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Modified spectral format based on probability level using site-specific uniform hazard spectrum



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Abstract

Deficiencies of the four spectral formats i.e., 2%/50-yr, 5%/50-yr, 10%/50-yr and AASHTO (American Association of State Highway Officials) 2009 demand modification of the spectral formats for bridge design application in Canada. Among them the 10%/50-yr spectrum is dropped from current investigation as its difference with Canadian Highway Bridge Design Code (CHBDC) 2006 is too large to modify. This study introduces an approach calibrating on the values of elastic seismic response coefficient to provide a new shape of the Canadian bridge design spectrum based on modified 2%/50-yr, modified 5%/50-yr and modified AASHTO spectral formats. A Digital Visual Fortran program was prepared to determine the optimum values of the modification factors incorporated into the three spectral formats calibrated on the data of 389 cities of Canada. Thus, here it is developed the strategies of modifying the three spectral formats based on the best probability level for CHBDC using site-specific Uniform Hazard Spectrum (UHS). Finally, select the most suitable spectral format to apply for the design base shear calculations for the bridges of Canada.

Keywords: Design spectrum, Probability level, Seismic hazard map, Uniform Hazard Spectrum, Elastic seismic response coefficient

1 Introduction

The standardized spectrum, which is constructed using an idealized shape anchoring on a single control point and has long been used in codes demonstrates several short-falls. Seismic provisions of many codes in the world, e.g., NBCC (National Building Code of Canada) in Canada, UBC (Uniform Building Code), IBC (International Building Code) and AASHTO in the USA (United States of America) etc. have already adopted uniform hazard spectrum construction method and formats. The concept of UHS that uses of multiple control points having corresponding site-specific spectral values does not differ from code to code. But their formats are different depending on many factors. Such factors include seismic performance of target structures of code application, seismic data specific to local geological conditions, modeling techniques of ground motion characterization, diverse perspective of acceptable risk level among code writers, and historical performances of structures (Naumoski et al. 2000).



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In Canada, major changes in the seismic provisions for building design have been made in NBCC (2005). The most noticeable changes include: (i) adoption of UHS as a spectral shape, and (ii) lowering the probability level for hazard maps. AASHTO (2009) has also embraced similar seismic provisions in the USA. For bridge design, CHBDC require similar steps toward that direction.

From the few decades back, several researchers are introduced a number of procedures keeping low probability level of hazard map to predict the seismic risk. Joyner with other researchers (1981) developed quarter-wave length approximation which was widely applied by Boore and Joyner (1997) to derive site amplification based on local V_{s30} measurements. The technique does not create peaks for ground-motion amplification function because of considering limited facts of seismic wave propagation within geotechnical layers. This procedure calculates average responses and models considering velocity gradients of that approach may underestimate the responses (Boore 2013).

Other researchers revised the empirical approach of Pacific Earthquake Engineering Research Center (PEER), Next Generation Attenuation (NGA) ground-motion prediction equations (GMPEs) (Boore and Atkinson 2008; Atkinson and Morrison 2009; Chiou et al. 2010), which is originally developed by Atkinson (2008) and found that GMPEs have inherent nature of overpredict the ground motions in the range from small-to-moderate ground-motion amplitudes. Atkinson and Boore's GMPE eqs. (2006) highly underestimate the ground-motion amplitudes at higher frequencies comparing with the recent moderate earthquake events occurred in eastern North America. Later those equations were incorporated by a regression analysis of the PEER-NGA strong-motion information compiled from shallow crustal earthquakes in active tectonic regions and adjusted by a ratio of observed and predicted ground-motion amplitudes (Atkinson and Boore 2011). Later, Atkinson and Adams developed an advanced model of GMPEs and their epistemic uncertainty directly applicable to the seismic hazard map in Canada (Atkinson and Adams 2013).

Further development on the NGA models had been initiated from the original NGA-West1 GMPEs and improved these GMPEs as a partial task of the large multidisciplinary NGA-West2 project to estimate ground motion and aleatory variability for shallow crustal earthquakes in active tectonic regions (Bozorgnia et al. 2014; Campbell and Bozorgnia 2014). NGA-West2 project was organized by the PEER. More than 30 NGA GMPE researchers and developers were collaborated and interacted closely to study a number of key issues in ground-motion seismic hazard and updated the NGA database in between the earthquake magnitude range of 3.0 and 7.9 (Ancheta et al. 2013, 2014). Accordingly, Bozorgnia and Campbell's (2004) simplified vertical design spectra for near-source ground motion developed based on the NEHRP Provisions (BSSC 2009) were updated to NGA-West2 ground-motion models implementing extensive NGA-West2 database (PEER 2013).

Besides the effort of other researchers, an approach of determining the elastic seismic response coefficient, C_{sm} using various design spectra of (i) NBCC (2005) format using 4th generation seismic hazard maps of 2% in 50-yr, 5% in 50-yr, 10% in 50-yr as defined in CHBDC (2006), (ii) AASHTO (2009) format, and (iii) CHBDC (2006) format has been evaluated in the most recent study. It compared the C_{sm} values with those of CHBDC (2006), tracked the magnification and reduction of C_{sm} for a set of periods and

investigated the best probability level for CHBDC using site-specific UHS. The outcome of that study indicated that those spectral formats need modification in order to bring the base shear level in an acceptable range for CHBDC incorporation (Ahmed et al. 2016).

The implication of adopting the uniform hazard spectrum (UHS) in association with recently published seismic hazard maps for Canada into CHBDC is investigated in this phase of study. To have a statistically justifiable and broad based conclusion, this research used seismic data for 389 Canadian cities. Three issues are intricately associated in the analyses: (i) the spectral format, (ii) the probability level of seismic hazard maps, and (iii) confidence levels of hazard maps. Two code (UHS) formats are considered to be most relevant for CHBDC application: NBCC (2005) and AASHTO (2009). It is relevant to recall that current and past seismic maps and elastic design spectra of CHBDC (e.g., those of CHBDC 2006 and previous editions) are primarily developed based on NBCC and AASHTO provisions.

As far as probability level of hazard maps is associated, during the process of UHS implementation into the NBCC (2005), the Geological Survey of Canada (GSC) 2009 published 4th generation seismic hazard maps for several probability levels such as 2%, 5%, 10% and 40% probability of exceedance in 50 years. NBCC lowered the probability level from 10% to 2% during its most recent revision. Other major building codes in North America also lowered the probability level to 2% while incorporating UHS and updated maps into the codes (e.g., UBC and IBC in the USA). One thing is also important to recall that 4th generation seismic hazard maps used 50th percentile confidence level while the old maps for NBCC (1995) used 84th percentile. The influence of changing confidence level is significant. Heidebrecht (1997, 1999) reported that the ratios of 4th generation hazard values of 84th and 50th percentiles vary in the range of 1.5 s to 3.0 s. Similar observations are made in this study. On the other hand, for bridge application, AASHTO (2009) also lowered the probability level but not to the level of 2% but of 5%. In this backdrop, this study brought three sets of hazard maps corresponding to 2%, 5% and 10% probability of exceedance in 50 years developed by the GSC under investigations.

Following five spectral shapes are studied and their description is repeated here for clarity of presentation:

- a. 2%/50-yr – a spectrum that is drawn using spectral coefficients $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$ of 4th generation seismic hazard maps with 2% probability of exceedance in 50-year according to Section 4.1.8.4 of NBCC (2005).
- b. 5%/50-yr – a spectrum that is drawn using spectral coefficients $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$ of 4th generation seismic hazard maps with 5% probability of exceedance in 50-year according to Section 4.1.8.4 of NBCC (2005).
- c. 10%/50-yr – a spectrum that is drawn using spectral coefficients $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$ of 4th generation seismic hazard maps with 10% probability of exceedance in 50-year according to Section 4.1.8.4 of NBCC (2005).
- d. CHBDC – a spectrum that is drawn using zonal acceleration ratio A of CHBDC (2006) with 10% probability of exceedance in 50-year according to Section 4.4.7 of CHBDC (2006).

- e. AASHTO – a spectrum that is drawn using spectral coefficients $S_a(0.2)$ and $S_a(1.0)$ of 4th generation seismic hazard maps with 5% probability of exceedance in 50-year according to Section 3.4.1 of AASHTO (2009).

The statistical analysis conducted for the 10%/50-yr spectrum shows that more than 95% of the cities (i.e., about 370 cities out of 389) will have significant drop of base shear comparing with current shear level of CHBDC (2006). The extents of reduction of base shear are also quite high: at least 50% reduction for 90% of the 389 cities. There is a general trend of more reduction with increasing period. This result is neither surprising nor unexpected. Despite the fact that both CHBDC (2006) and 10%/50-yr spectra use maps of the same probability level (i.e., 10% probability of exceedance in 50 years), the reason of big differences of base shears between two spectra is that they use hazard maps of two different confidence levels; i.e., CHBDC (2006) uses 50th percentile but 10%/50-yr uses 84th percentile. The big drop of base shear makes the 10%/50-yr spectrum unacceptable of use in the future CHBDC. In other words, 4th generation seismic hazard maps with 10% probability of exceedance in 50-year should not be used for next CHBDC edition.

The statistical analyses conducted for the 5%/50-yr spectrum show similar trend of 10%/50-yr spectrum but the extents of amplification happen in a lesser scale. Again the drop of base shear is observed for most of the cities. The magnitudes of reduction of base shear are big enough to be concerned. Same general trend of more reduction with increasing periods are noticeable. In general, it is concluded that the adoption of this spectrum in its present shape into CHBDC is not practical. However, the nature of base shear level variation suggests that this spectrum can be 'modified' to bring the base shear level in an acceptable range.

For the 2%/50-yr spectrum, the statistical analyses reveal that for shorter period range, there will be an increase but for longer period range, there will be significant decrease of base shear from that of the current CHBDC provision. Similar to the 5%/50-yr spectrum, the nature of base shear level variation for 2%/50-yr suggests that this spectrum can also be 'modified' to bring the base shear level in an acceptable range. However, the degree of modification will not be as high as of 5%/50-yr spectrum.

Since, AASHTO uses 4th generation seismic hazard maps with 5% probability of exceedance in 50-year, the comments made for the statistical analyses of 5%/50-yr spectrum work well for AASHTO spectrum. Again, the nature of base shear level variation suggests that this spectrum needs to be 'modified' for CHBDC incorporation to bring the base shear level in an acceptable range. However, a different approach is needed for modification.

On the backdrop of the aforementioned observations made from the statistical analyses, it is observed that the design spectra under consideration need to be fixed if the concept of UHS and the new hazard maps are to be implemented into CHBDC. An approach to select an appropriate design spectrum likely to be implemented in the next CHBDC will require a combination of engineering judgment and calibration to existing practice. The spectral shapes represent the hazard which must be the same for any type of bridges. From that perspective, variations on how to resist the hazard should be handled in the design approach. Therefore, this

extended study work out the strategies of modifying the three spectral formats (i.e., 2%/50-yr, 5%/50-yr and AASHTO). Eventually, the most suitable spectral format from those modified spectra is recommended for next CHBDC edition.

2 General trend of design spectra based on 4th generation seismic hazard maps

The statistical analyses using the seismic hazard data of 389 cities well demonstrated the fact that none of the uniform hazard spectral formats based on 4th generation seismic hazard maps (2%/50-yr, 5%/50-yr, 10%/50-yr and AASHTO) produces consistent results in terms of normalized elastic seismic coefficient C_{sm}^* across the geographical boundary of application as well as across the range of period (Ahmed et al. 2016). The major concern of using the 4th generation seismic hazard maps is that the resultant base shear will be very low irrespective of period range based on 4th generation hazard maps compared to current level. The implication here is that the seismic hazard maps of CHBDC (2006) and NBCC (1995) are 'very conservative'. It is also noteworthy that the degree of conservatism is not constant with period and varies with period and probability level. Any new spectral format based on 4th generation seismic hazard maps (of any probability levels under consideration) is bound to reduce the magnitude of base shear values from the current CHBDC (2006) level for most of the cases. There will be a huge discomfort to adopt the 4th generation seismic hazard maps in the CHBDC with such prospects because the historical performances of thousands of bridges which have been designed and constructed during last several decades in Canada do not have any noticeable records of poor performances during and after the seismic events occurred. Such history of satisfactory performance of bridges in Canada does not permit big change in the level of current base shear. On the other hand, the 4th generation seismic hazard maps are based on enriched inventory of seismic data/events, better hazard modeling techniques and significant progress on ground motion characterization. The same is true for uniform hazard spectral format. Adoption of these two important facets of seismic engineering development into CHBDC is inevitable and unavoidable. To that end, this study proposes some modification of the 2%/50-yr, 5%/50-yr and AASHTO formats and establishes the validity of such modification.

3 Approach for spectra modification

Present analysis is focused on introducing and applying modification factors to the code specified formats that will bring improvement of C_{sm}^* distribution corresponding to 389 Canadian cities in the C_{sm}^* vs. T diagram, where C_{sm}^* is defined as

$$C_{sm}^*(T) = C_{sm-sq}(T)/C_{sm-CHBDC}(T) \quad (1)$$

where $C_{sm-sq}(T)$ is the elastic seismic coefficient for a period T obtained from the spectrum in question, and

$C_{sm-CHBDC}(T)$ is the elastic seismic coefficient for a period T obtained from the spectrum defined by CHBDC (2006).

As this study is in search of a UHS spectrum in a modified format that does not bring a radical change in the magnitude of current CHBDC base shear level (i.e., no large

magnification/reduction of C_{sm}^*), the objective of this research is to find a spectrum for which most of the C_{sm}^* data lie in the vicinity of $C_{sm}^* = 1.0$ line (Fig. 1).

To achieve those objectives, the general approach of modifying uniform hazard spectral format of the two codes (NBCC and AASHTO) is focused on (i) having maximum data in the preferred bandwidth of $0.9 \leq C_{sm}^* \leq 1.5$ and (ii) having minimum data below the $C_{sm}^* = 0.9$ level. The implication here is twofold:

i. ***Adopt conservative approach***

Maximize data in the preferred bandwidth so that the base shear values corresponding to the modified spectra neither derive too much increase (more than 50%) nor derive too much decrease (less than 10%) of current CHBDC base shear level, and

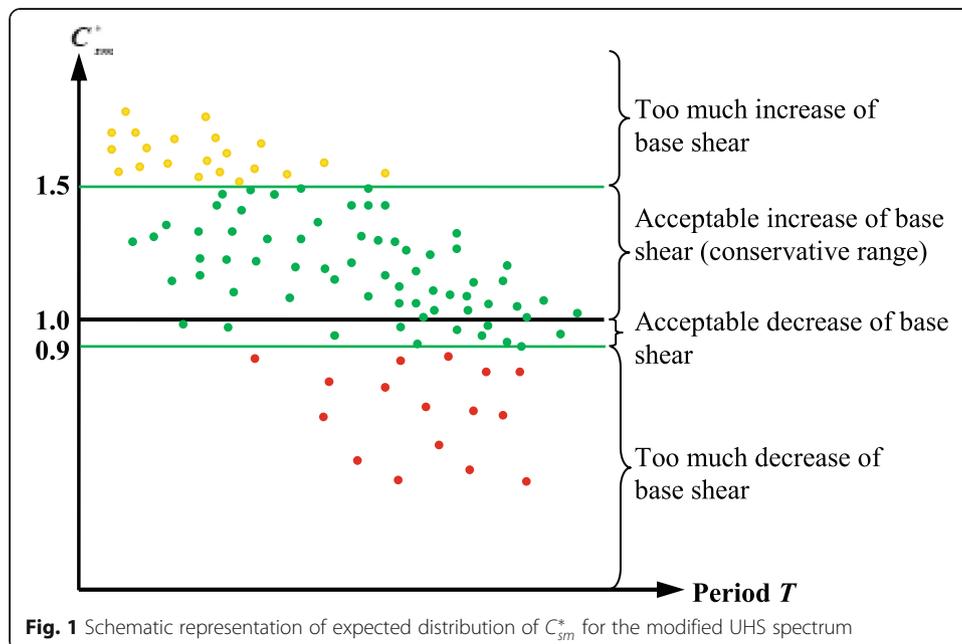
ii. ***Avoid unsafe data***

Do not allow too much data that will result low base shear (less than 10% of current CHBDC level) to remain in the unsafe zone ($C_{sm}^* < 0.9$).

The points of the approach adopted in this study for modifying the code specified spectral format with reference to relative position of C_{sm}^* distribution are illustrated in Fig. 1.

4 Modification of NBCC 2005 UHS format with 2%/50-yr hazard maps

The 2%/50-yr spectrum in UHS format as defined in our previous article (Ahmed et al. 2016) uses a linear interpolation and extrapolation of four spectral ordinates viz., $S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$ and $S_a(2.0)$. These amplitudes are in need of reduction or magnification to fit the goal described above. To that end, four modification factors (F_T) are introduced as follows:



- $F_{0.2}$ = Multiplying factor for $S_a(0.2)$
- $F_{0.5}$ = Multiplying factor for $S_a(0.5)$
- $F_{1.0}$ = Multiplying factor for $S_a(1.0)$
- $F_{2.0}$ = Multiplying factor for $S_a(2.0)$

The main features of 2%/50-yr spectrum remain the same as described in our previous article (Ahmed et al. 2016).

With the modification factors, the modified spectrum takes the shape as follows:

For period, $T = 0.2$ s,

$$S(T) = F_{0.2} F_a S_a(0.2) \quad (2)$$

For period, $T = 0.5$ s, the smallest value from the following two equations is to be taken:

$$S(T) = F_{0.5} F_v S_a(0.5) \quad (3)$$

or,

$$S(T) = F_{0.2} F_a S_a(0.2) \quad (4)$$

For period, $T = 1.0$ s,

$$S(T) = F_{1.0} F_v S_a(1.0) \quad (5)$$

For period, $T = 2.0$ s,

$$S(T) = F_{2.0} F_v S_a(2.0) \quad (6)$$

For period range 4.0 s or more,

$$S(T) = F_{2.0} F_v S_a(2.0)/2 \quad (7)$$

where F_a and F_v are the acceleration and velocity based site coefficients, respectively and they can be determined conforming to Tables 4.1.8.4.B and 4.1.8.4.C (NBCC 2005) using linear interpolation for intermediate values of $S_a(0.2)$ and $S_a(1.0)$. For site Class F, F_a and F_v are determined by site-specific geotechnical investigations and performing dynamic site response analyses.

5 Computer program for analyses

The Digital Visual Fortran program (1998) developed in the previous study (Ahmed et al. 2016) is modified with an eventual goal to obtain optimum values of the modification factors and to establish the validity of the modified spectrum. It consists of a main program (*uhs.f*) and several subroutines (*gsc.f*, *aashto.f* and *initial.f*). The program does the following tasks:

- Reads all input data for 389 cities from spectra.in file and store them in array format.
- Creates output files echoing input data to make sure that input data are correctly read by the program.
- Calculates data for spectra construction (C_{sm} vs. Period).
- Calculates normalized elastic seismic coefficient C_{sm}^* corresponding to a set of periods.

- Does the statistical analyses from the distribution of C_{sm}^* of 389 cities to examine the trend of magnification/reduction of C_{sm} values corresponding to those of current CHBDC [2006] along the range of period.
- Writes several output files to save the aforementioned numerical results for subsequent analyses and plotting.
- Present and discuss the aggregate results based on statistical analyses using all data corresponding to 389 cities.

6 Modification factors for 2%/50-yr spectrum

The modification factors those have been introduced above discussion have significant impact on the base shear values. Obtaining optimum modification factors requires iterative analyses similar to the statistical analyses presented in the previous article (Ahmed et al. 2016). For the current purpose, the computer program was modified to accommodate the roles of four modification factors and corresponding statistical analyses were conducted. Fig. 2 shows an output results of the first execution of the computer program (CP) Run 1 for distribution of C_{sm}^* data without any modification as specified for 2%/50-yr spectrum (i.e., $F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$). It is observed in this figure that the amount of ‘unsafe’ data for $C_{sm}^* < 0.9$ is unacceptably high as 16.7%, 43.5%, 72.2%, 85.4% and 85.4% for Period Ranges 1, 2, 3, 4 and 5, respectively. The percentage of data for $0.9 \leq C_{sm}^* \leq 1.5$ are 51.3%, 42.2%, 13.5%, 11.2% and 11.4% corresponding to period ranges 1, 2, 3 and 4, respectively. That means the 2%/50-yr spectrum produces unacceptable results especially in the longer period ranges. The same fact is reflected with the low values of mean C_{sm}^* 0.79, 0.54 and 0.53 for the last three period ranges.

The above interpretation of computer program output indicates that in order to modify the 2%/50-yr spectrum and to meet the present purpose, two things should be done:

- Reduce the spectral amplitudes at 0.2-s period (i.e., find a value of $F_{0.2}$ where $F_{0.2} < 1.0$), and
- Increase the spectral amplitudes at periods of 0.5, 1.0 and 2.0 s (i.e., find values of $F_{0.5}$, $F_{1.0}$ and $F_{2.0}$ where $F_{0.5} > 1.0$, $F_{1.0} > 1.0$ and $F_{2.0} > 1.0$).

Finding the optimum values for the modification factors have been conducted through iterative runs of the computer program and has been described in the following sections.

PERCENTAGE OF NORMALIZED CSM VALUES (2%/50 YR) BELOW THE CRITERIA VALUE: $C_{sm}^* < n$													
SPECTRAL ORDINATE MODIFICATION FACTORS:													
	AT 0.2 S: 1.00				AT 0.5 S: 1.00				AT 1.0 S: 1.00				AT 2.0 S: 1.00
T range	<0.5	<0.6	<0.7	<0.8	<0.9	<1.0	<1.1	<1.2	<1.3	<1.4	<1.5	MEAN	
0-0.5	0.9	2.1	5.1	9.2	16.7	24.4	33.0	43.1	51.7	61.6	68.0	1.38	
0.5-1.0	2.0	8.2	16.6	29.9	43.5	52.4	62.0	70.5	76.3	82.7	85.7	1.09	
1.0-2.0	25.4	43.5	54.4	64.3	72.2	78.5	83.6	87.3	89.6	93.5	95.7	0.79	
2.0-4.0	70.6	79.5	81.9	83.6	85.4	87.7	90.2	93.4	95.0	95.7	96.6	0.54	
4.0-5.0	71.3	79.4	82.0	83.7	85.4	87.9	90.6	93.1	95.0	95.8	96.5	0.53	

Fig. 2 CP Run 1: Distribution of C_{sm}^* with all modification factors $F_T = 1.0$ (2%/50-yr spectrum)

The second trial execution Run 2 is performed taking the first modification factor $F_{0.2} = 0.9$ and other factors are kept equal to unity $F_{0.5} = F_{1.0} = F_{2.0} = 1.0$. The results obtained from the execution of the program are shown in Fig. 3. A close examination on the results of the Runs shown in Figs. 2 and 3 demonstrates clear signs of improvement and has been highlighted in Table 1. Percentage of data distributed in the preferred bandwidth ($0.9 \leq C_{sm}^* \leq 1.5$) has increased from 51.3% to 53.7% and percentage of data below $C_{sm}^* = 1.5$ has also increased from 68% to 74.6%. However, since the spectrum has been lowered in the short period zone, the amount of data below $C_{sm}^* = 0.9$ line has also increased 16.7% to 20.9% which in fact has gone in the opposite direction it is looked for. But that negativity can be addressed by increasing spectral amplitudes at other three control points.

Results of a subsequent execution of Run 3 is shown in Fig. 4 where $F_{0.5}$ is raised to 1.1 from 1.0 and other factors are kept unchanged as those of Run 2 (i.e., $F_{1.0} = 0.9$ and $F_{1.0} = F_{2.0} = 1.0$). As expected, the previous negativity has disappeared as data for $C_{sm}^* < 0.9$ has improved from 20.9% to 16.0%, i.e., more data are on the conservative side. Data in the preferred bandwidth $0.9 \leq C_{sm}^* \leq 1.5$ also increased from 53.7% to 56.4%. The other two indicators, however, have shown insignificant changes (Table 2).

Discussion of results obtained from three executions displays the necessity of more computer program executions to obtain the optimum values of the modification factors. To that end, a set of modification trial factors have been used and corresponding percentage of data in the preferred band width ($0.9 \leq C_{sm}^* \leq 1.5$) has been recorded. The results are then plotted in Fig. 5a. It is clear from Fig. 5a that the optimum values of modification factors are: $F_{0.2} = 0.8$, $F_{0.5} = 1.1$, $F_{1.0} = 1.5$ and $F_{2.0} = 4.0$ that produce maximum percentage of data in the preferred bandwidth.

The performance of the modification factors are also recorded with reference to the second criterion viz., percentage of data in the $C_{sm}^* < 0.9$ and corresponding graphical plot is presented in Fig. 5b. As expected, a general trend is obvious that with increasing values of modification factors, percentage of data in the $C_{sm}^* < 0.9$ zone reduces. However, the rate of decrement does not change significantly as the modification factors reach the optimum values. Therefore, reading Fig. 5b in association of Fig. 5a endorses the validity of the optimum modification factors obtained from Fig. 5a.

It should be noted that to trace the performance of modification factors $F_{0.2}$, $F_{0.5}$, $F_{1.0}$ and $F_{2.0}$ and the data in the period ranges 1, 2, 3 and 4 are considered to be directly influenced. This consideration has been the basis of developing Figs. 5a and b.

PERCENTAGE OF NORMALIZED CSM VALUES (2%/50 YR) BELOW THE CRITERIA VALUE: $C_{sm}^* < n$												
SPECTRAL ORDINATE MODIFICATION FACTORS:												
	AT 0.2 s: 0.90			AT 0.5 s: 1.00			AT 1.0 s: 1.00			AT 2.0 s: 1.00		
T range	<0.5	<0.6	<0.7	<0.8	<0.9	<1.0	<1.1	<1.2	<1.3	<1.4	<1.5	MEAN
0-0.5	1.1	2.8	5.9	11.0	20.9	30.1	40.9	51.0	61.2	68.7	74.6	1.29
0.5-1.0	2.0	8.2	16.6	29.9	43.5	52.4	62.0	70.5	76.3	82.7	85.7	1.09
1.0-2.0	25.4	43.5	54.4	64.3	72.2	78.5	83.6	87.3	89.6	93.5	95.7	0.79
2.0-4.0	70.6	79.5	81.9	83.6	85.4	87.7	90.2	93.4	95.0	95.7	96.6	0.54
4.0-5.0	71.3	79.4	82.0	83.7	85.4	87.9	90.6	93.1	95.0	95.8	96.5	0.53

Fig. 3 CP Run 2: Distribution of C_{sm}^* with $F_{0.2} = 0.9$, $F_{0.5} = F_{1.0} = F_{2.0} = 1.0$ (2%/50-yr spectrum)

Table 1 Comparison between CP Run 1 and Run 2 corresponding to Figs. 2 and 3

Values of Modifiers	Influence of $F_{0.2}$ on period range 1 ($T=0$ to 0.5 s)			
	$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$	$C_{sm}^* \leq 1.5$	Mean
$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	51.3%	16.7%	68%	1.38
$F_{0.2} = 0.9, F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	53.7%	20.9%	74.6%	1.29

After obtaining the optimum values of the modification factors, the program Run 4 is executed to calculate the final results. The comparison between the original 2%/50-yr spectrum (i.e., NBCC 2005 specified UHS using 2%/50-yr hazard map) and the modified spectrum is presented in Table 3. An obvious and significant improvement of the modified spectrum is visible in this table. The improvement is marked with distinct increase of data in the preferred bandwidth ($0.9 \leq C_{sm}^* \leq 1.5$) and significant decrease of data in the unsafe range ($C_{sm}^* < 0.9$). This establishes the validity and superiority of the modified spectrum without reservation.

An example of excellent outcome of the modified spectrum for Montreal is shown in Figs. 6a and b. The detail results for all of 389 cities are presented in Fig. 7 for period ranges from 0 to 5.0 s. It is observed that there are some cases of excessive magnification. However, their share to the total number of cases is insignificant. They should be considered as aberrant cases and do not have influence on the general findings of this study.

7 Modification of NBCC 2005 UHS format with 5%/50-yr hazard maps

Similar steps are followed to obtain the optimum modification factors for modified 5%/50-yr spectrum as defined in previous section. The results of first computer program Run 1 execution for distribution of C_{sm}^* data without any modification as specified for 5%/50-yr spectrum (i.e., $F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$), It can be again observed from Table 4 that the amount of data for $C_{sm}^* < 0.9$ is unacceptably very high as 59.4%, 79.9%, 90.5%, 94.8% and 94.9% for period ranges 1, 2, 3, 4 and 5, respectively and the percentage of data in the preferred bandwidth $0.9 \leq C_{sm}^* \leq 1.5$ is very low as 35.2%, 17.4%, 6.8%, 3.6% and 3.6% corresponding to period ranges 1, 2, 3, 4 and 5, respectively. That means the 5%/50-yr spectrum produces quite unacceptable results for both intermediate and long period ranges. The same fact is reflected with the very low values of mean C_{sm}^* (0.71, 0.51, 0.35 and 0.35) for the last four period ranges.

Using the same procedural steps as described earlier, Figs. 8a and b show the graphical representations of program data in the preferred bandwidth $0.9 \leq C_{sm}^* \leq 1.5$ and in

PERCENTAGE OF NORMALIZED CSM VALUES (2%/50 YR) BELOW THE CRITERIA VALUE: $C_{sm}^* < n.n$												
SPECTRAL ORDINATE MODIFICATION FACTORS:												
	AT 0.2 s: 0.90			AT 0.5 s: 1.10			AT 1.0 s: 1.00			AT 2.0 s: 1.00		
T range	<0.5	<0.6	<0.7	<0.8	<0.9	<1.0	<1.1	<1.2	<1.3	<1.4	<1.5	MEAN
0-0.5	0.9	2.2	5.2	8.3	16.0	26.3	37.8	47.2	57.6	65.9	72.4	1.33
0.5-1.0	1.7	7.2	13.9	22.6	35.5	47.8	55.9	64.7	71.4	77.5	82.2	1.16
1.0-2.0	25.4	43.5	54.4	64.3	72.2	78.5	83.6	87.3	89.6	93.5	82.2	0.79
2.0-4.0	70.6	79.5	81.9	83.6	85.4	87.7	90.2	93.4	95.0	95.7	96.6	0.54
4.0-5.0	71.3	79.4	82.0	83.7	85.4	87.9	90.6	93.1	95.0	95.8	96.5	0.53

Fig. 4 CP Run 3: Distribution of C_{sm}^* with $F_{0.2} = 0.9, F_{0.5} = 1.1, F_{1.0} = F_{2.0} = 1.0$ (2%/50-yr spectrum)

Table 2 Comparison between Run 2 and Run 3 corresponding to Figs. 3 and 4

Values of modifiers	Influence of $F_{0.2}$ on Period Range 1 ($T=0$ to 0.5 s)			
	$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$	$C_{sm}^* \leq 1.5$	Mean
$F_{0.2} = 0.9, F_{0.5} = 1.0, F_{1.0} = F_{2.0} = 1.0$	53.7%	20.9%	74.6%	1.29
$F_{0.2} = 0.9, F_{0.5} = 1.1, F_{1.0} = F_{2.0} = 1.0$	56.4%	16.0%	72.4%	1.33

the unsafe zone $C_{sm}^* < 0.9$, respectively. Optimum values are found in Fig. 8a to be $F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$.

A comparison between the results of final execution and the first execution is also presented in Table 4. The comparison clearly shows significant improvement in results brought by the modified 5%/50-yr spectrum. An ideal example of a successful case for Montreal is shown in Figs. 9a and b. The detail results for all of 389 cities are presented

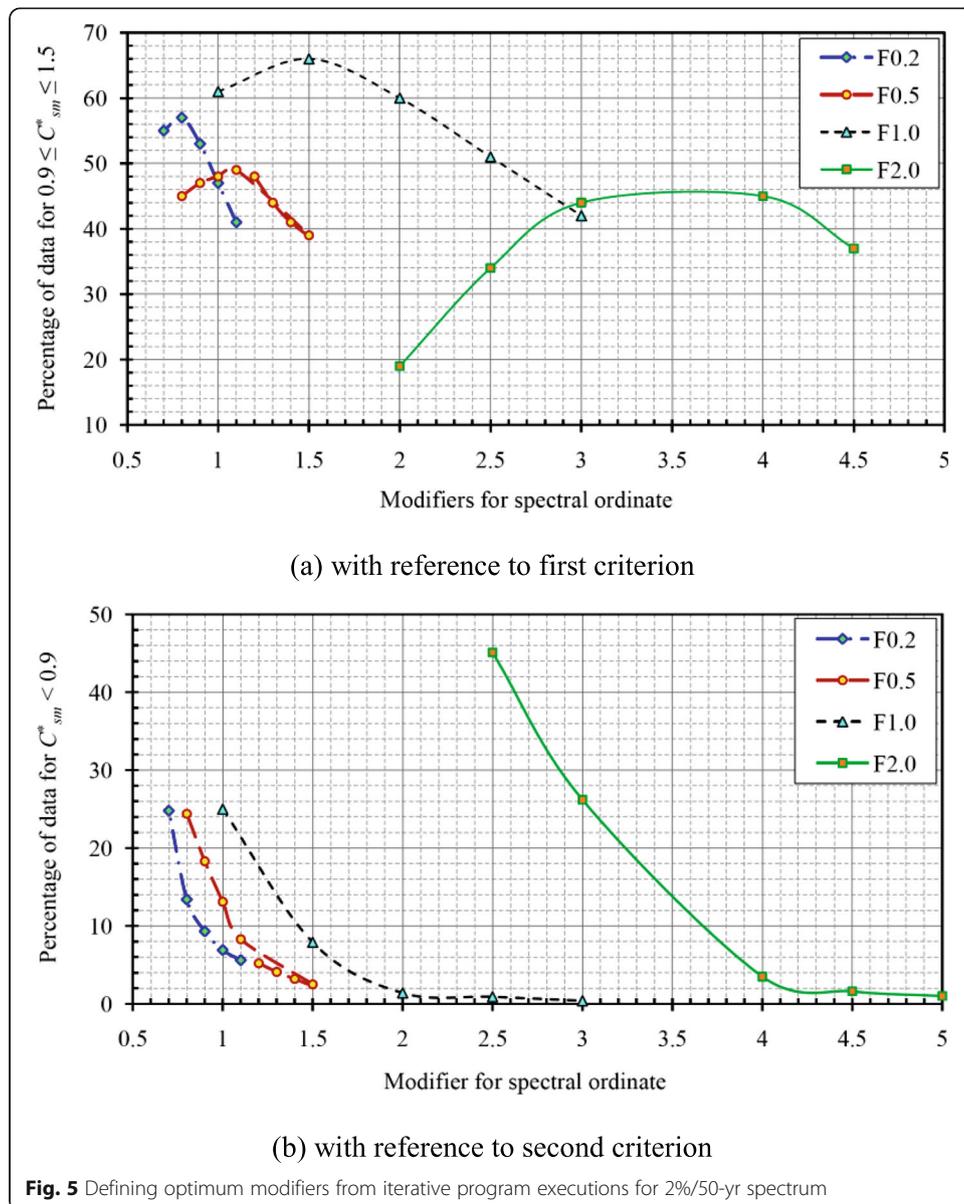


Table 3 Comparison between Run 1 and Run 4 for 2%/50-yr spectrum

Spectrum	Values of Modifiers	Influence of modification factors on C_{sm}^* distribution	
		$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$
Period range 1: 0 to 0.5 s			
2%/50-yr NBCC spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	51.3%	16.7%
Modified spectrum	$F_{0.2} = 0.8, F_{0.5} = 1.1, F_{1.0} = 1.5, F_{2.0} = 4.0$	57.9%	21.3%
Period range 2: 0.5 to 1.0 s			
2%/50-yr NBCC spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	42.2%	43.5%
Modified spectrum	$F_{0.2} = 0.8, F_{0.5} = 1.1, F_{1.0} = 1.5, F_{2.0} = 4.0$	51.4%	18.2%
Period range 3: 1.0 to 2.0 s			
2%/50-yr NBCC spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	13.5%	72.2%
Modified spectrum	$F_{0.2} = 0.8, F_{0.5} = 1.1, F_{1.0} = 1.5, F_{2.0} = 4.0$	61.7%	7.9%
Period range 4: 2.0 to 4.0 s			
2%/50-yr NBCC spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	11.2%	85.4%
Modified spectrum	$F_{0.2} = 0.8, F_{0.5} = 1.1, F_{1.0} = 1.5, F_{2.0} = 4.0$	45.1%	3.5%
Period range 5: 4.0 to 5.0 s			
2%/50-yr NBCC spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	11.1%	85.4%
Modified spectrum	$F_{0.2} = 0.8, F_{0.5} = 1.1, F_{1.0} = 1.5, F_{2.0} = 4.0$	45.6%	3.5%

in Fig. 10 for period ranges from 0 to 5.0 s. There are some cases of excessive magnification and other cases of far below from $C_{sm}^* = 0.9$ level; however, their share to the total number of case is insignificant. They should be treated as divergent issues and do not have any effect on the general findings of this study.

8 Modification of AASHTO 2009 UHS format with 5%/50-yr hazard maps

The modified version of the AASHTO spectrum proposed here consists of two line segments: (i) one horizontal line starting right from zero period until a period T_s which marks the end point of constant pseudo-acceleration region and (ii) an exponential line segment as a function of T^k starting from the period T_s and continued until the practical range of period of applicability marking typically the zones of constant pseudo-velocity and constant displacement zones. The exponential k is introduced here to control the decay rate of spectral amplitudes in the intermediate and long range periods with an objective to avoid the too much reduction of elastic seismic response coefficient C_{sm} comparing to current CHBDC provision. Similar approach is adopted to obtain T_s as given by AASHTO (2009).

The mathematical expressions of the modified AASHTO spectrum are given in the following equations:

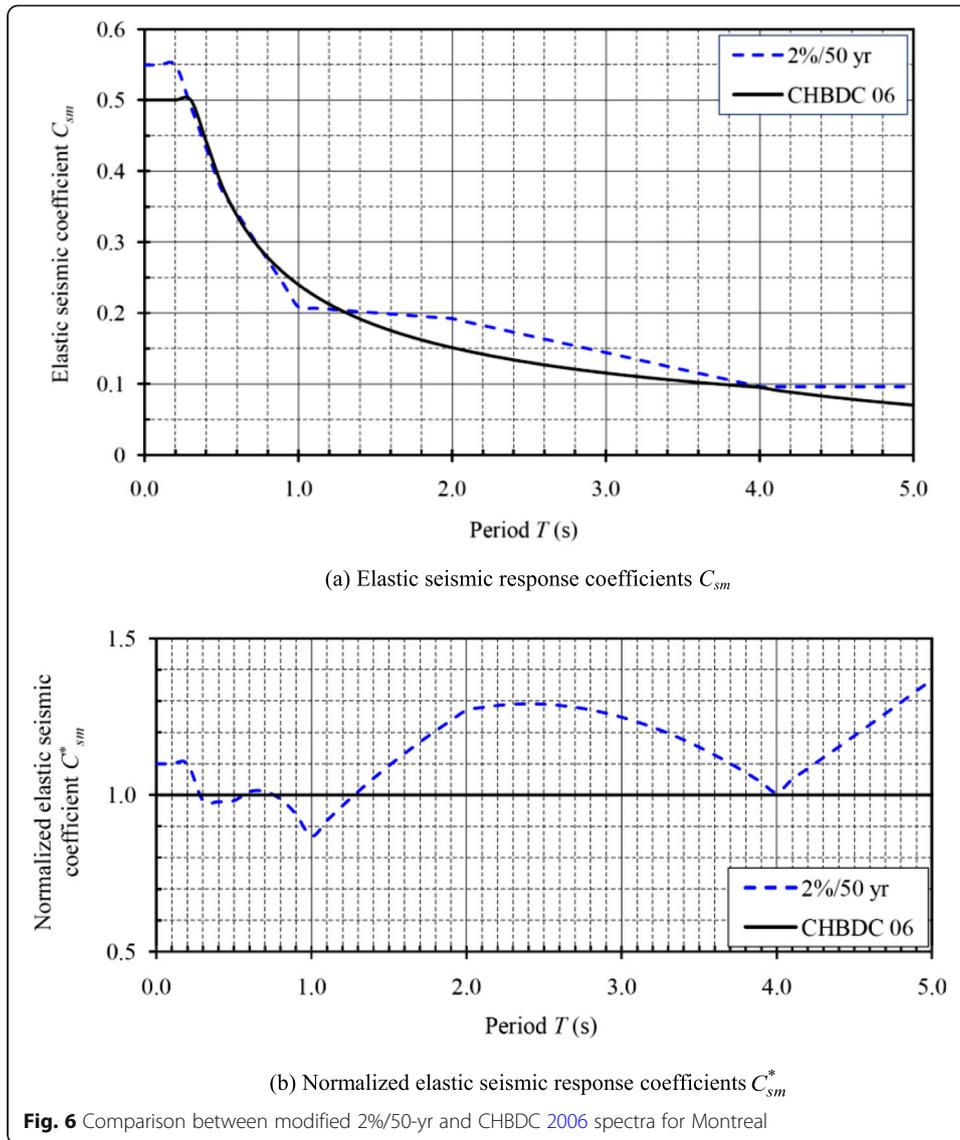
For $T \leq T_s$, the design response spectral acceleration coefficient S_a is

$$S_a = F_{0.2} F_a S_{0.2} \tag{8}$$

in which

$$T_s = ((F_{1.0} F_v S_{1.0}) / (F_{0.2} F_a S_{0.2}))^{1/k} \tag{9}$$

The design response spectral acceleration coefficient S_a is defined for periods greater than T_s as follows:



$$S_a = F_{1.0} F_{av} S_{1.0} / T^k \tag{10}$$

where $F_{0.2}$ = modification factor for spectral amplitude $S_{0.2}$.

$F_{1.0}$ = modification factor for spectral amplitude $S_{1.0}$.

k = decay rate of spectral amplitudes.

A graphical representation of the spectrum is shown in Fig. 11. As evident from mathematical and graphical representation of the modified spectrum, this study is involved in the search of three modification factors: $F_{0.2}$, $F_{1.0}$ and k that work well to achieve target of the study. The 4th generation hazard maps with 5%/50-yr probability level are used for next step statistical analyses.

Output results of first computer program Run 1 execution for distribution of C_{sm}^* data without any modification (with the exception of removing step accession and replacing a horizontal plateau right from the zero period) as specified for AASHTO spectrum (i.e., $F_{0.2} = F_{1.0} = k = 1.0$) show that the amount of data for

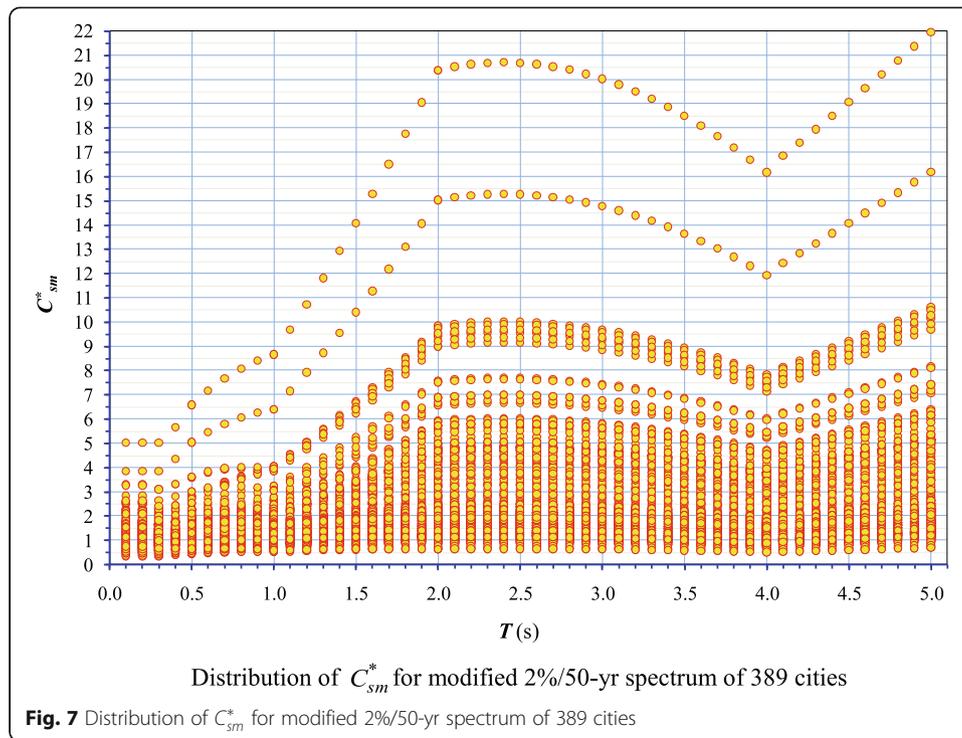
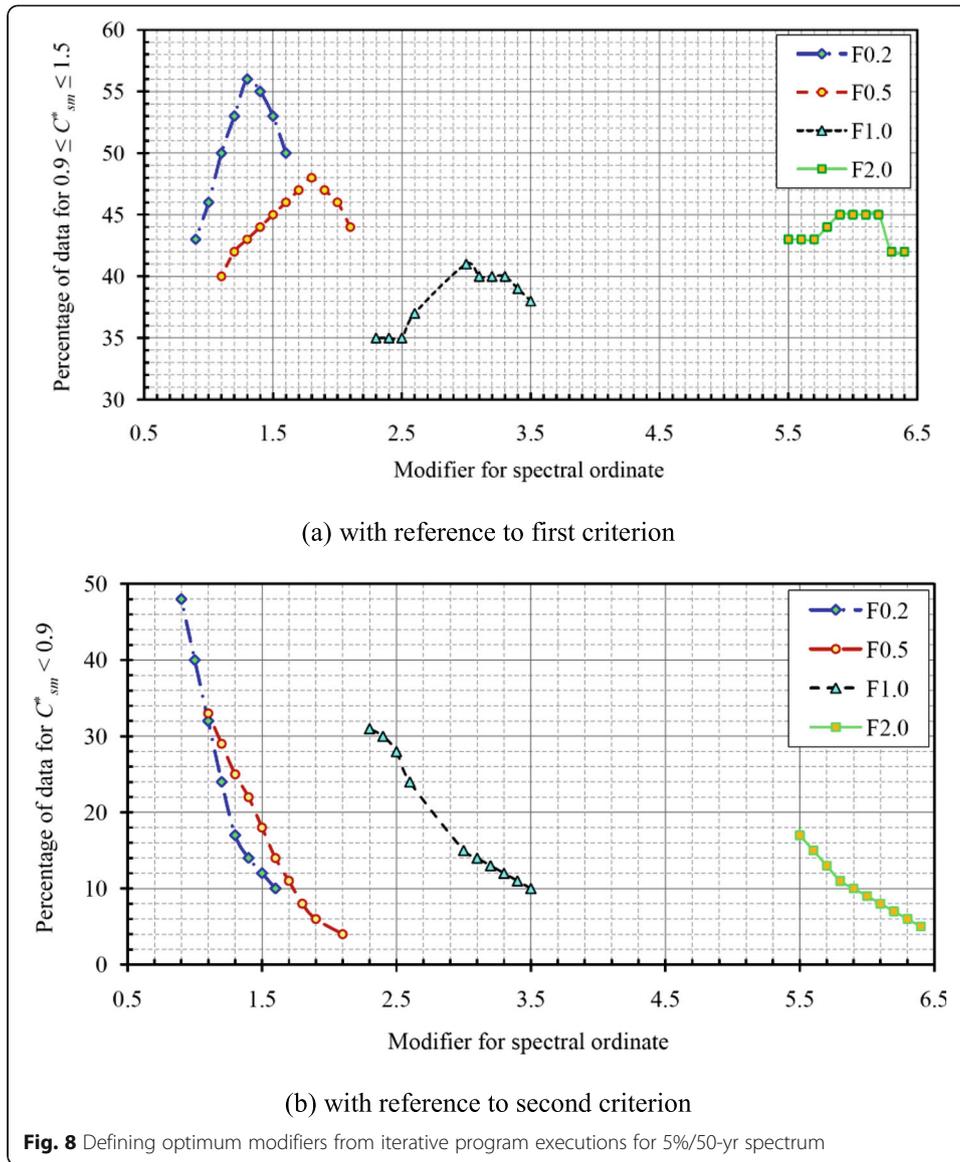


Table 4 Comparison between Run 1 and Final Run for 5%/50-yr spectrum

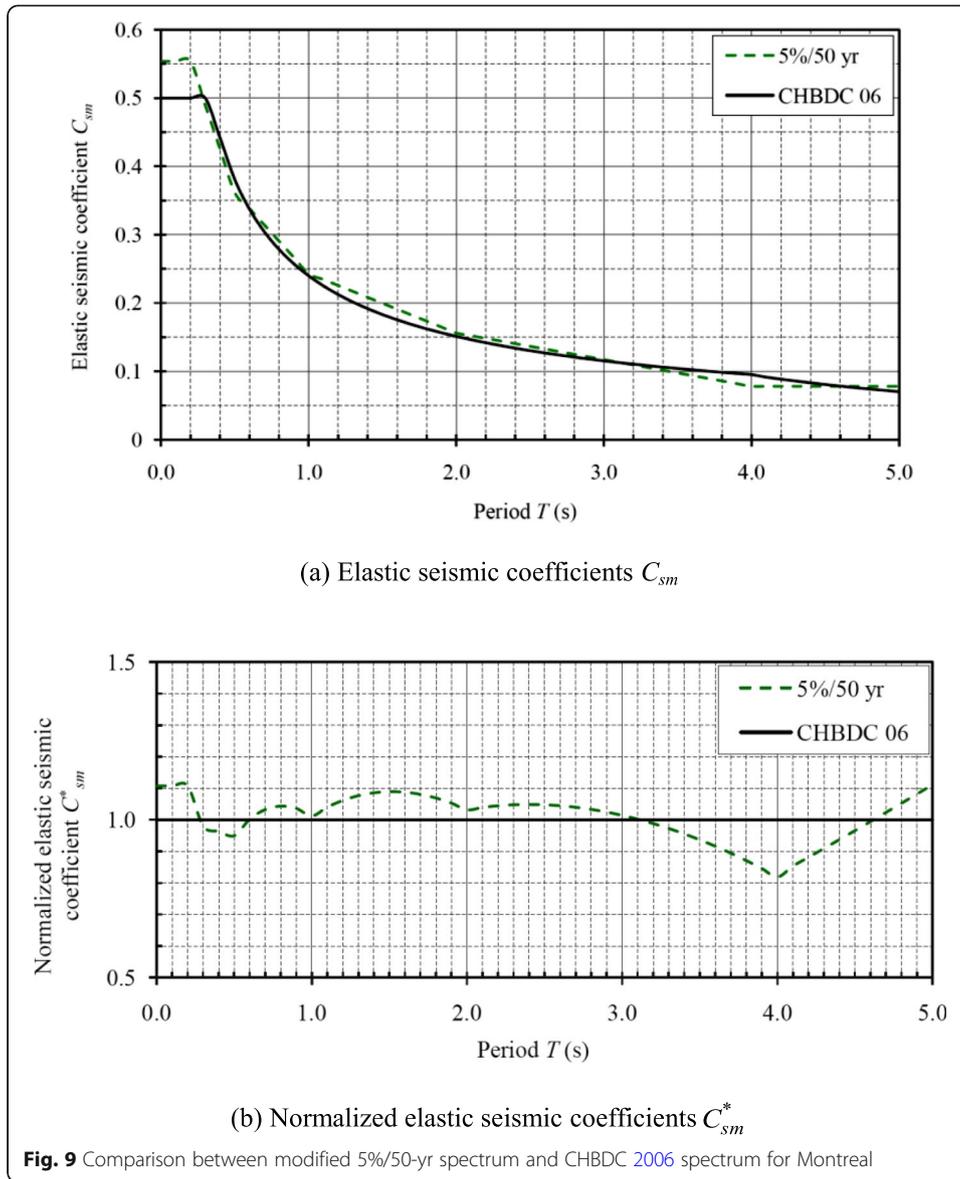
Spectrum	Values of Modifiers	Influence of modification factors on C_{sm}^* distribution	
		$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$
Period range 1: 0 to 0.5 s			
5%/50-yr spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	35.2%	59.4%
Modified spectrum	$F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$	56.1%	17.2%
Period range 2: 0.5 to 1.0 s			
5%/50-yr spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	17.4%	79.9%
Modified spectrum	$F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$	47.7%	7.7%
Period range 3: 1.0 to 2.0 s			
5%/50-yr spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	6.8%	90.5%
Modified spectrum	$F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$	52.9%	2.5%
Period range 4: 2.0 to 4.0 s			
5%/50-yr spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	3.6%	94.8%
Modified spectrum	$F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$	44.3%	9.1%
Period range 5: 4.0 to 5.0 s			
5%/50-yr spectrum	$F_{0.2} = F_{0.5} = F_{1.0} = F_{2.0} = 1.0$	3.6%	94.9%
Modified spectrum	$F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$	54.5%	9.7%



$C_{sm}^* < 0.9$ is unacceptably high as 59.3%, 85.6%, 94.1%, 96.9% and 97.2% for period ranges 1, 2, 3, 4 and 5, respectively. Hence, the percentage of data in the preferred bandwidth $0.9 \leq C_{sm}^* \leq 1.5$ are very low as 34.8%, 11.6%, 4.2%, 2.6% and 2.3% corresponding to period ranges 1, 2, 3, 4 and 5, respectively. That means the AASHTO spectrum produces unacceptable results. The same fact is reflected with the low values of mean C_{sm}^* (0.66, 0.52, 0.41 and 0.39) for the last four period ranges.

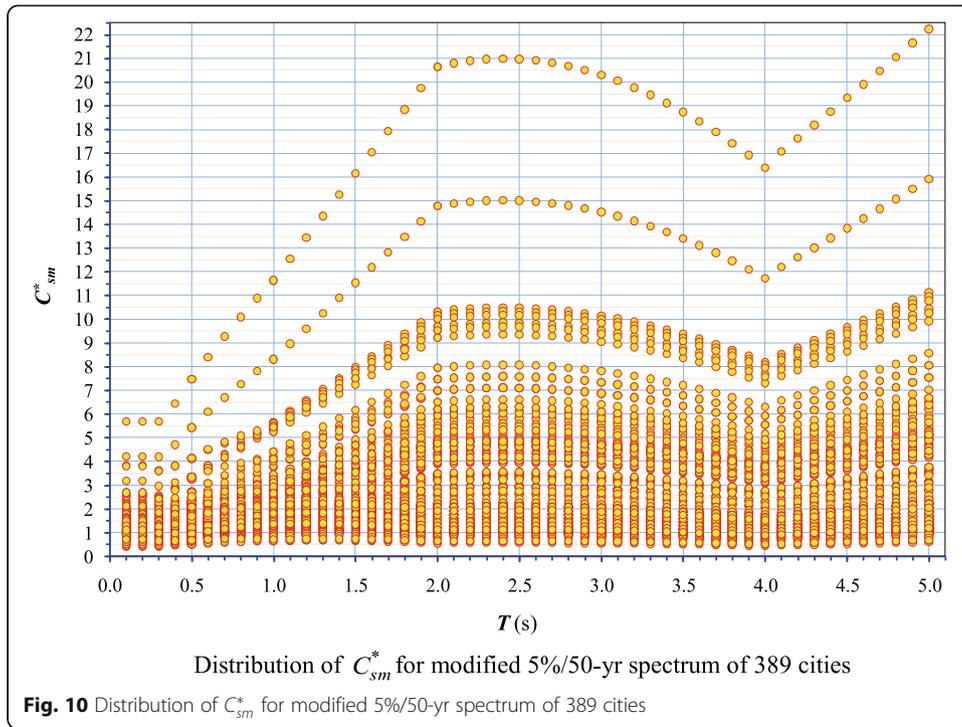
The above interpretation of computer output indicates that the AASHTO spectrum is required modification to meet the present purpose, two things should be done:

- (i) Increase the spectral amplitudes both at 0.2 s and 1.0 s (i.e., find value of $F_{0.2}$, $F_{1.0}$ where $F_{0.2} > 1.0$ and $F_{1.0} > 1.0$), and



- (ii) Slowdown the decay rate for the intermediate and long period range by introducing an effective k value where $k < 1.0$.

The search of the optimum values for the modification factors have been conducted through iterative runs of the computer program in a trial-and-error basis. The results of first trial execution (Run 2) with $F_{0.2} = 1.0$, $F_{1.0} = 2.5$, $k = 0.75$ are compared with the first executions Run 1 and it is summarized in Table 5. A clear improvement is observed by increase of data in the preferred bandwidth $0.9 \leq C_{sm}^* \leq 1.5$ and decrease of data in the unsafe zone $C_{sm}^* < 0.9$. Next trial execution Run 3 made by increasing values of $F_{0.2}$ and $F_{1.0}$ from 1.0 to 1.2 and 2.5 to 3.0, respectively (i.e., $F_{0.2} = 1.2$, $F_{1.0} = 3.0$) and keeping the decay rate unchanged $k = 0.75$ is shown in Table 6. This change in the modification factors brought further



improvement of C_{sm}^* data distribution with reference to two criteria and this is clearly displayed in Table 6.

Another trial execution is made in Run 4 by increasing values of $F_{0.2}$ and $F_{1.0}$ from 1.2 to 1.3 and 2.5 to 3.0, respectively (i.e., $F_{0.2} = 1.3$) and keeping other factors unchanged $F_{1.0} = 3.0$, $k = 0.75$. Comparison between Run 3 and Run 4 as shown in Table 7 shows the only improvement for period range 0 to 0.5 s with reference to $C_{sm}^* < 0.9$. For all other period ranges and with reference to both criteria no considerable improvement is obtained.

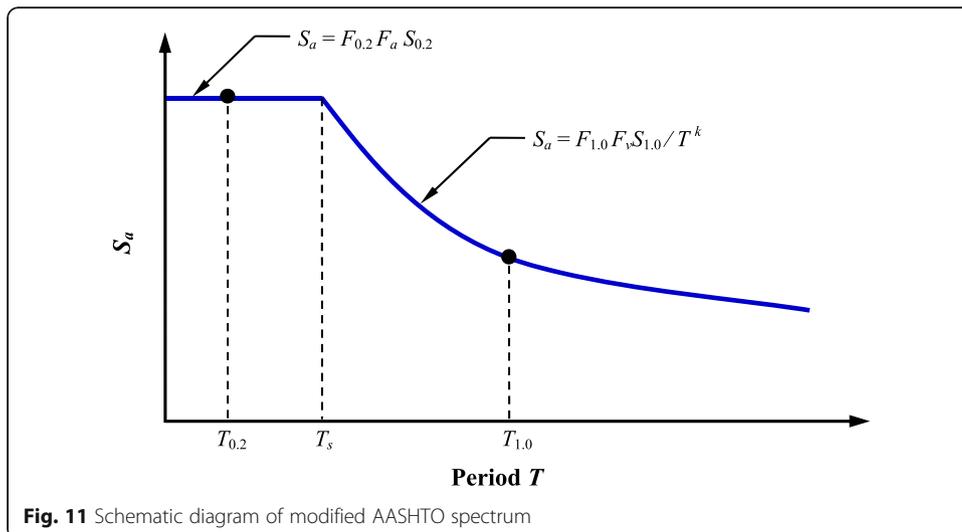


Table 5 Comparison between Run 1 and Run 2 for AASHTO spectrum

Spectrum	Values of modifiers	Influence of modification factors on C_{sm}^* distribution	
		$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$
Period range 1: 0 to 0.5 s			
AASHTO Spectrum	$F_{0.2} = F_{0.5} = k = 1.0$	34.8%	59.3%
Modified AASHTO Spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	48.8%	37.2%
Period range 2: 0.5 to 1.0 s			
AASHTO Spectrum	$F_{0.2} = F_{0.5} = k = 1.0$	18.7%	85.6%
Modified AASHTO Spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	42.1%	22.1%
Period range 3: 1.0 to 2.0 s			
AASHTO Spectrum	$F_{0.2} = F_{0.5} = k = 1.0$	7.7%	94.1%
Modified AASHTO Spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	37%	27.4%
Period range 4: 2.0 to 4.0 s			
AASHTO Spectrum	$F_{0.2} = F_{0.5} = k = 1.0$	2.6%	96.9%
Modified AASHTO Spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	39.4%	30.0%
Period range 5: 4.0 to 5.0 s			
AASHTO Spectrum	$F_{0.2} = F_{0.5} = k = 1.0$	2.3%	97.2%
Modified AASHTO Spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	37.1%	27.0%

Another computer program execution Run 5 is to monitor the effects of having the decay rate equal to unity, i.e., $k = 1.0$. Again this change did not bring any positive results as it pushed the resultant spectrum to much down and brought more data on the unsafe side. Therefore, final values of modification factors recommended for modified AASHTO spectrum with 5%/50-yr hazard maps are: $F_{0.2} = 1.3, F_{1.0} = 3.0$ and $k = 0.75$.

Table 6 Comparison between Run 2 and Run 3 for modified AASHTO spectrum with 5%/50-yr hazard maps

Spectrum	Values of modifiers	Influence of modification factors on C_{sm}^* distribution	
		$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$
Period range 1: 0 to 0.5 s			
Modified AASHTO spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	48.8%	37.2%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	55.6%	16.3%
Period range 2: 0.5 to 1.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	42.1%	22.1%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	43.6%	4.2%
Period range 3: 1.0 to 2.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	37%	27.4%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	43.5%	5.5%
Period range 4: 2.0 to 4.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	39.4%	30.0%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	44.1%	9.3%
Period range 5: 4.0 to 5.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.0, F_{1.0} = 2.5, k = 0.75$	37.1%	27.0%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	42.9%	5.7%

Table 7 Comparison between Run 3 and Run 4 for modified AASHTO spectrum with 5%/50-yr hazard maps

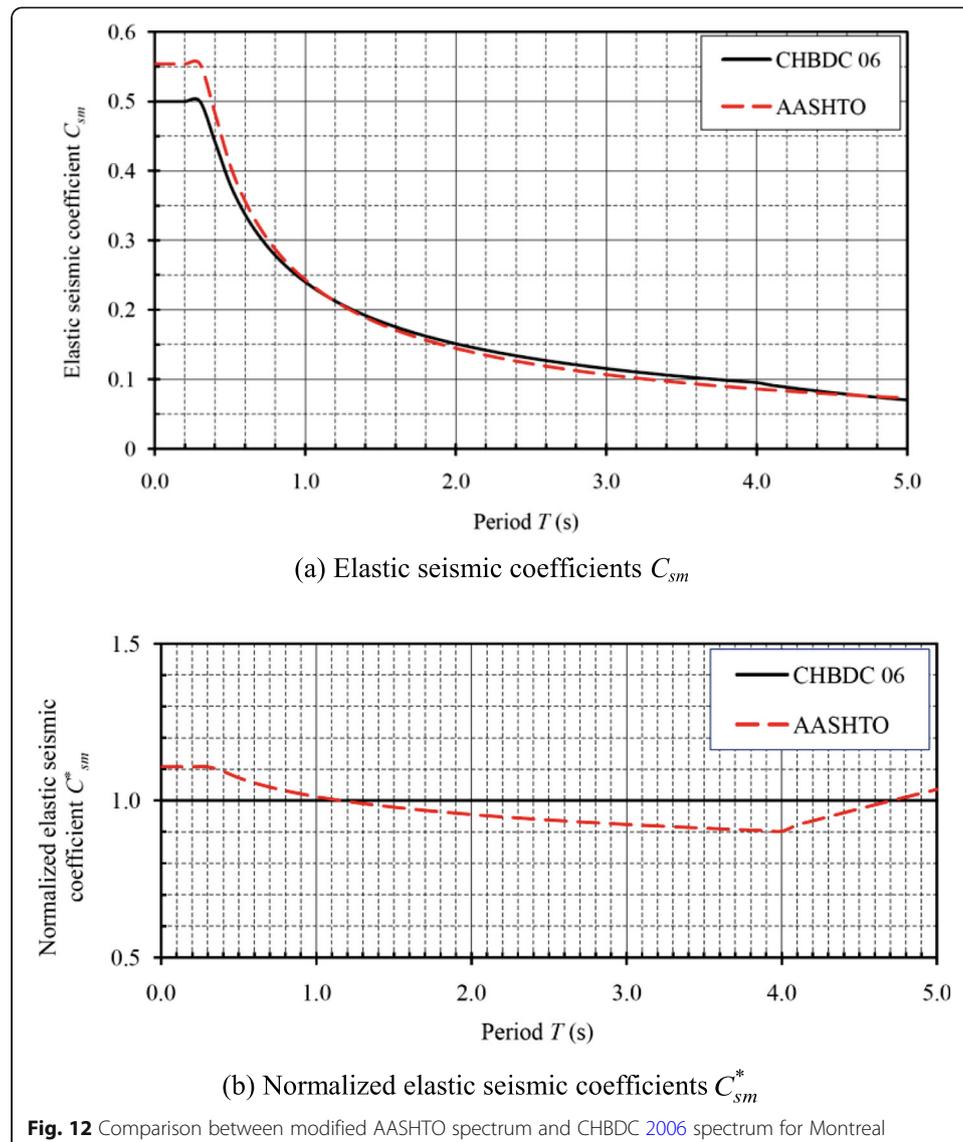
Spectrum	Values of Modifiers	Influence of modification factors on C_{sm}^* distribution	
		$0.9 \leq C_{sm}^* \leq 1.5$	$C_{sm}^* < 0.9$
Period range 1: 0 to 0.5 s			
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	55.7%	10.7%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	55.6%	16.3%
Period range 2: 0.5 to 1.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	42.3%	3.8%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	43.6%	4.2%
Period range 3: 1.0 to 2.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	43.4%	5.5%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	43.5%	5.5%
Period range 4: 2.0 to 4.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	44.1%	9.3%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	44.1%	9.3%
Period range 5: 4.0 to 5.0 s			
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	42.9%	5.7%
Modified AASHTO spectrum	$F_{0.2} = 1.2, F_{1.0} = 3.0, k = 0.75$	42.9%	5.7%

An example of success in modifying AASHTO spectrum for Montreal is shown in Fig. 12a and b. The detail results for of all 389 cities are presented in Fig. 13 for period ranges from 0 to 5.0 s. It is observed in the figure that there are some cases of excessive magnification and other cases of staying below $C_{sm}^* = 0.9$ level. However, their number in comparison to total number of cases is insignificant. They should be considered as outliers. Therefore, those irregular cases do not have any influences on the applicability of the proposed spectrum.

9 Selecting the most suitable spectrum among the three modified spectra

The performances of the three modified spectra, viz. 2%/50-yr, 5%/50-yr and AASHTO, have been elaborately examined in this phase of study. In general, without modification the application of uniform hazard spectral format with 4th generation seismic hazard maps brings dramatic changes from the current CHBDC base shear values. That means from statistical point of view, many cities will see huge increase in base shear and many cities will see huge decrease in base shear from current practice if the new concept of spectra construction and new hazard maps are adopted in CHBDC. The too low reduction for too many cities is of major concern considering the perceived and long-built confidence of historical performances of Canadian bridges constructed on the basis of CHBDC codes. Therefore, as a practical solution, modification of the probable candidate spectra is sought in this section.

Interestingly, the 4th generation maps intended for the uniform hazard spectra show huge increase in the low period range and significant decrease in the intermediate and long period ranges. As the uniform hazard spectral format uses period dependent spectral amplitudes, local adjustments are proposed to meet the objectives. To that end, more than one modification factors are introduced based on statistical analysis of 389 cities.

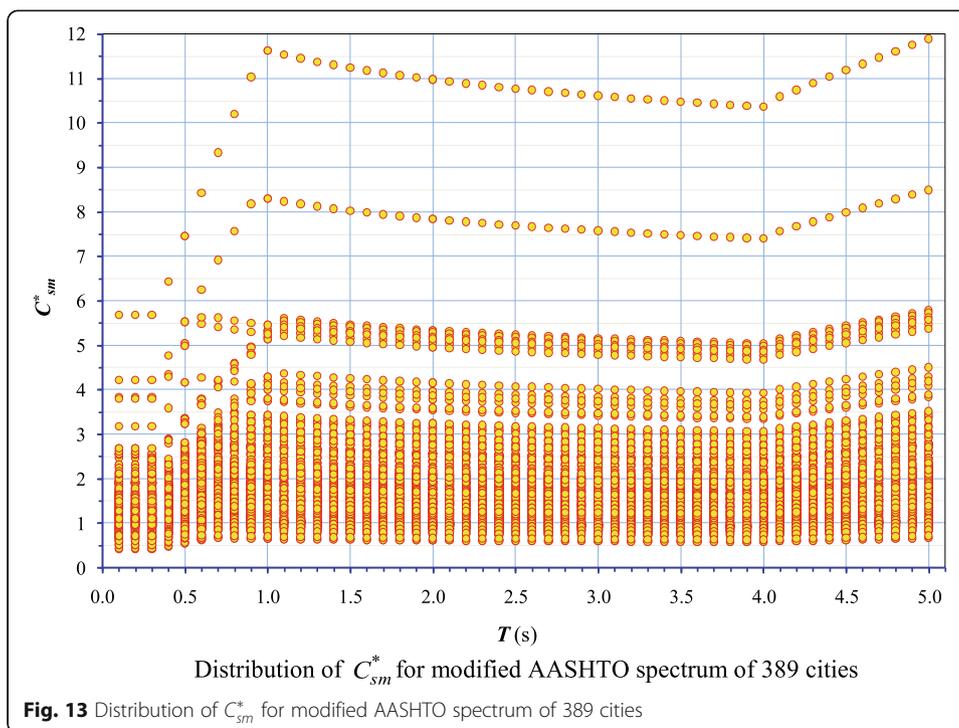


After threadbare statistical analyses, here it is recommended three sets of modification factors:

- $F_{0.2} = 0.8, F_{0.5} = 1.1, F_{1.0} = 1.5, F_{2.0} = 4.0$ for modified 2%/50-yr spectrum
- $F_{0.2} = 1.3, F_{0.5} = 1.8, F_{1.0} = 3.0, F_{2.0} = 6.0$ for modified 5%/50-yr spectrum
- $F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$ for modified AASHTO spectrum

In overall consideration, all three modified spectra stand more or less on the same or similar performance level. Before choosing the most suitable one, some relevant arguments/counter arguments are discussed in the following:

- Since the format of 2%/50-yr and 5%/50-yr spectra is developed for adoption in NBCC (2005), the question of applicability of this format for bridge design can be raised. It must not be forgotten that a design spectrum represents estimates of



seismic forces for a set of idealized oscillators (or SDOF systems) with specific periods of vibration. In other words, a design spectrum is generic in nature and its application should not be limited to specific structure such as the question of building or bridge as our case is. Hence, a format developed for building application can be imported for bridge application and its compatibility can be established through the use of appropriate factors such as, structure specific force modification factors (R), structure and site-specific soil factors (e.g., F_a and F_v or S) and importance factor (I).

- The uniform hazard spectrum is simply constructed by connecting several spectral ordinates obtained from hazard maps. This suggests that the shape/format of uniform hazard spectrum has little thing to do with the type of structure (e.g., building and bridge).
- Degree of increase and decrease of elastic seismic response coefficient is associated with the level of probability of the hazard maps. To use higher probability level maps, the values of modification factors are needed to be greater than those of lower probability level maps. The implication here is that the modified 2%/50-yr spectrum looks more attractive as it needs less ‘modification’ of ordinates obtained from hazard maps.
- There is no ambiguity of building-bridge compatibility issue for using modified AASHTO spectrum into CHBDC since the spectrum is specialized for bridge application. From this point, modified AASHTO spectrum looks very attractive.
- The appropriate probability level of hazard maps for Canadian bridge application is not an issue where consensus can be seen among the bridge design community in Canada. In absence of such guideline, the cue of the most recent development in

Table 8 Comparison of statistical analyses results between AASHTO and modified AASHTO spectra

Spectrum	Values of modifiers	Influence of modification factors on C_{sm}^* distribution	
		$0.9 < C_{sm}^* < 1.5$	$C_{sm}^* < 0.9$
Period Range 1: 0 to 0.5 s			
AASHTO spectrum	–	34.8%	59.3%
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	55.7%	10.7%
Period range 2: 0.5 to 1.0 s			
AASHTO spectrum	–	11.6%	85.6%
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	42.3%	3.8%
Period range 3: 1.0 to 2.0 s			
AASHTO spectrum	–	4.2%	94.1%
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	43.4%	5.5%
Period range 4: 2.0 to 4.0 s			
AASHTO spectrum	–	2.6%	96.9%
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	44.1%	9.3%
Period range 5: 4.0 to 5.0 s			
AASHTO spectrum	–	2.3%	97.2%
Modified AASHTO spectrum	$F_{0.2} = 1.3, F_{1.0} = 3.0, k = 0.75$	42.9%	5.7%

the USA can be adopted for Canadian application. That means, as AASHTO 2009 has adopted, the seismic hazard maps of the Geological Survey of Canada with 5% probability of exceedance in 50 years should be used for CHBDC.

Table 8 provides a comparison statistical analysis results between AASHTO and the modified AASHTO spectra up to the period range 5.0 s. The results of statistical analyses amply showed the validity of the modified spectra. In addition, modified AASHTO spectrum can be highlighted from the instances that the percentage of data in the acceptable range of base shear increase (i.e., in the preferred bandwidth) rose from 34.8% to 55.7% in the period range 0 to 0.5 s, 11.6% to 42.3 in the period range 0.5 s to 1.0 s, 4.2% to 43.4% in the period range 1.0 s to 2.0 s, 2.6% to 44.1% in the period range 2.0 s to 4.0 s and 2.3% to 42.9% in the period range 4.0 s to 5.0 s on the other hand percentage of data representing unsafe data (low base share value) dropped from 59.3% to 10.7% in the period range 0 s to 0.5 s, 85.6% to 3.8% in the period range 0.5 s to 1.0 s, 94.1% to 5.5% in the period range 1.0 s to 2.0 s, 96.9% to 9.3% in the period range 2.0 s to 4.0 s and 97.2% to 5.7% in the period range 4.0 s to 5.0 s (Table 8).

10 Conclusions

This study proposed a scheme of modification of the three spectra: 2%/50-yr, 5%/50-yr and AASHTO under twofold objectives to bring maximize amount of data in the preferred bandwidth (i.e., $0.9 < C_{sm}^* < 1.5$). All three modified spectra showed a significant improvement with reference to the objectives of the statistical analyses. Hence, the results of statistical analyses showed the validity of the modified spectra and the study recommends adoption of modified AASHTO spectral format for the following reasons:

- Since the format of 2%/50-yr and 5%/50-yr spectra is developed for adoption in NBCC (2005), the question of applicability of this format for bridge design can be raised.
- There is no ambiguity of building-bridge compatibility issue for using modified AASHTO spectrum into CHBDC since the spectrum is specialized for bridge application. From this point modified AASHTO spectrum looks very attractive.
- The appropriate probability level of hazard maps for Canadian bridge application is not an issue where consensus can be seen among the bridge design community in Canada. In absence of such guideline, the cue of the most recent development in the USA can be adopted for Canadian application. That means as AASHTO (2009) has adopted, the seismic hazard maps of the Geological Survey of Canada with 5% probability of exceedance in 50 years should be used for CHBDC.
- The modified AASHTO spectrum is simple to construct and uses only two spectral amplitudes. That means for this spectrum, the least number of hazard maps is needed.
- The results of statistical analyses amply showed the validity of the modified spectra. The success of the modified AASHTO spectrum can be highlighted as the percentage of data in the acceptable range of base shear increased up to 55.7% at low period range, 43.4% at intermediate period range and 44.1% at higher period range and percentage of data representing low base share value decreased to 10.7% at low period range, 3.8% at intermediate period range and 5.7% at higher period range.

To this backdrop, the study recommends adoption of modified AASHTO spectrum with modification factors: $F_{0.2} = 1.3$, $F_{1.0} = 3.0$ and $k = 0.75$ to apply for the calculations of design base shear of the bridges in Canada.

Abbreviations

AASHTO: American Association of State Highway Officials; CHBDC: Canadian Highway Bridge Design Code; UHS: Uniform Hazard Spectrum; NBCC: National Building Code of Canada; UBC: Uniform Building Code; IBC: International Building Code; PEER: Pacific Earthquake Engineering Research Center; NGA: Next Generation Attenuation; GMPE: Ground-motion prediction equation; NEHRP: National Earthquake Hazards Reduction Program; BSSC: Building Seismic Safety Council; GSC: Geological Survey of Canada; CP: Computer Program

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Author's contributions

The authors read and approved the final manuscript.

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Availability of data and materials

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Competing interests

The author declares that he has no competing interests.

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