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An alternative approach to site factors for NBCC2015

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Abstract

The site amplification factors in the 2015 edition of the National Building Code of Canada (NBCC2015) for South Western British Columbia (SWBC) were developed using only the single site term associated with the Boore and Atkinson (2008) Ground Motion Prediction Equation (GMPE) for crustal sources. The seismic hazard in SWBC is derived from three source types; crustal, subduction intraplate and subduction interface sources. Therefore site factors based only on a crustal site term are approximate. This study was conducted to assess the degree of approximation.

Alternative site amplification factors for Vancouver and Victoria, British Columbia were calculated using site specific look-up tables incorporating all the GMPEs associated with each seismic source type and their associated site terms. The alternative site factors are significantly greater than those given in NBCC2015 for periods 0.3s, 0.5s and 1.0s. These results suggest that the process for calculating site amplification factors should be reassessed by the committee currently reviewing seismic hazard for NBCC2020.

Keywords: Uniform Hazard Spectrum (UHS), Ground Motion Prediction Equation (GMPE), 2015

National Building Code of Canada, NBCC2015, Site Effects, Site Amplification Factor.

1. Introduction and Context

The National Building Code of Canada released updated seismic hazard maps in 2015 (NBCC2015) based on an updated seismic catalogue, revised seismic sources and new Ground Motion Prediction Equations (GMPEs). It is the first fully probabilistic hazard model for Canada. All three types of seismic sources; crustal, subduction intraslab and subduction interface are treated probabilistically. In previous hazard models the subduction interface earthquakes were treated deterministically and the crustal and subduction intraslab probabilistically. The greater hazard from the two assessments was adopted in the building code (Humar 2015).

Another new feature of the NBCC2015 is the adoption of tables of site amplification factors which are period, intensity and site class dependent. The Site Classes A to E, incorporated in NBCC2015 are described in Finn and Wightman (2003). A sampling of the NBCC2015 factors is shown in Table 1, for a period, T of 0.5s. These factors replace the two factor system, F_a and F_v , in NBCC2010, where F_a was the factor for short period structures (the average amplification over the period range 0.1s to 0.5s) and F_v for long period structures (the average factor over the 0.4s to 2.0s range).

The site amplification factors in NBCC2015 for South Western British Columbia (SWBC) were developed using only the single site term associated with the Boore and Atkinson (2008) Ground Motion Prediction Equation (GMPE) for crustal sources, as modified by Atkinson and Boore (2011). The seismic hazard in SWBC is derived from three source types; crustal, subduction intraplate and subduction interface sources. Therefore site factors based only on a crustal site term are approximate. This study was conducted to assess the degree of approximation.

Calculation of Seismic Hazard for NBCC2015

Detailed descriptions of the methodology used for developing the seismic hazard model for NBCC2015 may be found in Adams et al. (2015) and in the Geological Survey of Canada (GSC) Open File 7576 (Halchuk et al. 2014). A brief overview of the procedure is given below.

The seismic hazard for a given site is expressed as a Uniform Hazard Spectrum (UHS). The first step in hazard calculation is to develop ground-motion look-up tables appropriate for the Site Class of interest. These tables are incorporated into a hazard analysis program such as EZ-Frisk (EZ-Frisk, 2011), and the seismic hazard is then calculated for that Site Class.

The ground-motion look-up tables are first developed for Site Class B/C boundary conditions characterized by a time averaged shear wave velocity in the upper 30m of the site, $V_{s30} = 760\text{m/s}$. Site Class B/C is the boundary between Site Class B and Site Class C as defined in NBCC2015. Site Classes C, D and E are defined as having V_{s30} values in the range $360\text{m/s} \leq V_{s30} < 760\text{m/s}$, $180\text{m/s} \leq V_{s30} < 360\text{m/s}$ and $V_{s30} < 180\text{m/s}$, respectively (Finn and Wightman, 2003). The GMPEs used in calculating the ground-motion look-up tables for hazard assessment are shown in Table 2 together with the weighting factors (where applicable) that weight the GMPEs' individual contributions to the hazard. These ground-motion look-up tables are commonly used for Probabilistic Seismic Hazard Analysis (PSHA) in Canada, and they are a convenient way of providing ground-motion amplitudes for a range of magnitude-distance pairs at different periods. Note that each source type uses a different suite of GMPEs. The ground-motion look-up tables for the B/C boundary were converted to ground-motion look-up tables for Site Class C, the reference site adopted by the building code, using the conversion factors in Table 3. These factors are given in the GSC Open File 7576 (Halchuk et al. 2014). These amplification factors were developed from the linear soil term in the modified Boore and Atkinson (2008) GMPE using a characteristic velocity for Site Class C, $V_{s30} = 450\text{m/s}$. A similar approach, but which considered linear and nonlinear site terms, was employed to develop site amplification factor tables for Site Classes D and E, which were characterised

by shear wave velocities, $V_{s30} = 250\text{m/s}$ and 115m/s , respectively. All these site factors were derived from one GMPE only, the Boore and Atkinson (2008) GMPE, as modified by Atkinson and Boore (2011). The Boore and Atkinson (2008) GMPE was developed for crustal earthquakes in active tectonic regions, and was the backbone ground-motion model used in Atkinson and Adams (2013) for this tectonic region type. The subduction intraslab and subduction interface sources require sets of different GMPEs as shown in Table 2. The objective of this paper is to present an alternative approach to site factors for code use based on the site terms of the specific GMPEs associated with the crustal, subduction intraslab and subduction interface sources rather than the approximate approach of using just one GMPE for all sources as in NBCC2015.

It is a large undertaking to calculate the effects of using the appropriate GMPE and site terms for hazard evaluation for all British Columbia (BC) regions and all ground shaking intensity levels, so the present study is limited to investigating the significance of the effects of the new approach on hazards and site factors for the two major metropolitan centres in SWBC, for Vancouver (city hall, latitude 49.25, longitude -123.12) and Victoria (latitude 48.43, longitude -123.37) for different site conditions for the 2% in 50 years exceedance rate (a return period of 2,475 years). We shall present results for Site Classes C, D and E only.

2. The proposed UBC procedure for assessing site amplification factors

A brief outline of the proposed procedure for calculating source compatible site amplification factors is given here. This proposed procedure will be referred to as the University of British Columbia (UBC) procedure in this document for convenience. More details are introduced as needed in the course of describing the various sub-analyses leading to the development of alternative site factors. A computational model was developed using MatLab (The Mathworks, 2014) to calculate the ground

motion look-up tables needed for evaluating the seismic hazard for different tectonic region types. The hazard analyses were conducted using the program EZ-Frisk (EZ-Frisk, 2011). The properties of the 34 seismic sources identified for the south-west Canada region in NBCC2015 (Halchuk et al. 2014) were input into the EZ-Frisk data base.

3. Replicating the NBCC2015 Hazard for Site Class B/C, characterised by $V_{s30} = 760\text{m/s}$

The first step in validating the computational model used in this study is to replicate the NBCC2015 hazard for Site Class B/C. The contributions of the individual GMPEs to the hazard for an appropriate range of magnitudes and distances were calculated and then combined according to the weight factors assigned to them in Halchuk et al. (2014). This step yielded ground-motion look-up tables for hazard analysis for the different seismic sources. This was done for all sources types, but the results of this process are described here for subduction interface sources only, for brevity. A detailed discussion of this procedure may be found in Atkinson and Adams (2013) and Atkinson (2012). Sample spectral acceleration values, S_a , as a function of distance R were calculated for a M9.0 subduction interface earthquake for periods, $T=0.01\text{s}$ (PGA), 0.1s, 0.5s and 1.0s using the MatLab computational model. The distance R is the closest distance to the fault rupture surface. The calculated hazard at a site is dependent upon the combined weighted contributions of the subduction interface GMPEs as shown in Equation 1 (see Table 2).

$$S_a = 0.5 \times \text{AM09} + 0.2 \times \text{GA14} + 0.2 \times \text{Aa15} + 0.1 \times \text{Za06inter} \quad (1)$$

The weights presented in Eq. 1 are those specified in Atkinson and Adams (2013). The weighted average of the GMPEs is shown in Figure 1, together with the corresponding ground motion amplitudes for the Site Class B/C boundary (NBCC2015). The curves labelled 'NBCC2015' are those given in the Halchuk et

al. (2014) look-up tables. The 'Final' lines are the replicated equivalents. The comparison is an exact match which validates the computational model. Similar comparisons were obtained for crustal and subduction intraslab sources.

The next step in validating the computational process is to replicate the Uniform Hazard Spectra (UHS) for Site Class C for Vancouver and Victoria given in NBCC2015. This is done by first generating ground motion look-up tables for Site Class C from those generated at the B/C boundary by using the factors given in Table 3 (this is precisely the same way the Site Class C tables given in Open File 7576 are obtained). The calculated Uniform Hazard Spectra agrees exactly with those given in NBCC2015 as shown in Figure 2.

4. Calculating the Hazard for Site Classes, C, D and E using the proposed procedure

Ground motion look-up tables for Site Classes C, D, E are developed for evaluating the UHS for Vancouver and Victoria using the GMPEs and the site terms associated with each seismic source as presented in Table 2. This is in contrast to the procedure followed in NBCC2015 where the effects of site conditions were evaluated using a single site term associated with Boore and Atkinson (2008). In both procedures, site conditions are defined by characteristic V_{s30} values: 450m/s, 250m/s and 115m/s for Site Classes C, D, E.

The site term in the GMPEs is most commonly characterized by V_{s30} . However Zhao et al. (2006) groups sites into one of five classes, based on measured or assumed V_{s30} values or other information. The

Atkinson and Macias (2009) GMPE did not consider site effects at all and is the only GMPE proposed for use in NBCC2015 without a site term.

The look-up tables by the NBCC2015 procedure

The hazard given in NBCC2015, or obtained using the NBCC2015 procedure, uses look-up tables developed with the site term set to the B/C boundary ($V_{s30} = 760\text{m/s}$), as described in Section 2. These look-up tables are then modified by a site factor to convert to the Site Class of the specific site of interest. The site factors are developed from a single GMPE, Boore and Atkinson (2008), that is based on the amplification factors proposed by Choi and Stewart (2005).

The look-up tables by the UBC procedure

Weighted suites of GMPEs are used to develop Site Class C, D and E ground-motion look-up tables. In the development of the ground-motion look-up tables, the V_{s30} values (450m/s, 250m/s and 115m/s for Site Classes C, D, E) are used in the BA08, GA14 and Aa15 GMPEs; the site term is set to 2, 3 and 4 (Class C, D, E) for the Za06 (Za06inslab and Za06inter) GMPE. There is no site term associated with the subduction interface GMPE AM09. The NBCC2015 used the Boore and Atkinson (2008) site terms to supplement the AM09 GMPE. A decision was made to preserve this approach to account for site effects with the AM09 GMPE in the UBC procedure when calculating the subduction interface ground-motion look-up tables. Hence, where there is a site term in a GMPE, it is preferentially used in the development of the look-up tables for the different Site Classes, rather than a single site factor taken from a single GMPE being used for all tectonic region types as in NBCC2015.

Figure 3 presents the weighted sum of the individual subduction interface GMPEs calculated using the proposed procedure for Site Class C, which are the values used in the ground-motion look-up tables for the subduction interface sources. Also given for comparison are the corresponding values from NBCC2015. Both results agree very closely. These GMPE plots differ from those presented for the B/C boundary in Figure 1 because of the introduction of the relevant soil term for each GMPE to characterise Site Class C.

Because of the stiff nature of Site Class C the differences in the subduction interface ground-motion look-up tables from the proposed UBC procedure and those given in the NBCC2015 are not significant. There is however, a difference in the case of the inslab50 (subduction intraslab, depth=50km) ground-motion look-up tables, and resulting hazard values, as will be seen in the following section.

The hazard for Vancouver and Victoria is calculated now using the NBCC2015 and UBC procedures. The NBCC2015 gives site factors to convert from Site Class C to Site Classes D and E. These site factors can be obtained from the NBCC2015 period-dependent site factor tables, considering the PGA_{ref} (reference peak ground acceleration) = 0.367g for Vancouver and PGA_{ref} = 0.581g, for Victoria (NBCC, 2015). The relevant site factors are given in Tables 4 and 5. These factors are the product of the factors from site class B/C to C and C to D; B/C to C and C to E.

The probabilistic hazard was calculated also for Vancouver and Victoria using the proposed UBC ground-motion look-up tables. The relative contributions of the six different source types to the total hazard for Vancouver are shown in Figure 4, and the values obtained using the NBCC2015 are also given in each case for comparison. Upper and lower bounds on the hazards are also shown for each case. For logistical convenience Atkinson and Adams (2013) used a set of three alternative-weighted GMPEs to describe the epistemic uncertainty in median ground-motion amplitudes, labelled “lower”, “central” and “upper”

GMPEs. Their approach was adopted to produce the upper, central and lower hazard values of the UBC procedure shown in Figure 4. The inslab50 source type is the largest contributor to the hazard in this case, and shows a significant difference from NCBCC2015 hazards levels for periods of 0.2s, 0.3s and 0.5s. The subduction interface and crustal hazards contribute less than the inslab50 source type for periods approximately below 1.0s, but the differences between the proposed UBC and NBCC2015 procedures are less. The remaining three source types contribute very little in this case, barely visible in the Figure 4 with this y-axis scale. The differences for the inslab50 central case are 23%, 32% and 14% for 0.2s, 0.3s and 0.5s period values, respectively.

The hazards for Site Classes D and E for Vancouver were also calculated following the UBC procedure. The resulting hazard levels are shown in Figure 5 for the inslab50, subduction interface and crustal sources only, as the other three sources contributions are relatively minor in comparison (as shown in Figure 4).

Figure 5 instantiates the differences between the site term effects in the different attenuation relations used for each of the three different site conditions. For example, when comparing the Site Class D and E curves in the inslab50 and crustal plots in Figure 5, it is evident that the site effects, or the differences between the Site Class D and Site Class E curves, are much more pronounced for the 0.5s period in the crustal plot than in the inslab50 plot. The relative magnitudes of the increases due to site effects seen in the inslab50 and crustal hazard curves are also striking. The mean hazards for each of the three Site Classes by the two procedures are given in Figures 6(a)-(d) for Vancouver. Figures 6(a)-(c) present the results over a limited period range. The same information is presented in Figure 6(d) on a log-log scale in

order to present all the results for the three Site Classes over the whole period range up to 10.0s. The mean hazards for each of the three Site Classes are given in Figures 7(a)-(d) for Victoria.

The probabilistic spectra obtained using the two procedures for Victoria are shown in Figures 7(a)-(c) to a natural scale. Site Class C shows a modest increase for the UBC procedure relative to the NBCC2015 values for periods centred around 0.3s. UBC values for Site Class D are significantly greater than NBCC2015 within the range of 0.2s to 1.0s, with a peak increase of approximately 39% at a period of 0.5s. For Site Class E the hazard for the UBC procedure is greater than the NBCC2015 predictions over the range 0.3s to 2.0s, with an increase of approximately 37% at a period of 0.5s.

5. Site Factors

The response spectrum ordinates for Site Classes D and E obtained using the UBC procedure are generally greater than those tabulated in NBCC2015 in the period range below 2s. The data presented in Figures 6 and 7 are reinterpreted as site factors by dividing the Site Class D and E spectral ordinates by the corresponding Site Class C ordinates for both Vancouver and Victoria, to give site factors for Site Classes D and E, relative to C. These factors are tabulated below in Table 6.

There are significant differences between the UBC and NBCC2015 amplification factors for Site Class D for periods $T=0.5s$ and $T=1.0s$, and for Site Class E for periods $T=0.5s$, $1.0s$ and $2.0s$. For Site Class D sites in both Vancouver and Victoria the UBC factors exceed the NBCC2015 factors by 25% at $T=0.5s$ and by 7% at $T=1.0s$. For Site Class E sites the differences are much greater. For Vancouver at periods $T=0.5s$, $1.0s$ and $2.0s$ the differences are 15% 30% and 7% respectively. For Victoria Site Class E sites the corresponding increases are 25%, 35% and 25%.

The major differences between the UBC and NBCC2015 site factors can be attributed to the Zhao GMPE site term operating on the subduction intraslab sources. This term represents a 100% replacement for the BA08 site term. The replacement site terms in the subduction interface sources were weighted at only 50% of the hazard, with the Zhao et al. (2006) in this case accounting for only 10%.

The differences between NBCC2015 and UBC site amplification factors is significant enough to warrant a reassessment of the procedures for calculating site amplification factors for the 2020 edition of the National Building Code.

6. Conclusions

This study presents alternative site amplification factors for Vancouver and Victoria. The alternative factors were calculated using site-specific look-up tables incorporating all the GMPEs associated with each type of tectonic region and their associated site terms. In contrast NBCC2015 site amplification factors were developed using only the single site term associated with Boore and Atkinson (2008) GMPE for crustal sources. The alternative site factors are significantly greater than those given in NBCC2015 for periods 0.3s, 0.5s and 1.0s. For example, they are approximately 25%-30% greater at $T=0.5s$ for both Site Class D and E sites in Vancouver and Victoria. For Site Class E sites in Victoria the differences are much greater at 25%, 35% and 25% greater at $T=0.5$, 1.0 and 2s.

These results suggest that in determining site amplification factors for the 2020 edition of the NBCC the procedure for calculating site amplification factors should be reassessed. Whether the existing GMPE are retained or new GMPEs are adopted, it is imperative that source compatible site terms are used in estimating site amplification factors.

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Table 1. NBCC2015 F(T) factors for 0.5s for different intensities and site classes (PGA_{ref} is the reference peak ground acceleration).

	$PGA_{ref} \leq 0.1g$	$PGA_{ref} = 0.2g$	$PGA_{ref} = 0.3g$	$PGA_{ref} = 0.4g$	$PGA_{ref} \geq 0.5g$
A	0.57	0.57	0.57	0.57	0.57
B	0.65	0.65	0.65	0.65	0.65
C	1.0	1.0	1.0	1.0	1.0
D	1.47	1.30	1.20	1.14	1.10
E	2.47	1.80	1.48	1.30	1.17

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Table 2. GMPEs used in the proposed 2015 hazard calculations.

Source type	GMPE reference	Shorthand reference
Crustal	Boore and Atkinson (2008)	BA08
Crustal (faults)	Boore and Atkinson (2008)	
Crustal (offshore)	Boore and Atkinson (2008)	
Subduction intraslab	Zhao et al. (2006)	Za06inslab
(30km depth)	Boore and Atkinson (2008) - used for 10s period only	
Subduction intraslab	Zhao et al. (2006)	
(50km depth)	Boore and Atkinson (2008) - used for 10s period only	
Subduction	Atkinson and Macias (2009) - weighted $\times 0.5$	AM09
interface	Ghofrani and Atkinson (2014) - weighted $\times 0.2$	GA14
	Abrahamson et al. (2015) - weighted $\times 0.2$	Aa15
	Zhao et al. (2006) - weighted $\times 0.1$	Za06inter

Table 3. Factors to convert from Site Class B/C to C (Halchuk et al. 2014).

Period (s)	10	5	2	1	0.5	0.3	0.2	0.1	0.05	PGV	0.01
											(PGA)
Factor	1.406	1.481	1.466	1.443	1.369	1.259	1.176	1.140	1.164	1.369	1.208

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Table 4. Factors to convert from B/C to Site Classes D, E for Vancouver.

Period (s)	10	5	2	1	0.5	0.3	0.2	0.1	0.02	0.01
									(PGV)	(PGA)
B/C to D	1.898	2.044	1.950	1.833	1.588	1.209	1.129	1.094	1.588	1.148
Factor										
B/C to E	2.700	2.992	2.624	2.309	1.862	1.221	1.141	1.106	1.862	1.063
Factor										

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Table 5. Factors to convert from B/C to Site Classes D, E for Victoria.

Period (s)	10	5	2	1	0.5	0.3	0.2	0.1	0.02	0.01
									(PGV)	(PGA)
B/C to D	1.847	1.986	1.857	1.742	1.502	1.136	1.061	1.028	1.502	1.062
Factor										
B/C to E	2.514	2.725	2.313	2.007	1.600	1.069	0.998	0.968	1.600	0.889
Factor										

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Table 6. Comparing site factors for Vancouver and Victoria.

		PGA	0.2s	0.5s	1s	2s	5s	10s
Vancouver	NBCC2015 D/C	0.95	0.96	1.16	1.27	1.33	1.38	1.35
	UBC D/C	1.04	0.92	1.46	1.34	1.31	1.39	1.30
	NBCC2015 E/C	0.88	0.97	1.36	1.60	1.79	2.02	1.92
	UBC E/C	1.19	0.94	1.56	2.08	1.92	2.15	1.97
Victoria	NBCC2015 D/C	0.88	0.90	1.10	1.21	1.27	1.34	1.31
	UBC D/C	1.00	0.91	1.39	1.31	1.31	1.39	1.37
	NBCC2015 E/C	0.74	0.85	1.17	1.39	1.58	1.84	1.79
	UBC E/C	1.06	0.90	1.46	1.88	1.88	2.10	1.97

Figure Captions

Figure 1 – Subduction interface GMPEs in cm/s^2 plotted with closest distance to the fault rupture surface, R , for M9.0 and (a) PGA, (b) 0.1s, (c) 0.5s and (d) 1.0s, for the Site Class B/C.

Figure 2 – Reproduction of the NBCC2015 mean 2% in 50 years UHS for Vancouver and Victoria for Site Class C.

Figure 3 - Weighted sum of subduction interface GMPEs in cm/s^2 for M9.0 and (a) PGA, (b) 0.1s, (c) 0.5s and (d) 1.0s, compared with the NBCC2015 values for Site Class C.

Figure 4 - Comparison of NBCC2015 and UBC mean 2% in 50 year hazard for Vancouver for different source types for Site Class C.

Figure 5 - Mean 2% in 50 year hazard for Vancouver for three source types, for Site Classes D and E.

Figure 6 - Mean hazard probabilistic spectra for Vancouver: (a) Site Class C; (b) Site Class D; (c) Site Class E; (d) Site Classes C, D and E for Victoria using two different procedures.

Figure 7 - Mean hazard probabilistic spectra for Victoria: (a) Site Class C; (b) Site Class D; (c) Site Class E; (d) Site Classes C, D and E for Victoria using two different procedures.

Figure 1 - Subduction interface GMPEs in cm/s^2 plotted with closest distance to the fault rupture surface, R , for M9.0 and (a) PGA, (b) 0.1s, (c) 0.5s and (d) 1.0s, for the Site Class B/C

303x270mm (72 x 72 DPI)

Figure 2 - Reproduction of the NBCC2015 mean 2% in 50 years UHS for Vancouver and Victoria for Site Class C

178x72mm (96 x 96 DPI)

Figure 3 - Weighted sum of subduction interface GMPEs in cm/s^2 for M9.0 and (a) PGA, (b) 0.1s, (c) 0.5s and (d) 1.0s, compared with the NBCC2015 values for Site Class C

303x270mm (72 x 72 DPI)

Figure 4 - Comparison of NBCC2015 and UBC mean 2% in 50 year hazard for Vancouver for different source types for Site Class C

344x170mm (96 x 96 DPI)

Figure 5 - Mean 2% in 50 year hazard for Vancouver for three source types, for Site Classes D and E

344x170mm (96 x 96 DPI)

Figure 6 - Mean hazard probabilistic spectra for Vancouver: (a) Site Class C; (b) Site Class D; (c) Site Class E; (d) Site Classes C, D and E for Victoria using two different procedures

328x211mm (72 x 72 DPI)

Figure 7 - Mean hazard probabilistic spectra for Victoria: (a) Site Class C; (b) Site Class D; (c) Site Class E; (d) Site Classes C, D and E for Victoria using two different procedures

335x211mm (72 x 72 DPI)