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ESTIMATED SEISMIC DESIGN VALUES FOR CANADIAN MISSIONS ABROAD

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ABSTRACT

Seismic hazard design values are estimated for 161 Canadian Missions abroad. The method is broadly based on applying spectral shape and magnification factors to move from the 10%-in-50-year Peak horizontal Ground Acceleration (PGA) values given by the Global Seismic Hazard Assessment Program (GSHAP) to the 2%-in-50-year PGA and spectral acceleration values desired. Four sets of factors were derived from Canadian seismic hazard results for Continental Low Seismicity, Continental Moderate Seismicity, Plate Margin, and Plate Boundary tectonic environments. The resulting design spectra are intended to be a) used for screening studies to assess the relative need for remedial work; b) used for Rapid Visual Screening (FEMA 154); and c) applied in the context of the National Building Code of Canada, in conjunction with local hazard maps and national building codes, in order to deliver appropriate safety to the Missions and continuity of consular services.

Introduction

The Canadian Department of Foreign Affairs and International Trade (DFAIT) has embassies and related outposts ("Missions") in cities around the world that may be vulnerable to earthquake shaking, and it wished to consider the 2005 National Building Code of Canada (NBCC, 2005) provisions during future construction projects or retrofit of existing buildings. NBCC2005 uses 5%-damped spectral acceleration ("Sa(T)") at T = 0.2, 0.5, 1.0 and 2.0 second periods at the 2% probability of non-exceedence in 50 years ("2%/50yr") and no longer uses the Peak horizontal Ground Acceleration (PGA) at 10%/50yr of the 1995 and earlier editions.

Current State of Knowledge

Seismic hazard assessment across the world is very uneven in terms of technique and quality. In countries with well-developed seismic hazard maps (and the seismic design codes that flow from them) there is still a strong bias towards the Peak horizontal Ground Acceleration (PGA) measure of shaking severity, and to probability levels of 10% in 50 years (i.e., ~0.0021 per

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annum). Few countries have seismic hazard maps that give shaking in terms of spectral acceleration (Sa) at the probability level of 2% in 50 years (i.e., ~0.0004 per annum) that is the current basis for seismic designs in North America (2005 National Building Code of Canada and 2006 "International" Building Code in the U.S.).

A world-wide assessment of PGA values at 10%/50yr was completed as the Global Seismic Hazard Assessment Program (GSHAP). This enormous project used local, national and regional experts to produce a 10%/50 year PGA map, published in 1999 (Giardini et al., 1999). Documentation, the map, and the numerical values are available on the web at http://www.seismo.ethz.ch/GSHAP/. Aside from proprietary maps created mostly within the insurance/reinsurance industry, GSHAP provides the only current global map of seismic hazard. The greatest strength of the GSHAP process was the use of local and regional experts with their access to the best local earthquake catalogs and local information on the causes and rates of earthquakes. The greatest weakness was the same – the local and regional experts produced different estimates of the hazard for adjacent regions, and overall there were other inconsistencies in assembling the global map. For example, the seismic hazard for Canada and the U.S. was derived from mature national models and simply abutted at the border. A second example – unlike the rest of the map, both the Canada and U.S. mapped values were given for "firm ground", whereas the rest of the map is for "rock".

As printed, the GSHAP map shows only the seismic hazard on land, and appears quite convincing. However, the complete numerical dataset reveals that: some areas on land do not have any hazard values provided; some areas in the oceans do not have hazard values provided (as expected), but the hazard given in some places (western Pacific Ocean) is bizarre; in certain onshore and near-shore areas there are discontinuities between adjacent areas (presumably representing the joins between different group's models); and along various plate boundaries there are changes in hazard that are not very credible. Furthermore, the GSHAP map has become less relevant as a basis for engineering design because it maps only PGA, and only for the 10%/50 year probability. All of the above should not reduce the tremendous advance that the GSHAP map achieved in harnessing experts to produce the map. The GSHAP map still remains the only such global map (although a successor is in production: GEM (2009)). For all its flaws, GSHAP represented the best starting point for our project.

June 2005 Screening Report for DFAIT

In June 2005 Public Works and Government Services Canada (PWGSC) requested seismic hazard values to be used in screening decisions for the long-term management, upgrade or rebuilding of Canada's Missions abroad. The request was for a ranking of Missions at short and long periods. This was achieved from the GSHAP values by 1) converting the Canada and the U.S. values to rock, and 2) adjusting the PGA values by crude "tectonic" factors to better reflect the damage potential in different parts of the world (for plate-boundary, transitional and continental sites 1/1, 1/1.15, and 1/1.3 were applied to estimate short periods and factors of 1/1, 1/2, and 1/3 to estimate Sa(1.0)). While the final values were labeled "adjusted PGA" and "Estimated Sa(1.0)" they were for ranking and not design, and furthermore they reflected approximate ground motions for a probability of about 10%/50 years.

June 2007 Request for Design Values Equivalent to NBCC2005

In June 2007 DFAIT approached the GSC to provide spectral design values for Canadian Missions abroad that could be used for design purposes equivalent to NBCC2005. The intended method was to use a global earthquake catalog together with the "zone-less" seismic hazard code written by Art Frankel and colleagues (as used for the U.S. national seismic hazard maps) to calculate seismic hazard for each Mission. This approach failed (as is detailed in Adams et al., 2008), chiefly because the international earthquake catalogs (e.g. ISC, 2007; NEIC, 2007) contained too few earthquakes, included inhomogeneous magnitudes, and were unreliable. In low seismicity regions they provided just too few earthquakes to give a reliable estimate of seismic hazard. Nevertheless this method did provide some instructive illustrations of the history of earthquakes near high-seismicity areas.

Instead, the adopted approach (as discussed further below) was an extension of the (2005) screening method, and is as follows:

1. Values for PGA were determined from the GSHAP map for each Mission
2. Canada and U.S. values were converted to rock.
3. A manual adjustment (discussed in detail later) was made to certain values, this produces the "adjusted 10%/50yr PGA" value
4. A spectral shape category was assigned to each Mission depending on its tectonic environment
5. Depending on the spectral shape category, the "adjusted 10%/50yr PGA" was multiplied by a spectral shape factor to give the estimated PGA and estimated Sa(T) values at 2%/50yr
6. Values for low hazard regions that fell below the lowest values used for seismic design in Canada were replaced by those lowest Canadian values
7. Values for U.S. Missions were replaced by IBC values

Discussion of the Steps for the First Set of Adjustments

1. Values for PGA were determined from the GSHAP map for each Mission. We used the closest grid point from the digital data set, but sometimes interpolated between grid points where we felt it was warranted. In some cases the geographical coordinates for the Mission were not originally available and were taken to be the centre of the city (usually to the nearest 0.1 degree). When refined coordinates became available (as is usually evident by the accuracy of the coordinates) we did not check every new hazard value. These changes in coordinates do not matter in many parts of the world, as the hazard gradient is low. In higher seismic hazard areas, and particularly where there is an asymmetry in earthquake distribution, the hazard gradient may be higher and checking may be warranted. For Missions located close to active faults the seismic hazard is extremely sensitive to the distance from the closest fault. California is a good example (http://earthquake.usgs.gov/regional/qfaults/ca/index.php) where the position of the faults is quite well known, so the hazard varies greatly over short distances. In many other parts of the world the situation is similar, but the faults are more poorly known. For such areas the GSHAP 0.1 degree grid is too coarse, and a local zoning map (or site-specific hazard analysis) is needed.

2. Canada and U.S. values were converted to rock. As mentioned above the Canada and U.S. mapped values were given for "firm ground", whereas the rest of the map is for "rock". The PGA values for U.S. Missions (and the Canadian reference cities) were reduced by factors to convert them to Site Class B rock. The value used for the U.S. was 0.8, taken from the soil amplification table for Fa in NBCC2005. Strictly, the factor is amplitude dependent and varies between 1.0 and 0.8. Those correct factors were applied rigorously to the Canadian cities, but not to the U.S. Missions (because the de-amplified results for the US are not in fact used to give the final design values – see step 7).

3. A manual adjustment was made to certain values. The GSHAP map contains discontinuities attributable to its assembly from regional subsets. Such discontinuities are troubling where the GSHAP map gives different estimates of the hazard for adjacent regions along the same plate boundary. Particularly noticeable examples are Haiti vs Dominican Republic and Costa Rica vs Nicaragua and Guatemala. In these cases, we believe that the local seismic hazard will be substantially the same along the entire subduction zone, and the difference in estimates represents either a too-short earthquake history or a too-hopeful estimate of the hazard. In these cases we have arbitrarily increased the seismic hazard to be the same as adjacent regions.

Along some plate boundaries (and elsewhere within the continents) the local seismic hazard is a "bulls-eye", much higher than for neighboring regions. These bulls-eyes are sometimes due to a particular, well-known damaging earthquake that has been used to determine seismic hazard in its historical context. North American examples are Charleston (South Carolina) and Grand Banks (south of Newfoundland). Depending on the hypothesis used, the estimated seismic hazard might be too high in these regions. This problem is a quandary for national seismic hazard mapping agencies, and the tendency is to "respect the historic record". Issues like this are discussed by Adams and Halchuk (2003) for the construction of the model used for NBCC2005. For the current work we did not make manual reductions to the GSHAP values (that is, the factors are all >1), so the bulls-eye values were allowed to stand. In such places the estimated seismic hazard may be too high, and might be reduced by a site-specific study.

A more subtle flaw occurs where the GSHAP seismic hazard estimate may have missed some major contributor to seismic hazard, and in our view underestimates the true hazard. An example is Hanoi which sits close to a major plate boundary (extension of the Red River Fault). The region has had few recent historical earthquakes, and the seismic hazard map for Vietnam in the late 1990s considered its hazard to be very low. Adjustments in such cases are very subjective, both in terms of whether they should exist and in terms of the size of the manual adjustment. We list the manual adjustments we made, the reasons for them, and the reason for the factor chosen in Table 1 of Adams et al. (2008). As noted for the screening report, such adjustments would require verification if the estimates were used to initiate expensive work. Verification would involve a detailed examination of local information and seismic design codes, and perhaps a site-specific seismic hazard assessment incorporating current knowledge.

4. A spectral shape category is assigned. Crudely we could use one set of factors to move from the PGA at 10%/50yr to the spectral acceleration (uniform hazard spectrum or UHS) at 10%/50yr, and a second set of factors to move from the UHS at 10%/50 yr to the UHS at

2%/50yr. The first step was a common one in the past (for example the 1970 NBCC design spectrum in Canada was fixed to the PGA value) and is termed the “scaled-spectrum method”. It has many deficiencies because the shape of the actual UHS is a site-specific reflection of sizes and distance of the earthquakes contributing, and that obviously varies from site to site. The 1985/1990/1995 NBCC used a modified approach involving two-parameters, PGA and Peak horizontal Ground Velocity (PGV), but NBCC2005 abandoned the scaled-spectrum approach in favour of site-specific UHS. The second step – changing the probability level of the UHS – involves multiplicative factor for each period. Crudely the factors are in the range 1.5 – 3.5, but their values are also determined by the sizes and distance of the earthquakes contributing. These factors actually reflect the slope of the “hazard curve” for each ground motion period. In general, where there are many earthquakes the factors are smaller, and where there are few earthquakes, the hazard curve is steeper and the factors are larger. Four spectral shapes (categories) were considered sufficient:

* Continental regions of Low Seismicity (Canadian example = Winnipeg)
* Continental regions of Moderate Seismicity (Canadian example = Montreal)
* Plate Margin regions (Canadian example = Vancouver)
* Plate Boundary regions where the site is either very close to active faults or relatively near subduction zones capable of generating great (magnitude >8) earthquakes (Canadian example = Queen Charlotte City)

Mathematically, the derivation of factors for step 1 (PGA→ UHS at 10%/50yr) and step 2 (UHS at 10%/50yr → UHS at 2%/50yr) can be combined. This reduces the work (only 20 factors are needed, not 40) and reduces compounding uncertainties. The factors used in this report were obtained by inspection of Canadian seismic hazard results generated by GSC’s 4th Generation seismic hazard model (Adams and Halchuk, 2003). The method used for each ground motion parameter (GMP, being PGA and Sa(T)) was as follows. For the Continental regions of Low Seismicity, the factors were calculated directly from the 4th Generation Stable Canada model (because the factor is analytical). For the remaining three categories Canadian contour maps of the ratio [seismic hazard for GMP at 2%/50yr] / [seismic hazard for PGA at 10%/50yr] were constructed (the maps used are in Appendix A of Adams et al., 2008), from which representative values were determined by inspection. The values for the 20 factors are given in Table 1 together with their approximate uncertainty range.

Discussion of the Spectral Shapes

The spectral shape factors from Table 1 are displayed in Figure 1. PGA is plotted at a period of 0.01 second for convenience; note that most seismic codes do not permit a decrease in amplitude below 0.2 seconds. Effectively, for a constant PGA of 1 unit at 10%/50yr, Figure 1 shows how the 2%/50yr UHS would vary by tectonic category. All the curves have a similar shape, with a decrease from 0.2 seconds to longer periods, which is a characteristic of almost all UHS. Figure 1 also shows clearly the different proportions of short-period energy to be expected: the Continental Low Seismicity regions have a much higher Sa(0.2) for a given 10%/50yr PGA than do the other categories. For PGA in Continental Low Seismicity regions the shape factor (2.8) is high relative to the other regions (~2) because contributions to the 10%/50yr PGA hazard from events less than magnitude 4¾ (“Mmin” – see Halchuk and Adams, 2010) are normally discarded as not being of engineering significance. This is only an important effect in these very low seismicity regions)

A different representation of the spectral shapes can be made by normalizing the factors at T=0.5 seconds, a period in the mid-range for many designs (Fig. 2; values are in Table 4 of Adams et al., 2008). Figure 2 shows clearly that the spectral shapes for the pair of continental categories are quite similar, as are those for the pair plate margin/boundary regions. The difference between the two pairs is quite considerable, with the continental sites having much more short-period energy and less-long period energy (relative to their 10%/50yr PGA). This is the expected difference, as the seismic hazard of plate margin and plate boundary regions is dominated by great earthquakes that generate much long-period energy; such great earthquakes are rare-to-absent in the two continental regions.

Checking the Quality of the Method's Results

Rather few locations worldwide provide seismic hazard estimates at both 2%/50 and 10%/50 years, particularly for spectral values. However, quality assurance checks were made against the national code values in three countries that use 2%/50yr hazard values: Canada, the United States, and New Zealand.

Canada. Since Canadian hazard values were used to determine the amplification factors, it is not surprising that the application of the factors in Table 2 to the known 10%/50yr PGA comes close to reproducing the actual values. Figure 3 shows the UHS for selected cities as taken from Adams and Halchuk (2003), and as estimated by the above method. We judge the agreement to be satisfactory, although the larger percentage differences (and cost implications for design) are hidden at long periods.

United States of America. We compared NBCC2005 Canadian and USGS 2002 GMP values across our common border (Adams et al., 2008). The conclusion was the agreement was good with the exception of the eastern US 10%/50yr PGA values, which are smaller than expected from either the 10%/50yr Canadian values or the US 2%/50yr values. This would cause problems if the proposed spectral values for 2%/50yr were based on the GSHAP map PGA values using our spectral factor method. The proposed 2%/50yr spectra would then be too low (by a factor of about two), both relative to the actual USGS values and to values for nearby Canadian sites. The recommended solution is given below.

New Zealand. A check of the spectral-shape-category approach was made for New Zealand localities using the PGA values for 10%/50yr and 2%/50yr read off figure 9 of Stirling et al. (2002). The PGA ratios ranged from 1.4 to 2.3 (see Table 6 of Adams et al., 2008). Auckland, Wellington and Christchurch PGA ratios were in the range 1.8-2.0, which means that the 2%/50yr PGA values predicted using the chosen plate boundary/plate margin ratio of 1.9 would be within 10%. Dunedin, is under-predicted by 20%. Otira, the highest-hazard location given, would be over-predicted by 30%, emphasizing a need for site-specific analyses.

Discussion of the Steps for the Second Set of Adjustments

6. Values for low hazard regions were replaced by the lowest Canadian values. Seismic hazard is not given by GSHAP for some low-seismicity locations, and for others we consider the value to be too low relative to that used in Canada. NBCC2005 introduced a floor value for seismic design in Canada, such that for even the lowest seismic regions some seismic design is required for sites not on rock (i.e. for Site Class C, D, E, and F). The NBCC2005 floor level PGA at 10%/50yr on soil class B is 0.017g. Consequently, for all Missions with GSHAP "adjusted" values of 0.017g or smaller, the following larger values were substituted in the spreadsheet:- PGA=0.047, Sa(0.2)=0.096, Sa(0.5)=0.034, Sa(1.0)=0.014, Sa(2.0)=0.0036g. These substitutions were made for approximately 30 localities outside the U.S.

7. Values for U.S. Missions were replaced by IBC values. The most obvious fix for the mis-prediction that would be consequent on the low eastern U.S. 10%/50yr PGA values is to simply adopt the most recent U.S. 2%/50yr values in place of the computed values for the entire U.S. This will ensure more reasonable numbers and also assists compliance with U.S. code design levels (which we consider will give acceptable performance compared to Canada's). Consequently, the values for U.S.-located Missions have been replaced by IBC2006 code values (taken from http://earthquake.usgs.gov/research/hazmaps/design/). The IBC code does not give (nor require for design) values for Sa(0.5), Sa(2.0), and PGA.

Results and Uncertainty in the Results

Table 7 (ordered by Sa(0.2) value) contains selected results of the estimation. The derived values are for Class B rock, and would need adjustment for actual site conditions. Comparable values for representative Canadian cities (adjusted from NBCC2005 Site Class C) are inserted to give an indication of the relative seismic hazard level. The results in Table 7 would not be complete without considering the uncertainties, which is done in Adams et al., 2008. Overall we think that the uncertainty in the design values in Table 7 is about ±20% for a majority of values, but users should be aware that the uncertainty for specific Missions could be much larger.

Discussion and Conclusions

The seismic design values in Table 7 represent our best estimate for the effort available, as substantially better estimates would require site-specific assessments. For the majority of Missions the seismic hazard is quite low, and even if the estimate is very uncertain the implications of that uncertainty are unlikely to be large. Missions with greater than low hazard fall into two classes:

A. Hazard is high or moderate, and there is a credible national assessment and seismic hazard code – It is recommended that the estimated values be compared to the national values. If the national values are higher, they should be adopted as they are likely more soundly based. If the national values are lower than the estimates, see class B.

B. Hazard is high or moderate but there is no credible national assessment (or only poor design codes) – It is recommended that the uncertainties in the analysis (both in the factors and in any manual adjustment) be considered very carefully before decisions are made. A site-specific analysis may be cost-effective.

Estimated seismic design values have been provided for 161 Canadian Missions abroad. The values are for NBCC2005 Class B rock at a probability of 2% in 50 years. The resulting design spectra are intended to be a) used for screening studies to assess the relative need for remedial work; b) used for Rapid Visual Screening (FEMA, 2002); and c) applied in the context of the National Building Code of Canada, in conjunction with local hazard maps and national building codes, in order to deliver appropriate safety to the Missions and continuity of consular services.

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References

Adams, J. and Halchuk, S. 2003. - Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada. Geological Survey of Canada, Open File 4459, 155 pp. Available at http://earthquakescanada.nrcan.gc.ca/hazard-alea/OF4459/index-eng.php

Adams, J., Halchuk S. and Awatta, A. 2008. Estimated Seismic Design Values for Canadian Missions Abroad, Geological Survey of Canada, Open File 5814, 46 p. plus digital appendix. Available at http://geopub.nrcan.gc.ca/moreinfo_e.php?id=225934

FEMA, (2002) Rapid Visual Screening of Buildings for Potential Seismic Hazards - A Handbook. FEMA 154, Edition 2, March 2002, 164 pp.

GEM, 2009. http://www.globalquakemodel.org/ last accessed October 2009.

Giardini, D., Grunthal, G., Shedlock, K., Zhang, P. 1999. Global Seismic Hazard Map. Produced by the Global Seismic Hazard Assessment Program (GSHAP).

Halchuk, S. and Adams, J. 2010. M_{min} - Implications of its choice for Seismic Hazard and Seismic Risk , 10th US 9th Canadian Conference on Earthquake Engineering, 10 pp.

ISC, 2007. http://www.isc.ac.uk/ , accessed September 2007.

NBCC, 2005. National Building Code of Canada 2005. Document NRCC 47666. National Research Council of Canada, Ottawa, Ontario.

NEIC, 2007. http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1 accessed September 2007.

Stirling, M.W., McVerry, G.H. and Berryman, K.R. 2002. A New Seismic Hazard Model for New Zealand. Bulletin of the Seismological Society of America, Vol. 92, No. 5, pp. 1878–1903.

Table 1. Spectral shape factors

		Period (second)				
Spectral Shape Category		PGA	0.2	0.5	1.0	2.0
Continental Low Seismicity	1	**2.8** NA	**5.4** NA	**2.6** NA	**1.1** NA	**0.3** NA
Continental Mod. Seismicity	2	**2.1** 1.9-2.3	**3.5** 3.3-3.9	**1.7** 1.5-2.0	**0.8** 0.7-1.0	**0.25** 0.2-0.3
Plate Margin	3	**1.9** 1.8-2.0	**3.9** 3.7-4.2	**2.8** 2.5-3.2	**1.5** 1.2-1.8	**0.8** 0.55-1.0
Plate Boundary	4	**1.9** NA	**4.4** NA	**3.5** NA	**1.8** NA	**1.0** NA

Bold denotes spectral shape factors, representing ratio of (2%/50 yr Spectral and PGA) to 10%/50 yr PGA; regular font denotes range of factors; “NA“ denotes no useful information on the range.

Table 2. Selected estimated design values for missions abroad and representative Canadian cities (green rows). Original report has entries for all 161 Missions.

Mission	Lat	Long	PGA from GSHAP (m/s-s)	Adjusted PGA at 10%/50yr (g)	Spectral Shape category	Estimated PGA at 2%/50yr (g)	Estimated Sa(0.2) at 2%/50yr (g)	Estimated Sa(0.5) at 2%/50yr (g)	Estimated Sa(1.0) at 2%/50yr (g)	Estimated Sa(2.0) at 2%/50yr (g)
Almaty	43.2500	76.9100	7.8301	0.798	4	1.517	3.512	2.794	1.437	0.798
Lima	-12.0800	-77.0400	7.0056	0.714	4	1.357	3.142	2.499	1.285	0.714
Taipei	25.0607	121.5440	6.5002	0.663	4	1.259	2.915	2.319	1.193	0.663
Chandigarh	30.7300	76.7800	2.9769	0.607	4	1.153	2.670	2.124	1.092	0.607
Managua	12.1400	-86.2700	3.7262	0.570	4	1.083	2.507	1.994	1.026	0.570
San José	9.9200	-84.0800	5.4818	0.559	4	1.062	2.459	1.956	1.006	0.559
La-Malbaie	47.6500	-70.1400				1.100	2.300	0.960	0.480	0.152
San Salvador	13.7000	-89.2000	3.3480	0.512	4	0.973	2.253	1.792	0.921	0.512
Guatemala City	14.6000	-90.5100	3.2998	0.505	4	0.959	2.220	1.766	0.908	0.505
Los Angeles	34.0496	-118.2560	4.4712	0.365	4		2.133		0.716	
Wellington	-41.2834	174.7740	4.4665	0.455	4	0.865	2.003	1.594	0.820	0.455
Quito	-0.2200	-78.5200	4.0329	0.411	4	0.781	1.809	1.439	0.740	0.411
Santiago	-33.4165	-70.6058	3.9290	0.401	4	0.761	1.762	1.402	0.721	0.401
Manila	14.5500	121.0100	3.7808	0.385	4	0.732	1.696	1.349	0.694	0.385
Tehran	35.7907	51.4265	4.2584	0.434	3	0.825	1.693	1.215	0.651	0.347
Tokyo	35.6665	139.7330	3.6428	0.371	4	0.706	1.634	1.300	0.668	0.371
San Diego	32.7158	-117.1670	2.6278	0.214	3		1.567		0.614	
Santo Domingo	18.4700	-69.8900	3.3917	0.346	4	0.657	1.521	1.210	0.622	0.346
Port of Spain	10.6500	-61.4700	3.3445	0.341	4	0.648	1.500	1.193	0.614	0.341
San Francisco	37.7928	-122.4040	5.8980	0.481	4		1.500		0.615	
Anchorage	61.2192	-149.9020	3.7713	0.308	4		1.484		0.548	
Guadalajara	20.6300	-103.4300	3.2240	0.329	4	0.624	1.446	1.150	0.592	0.329
Port-au-Prince	18.5300	-72.3200	1.5560	0.317	4	0.603	1.396	1.110	0.571	0.317
Beirut	33.9094	35.5780	2.9672	0.302	4	0.575	1.331	1.059	0.544	0.302
Victoria	48.5000	-123.3000				0.620	1.200	0.647	0.296	0.148
Islamabad	33.7241	73.1149	2.5112	0.256	4	0.486	1.126	0.896	0.461	0.256
Kabul	34.5300	69.1700	2.4376	0.248	4	0.472	1.093	0.870	0.447	0.248
Vancouver	49.2000	-123.2000				0.480	0.960	0.488	0.252	0.133
Hiroshima	34.4060	132.4570	2.0588	0.210	4	0.399	0.923	0.735	0.378	0.210
Beijing	39.9383	116.4220	1.0857	0.221	2	0.465	0.775	0.376	0.177	0.055
Damascus	33.5033	36.2600	1.5519	0.158	4	0.301	0.696	0.554	0.285	0.158
Montreal	45.5000	-73.6000				0.377	0.604	0.218	0.090	0.031
Mexico	19.4200	-99.1200	1.1103	0.113	4	0.215	0.498	0.396	0.204	0.113
Barcelona	41.3876	2.1687	1.1665	0.119	2	0.250	0.416	0.202	0.095	0.030
Niagara Falls	43.1000	-79.1000				0.240	0.328	0.120	0.044	0.013
Budapest	47.5111	19.0368	0.9052	0.092	2	0.194	0.323	0.157	0.074	0.023
Geneva	46.2250	6.1359	0.8955	0.091	2	0.192	0.320	0.155	0.073	0.023
Canberra	-35.3026	149.1240	0.8880	0.091	2	0.190	0.317	0.154	0.072	0.023
Sydney	-33.8613	151.2070	0.8657	0.088	2	0.185	0.309	0.150	0.071	0.022
Toronto	43.6500	-79.4000				0.160	0.224	0.084	0.033	0.010
Havana	23.1200	-82.3900	0.5468	0.056	3	0.106	0.217	0.156	0.084	0.045
Halifax	44.6000	-63.6000				0.096	0.184	0.078	0.042	0.011
Shanghai	31.2287	121.4480	0.3308	0.034	1	0.094	0.182	0.088	0.037	0.010
Warsaw	52.2600	21.0200	0.2255	0.023	1	0.064	0.124	0.060	0.025	0.007
Stockholm	59.3200	18.0600	0.1462	0.015	1	0.047	0.096	0.034	0.014	0.004
Winnipeg	49.8900	-97.1500				0.047	0.096	0.034	0.014	0.004
Miami	25.1280	-80.0310	0.0383	0.003	2		0.033		0.016	

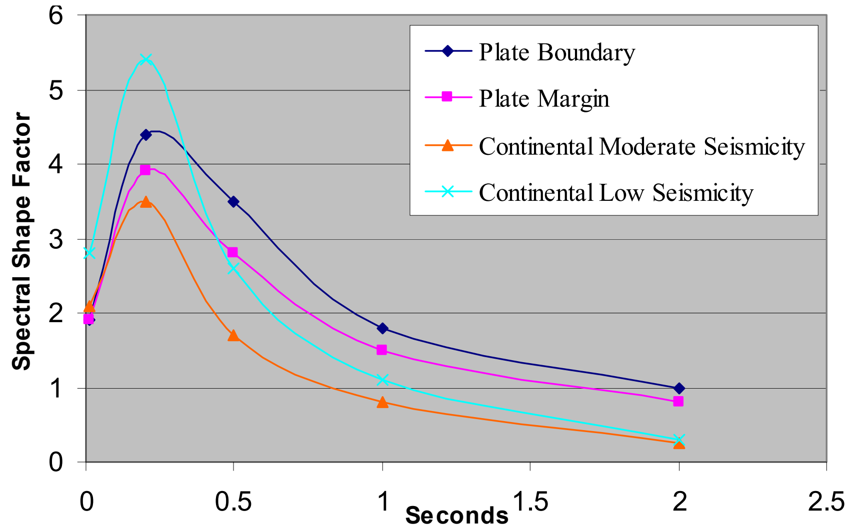

Figure 1. Ratio of (2%/50 yr Spectral and PGA) to 10%/50 yr PGA (PGA is plotted at 0.01 s)

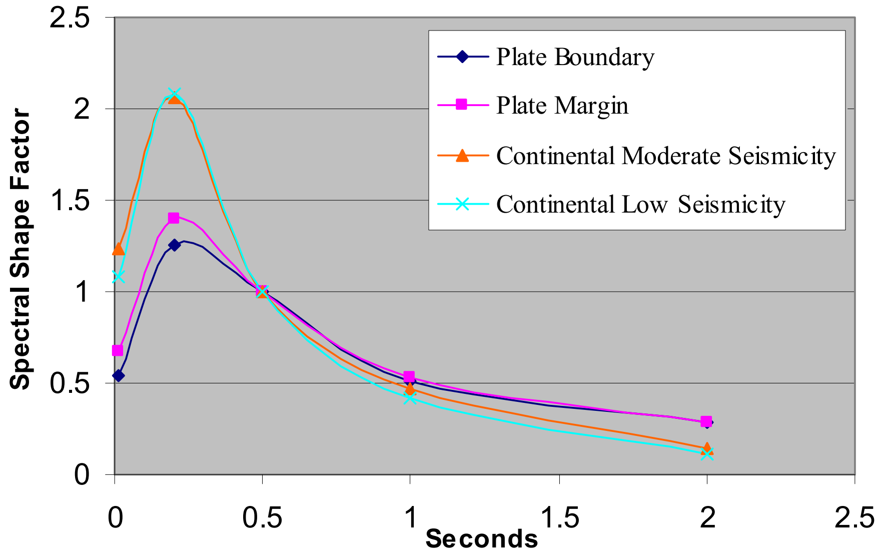

Figure 2. Spectral shape factors normalized at T=0.5 s (PGA is plotted at 0.01 s)

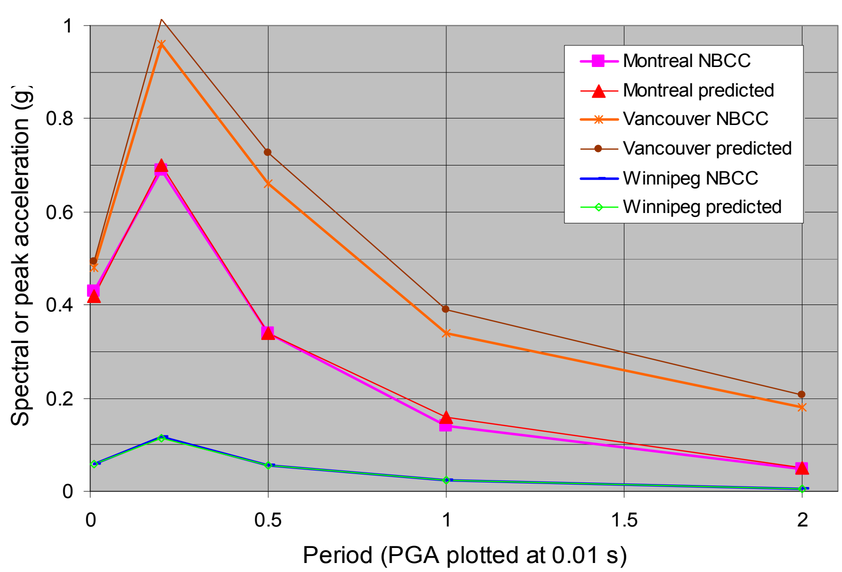

Figure 3. Comparison of NBCC and predicted (ratio-derived) UHS for Vancouver, Montreal, Winnipeg