment of the earthquake sources, but it also needs the selection of the probability level for the assessment and a wise choice of earthquake parameters. Canada's national hazard mapping efforts have moved from qualitative assessment in 1953, to probabilistic assessment at 0.01 p.a. using peak horizontal ground acceleration (PGA) in 1970, and to probabilistic assessment at 0.0021 p.a. using both PGA and peak horizontal ground velocity (PGV) in 1985. With the 4th Generation probabilistic assessment at 0.000404 p.a., Canada will use spectral acceleration parameters as the basis for the 2005 edition of the National Building Code of Canada (NBCC2005). In this paper we set out the new features of the 4th Generation hazard assessment, its consequences for geotechnical design and urban risk assessment, and the need for microzonation of Canada's cities.

2.0 METHOD

The new hazard model incorporates a significant increment of earthquake data, recent research on source zones and earthquake occurrence, together with complementary research on strong ground motion relations. Detailed information on the model's parameters is given by Adams and Halchuk (2003), and overviews are provided by Adams and Atkinson (2003) and Adams and Halchuk (2004a). The April 2003 special issue of the Canadian Journal of Civil Engineering also contains 12 papers related to NBCC2005. We apply the same Cornell-McGuire methodology as was adopted by Basham et al. (1982, 1985) for Canada's 3rd generation maps and NBCC1995 (NBCC, 1995), but we have used a customized version of the FRISK88 hazard code (FRISK88 is a proprietary software product of Risk Engineering Inc.) in order to incorporate uncertainty. The new seismic hazard model for Canada considers two types of uncertainty: aleatory uncertainty due to randomness in process and epistemic uncertainty due to uncertainty in knowledge; the former cannot be reduced by collecting additional information, but the latter can be (Adams and Atkinson 2003). The treatment of uncertainty is detailed in Adams and Halchuk (2003).

2.1 Regionalization of Canada and Strong Ground Motion Relations

Of necessity, eastern and western Canada must be treated slightly differently because of the different properties of the crust. Figure 1 shows the earthquakes and the regionalization used and identifies in a general way the low-seismicity central part of Canada we discuss later as "stable Canada". The different physical properties of the crust in eastern and western Canada and the different nature of the earthquake sources in southwestern Canada required the use of four separate strong ground motion relations as detailed by Adams and Halchuk (2003). Seismic hazard to the west of the leftmost dashed line on Figure 1 has been calculated using western strong ground motion relations; eastern relations are used for the remaining regions.

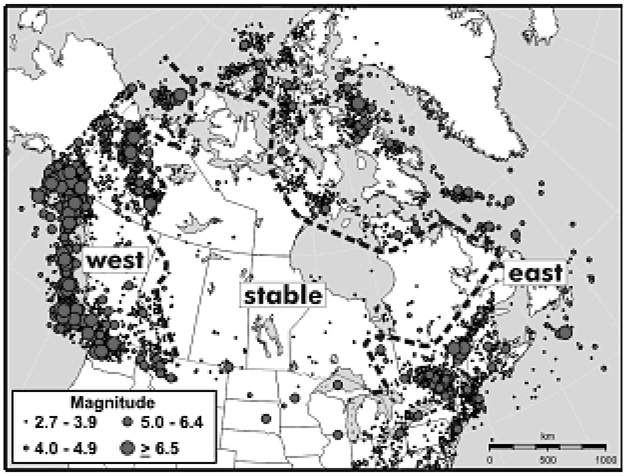

Figure 1. Map of Canada showing the earthquake catalog used for the 4th Generation model together with dashed lines delimiting the eastern and western seismic regions and the “stable Canada” central region.

In contrast to the 1985 maps used in NBCC1995, which gave values for PGA and PGV, we present 5% damped horizontal spectral acceleration values for the 0.2, 0.5, 1.0, and 2.0 second periods that will be used in NBCC 2005. The spectral acceleration parameters are denoted by Sa(T), where T is the period. We also present PGA values, which are only used for liquefaction analyses. All values are in units of g and we report them to 2 significant figures (an appropriate level of precision), except for some small Sa(2.0) values for which one significant figure is appropriate.

2.2 Probability Level and Choice of Confidence Level

The new code will use hazard computed at the 2% in 50 year probability level (1/2475 or 0.000404 per annum) instead of the 10% in 50 year (1/475 p.a.) level of the 1995 code. This change is consistent with expected building performance i.e., although buildings were apparently being designed to 1/475 p.a. in NBCC1995, engineering judgment suggests 1/2500 p.a. performance was attained (Heidebrecht, 2003). It was necessary to calculate hazard at the new lower probability because the distribution of hazard across Canada at 1/475 p.a. differs from that at 1/2475 p.a. Thus applying a constant conservatism (possibly an implied Factor of Safety in the 1995 code) did not achieve the same reliability across the country. For example if the reliability in Vancouver was 1/2475 p.a., the reliability in Montreal was only 1/1600 p.a. (Figure 2).

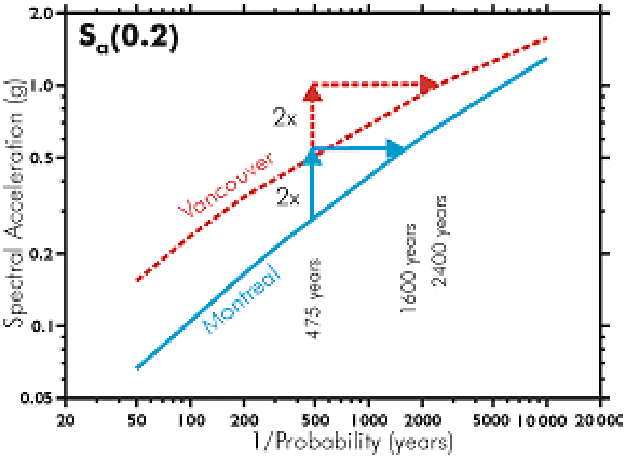

Figure 2. Sa(0.2) hazard curves for Vancouver and Montréal, showing how increasing the 10%/50 year hazard by a factor of two produces different increases in safety.

It should be noted that while the general increase in ground motions from NBCC1995 to NBCC2005 is by a factor of 2 +/- 0.3, the increase is taken into account in the design process for most common buildings through the use of new R_o factors that explicitly quantify overstrength (Heidebrecht 2003). Thus in a general way the large increases in ground motions due to the drop in probability level do not lead to a proportional increase in building “strength” or robustness.

The 4th Generation model provides an assessment of uncertainty, and so instead of presenting just one value for a given probability level, values are available for each percentile of the distribution. However instead of the mean (which is the expected value given the uncertainty) or the 84th percentile (which uses the uncertainty to provide a higher confidence that the specified ground motion will not be exceeded), NBCC2005 uses the median (50th percentile) because it is less sensitive to the exact amount of uncertainty included in the model.

2.3 The Four Seismicity Models - **H**, **R**, **F**, and **C**, and the Robust Hazard Values

To capture epistemic uncertainty in source, two complete probabilistic seismic hazard models were created for Canada, an “**H**” model that uses relatively small source zones drawn around historical seismicity clusters, and a “**R**” model that establishes larger, regional zones reflecting seismotectonic units. Both models are composed chiefly of areal sources, with only the Queen Charlotte Fault being modeled as a fault source. Standard methods were applied to define the source zone boundaries, select the earthquakes that pass completeness, choose upper bound magnitudes, and fit the magnitude-recurrence curves. Details of the method and listing of the parameters chosen are given in Adams and Halchuk (2003). For the relatively aseismic central part of Canada a “stable Canada” probabilistic “**F**” model with arbitrary boundaries was used to integrate knowledge about earthquake activity rates in similar parts of the world’s continents. The **F** model provides a “floor” value to seismic hazard for all parts of Canada.

A great earthquake occurred off Vancouver Island on the Cascadia subduction zone in 1700 A.D. We chose to adopt a realistic scenario for this earthquake involving a line source with magnitude 8.2 (Adams and Halchuk, 2003, Fig. 6), and so provide a deterministic ("**C**" model), rather than probabilistic, estimate of its ground motions. The results from the four seismicity models are combined using the method termed "robust". The "robust" value is just choosing the highest value from the four models for each grid point across Canada.

2.4 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. Thus a "reference" ground condition is needed in order to make the 2005 hazard values both numerically comparable between east and west, and roughly comparable in intent to the past (1985) hazard maps. NBCC2005 has adopted "Site Class C", defined by a 360 to 750 m/s average shear wave velocity in the uppermost 30 m (Finn and Wightman 2003) for the Canada-wide reference ground condition because it: represents the larger number of strong motion recordings in well-instrumented places like California; is in the mid-range between very hard and very soft ground (thus minimizing uncertainty in the amplification or deamplification factors); and is close to the ground conditions that were implied by the strong ground motion relationships used for the 1985 maps. The soil classification in Table 1 leads to the soil modification factors F_a and F_v in Table 2, to be discussed later.

Table 1. NBCC2005 Site Classification for Seismic Site Response (after Finn and Wightman, 2003).

Site Class	Soil Profile Name	Average Properties in Top 30 m as per Appendix A		
		Soil Shear Wave Average Velocity, $\overline{V}_s$ (m/s)	Standard Penetration Resistance, $\overline{N}_{60}$	*Soil* Undrained Shear Strength, s_u
A	Hard Rock	$\overline{V}_s > 1500$	Not applicable	Not applicable
B	Rock	$760 < \overline{V}_s \leq 1500$	Not applicable	Not applicable
C	Very Dense Soil and Soft Rock	$360 < \overline{V}_s < 760$	$\overline{N}_{60} > 50$	$s_u > 100$kPa
D	Stiff Soil	$180 < \overline{V}_s < 360$	$15 \leq \overline{N}_{60} \leq 50$	$50 < s_u \leq 100$kPa
E	Soft Soil	$\overline{V}_s < 180$	$\overline{N}_{60} < 15$	$s_u < 50$kPa
E		Any profile with more than 3 m of *soil* with the following characteristics: ▪ Plastic index PI > 20 ▪ Moisture content $w \geq 40\%$, and ▪ Undrained shear strength $s_u < 25$ kPa		
F	Others[1]	Site Specific Evaluation Required		

[1] Other soils include: a) Liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils, and other soils susceptible to failure or collapse under seismic loading, b) Peat and/or highly organic clays greater than 3 m in thickness, c) Highly plastic clays (PI > 75) with thickness greater than 8 m, and d) Soft to medium stiff clays with thickness greater than 30 m.

Table 2. Values of F_a and F_v as a Function of Site Class and $S_a(0.2)$ and $S_a(1.0)$ (after Finn and Wightman, 2003).

Site Class	Values of F_a					Values of F_v				
	$S_a(0.2) \leq 0.25$	$S_a(0.2) = 0.50$	$S_a(0.2) = 0.75$	$S_a(0.2) = 1.00$	$S_a(0.2) \geq 1.25$	$S_a(1.0) \leq 0.1$	$S_a(1.0) = 0.2$	$S_a(1.0) = 0.3$	$S_a(1.0) = 0.4$	$S_a(1.0) \geq 0.5$
A	0.7	0.7	0.8	0.8	0.8	0.5	0.5	0.5	0.6	0.6
B	0.8	0.8	0.9	1.0	1.0	0.6	0.7	0.7	0.8	0.8
C	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
D	1.3	1.2	1.1	1.1	1.0	1.4	1.3	1.2	1.1	1.1
E	2.1	1.4	1.1	0.9	0.9	2.1	2.0	1.9	1.7	1.7
F	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)

(1) To determine Fa and Fv for site Class F, site specific geotechnical investigations and dynamic site response analyses shall be performed.

3.0 RESULTS

Adams and Halchuk (2003) give the NBCC2005 values for over 650 localities across Canada. Seismic hazard values were calculated for a grid extending over Canada and used to create national contour maps such as Figure 3. The four spectral values used by NBCC2005 (together with values at a few other periods) were used to construct Uniform Hazard Spectra (UHS) for a few major cities to illustrate the range and period dependence of seismic hazard across Canada (Figure 4). Other UHS are given by Adams and Halchuk (2003), and yet more can be constructed from the tabulated values therein. The UHS for Winnipeg is representative of many localities in low-seismicity parts of Canada where the F model dominates. The UHS shown are for Site Class C, while Figure 5 shows the design UHS for Montreal on various Site Classes to be used for NBCC2005. The change of Sa(0.2) hazard as a function of probability ("hazard curve") for selected cities is illustrated in Figure 6. Other hazard curves are given in Adams and Halchuk (2004b). The slopes of the hazard curves also vary considerably within one geographic area.

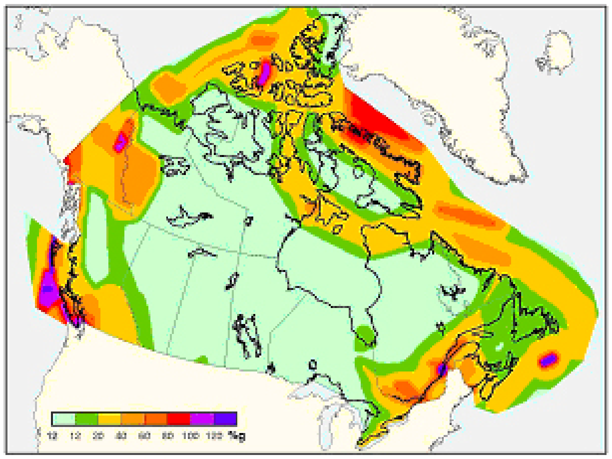

Figure 3. Sa(0.2) for Canada (median values of 5% damped spectral acceleration for Site Class C and a probability of 2%/50 years).

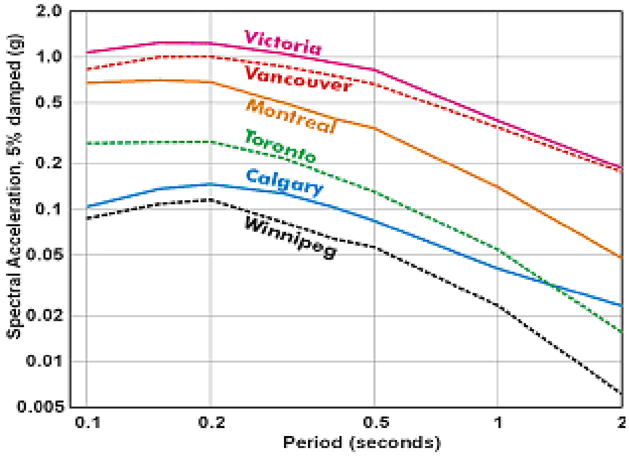

Figure 4. Uniform Hazard Spectra for median 2%/50 year ground motions on Site Class C for key cities.

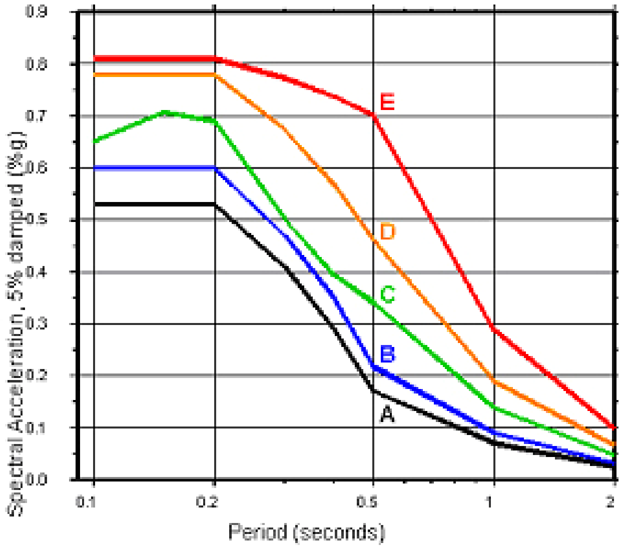

Figure 5. Seismic hazard for Montréal depicted as Uniform Hazard Spectra on various ground conditions (site classes A through E from Table 1). Class C represents the actual UHS, the others are design spectra.

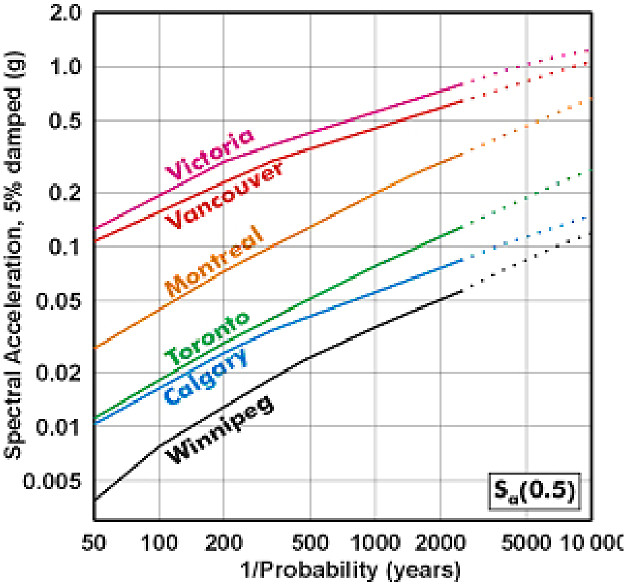

Figure 6. Sa(0.5) hazard curves for key cities.

Halchuk and Adams (2004) discuss the deaggregation of Canadian seismic hazard and illustrate the magnitudes and distances of the earthquakes making the largest contribution to the seismic hazard for selected cities. An example is given in Figure 7.

4.0 DISCUSSION

4.1 Improvements in Estimated Hazard from New Knowledge about Earthquake Distribution and how Hazard Values are Used

While the general pattern of earthquakes in the two decades since the 1985 maps were compiled has not changed, there have been a few significant earthquakes that have caused re-evaluation of the earthquake sources together with an upward revision of many upper bound magnitudes. Two completely new components have been added into the 2005 maps: the Cascadia subduction earthquake, and the occurrence of earthquakes in the "stable" part of Canada. These two additions have increased the estimated hazard along the Pacific edge of Vancouver Island and throughout many areas of Canada hitherto thought to be aseismic respectively. While only a small increment of earthquakes has been added to the 1985 active zones, the approach used for the R model has increased estimated seismic hazard at places that lie near potentially-seismogenic features with few historical earthquakes, such as the St. Lawrence valley near Trois-Rivières.

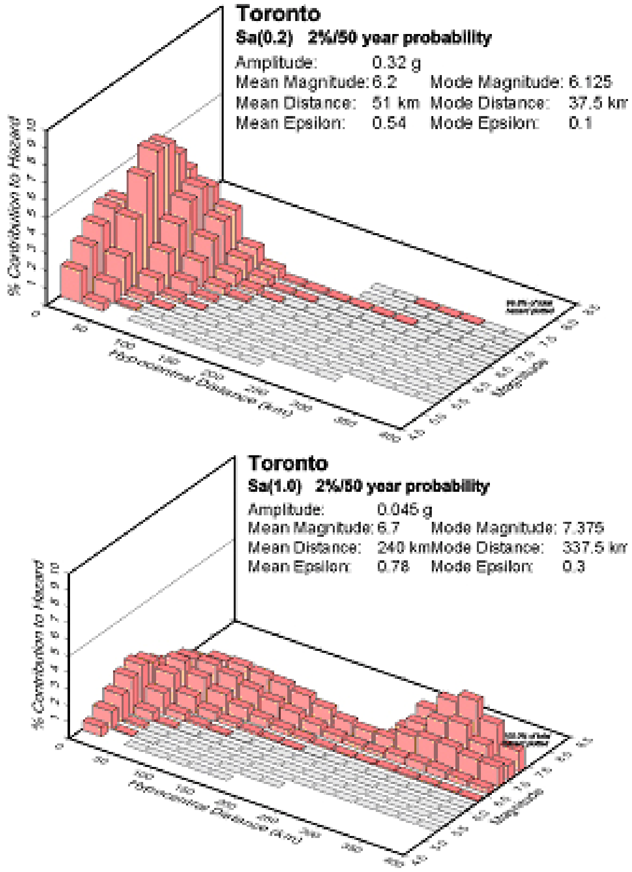

Figure 7. Deaggregation of Sa(0.2) (top) and Sa(1.0) (bottom) hazard for Toronto, showing the relative contributions of magnitude-distance combinations (from Halchuk and Adams, 2004).

NBCC2005 implements several improvements in the use of the calculated hazard through the use of site-specific values instead of zonal average values, the use of uniform hazard spectra instead of a standard spectrum scaled to PGV and partially adjusted by PGA, the use of a probability reflecting required performance, and the use of site-specific geotechnical values with an improved soil classification which also accounts for non-linear effects at strong shaking.

The more rigorous definition of foundation conditions in the new code will require more involvement from geotechnical engineers, as will the extension of seismic design to Class D, E and F sites for the large low-seismicity region between Sudbury and Calgary.

4.2 Changes in Estimated Hazard Relative to the 1985 Maps

Improved understanding of seismicity patterns, their cause and recurrence rates, and increased knowledge of strong ground motion has led to significant changes in estimated hazard relative to those of the 1985 maps. Table 3 compares 1985 and 2005 seismic hazard values for PGA at 10%/50 year probability. The comparison is not ideal because PGA is a short-period measure that captures the damage potential of ground motions much more poorly than spectral acceleration at short or long periods. The changes arise from:! new strong ground motion relations used, new earthquake sources (discussed above), changes in source zone boundaries, increases in upper bound magnitudes, and lowered impact of large historical earthquakes thought less likely to reoccur. They represent the net result of many effects, some acting to increase and some to decrease the estimated hazard.

4.3 Changes in Estimating Soil Response

Seismic hazard as calculated for the NBCC represents motions on the Class C reference site condition, and will be used together with shaking modification factors developed by Finn and Wightman (2003) for simplified design of buildings and their foundations. These factors are period dependent as shown by the short and long period parts of Table 2. The key points about Table 2 are: a) there is an explicit credit for buildings on rock (formerly these were designed the same as those on firm soil), b) the range of amplification has increased from a factor of 2 in NBCC1995 to a factor of 3 - 4, c) the amplification changes with the strength of shaking, d) short period structures on poor soils may experience deamplification at strong shaking levels.

Where site-specific modeling of soil amplification is required by the code or represents standard or prudent engineering practice, the NBCC values should be modified to obtain the input values for the model. For sites with soil overlying rock, the NBCC values can be adjusted from Class C values to rock values using either the modification factors in Table 2 or the "RGC" values in Adams and Halchuk (2003). The RGC values are scientifically correct for eastern and central Canada, whilst the tabular values include a measure of engineering judgment.

5.0 IMPLICATIONS FOR POST-2004 GEOTECHNICAL DESIGN

While structural engineers have increased their design loads only slightly in response to NBCC2005 (section 2.2), conventional geotechnical engineering designs for liquefaction, for earth pressure due to an earthquake and for slope stability during an earthquake involve terms that are directly proportional to the PGA. Hence application of the 2%/50 year values from the 2005 Code to current practice might be expected to lead to over-conservative designs (T. Law, pers comm., 2004). We illustrate this below for liquefaction susceptibility, though this may be the least critical of the three, as it is less sensitive to ground motion increase.

Table 3. Comparison of 1985 with 2005 PGA, 10%/50 year values on firm-ground (units=g).

City	1985* (g)	2005 (g)	change	chief reasons
St. John's	0.054	0.036	down	1 and 2
Halifax	0.056	0.057	slight	--
Moncton	0.085	0.072	down	2
Fredericton	0.096	0.094	slight	--
La Malbaie	0.70	0.59	down	2
Québec	0.19	0.16	down	2
Trois-Rivières	0.12	0.18	up	3
Montréal	0.18	0.20	slight	--
Ottawa	0.20	0.20	--	--
Niagara Falls	0.084	0.12	up	4 and 5
Toronto	0.056	0.080	up	4 and 5
Windsor	0.029	0.040	up	3 and 5
Winnipeg	0.0	0.021	up	6
Calgary	0.019	0.040	up	5
Kelowna	0.054	0.071	up	5
Kamloops	0.056	0.071	up	5
Prince George	0.034	0.033	slight	--
Vancouver	0.21	0.26	up	4
Victoria	0.28	0.34	up	7
Tofino	0.35	0.27	down	4 and 8
Prince Rupert	0.13	0.095	down	2
Queen Charlotte	0.57	0.22	down	2
Inuvik	0.060	0.032	down	2

* 1985 values are from the 1985 NBCC Commentary where possible. Other values from the 1985 seismic hazard model. The chief reasons are: 1. less impact of 1929 Grand Banks earthquake; 2. new strong ground motion relations used; 3. effect of **R** model; 4. change in source zone boundary position; 5. larger upper bound magnitudes used; 6. effect of stable Canada model; 7. Coordinates corrected to downtown (in 1995); 8. Less impact of 1946 Vancouver Island-type earthquakes].

5.1 Parameters for Liquefaction Design

NBCC1995 was based on the philosophy that the foundation should not fail before the structure that it supports. Resistance to soil liquefaction was often based on Seed's criteria which uses the site NBCC PGA together with a representative magnitude. Neither the NBCC nor the Canadian Foundation Engineering Manual contains advice on the selection of an earthquake magnitude for the assessment of liquefaction.

The move to 2%/50 year hazard has had two effects that seem likely to result in more conservative anti-liquefaction designs than NBCC1995. Firstly, the firm ground 2%/50 year ground motions are about twice the 10%/50 year motions. Secondly, deaggregation (Fig. 7) of hazard at the 2%/50 year probability level (Halchuk and Adams, 2004) reveals that more of the hazard is coming from larger earthquakes than before, thus leading to larger modal (or mean) magnitudes (which may be those chosen for the liquefaction assessment). These increases are only partially offset by the smaller amplification of surface ground motions on soft soil sites in high-seismic regions:-

	mapped PGA (% g)	PGA for liquefaction design for F=1.5 soil (% g)
Vancouver		
1995	22	22*1.5 = 33
2005	48	48*0.9[a] = 43
Ottawa (similar for Montreal)		
1995	20	20*1.5 = 30
2005	42	42*1.2[b] = 50

[a] using Sa(0.2)=0.96 hence Fa for Class E = 0.9
[b] using Sa(0.2)=0.67 hence Fa for Class E = 1.2

The net effect is a design increase of about 30% in the high-seismicity Vancouver/Richmond area (confirmed by the Richmond Task Force Report which used extensive modeling analysis, A. Wightman, pers. comm., 2004), but an increase of 60+% for eastern sites in areas of low seismicity.

The problem is compounded by basing liquefaction analysis on the PGA ground motion parameter. Eastern earthquakes generate shaking that is rich in short-period motions that control the amplitude of PGA, and the crust of eastern Canada attenuates them slowly. Hence PGA values that in California represent strong earthquakes capable of causing liquefaction can be produced in eastern Canada by moderate earthquakes that lack the shaking duration needed to induce liquefaction. Clearly a thoughtful analysis of the problem is required to ensure that application of California-based experiential rules to eastern NBCC2005 ground motions does not produce unduly conservative designs. Site-specific analyses (or model solutions for certain cities) appear to be appropriate.

5.2 Possible Solutions for Geotechnical Design

NBCC2005 will be implemented in the Spring of 2005, so there is an urgent need to ensure appropriate application of the 2%/50 year values in a way that matches the performance of the new structural engineering designs. Incorporating appropriate revisions into the Canadian Foundation Engineering Manual, currently under revision, would seem to be the simplest solution. Speculatively, such solutions might either approve design to a fixed fraction of the 2%/50 year values as meeting the performance requirement, or use a reduced factor of safety (FoS) with the 2%/50 year values (i.e. instead of FoS=2 for 10%/50 year values use FoS=1 with 2%/50 year values), which might result in designs with similar reliability to the present.

6.0 MICROZONATION AND FUTURE ASSESSMENT OF RISK FOR CANADA'S CITIES

An earlier generation of strong motion instruments has already given some sparse information about soil amplification in Vancouver (Cassidy and Rogers, 2004), Victoria (Molnar et al., 2004) and Ottawa (Al-Khoubbi and Adams, 2004), but while we wait for strong, damaging earthquakes, the current instruments will provide many more weak ground motion records on a variety of soil sites and hence direct measurements of soil amplification. These will provide ground truth for other microzoning methods such as those using ambient noise that provide a more finely-detailed picture of ground conditions on a block-by-block basis. Such studies are underway in Montreal (Chouinard et al., 2004), Vancouver (Ventura et al., 2004) and Victoria (Molnar et al., 2004), and in turn these efforts will feed back into the more effective deployment of any future accelerographs.

NBCC seismic hazard values provide a useful way to allocate earthquake protection across the nation and can be used as a first-order estimate of seismic risk (taking seismic risk to be proportional to "likelihood of damaging ground motion * population at risk"). Such an analysis ranks the cities as:- Vancouver, Montreal, Ottawa-Gatineau, Victoria, Toronto, Quebec City, etc (Fig. 8), and provides a basis for allocating mitigation efforts (Adams et al., 2002). Improved strong motion monitoring of the cities at risk (articulated in the Canadian Urban Seismology Proposal, CUSP) could place up to 1000 internet-linked real-time strong motion accelerographs across Canada, with their distribution reflecting the national urban risk as in Figure 8. Direct monitoring of urban shaking at this level of detail together with a GIS system containing the age/fragility/occupancy of buildings will allow estimation of the likely damage and injuries, possibly within a handful of minutes after a large earthquake, thus enabling more effective emergency response efforts (e.g. Fig. 9). A pilot project of 60 stations on a 1-km grid is underway in greater Vancouver (Rosenberger et al, 2004). The combination of CUSP-style monitoring together with more detailed microzonation should lead to better and safer cities for the future.

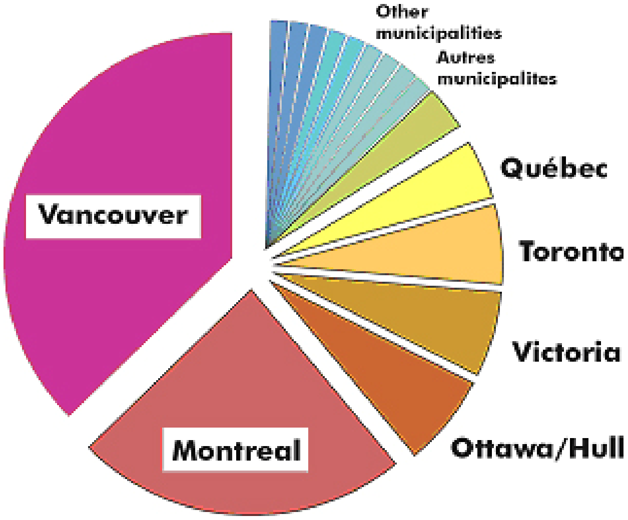

Figure 8. Approximate distribution of seismic risk among Canada's urban population (Adams et al., 2002).

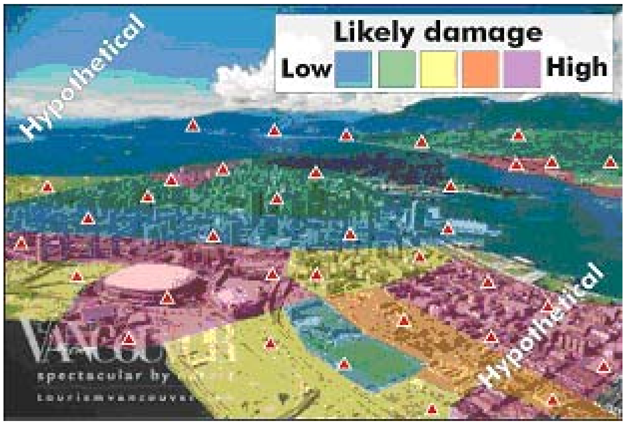

Figure 9. Hypothetical rapid damage assessment (colored polygons) to be generated by a dense urban strong motion array (triangles) in combination with an urban microzonation and infrastructure GIS (Adams et al., 2002).

6.0 CONCLUSIONS

The new national hazard model for NBCC2005 will combine the results from two complete earthquake source models (to represent the uncertainty in where and why earthquakes will happen in the future) together with a deterministic model for a Cascadia subduction earthquake and a "stable craton" model that provides floor design values for the low seismicity parts of Canada. New soil classes will convert the "firm ground" values to other foundation conditions. These factors depend on the strength of the shaking (to account for non-linear behavior of soils under strong shaking) and act to reduce design ground motions on rock and increase them on soft soils. For very soft or liquefiable soils a site-specific analysis is required. Geotechnical proceedures may need to be adjusted to provide the correct performance expected by the structural engineers.

NBCC2005 values allocate earthquake protection across the nation and can be used for a first-order estimate of seismic risk. Risk can be mitigated by safer geotechnical and structural designs and better emergency response. More detailed microzonation of Canadian cities together with direct monitoring of urban shaking by dense accelerometer arrays will allow rapid estimation of the earthquake damage and should lead to better and safer cities for the future.

7.0 ACKNOWLEDGMENTS

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