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Application of kernel smoothing approach to assess seismic hazard for selected regions in Canada

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ABSTRACT

The frequent used approach for the probabilistic seismic hazard assessment is based on delineated seismic source models. The approach is employed to develop several generations of seismic hazard map for Canada. The method requires the knowledge of delineated seismic source models, the magnitude-recurrence relation, and the ground motion prediction equation. One of the major uncertainties in this approach is the assignment of the delineated source models. Alternative to this assignment is the use of smoothed source models that are obtained by applying the kernel smoothing techniques to the historical earthquake catalogue. Application of a smoothing technique for assessing the seismic hazard for selected regions in Canada is presented in this study. For the assessment, the ground motion predictions used to develop the seismic hazard map by the Geological Survey of Canada (GSC) are adopted. Comparison is made between the estimated seismic hazard to those given by GSC.

Keywords: seismic hazard, kernel smoothing, Eastern Canada, peak ground acceleration, spectral acceleration.

INTRODUCTION

Earthquakes occurrence is random in time and space. Their effects on the structures are often characterized using response spectra, which represent a collection of the peak responses of a series of linear elastic single-degree-of-freedom (SDOF) systems. As the earthquake occurrence and their effects are uncertain, the response spectra with consistent probability of exceedance, known as the uniform hazard spectra (UHS), has been adopted in the National Building Code of Canada (NBCC) ([1] to [3]). More specifically, the UHS are defined by the α-fractiles of peak responses of a series of linear elastic SDOF systems, where α is a specified probability of non-exceedance. The assessment of the UHS and the fifth-generation seismic hazard maps of Canada (SHMC) have been given in [2].

The methodology used to develop the fifth generation SHMC is essentially based on the approach given in [4] and [5], where delineated seismic source zones are assigned. The method integrates the information on seismic source zones, magnitude-recurrence relations and ground motion prediction equations (or attenuation relations) to estimate the seismic hazard (e.g., seismic response spectra). The method requires judiciously define the (boundary of) seismic source zones based on historical seismic activities and tectonic features. Other methods used for seismic hazard mapping include those proposed in [6] to [10]. Some of these methods has been reviewed and compared in [11]. These methods differ on how the historical seismicity is used to define and to spatially smooth seismic source activities. A criticism of the use of spatial smoothing methods may be that they cannot incorporate geological and tectonic features while that of using delineated source zones is often related to the subjective definition of the seismic source zones. The advantage of the latter in incorporating the tectonic features was refuted in [11] by arguing that a circular argument exists between the selection of seismicity patterns and the shape of tectonic plates.

The main objective of the present study is to apply a smoothing technique given in [10] to evaluate seismic source model for assessing the seismic hazard for selected regions in Canada. For the seismic hazard assessment, the ground motion predictions used to develop the fifth generation SHMC by the Geological Survey of Canada (GSC) are adopted. The analysis of seismic hazard is carried out by using the simulation procedure [11]. The uniform hazard spectra (UHS) with 2% probability of exceedance in 50 years for 6 selected sites are obtained and compared with the UHS given in NBCC 2015 [3].

HISTORICAL EARTHQUAKE CATALOGUE AND COMPLETENESS ANALYSIS

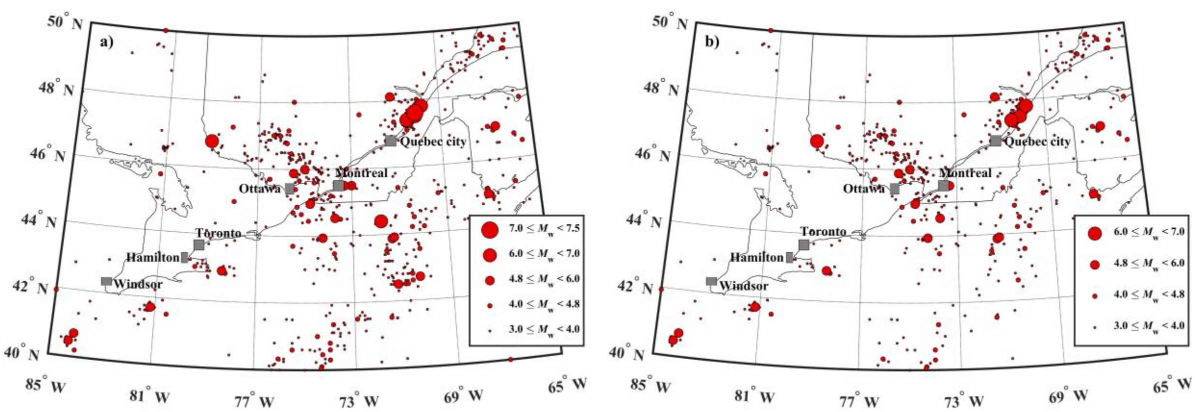
Selected target regions and historical earthquake catalogue for seismic hazard assessment

For the present study, parts of the Eastern Canada are considered. The historical earthquake catalogue given in the Canadian Composite Seismicity Catalogue (CCSC-2011) is considered. The CCSC-2011 consists of West Catalogue and East Catalogue. The East catalogue of CCSC-2011 is employed for the considered region. Some detailed information of the CCSC-2011 is available at https://www.seismotoolbox.ca/Documents/ccsc11east.txt. A short summary is given below.

The East catalogue in CCSC-2011 contains information on 11893 earthquake events that occurred from January 1534 to December 2010. Each event listed in the catalogue has a latitude within (35°N, 80°N) and longitude within (-110°, -45°). For each event, the catalogue documents the occurrence time, epicentral location, available focal depth, reported magnitude (with different magnitude types), preferred magnitude, flags for seismic source zone that it belongs, and assigned moment magnitude M_w. It is noted that the magnitude of seismic events was not always reported in M_w, the assigned M_w is obtained based on the magnitude conversion between reported M_N (Nuttli magnitude), M_B (body wave magnitude), M_L (local magnitude), M_s (surface-wave magnitude), M_c (coda magnitude) to M_w. In some cases, M_w for an earlier event is assigned based on the Modified Mercalli Intensity (MMI) data [12].

Completeness analysis for the considered earthquake events

The seismic events in East catalogue in CCSC-2011 for the considered region is used in the present study. According to [13], the catalogue that contains seismic events occurred before 1660 is incomplete. For the completeness analysis to be carried out below, only events occurred after 1660 and with $M_w \geq 3.0$ is considered. The consideration of $M_w \geq 3.0$ is justified since the minimum M_w, M_{wmin}, used to assess the fifth generation of SHMC is 4.8 [2]. The epicentral location as well as the magnitude of the considered events are shown in Figure 1a. There is a total of 36 seismic events with magnitude greater than 4.8.



(a) Seismic events with M_w (b) Seismic events considering completeness.

Figure 1. Spatial distribution of historical seismic events.

The analysis of the catalogue completeness is carried out based on the approach proposed by [14]. By applying this procedure, it is concluded that the time after which the catalogue for a given magnitude being complete, (denoted as T_c), is given in Table 1, where $T_{c,p}$ denotes the p-quantiles of T_c. As expected, $T_{C,p}$ decreases with increasing M_w. That is, the duration of completeness of the observed events with greater magnitude is longer. By removing the events occurred before $T_{c,0.5}$, the remaining events is shown in Figure 1b. In this case, there are 25 seismic events with magnitude greater than 4.8. Note that removing events before $T_{c,p}$ does not imply a decreased occurrence rate since the duration of observation which is from $T_{c,p}$ to the present is less than that from 1660 to the present.

Table 1. Tc for the considered earthquake events with $M_w \geqslant 3.0$.

$T_{c,P}$	$M_w \geq 3$	$M_w \geq 4.25$	$M_w \geq 4.5$	$M_w \geq 4.75$	$M_w \geq 5.25$	$M_w \geq 6$	$M_w \geq 6.25$	$M_w \geq 6.5$	$M_w \geq 6.75$
$T_{c,0.25}$	1972	1923	1910	1910	1896	1865	1854	1812	1812
$T_{c,0.5}$	1925	1903	1887	1884	1841	1808	1796	1767	1767
$T_{c,0.75}$	1914	1885	1867	1858	1755	1755	1747	1726	1663

SPATIAL SMOOTHING OF THE EARTHQUAKE OCCURRENCE RATE

Considered kernel smoothing technique

The kernel smoothing technique proposed in [10] is considered in the following to develop spatially smoothed seismic source model. For the smoothing, the grid system with 0.25° increment in latitude and longitude is used. The kernel function used for the smoothing is the one given in [15],

$$K\left(\mathrm{M}_{\mathrm{w},m}, \mathbf{x}-\mathbf{x}_m\right) = \frac{\alpha-1}{\pi\left[H\left(\mathrm{M}_{\mathrm{w,m}}\right)\right]^2}\left[1+\frac{\left|\mathbf{x}-\mathbf{x}_m\right|^2}{\left(H\left(\mathrm{M}_{\mathrm{w},m}\right)\right)^2}\right]^{-\alpha} \quad (1)$$

where $M_{w,m}$ represents M_w for the m-th earthquake event, $\mathbf{x}$-$\mathbf{x}_m$ represents the distance between the grid point $\mathbf{x}$ to the m-th events; α is a constant value with a typical value ranging from 1.5 to 2.0, and α equal to 1.8 is considered in this study; and $H(M_{w,m})$ is the bandwidth parameter that can be expressed as:

$$H(\mathrm{M}_{\mathrm{w},m}) = a_1 \exp(a_2 \mathrm{M}_{\mathrm{w},m}) \quad (2)$$

in which a_1 and a_2 are model coefficients. The occurrence rate for $M_w \geq M_{wmin} = 4.8$ at the j-th cell, $\lambda_{j,\mathrm{cell}}$ (M_{wmin}) (per year and per cell), is,

$$\lambda_{j,cell}(\mathrm{M}_{\mathrm{wmin}}) = \sum_{m=1}^{m_T}\left(K(\mathrm{M}_{\mathrm{w,m}}, \mathbf{x}_j - \mathbf{x}_{\mathrm{m}}) / T(\mathbf{x}_m)\right) \quad (3)$$

where m_T is the total number of the considered seismic events, $T(\mathbf{x}_m)$ is the effective observation period for $M_{w,m}$, $T(\mathbf{x}_m) = T_p - T_{c,0.5}$, and T_p is the time at present (i.e., the end-time of the catalogue).

By using the completed seismic events with $M_w \geqslant 3.0$ based on Table 1, the parameter for a_1 and a_2 are estimated based on three different options. Option 1 is suggested in [16]. In this option, the earthquake events are grouped in bins, the shortest distance to other events in the same M_w group is estimated, and the estimated shortest distance and the corresponding M_w are employed to estimate the model coefficients shown in Eq (2). In Option 2, rather than using the shortest distance between events within each of the bins, the used of the average of the minimum distance for all the earthquake events in each bin is considered in [17]. In Option 3, all the magnitudes of the events and their minimum distance to the events within the bin are considered in [18]. The fitted curves by considering these options are shown in Figure 2, indicating that the curve corresponding to Option 3 fall within those of Option 1 and Option 2 for events with magnitude up to M_w = 6. This curve (as well as the corresponding model parameters a_1 and a_2) are used in the following analysis.

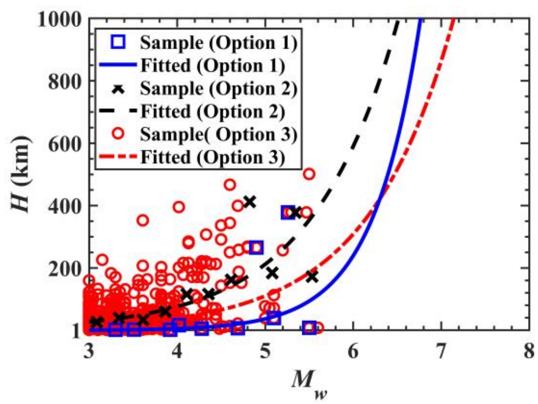


Figure 2. Regression for Eq. (6) and Samples.

By using Eqs. (1) to (3), $\lambda_{j,\mathrm{cell}}(M_{wmin})$ for the selected region is calculated and shown in Figure 3. As expected, the concentrated seismic occurrence rate follows the spatial distribution for historical seismic events shown in Figure 1b. For six selected sites, the estimated $\lambda_{j,\mathrm{cell}}$ (M_w) using the procedure given in [10] is shown in Figure 4 to illustrate the magnitude recurrence relations.

Note that the maximum observed magnitude is lower than the maximum magnitude adopted to develop fifth generation SHMC [2]. To extend the magnitude recurrence relation to the best maximum magnitude, M_{wmax}, recommended in [2] which equal to 7.8, the following relation is considered,

$$\lambda(M_w) = \lambda_0 \left(\exp(-\beta M_w) - \exp(-\beta M_{wmax}) \right) \tag{4}$$

where $\lambda(M_w)$ is the occurrence rate (per year) for earthquakes with magnitude greater than M_w, λ_0 is annual occurrence rate for earthquakes with $M_w \geqslant 0$, and β is the magnitude recurrence relation parameter. The value of β in Eq. (4) is estimated using the catalogue shown in Figure 1b and least-squares method. The obtained fit is shown in Figure 5, indicating the adequacy of the fit.

Using the obtained β value, the occurrence rate for M_w greater than the maximum observed M_w, M_{wo}, is then given by

$$\lambda(M_w) = \lambda(M_{wo}) \left(\exp(-\beta M_w) - \exp(-\beta M_{wmax}) \right) / \left(\exp(-\beta M_{wo}) - \exp(-\beta M_{wmax}) \right) \tag{5}$$

where $\lambda(M_{wo})$ is the estimated occurrence rate for the maximum observed magnitude M_{wo} according to the procedure given in [10]. Using Eq. (5) the magnitude-recurrence relation is extrapolated to M_{wmax} and shown in Figure 4 in dotted lines.

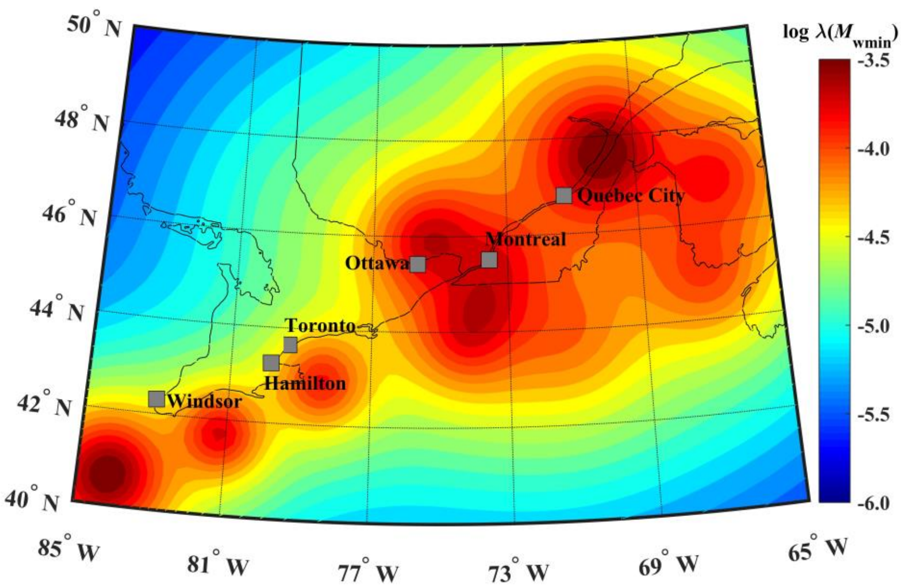


Figure 3. log($\lambda_{j,cell}$(M_{wmin})) for the considered region based on spatial smoothing approach.

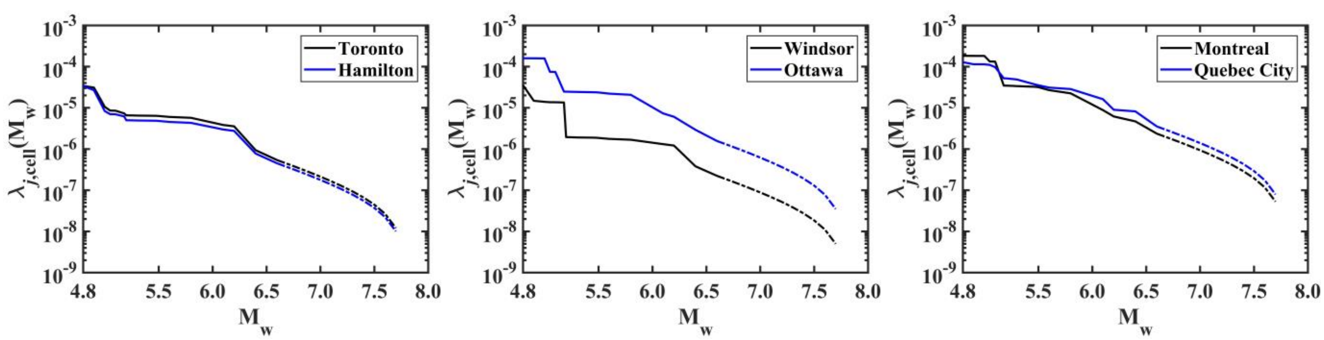


Figure 4. Estimated $\lambda_{j,\text{cell}}$ (M_w) for six selected locations.

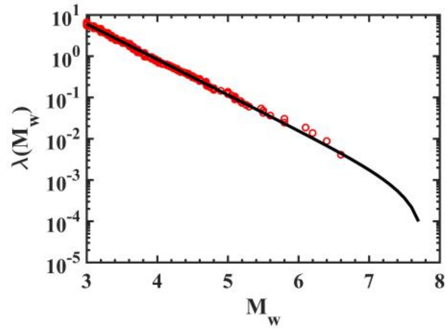


Figure 5. Fitted magnitude-recurrence relation by using all events shown in Figure 1b.

Comparison of magnitude recurrence relations

In this section, the obtained seismic occurrence rate is compared with those given or inferred from the models adopted for the development of the fifth generation SHMC. The model used for the assessment of the seismic hazard for the considered region is the southeastern model; it consists of H2 sub-model, HY sub-model, and R2 sub-model [2]. The weights assigned to H2 sub-model, HY sub-model, and R2 sub-model are 0.4, 0.4 and 0.2, respectively. The magnitude-recurrence relation adopted in [2] is as shown in Eq. (4). It is noted that for each sub-model, values of λ_0 or β or M_{max} are given for three cases (best, lower and upper), where a weight is assigned for each case. This results in a total of nine combinations of (λ_0, β, M_{max}), and each with an associated weight (or probability).

To see the possible differences in the magnitude-recurrence relation developed based on the spatial smoothing and those adopted for the development of the fifth generation SHMC, consider that a circular area with 250 km radius is centered at each of the considered site shown in Figure 4. The consideration of 250 km is justified since the seismic hazard for the center of a circle is dominated by the seismic events occurred within the circle with a 250 km radius [19]. The calculated occurrence rate within the circular area based on spatial smoothing approach described in the previous section as well as that calculated based on the source zone model given in [2] are illustrated in Figure 6 for H2 sub-model only. The figure shows that the former is lower than the average trend obtained based on the source zone models, especially for large magnitudes. Therefore, it is expected that the use of the spatially smoothed source model shown in Figures 4 and 5 is likely to result in the estimated UHS that are lower than those given in [2].

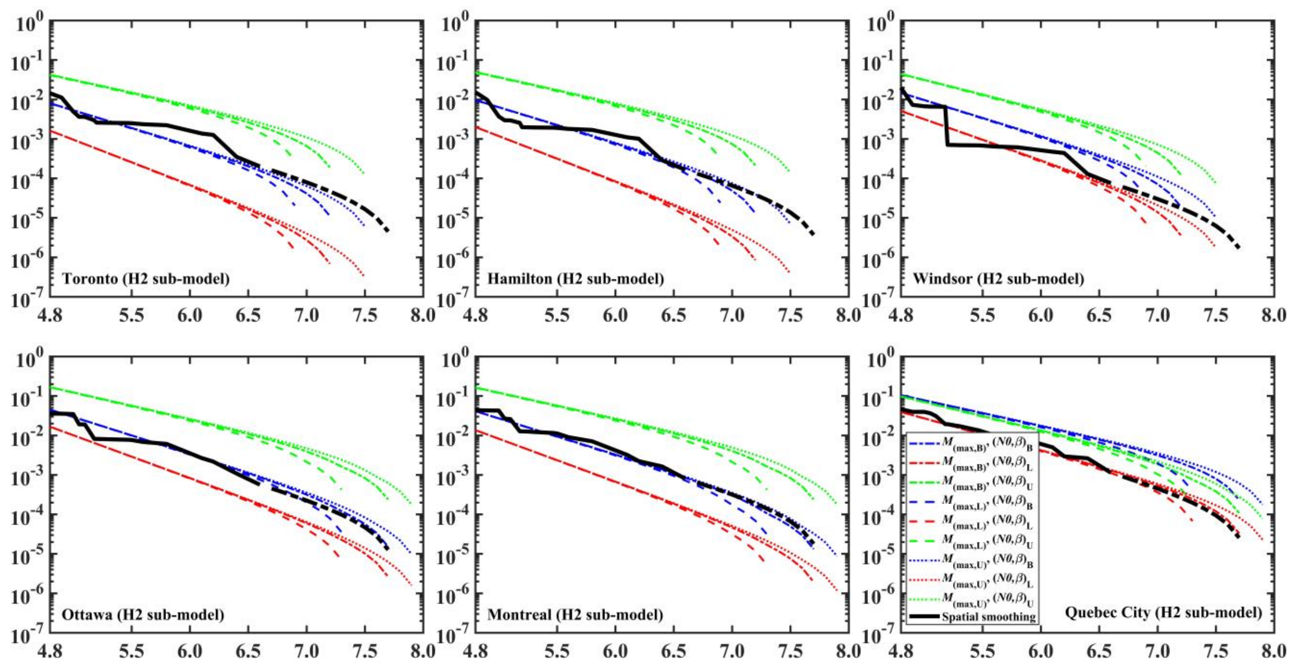


Figure 6. Comparison of occurrence rate within the circular area (subscript "B", "L", and "U" represent best estimated, lower estimated and upper estimated magnitude-recurrence relation parameter of Eq. (4).

GROUND MOTION PREDITION EQUATION (GMPE) FOR EASTERN CANADA

The GMPEs employed for the development of the fifth generation SHMC are developed in [20]. The development of these GMPEs are based on the weighting of the five pre-selected GMPEs. The obtained GMPEs are illustrated in Figure 7, where the option (upper median and lower) GMPEs are associated with weights of 0.25, 0.5 and 0.25, respectively.

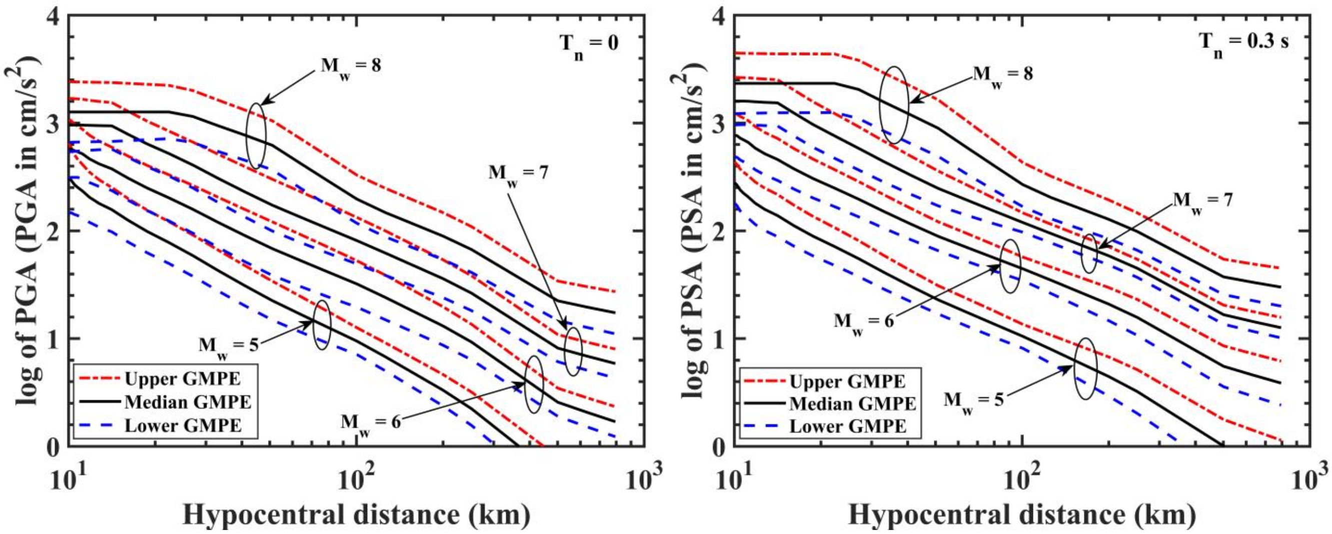


Figure 7. Upper, median and lower GMPEs for Tn = 0, and 0.3s with M_w = 5, 6, 7 and 8.

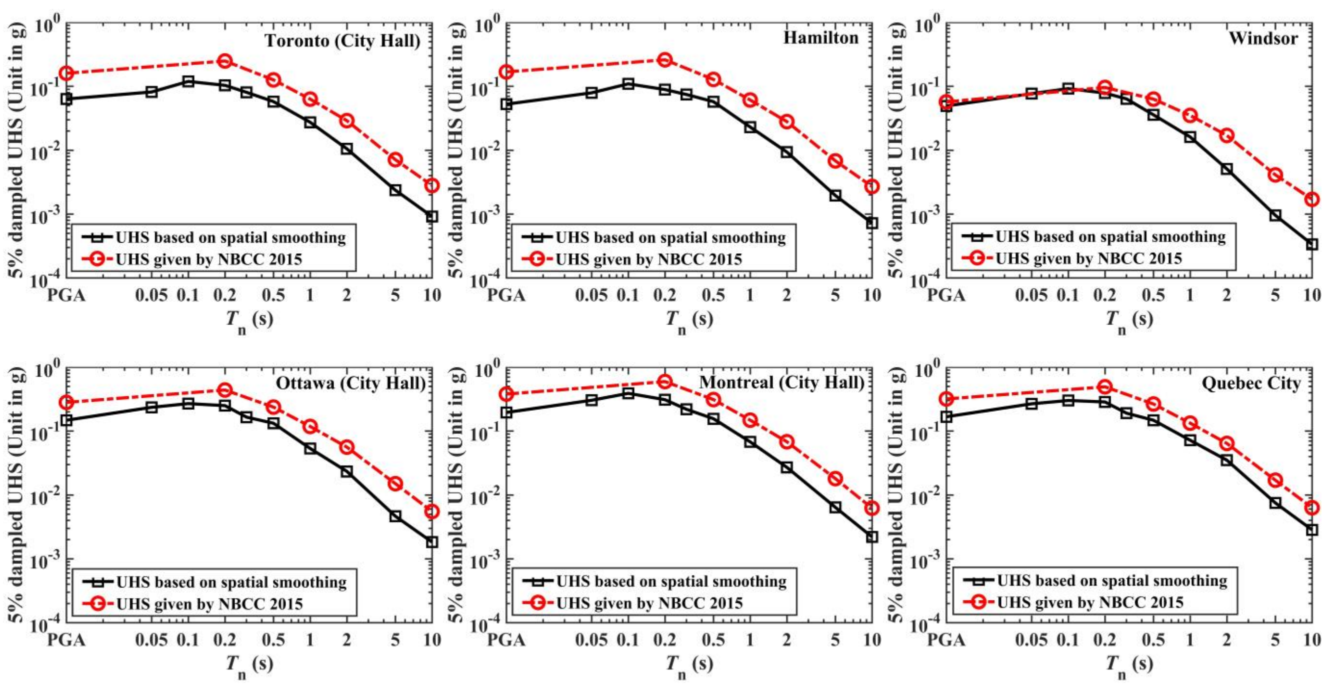


Figure 8. Plots of the obtained UHS in this study and the UHS given by NBCC with 2% probability exceedance in 50 years for NBCC site class C (average shear wave velocity 450 m/s)

ASSESSMENT OF UHS BASED ON SMOOTHED SOURCE MODEL

UHS for ξ = 5% with 2% probability of exceedance in 50 years

The UHS for a return period of 2475 years (i.e., 2% probability of exceedance in 50 years) are calculated for the six selected sites by using the smoothed source model. The calculation considers the sites are classified as Site Class C with an average shear wave velocity of 450 m/s [3]. The calculation procedure follows that given in [11]. The obtained values are shown in Figure 8 and compared with those given in [3]. From the figure, it is observed that the trends for the obtained UHS in this study are similar to those given in [3]. In all cases, the obtained UHS based on smoothed source model are lower than those given by NBCC. For $T_n < 2.0$ s, the average ratio of the value of the UHS given in [3] to that calculated in the present study ranged from 1.2 to 3.2, the average for the ratio is about 2.1, and for $T_n \geqslant 2.0$ s the ratio ranges from 1.8 to 5.1, the average for this ratio is about 3.0. It must be emphasized that the use of the spatially smoothed seismic source model may not necessarily results in a lower estimated seismic hazard for other regions. For example, the results shown in [21] indicate that the difference in the estimated seismic hazard by using the delineated seismic source zone model and the spatially smoothed source model is site dependent, and the estimate by using the former can be smaller or greater than that by using the latter.

CONCLUSIONS

The completeness analysis is carried out for the historical earthquake events in the selected Eastern Canadian region, the smoothing approach proposed in [10] is employed to smooth the completed seismic events to have the spatially smoothed seismic source model. By considering a few selected sites, it is found that the cumulative seismic event count (per year) for a circular area with a 250 km radius centred at a site is lower than the value that can be calculated based on delineated seismic source model given in GSC to develop the seismic hazard values recommended in NBCC 2015.

PSHA is carried out using simulation technique, and UHS for the damping ratio of 5% and 2% probability exceedance in 50 years for a few selected sites are obtained and compared with the UHS given in NBCC 2015 [3]. Therefore, the values recommended in the code are significant conservative as compared to the values estimated in the present study.

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