The 11th Canadian Conference on Earthquake Engineering

Canadian Association for Earthquake Engineering

SELECTION AND SCALING OF GROUND MOTION TIME HISTORIES FOR SEISMIC ANALYSIS USING NBCC 2015

Robert TREMBLAY
Professor, Polytechnique Montreal, Canada
robert.tremblay@polymtl.ca

Gail M. ATKINSON
Professor, Western University, Canada
gatkins6@uwo.ca

Najib BOUAANANI
Professor, Polytechnique Montreal, Canada
najib.bouaanani@polymtl.ca

Poulad DANESHVAR
Research Associate, Polytechnique Montreal, Canada
poulad.daneshvar@polymtl.ca

Pierre LÉGER
Professor, Polytechnique Montreal, Canada
pierre.leger@polymtl.ca

Sanda KOBOEVIC
Assistant Professor, Polytechnique Montreal, Canada
sanda.koboevic@polymtl.ca

ABSTRACT: This paper describes the new guidelines that are proposed for selection and scaling of ground motion time histories for linear or nonlinear dynamic response history analysis of structures designed in accordance with the 2015 edition of National Building Code of Canada. Definitions are given for the Design Spectrum, Period Range and Target Response Spectrum that must be considered in the procedure. Use of seismic hazard deaggregation results to identify potential sources of earthquakes and dominant magnitude-distance (M-R) scenarios of earthquakes for the site is discussed. Criteria are given for the selection of appropriate ground motion time histories and minimum requirements for scaling are described and explained. Consideration of vertical ground motions is presented. Acceptance criteria are discussed. Two examples are presented to illustrate the application of the procedure.

1. Introduction

In the National Building Code of Canada (NBCC), two types of analysis are specified for seismic design of building structures: equivalent static force procedure and dynamic analysis. The second method is the preferred one as it more accurately takes into account the dynamic properties of the structure that may affect its seismic response. Dynamic analysis can be either response spectrum analysis or response history analysis. In the first method, peak deformation and force demand parameters used for design are obtained by combining the contribution of the structure principal modes of vibrations. The method uses the linear elastic properties of the structure and the seismic input is the design spectrum specified in the NBCC. In the second method, equations of dynamic equilibrium are solved at every time step such that time histories of the seismic demand parameters are obtained for the duration of the ground motion. Response history analysis can be performed using a linear elastic model of the structure or a more comprehensive structural model where the nonlinear inelastic response under reversed cyclic loading of the material or structural components is explicitly considered in the analysis. In either linear or nonlinear response history analysis, the seismic input is a ground motion time history.

In practice, response spectrum analysis is widely used for structural design as it directly generates maximum anticipated values of deformation and force response parameters. Although the analysis method can provide accurate results for elastic structures, it has severe limitations for the design of seismic force resisting systems that rely on ductile inelastic response to withstand earthquake effects. For these structures, inelastic response can only be approximated from elastic analysis results, most often using the equal displacement principle, and local inelastic demand on critical elements or global stability of structures subjected to cyclic inelastic demand cannot be predicted from response spectrum analysis. Additional manual calculations are also generally required to determine design forces for the capacity-protected elements of ductile seismic force resisting systems. The same limitations apply when using seismic protection systems exhibiting nonlinear response such as viscous dampers, energy dissipating devices or base isolation. For these cases, nonlinear response history analysis (NLRHA) is used to obtain the information required to complete the design. For some structures, such as buildings equipped with base isolation, NLRHA is mandatory.

Proper assessment of the seismic response or demand from response history analysis requires an ensemble of representative ground motion time histories for the site. An ensemble is needed to account for the inherent variability and uncertainty of future earthquakes that can occur in a region and the characteristics of the ground motions they will generate at the site. These characteristics include the amplitude, frequency content and duration which, in turn, depend on the earthquake magnitude and distance. The selected ground motions should be consistent with the seismic hazard probability level considered for design. Interpretation of analysis results to assess the performance of the structure also needs attention. Over the years, selection and scaling of ground motion time histories suitable for seismic analysis has always represented a challenge. Several methods or procedures have been proposed for Canadian application (e.g., Atkinson and Beresnev, 1998; Atkinson, 2009; Koboevic et al., 2011; Lin et al., 2013; Michaud and Léger, 2014; Dehghani and Tremblay, 2015). Possible approaches and recommendations for the United States are presented and discussed in NERHP (2011). As part of the NSERC Canadian Seismic Research Network, guidelines have been developed to assist engineers performing NLRHA of structures designed in accordance with the NBCC 2015. These guidelines, referred to as the *NBCC Guidelines*, were developed based on the provisions proposed for Chapter 16 of ASCE 7-16 (Haselton et al., 2014). However, several differences were included to reflect the provisions of the NBCC. This article introduces and comments on the *NBCC Guidelines* for the selection and scaling of ground motion time histories. It also includes two illustrative examples, one for eastern Canada and one for western Canada.

2. NBCC Guidelines

2.1. Period Range and Target Response Spectrum

Ground motion time histories are selected and scaled with reference to a target response spectrum based on the design spectrum S(T) over a period range of interest. The design spectrum is prescribed based on a probabilistic seismic hazard analysis that determines the Uniform Hazard Spectrum (UHS) for a specified probability of exceedance.

2.1.1. Design Spectrum, S(T)

The reference design spectrum S(T) corresponds to the design spectrum specified in the NBCC. For the 2015 NBCC, it is proposed to determine S(T) from linear interpolation between the following values of $F(T)S_a(T)$, where F(T) are site coefficients and $S_a(T)$ are the UHS ordinates for a probability of exceedance of 2% in 50 years: (i) maximum of $F(0.2)S_a(0.2)$ and $F(0.5)S_a(0.5)$ for T = 0 and 0.2 s, and (ii) $F(0.5)S_a(0.5)$, $F(1.0)S_a(1.0)$, $F(2.0)S_a(2.0)$, $F(5.0)S_a(5.0)$, and $F(10)S_a(10)$ for T = 0.5, 1.0, 2.0, 5.0 and 10 s, respectively. For periods longer than 10 s, S(T) = $F(10)S_a(10)$. Values $S_a(T)$ will be specified in the NBCC along with the site factors F(T) that allow the local soil conditions to be considered. The plateau at short periods is aimed at preventing excessive ductility demand due to period elongation upon yielding of the structure and does not reflect actual spectral acceleration demand at these periods. In the *NBCC Guidelines*, it is therefore permitted to obtain S(T) for periods shorter than 0.5 s using linear interpolation between F(PGA)PGA, F(0.05)S_a(0.05), F(0.1)S_a(0.1), F(0.2)S_a(0.2), F(0.3)S_a(0.3), and F(0.5)S_a(0.5). Values of PGA (peak ground acceleration) and F(PGA) will be specified in the NBCC. Values of F(0.05), F(0.1), and F(0.3) will be given in Commentary J of the NBCC and S_a(0.05), S_a(0.1), and S_a(0.3) will be available from the Geological Survey of Canada (www.earthquakescanada.ca). Examples of S(T) proposed for NBCC 2015 with modification for selection and scaling of ground motion time histories are shown in Fig. 1 for two different site classes in Vancouver, British Columbia, and Montreal, Quebec.

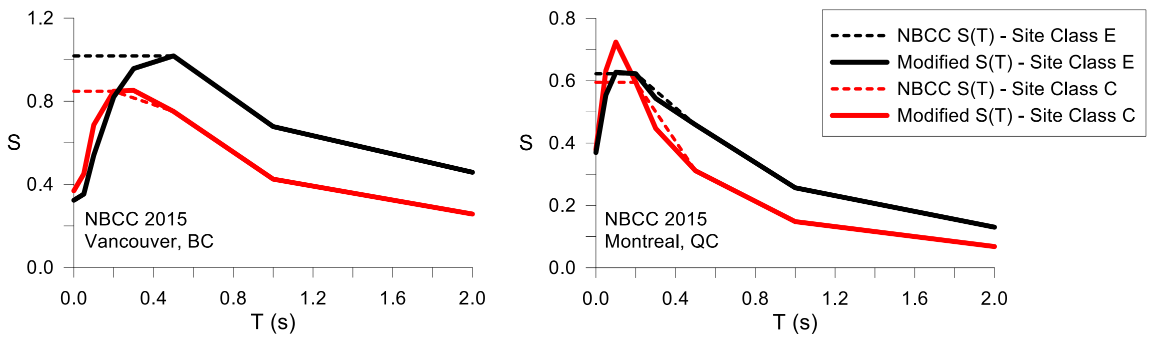

Fig. 1 – Examples of NBCC 2015 design spectra and modified design spectra S(T); values of S_a(T) from Halchuk et al. (2014) and F(T) from CCBFC (2014).

2.1.2. Period Range, T_R

Reference to S(T) for the definition of the target spectrum, or spectra, must be satisfied over a range of periods, T_R, that can significantly contribute to the inelastic seismic response of the structure in translational directions and/or torsion. The lower limit of this period range, T_{min}, is therefore set equal to the period of the highest vibration mode required to cumulate a minimum participating mass of 90% of the structure mass ($T_{90\%}$). The period T_{min} must not exceed 0.2 times the period of the structure fundamental mode, T_1. To account for inelastic behaviour, the upper limit of the period range, T_{max}, is equal to two times the period T_1 (2.0 T_1). In addition, the period T_{max} must not be less than 1.5 s so that the ground motion records for the analysis of stiff structures reflect the seismic demand over the period range where a large portion of the energy of typical seismic motions lies. Thus, the period range for ground motion selection and scaling purposes is defined as:

$$\begin{aligned} T_{min} &= \min\left[0.2T_1, T_{90\%}\right] \\ T_{max} &= \max\left[2.0T_1, 1.5\text{ s}\right] \end{aligned} \qquad (1)$$

The period range given by Eq. 1 is expected to be adequate for most building structures having periods up to approximately 3 to 5 s. Engineering judgement must be exercised in case of buildings that have longer fundamental periods, such as very tall or base isolated structures. For these situations, shorter values of T_{min} may be necessary to ensure that higher mode response to high frequency ground motions is properly predicted. When tri-dimensional dynamic analysis is carried out using two simultaneous orthogonal horizontal ground motion components, T_{min} should be determined with T_1 equal to the shorter of the two periods associated to the first translational modes of the structure along its two principal directions.

2.1.3. Target Response Spectrum, S_T(T)

Two methods are proposed in the *NBCC Guidelines* to establish the target response spectrum, S_T(T). Both methods are illustrated in Fig. 2a. In Method A, S_T(T) corresponds to the design spectrum S(T) over the entire period range T_R. In Method B, the target response spectrum is composed of one or more target spectra (S_{T1}, S_{T2}, etc.) that are established for magnitude-distance (M-R) scenarios contributing significantly to the seismic hazard at selected periods between T_{min} and T_{max}, and each scenario (i = 1, 2,

…) is assigned a portion or segment of the period range T_R, which is referred to as a scenario-specific period range, T_{RSi}. Scenario-specific period ranges typically span on either sides of the selected scenario-specific periods, with the first and last period ranges T_{RSi} being respectively bounded by the periods T_{min} and T_{max}. For each scenario, the target spectrum may be obtained using site-specific ground motion prediction equations (GMPE) for the magnitude, distance, and period of the scenario. In this case, mean spectral ordinate predictions would be used to build the target spectra. Alternatively, a conditional mean spectrum (CMS) or multiple CMSs computed at the selected scenario-specific periods may be used as scenario-specific target spectra $S_{Ti}(T)$ (Baker, 2011; Goda and Atkinson, 2011; Daneshvar et al., 2014, 2015b). In the *NBCC Guideline*s, the individual target spectra $S_T(T)$ in Method B must be linearly scaled to match or exceed S(T) at the scenario periods and the envelope of all spectra must not fall below 75% of S(T) over the period range T_R, as illustrated in Fig. 2a.

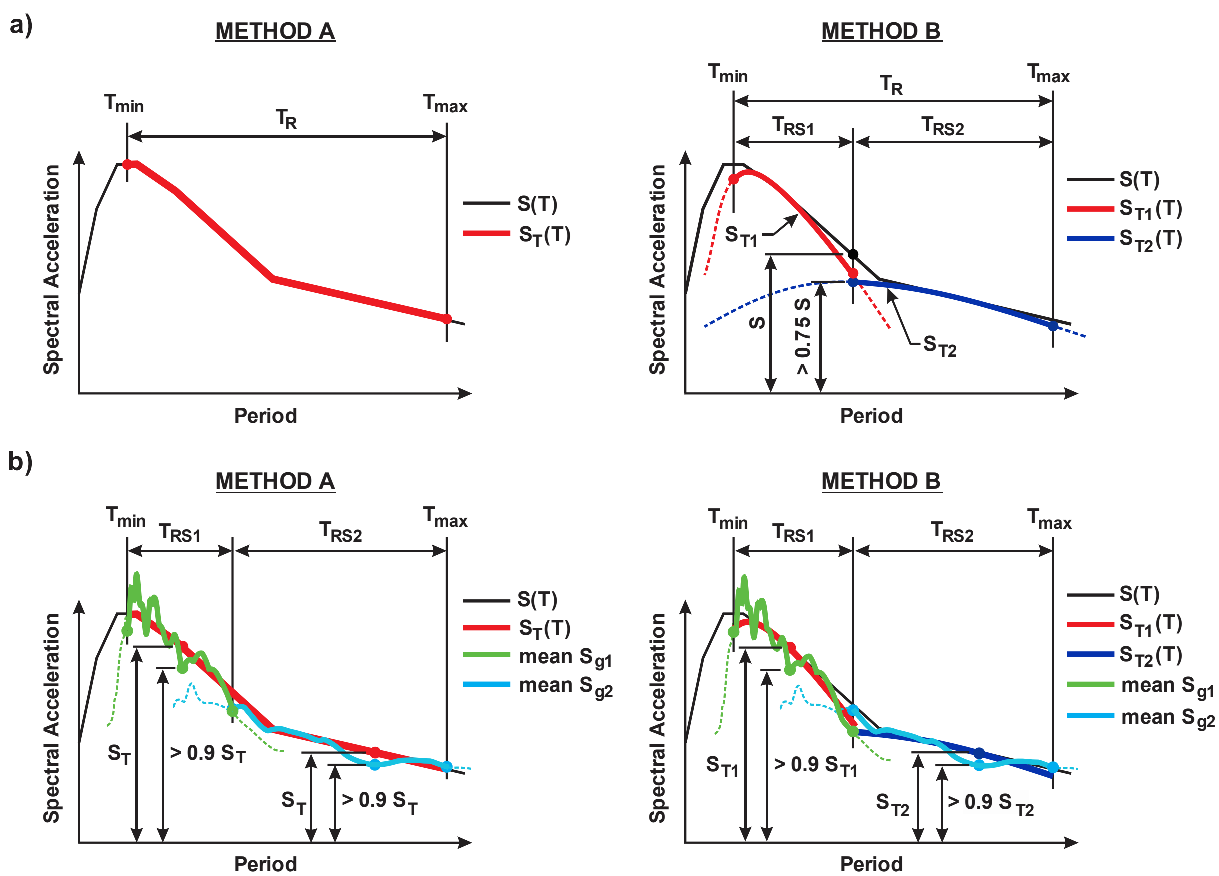

Fig. 2 – a) Target spectra according to Methods A and B;
b) Selection and scaling of ground motion time histories using Methods A and B.

For Method B, the *NBCC Guidelines* do not provide specific requirements for the definition of the M-R scenarios and period ranges T_{RS}, nor for the development of the target spectra $S_T(T)$. Typically, the scenarios are established from examination of the deaggregation of the seismic hazard contributions at intermediate periods within T_R. For most sites, no more than three scenarios generally suffice to represent the governing seismic demands. Scenarios should also reflect the input from various seismic sources when multiple earthquake types or fault mechanisms contribute to the hazard at the site within the period range T_R. This would be the case for locations in the south west part of British Columbia where seismic hazard results from a combination of crustal, in-slab (or sub-crustal), and interface (or subduction) earthquakes. As described below, marked differences between $S_T(T)$ and S(T) after matching the target spectra $S_{Ti}(T)$ to S(T) may also reveal portions of T_R where an additional scenario is needed to adequately represent seismic hazard. It is noted that period ranges T_{RSi} may overlap as would be the case when seismic hazard at the same or closely spaced periods is due to more than one main contributing M-R scenario.

For consistency with the methodology adopted for the development of S(T) in the NBCC (Atkinson and Adams, 2013), GMPEs and CMS correlation coefficients used in the development of the target spectra must be based on geometric mean spectral values or equivalent. Attention must be paid to local soil conditions (site class); if they differ from those assumed in the GMPEs or CMS correlation coefficients, the resulting target spectra will have to be modified to account for the local soil conditions. Information on modification factors can be found in Atkinson (2009). In addition, GMPEs and CMS correlation coefficients must be derived for the earthquake types or fault mechanisms considered in the scenarios.

Matching the target spectra with respect to S(T) is necessary in Method B as $S_T(T)$ will serve as target for scaling the selected ground motion records. Individual target spectra typically have a convex shape with a maximum value near the selected scenario periods, and the minimum 75% matching criteria typically governs at boundaries of the scenario-specific period ranges T_{RSi}. The upper and lower limits of the period ranges T_{RSi} may be adjusted to achieve more uniform matching when $S_{Ti}(T)/S(T)$ ratios at the two ends of a T_{RSi} range are significantly different or when marked discontinuities exist between target spectra at the boundary of two adjacent T_{RSi} ranges. The situation where $S_{Ti}(T)$ becomes significantly larger than S(T) within a T_{RSi} range, while satisfying the minimum 75% matching criteria elsewhere in the same period range, may suggest that an additional M-R scenario is required at periods where $S_{Ti}(T)/S(T)$ is minimum.

In Method B, target spectra $S_{Ti}(T)$ are deemed to represent the seismic demand from natural earthquakes dominating the hazard at given periods, recognizing that a UHS spectrum such as S(T) does not generally reflect actual acceleration demands from individual seismic ground motions over a large period range. Therefore, the target spectrum from Method B is generally a better target for the selection and scaling of ground motion time-histories compared to the unique $S_T(T)$ used in Method A. However, the simpler Method A still represents a valid option provided that the records are selected and scaled with consideration of the dominant M-R scenarios for the site, as discussed in the next section.

When vertical ground motions must be included in the seismic analysis, the *NBCC Guidelines* recommend using the vertical components of the ground motion records that are selected based on the horizontal target spectrum. Hence, a vertical target spectrum is generally not required in the process, as will be described later. However, when needed, the vertical target spectrum can be defined as a period-dependent fraction of the horizontal target spectrum $S_T(T)$.

2.2. Selection and Scaling of Ground Motion Records

2.2.1. Selection of Ground Motions

Appropriate ground motions should be selected considering the tectonic regime, magnitudes and distances that control the seismic hazard at a given site. When Method B is adopted to establish $S_T(T)$, ground motion selection is performed for each of the M-R scenarios identified for the definition of the target spectrum. If $S_T(T)$ from Method A is used, the dominating M-R seismic scenarios for the site must be selected first, as described for Method B in the previous section, and ground motion records are then selected for each individual scenario. For each M-R scenario, acceptable magnitude and distance ranges (or bins) should be established to ease the selection. For instance, for an M6.7-R25 km scenario, ground motion time-histories could be selected among those produced by earthquakes having a magnitude between 6.5 and 7.0 and recorded at distances between 20 and 30 km. Magnitude and distance definitions must be the same as those used in seismic hazard calculations; otherwise, adjustments may be needed. UHS values for the NBCC are obtained using moment magnitudes M_w and hypocentral distances (Halchuck et al., 2014). One should also consider in particular earthquake records that are compatible with the earthquake type or fault mechanism of the M-R scenario (e.g., crustal or subduction earthquakes) and that are compatible with the site class considered. The average shear-wave velocity as defined in the NBCC is generally used to characterize local ground conditions at recording stations.

According to the *NBCC Guidelines*, records from historical earthquakes are preferred, although ground motions simulated using a seismological model are acceptable if suitable historical records are not available. When possible, no more than two ground motion records from the same event should be retained to include minimum variability in ground motion characteristics. For western Canada, engineers can access the Pacific Earthquake Engineering Research (PEER) Center NGA-West2 database of three-component ground motions recorded in past shallow crustal earthquakes from worldwide active tectonic regions (Ancheta et al., 2013). A complementary NGA-East database of three-component ground motions will be available from the stable continental regions of eastern North America (Goulet et al. 2014, PEER 2015). These databases have tools that select and linearly scale records to achieve the best average fit to the target spectrum for a number of records selected. Simulated time histories for site classes A, C, D, and E representative of crustal and sub-crustal earthquakes in eastern and western Canada can be downloaded from the Engineering Seismology Toolbox website (www.seismotoolbox.ca) (Atkinson, 2009), which may be suitable for some applications. Ground motions representative of the Cascadia subduction earthquakes can also be obtained from this website.

In the *NBCC Guidelines*, an ensemble containing at least eleven ground motion time histories is required for dynamic analysis. When two or more seismic M-R scenarios are considered, a minimum of five ground motions must be selected for each scenario. Those are referred to as suites. For instance, a suite of five ground motions and a suite of six ground motions would be needed for the case where two M-R scenarios are considered. These recommended minimum numbers of motions represent a compromise to achieve statistically reliable estimates of mean structural responses while keeping the computational effort within practical limits (Haselton et al., 2004). Eleven records is also sufficiently large to allow discarding the results from one ground motion when deemed unacceptable, as discussed below. It is noted that these numbers are deemed suitable to obtain the demand corresponding to the design spectrum, but not its dispersion. A much larger number of records (at least 30 for the entire ensemble) would be needed if the dispersion were to be characterized.

When analysis of the structure is performed independently in one horizontal direction, ground motions should consist of appropriate single horizontal ground-motion components. When the analysis is performed under orthogonal horizontal ground motion time-histories being applied simultaneously, ground motions should consist of pairs of appropriate horizontal ground-motion components. When available, pairs of horizontal ground motion components recorded during the same event at a given site are typically used for this purpose. A set of two statistically independent simulated ground motions generated for the same M-R and fault conditions may also be used for this purpose for some applications (Atkinson, 2009). If vertical ground motions also need to be included in the analysis, sets comprising a vertical and two horizontal ground motion components recorded during the same event at a given site are generally used. Alternatively, a set of three consistent simulated records may be used to represent two orthogonal horizontal components plus a vertical component. When two orthogonal horizontal time histories are applied simultaneously in three-dimensional analysis, the analysis is typically repeated by rotating the records by 90 degrees; however, the two analysis cases count as one ground motion.

The response spectrum of each ground motion, $S_g(T)$, is used for selection and scaling purposes. For consistency with the NBCC spectrum S(T), the response spectrum $S_g(T)$ should be taken as the 5% damped pseudo-acceleration spectrum. When pairs of horizontal ground motions are used in the analysis, $S_g(T)$ should be the geometric mean of the 5% damped spectra of the two horizontal ground motion components. When single horizontal ground-motion components are used, $S_g(T)$ is the response spectrum of the individual ground-motion component considered. As a minimum, spectral accelerations $S_g(T)$ must be calculated at 20 period points equally spaced on a frequency scale (f = 1/T) over the period range T_R.

Among the acceptable ground motion candidates available for a given M-R scenario, selection refinement may be needed to retain the most appropriate ones. Final selection may be performed by keeping the motions with spectral shapes that are closer to that of the target response spectrum over the corresponding period range T_{RSi}. For this purpose, one can rank the ground motions based on the standard deviation of the $S_T(T)/S_g(T)$ ratio calculated at each period point over the period range T_{RS}. Alternatively, the selection can be refined by using techniques that will result in ground motions having key duration or frequency content characteristics that are anticipated for the hazard level (e.g., Bradley, 2010, 2012; Dehghani and Tremblay, 2015). As discussed in the next section, the selection may need to be revised after scaling the ground motions.

2.2.2. Scaling of Ground Motions

According to the *NBCC Guidelines*, each ground motion must be scaled such that its response spectrum $S_g(T)$ generally equals or exceeds the target spectrum $S_T(T)$ over the appropriate period range. When Method B is used to generate $S_T(T)$, scaling is performed for each period range T_{RSi} of the M-R scenario considered for the selection of the ground motion. The same approach must be used if $S_T(T)$ is established from Method A, which means that a scenario-specific period range T_{RS} must be defined for each of the M-R scenarios considered in the ground motion selection process. Specific scaling requirements are not given in the *NBCC Guidelines* to achieve proper scaling. Methods where the scaling factor is established by minimizing the standard deviation of $S_g(T)/S_T(T)$ ratios of the sum of the squared errors between $S_g(T)$ and $S_T(T)$ or by equalling the area under $S_g(T)$ to that under $S_T(T)$ may be used. However, the *NBCC Guidelines* require that the mean response spectrum of each scenario-specific suite of time histories does not fall more than 10% below $S_T(T)$ over the corresponding period range. This criteria is illustrated in Fig. 2b. The *NBCC Guidelines* do not specify means to satisfy this second criteria. When needed, the user may apply a second, unique, scaling factor to all motions of the suite, or increase the scaling factor of individual ground motions of the suite contributing most to the low mean value. Scaling is expected to be less pronounced when $S_T(T)$ is determined from Method B rather than Method A because $S_g(T)$ are matched to a target spectrum that more closely reflects the demand from natural earthquakes.

The *NBCC Guidelines* suggest using the simple linear scaling of ground motions so that the original signature and frequency distribution of energy of the ground motions are maintained. Frequency-domain and time-domain spectral matching techniques intended to closely match the target spectrum are not recommended for nonlinear structural analysis. These techniques may be used with caution, carefully evaluating the behaviour of the acceleration, velocity and displacement traces, including the presence of acceleration pulses, before and after spectral matching.

When performing analysis with pairs of orthogonal simulated or recorded horizontal ground motion time histories, the spectrum $S_g(T)$ used for scaling should be the geometric mean of the spectra of the two orthogonal horizontal components, as described in the selection phase. A single scaling factor therefore applies to both horizontal components. Similarly, when the vertical component of recorded ground motions is applied in the analysis, it should be scaled by the same factor determined and used for the corresponding horizontal component(s). When simulated ground motion components are used in the analysis, the vertical component should be scaled with respect to the vertical target spectrum (defined in Section 2.1.3.) using the criteria applicable to the horizontal ground motion components.

The selection of the ground motions may need to be revisited when scaling previously selected records. For instance, excessively low or high scaling factors may indicate that a record is not appropriate for the site or hazard level being considered. However, recognizing that high variability exists in ground motion properties and that ground motions producing spectral accelerations comparable to design spectrum $S_T(T)$ with small probability of exceedance (2% in 50 years) are rare, scaling factors comprised between 0.2 and 5.0 can be considered as acceptable and should not be the cause of rejecting previously selected records. Another example where scaling may reveal non-appropriate motions is when, after scaling, a ground motion exhibits $S_g(T)$ values much higher than S(T) at periods outside of its period range T_{RSi}. Although the ground motion has been produced by an earthquake with compatible M-R properties for the period range, its effects likely considerably differ from those assumed in seismic hazard calculations. Such a record should be carefully examined before it is kept in the suite or ensemble of selected ground motions.

2.3. Acceptance criteria

The *NBCC Guidelines* include guidance for the acceptance criteria to be used when assessing the seismic performance of structures from dynamic response history analysis. For compatibility with seismic hazard calculations in NBCC, the mean value of structural response parameters (drifts, member forces, etc.) from all ground motions should be used to assess the seismic performance of structures.

When two or more M-R scenario-specific suites of ground motions are used to form the ground motion ensemble used in the analysis, a fraction of the ground motions may impose limited demand and lower the average response, especially when selected and scaled at periods away from the periods that significantly influence the actual nonlinear response of the structure. For multi-suite ground motion ensembles, it is therefore recommended that the structural parameters be established using a higher percentile of the responses, such as the mean plus one standard deviation value or the 84^{th} or 90^{th} percentile values. Alternatively, the mean value from the critical subgroup of ground motions inducing the highest demand of the structural response parameter could be selected. For instance, the mean value of the largest 5 response values of an ensemble of 15 records composed of 3 suites of 5 records could represent a possible choice. When the response is largely dominated by one scenario-specific suite of motions, another option consists in expanding that critical suite of motions to include a minimum of eleven ground motion time histories and then use the mean value of the structural response parameter from that expanded suite of motions. It is noted that the acceptance criteria for multi-suite ground motion ensembles still remains open for research work and the recommendations of the *NBCC Guidelines* are expected to evolve as more experience and knowledge is gained in the future.

Ground motions may produce an unacceptable response such as a dynamic instability, a non-convergent analysis or a response that significantly exceeds the valid range of modelling assumptions. According to the *NBCC Guidelines*, a single unacceptable response should be permitted only if additional evaluations indicate that the predicted response is not indicative of unacceptable performance. In such case, the results of the analysis producing the unacceptable response may be discarded and performance evaluation should utilize the results of the remaining motions.

3. Application Examples

Two examples are used herein to illustrate the application of the *NBCC guidelines* for selection and scaling of ground motion time histories. In the first example, the structure is located on a class C site in Montreal, Quebec, representative of eastern Canada. A site class D in Vancouver, British Columbia, is chosen to represent western Canada in the second example. In both cases, Method A is used to establish the target spectrum $S_T(T)$ and single horizontal ground-motion components are selected and scaled for two-dimensional seismic analysis of building structures.

3.1. Eastern Canada

Step 1: Determination of the period range and target spectrum

The building studied has a fundamental period T_1 = 1.0 s. From Eq. 1, the period range of interest T_R is therefore between 0.2 s and 2.0 s. According to Method A, the target spectrum $S_T(T)$, shown in Fig. 3a, is the NBCC design spectrum S(T) with modifications in the short-period range as indicated in Section 2.1.1.

Step 2: Selection of the ground motions

Eastern Canada is a region of moderate seismic activity and there is a lack of recorded ground motions from earthquake events compatible with those dominating the hazard level adopted in the NBCC. For this reason, simulated ground motions from the Engineering Seismology Toolbox website are used as alternatives to historical records. The simulated ground motions in that database have been generated for M-R scenarios that govern the seismic demand in Canada. For areas of higher seismicity in eastern Canada, such as the Montreal location considered herein, Atkinson (2009) identified the following two scenarios from deaggregation results given in Halchuk et al. (2007): (1) M6 events having a fault distance ranging between 10 and 30 km for the 0.2-1.0 s portion of T_R; and (2) M7 events occurring at larger distances between 20 and 70 km which contribute to the hazard at periods between 0.5 and 2.0 s. The corresponding period ranges T_{RS1} and T_{RS2} are illustrated in Fig. 3b.

For eastern Canada, the database contains four sets of 45 simulated ground motion time histories: M6.0 at 10 to 15 km, M6.0 at 20 to 30 km, M7.0 at 15 to 25 km and M7.0 at 50 to 100 km. For the first scenario, a suite composed of five ground motions from M6 events was created using three ground motions at shorter distances (10-15 km) and two ground motions at longer distances (20-30 km). A second suite consisting of six simulated ground motions from M7 earthquakes comprises three ground motions in the 15-25 km range and three ground motions in the 50-70 km range. Among all simulated ground motions that met the M-R combinations, selection refinement was performed as follows (Atkinson, 2009):

1. For each candidate record, the ratio between the target spectral amplitude $S_T(T)$ and the spectral amplitude $S_g(T)$ was computed and the mean and standard deviation of the computed $S_T(T)/S_g(T)$ ratios were determined over the corresponding scenario-specific period T_{RS}.
2. The records having the lowest standard deviation and a mean $S_T(T)/S_g(T)$ ratio between 0.5 and 2.0 were selected.

In this example, magnitude and distance measures in the deaggregation results from Halchuk et al. (2007) were Nuttli (m_N) magnitudes and hypocentral distances whereas the simulated ground motions database uses the moment magnitude (M_W) and distances that are expressed as minimum or closest distance to fault plane. Hence, the two properties had to be converted to ensure consistency. The records were selected from the set of motions generated for a site Class C; hence, no adjustment was needed for local geotechnical conditions.

Step 3: Scaling of the ground motions

For each selected record, the mean $S_T(T)/S_g(T)$ ratio that was considered in the selection process was used as the scaling factor S_F. The response spectra of the individual scaled ground motions are plotted in Fig. 4a. In Fig. 4b, the mean response spectra of each suite of records are plotted over their corresponding period ranges T_{RS1} and T_{RS2}. The error between the mean values of $S_g(T)$ of the selected and scaled ground motions and $S_T(T)$ is illustrated for each scenario in Fig. 5. As shown, the error for both scenarios slightly exceeds the 10% allowable limit and a second scaling factor had to be applied to meet the minimum 90% matching requirement. These factors are equal to 1.03 and 1.01 for scenarios 1 and 2, respectively.

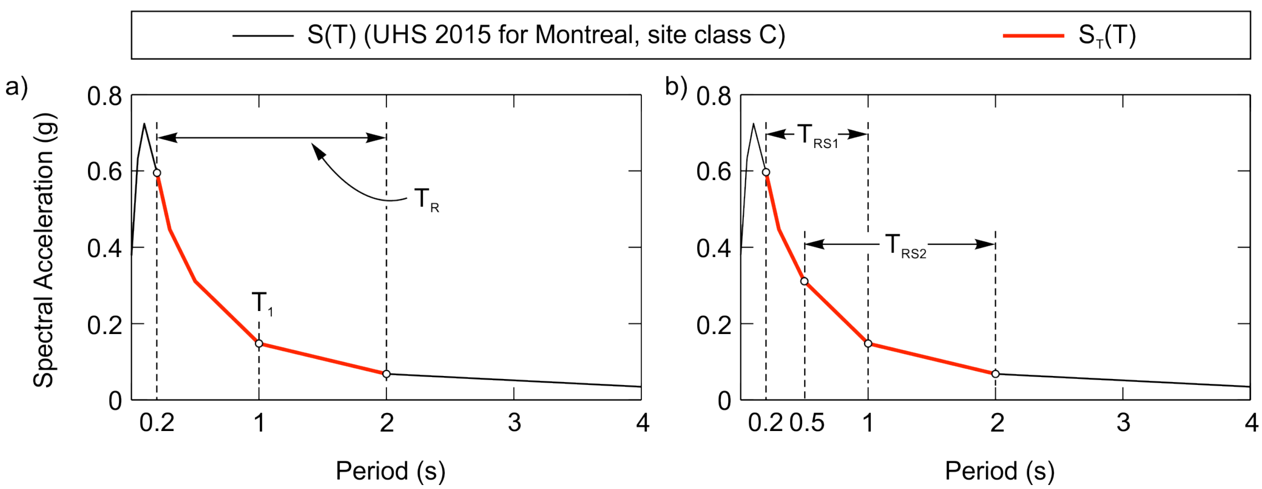

Fig. 3 – Determination of: a) Period range T_R and target spectrum; and b) Scenario-specific period ranges T_{RS1} and T_{RS2} for the Montreal example.

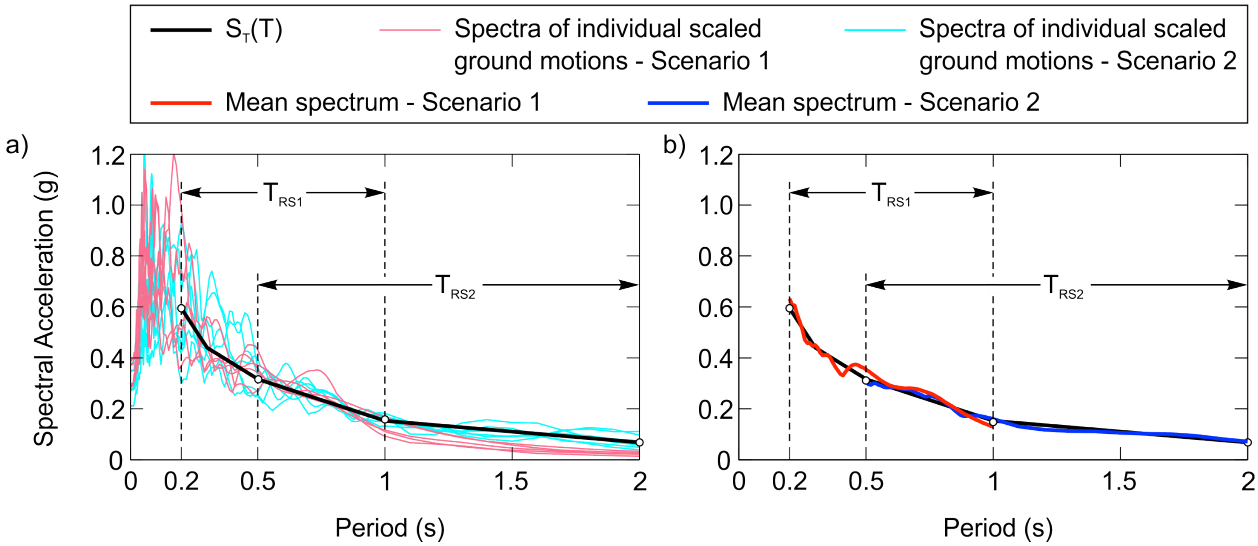

Fig. 4 – a) Acceleration spectra of the selected and scaled individual ground motion time histories; b) Mean acceleration spectra for Scenarios 1 and 2.

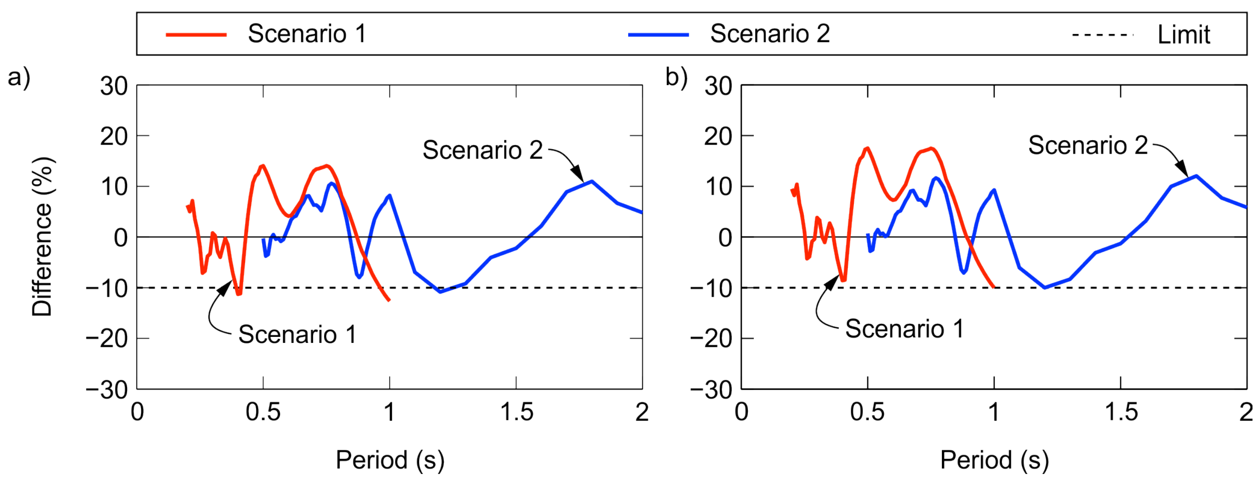

Fig. 5 – Difference between the mean $S_g(T)$ of the scaled records and $S_T(T)$ within each scenario-specific period range.

3.2. Western Canada

Step 1: Determination of the period range and target spectrum

In this example, a building structure with a fundamental period T_1 = 1.5 s is considered. For this building, a period range T_R spanning from 0.2 s to 3.0 s was selected, where the lower limit is governed by the 90% mass participation requirement for the structure studied. The design spectrum is illustrated in Fig. 6a.

Step 2: Selection of the ground motions

Seismic hazard deaggregations for a probability of 2% in 50 years in Vancouver, BC, are illustrated in Fig. 7 for periods of 0.2, 0.5, 1.0, 2.0, and 5.0 s. The calculations were performed for the UHS values proposed for the upcoming NBCC 2015. The hazard in south western British Columbia essentially arises from movements of tectonic plates along the Pacific Ocean plate, more specifically from: 1) shallow earthquakes in the North American plate, 2) deep sub-crustal or in-slab events within the down-going Juan de Fuca plate, at a depth of 50 km or more, and 3) large magnitude (M9) interface or subduction earthquakes occurring at the boundary of the two plates, away from the coast at a depth of approximately 20 km. In Fig. 7, seismic hazard at shorter periods is dominated by crustal earthquakes for distances less than 50 km and from both crustal and in-slab events at distances greater than 50 km. As the period is increased, UHS values are gradually dominated by the larger magnitude interface earthquakes. Mean magnitude and distance values of the contributions to hazard from each type of event were obtained from the seismic hazard model of western Canada by Goda and Atkinson (2011) and values are given in Table 1 for four periods within T_R (Daneshvar et al., 2015a). As shown, the dominant M-R scenarios for each fault mechanism do not vary much with the periods. Based on these observations, an M-R scenario was defined for each type of events and the scenario-specific period ranges are illustrated in Fig. 6b: 0.2-0.8 s for crustal events, 0.3-1.5 s for in-slab events, and 1.0-3.0 s for interface earthquakes. Mean M-R scenarios of Table 1 at periods of 0.5, 1.0, and 2.0 s, respectively, served as a basis for ground motion selection.

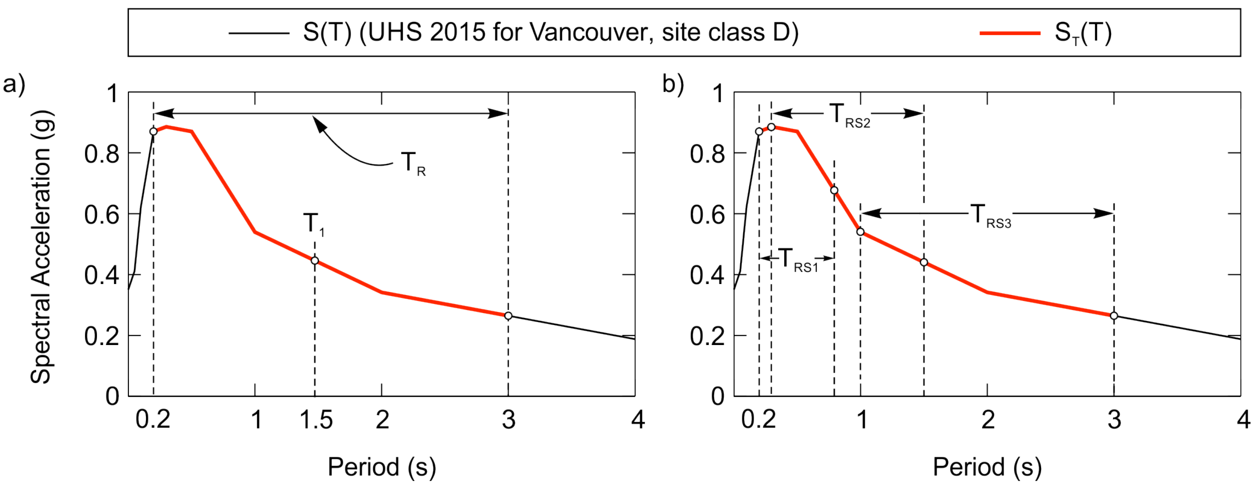

Fig. 6 – Determination of: a) Period range T_R and target spectrum; and b) Scenario-specific period ranges T_{RS1}, T_{RS2}, and T_{RS3} for the Vancouver example.

The ground motions were selected from the databases of earthquakes described in Daneshvar et al. (2015a): the PEER-NGA database for the shallow crustal events and the K-NET, KiK-net and SK-net databases for the in-slab and interface events. Magnitude and distance definitions used in these databases were the same as in the deaggregation results shown in Table 1 (moment magnitude and closest distance to fault). Only the records at sites with shear wave velocity between 180 and 360 m/s corresponding to site class D were retained. In addition, M-R trade-offs of 40 km, 60 km, and 60 km were adopted for the crustal, in-slab and interface events, respectively. For example, a crustal record with a magnitude of one unit lower than the mean magnitude from deaggregation could be selected as long as it had a distance 40 km shorter than the mean distance in Table 1. The same applied for events with larger magnitudes by selecting records at distances longer than those given in Table 1. This process led to a pre-selection of 200 ground motion time histories for each ground motion type.

For each scenario, a suite of five ground motion time histories was needed and selection refinement was performed as was done in the previous example, i.e., by ranking ground motions based on their spectral shapes and scaling factors. However, the historical records selected in this example showed greater variability in spectral shapes in comparison with the simulated ground motions used in the first example and the upper limit on the mean $S_T(T)/S_g(T)$ ratio over the period range T_{RS} was relaxed to 5.0.

For the interface ground motions, an additional selection criterion was applied during the subsequent scaling process: scaled records having a mean $S_T(T)/S_g(T)$ ratio larger than 1.2 computed for periods up to 1.0 s were excluded from the final suites. This condition was added to avoid unrealistic excessive demands at short periods from subduction earthquakes resulting from the scaling process performed at longer periods (T_{RS3} = 1.0-3.0 s for this earthquake type).

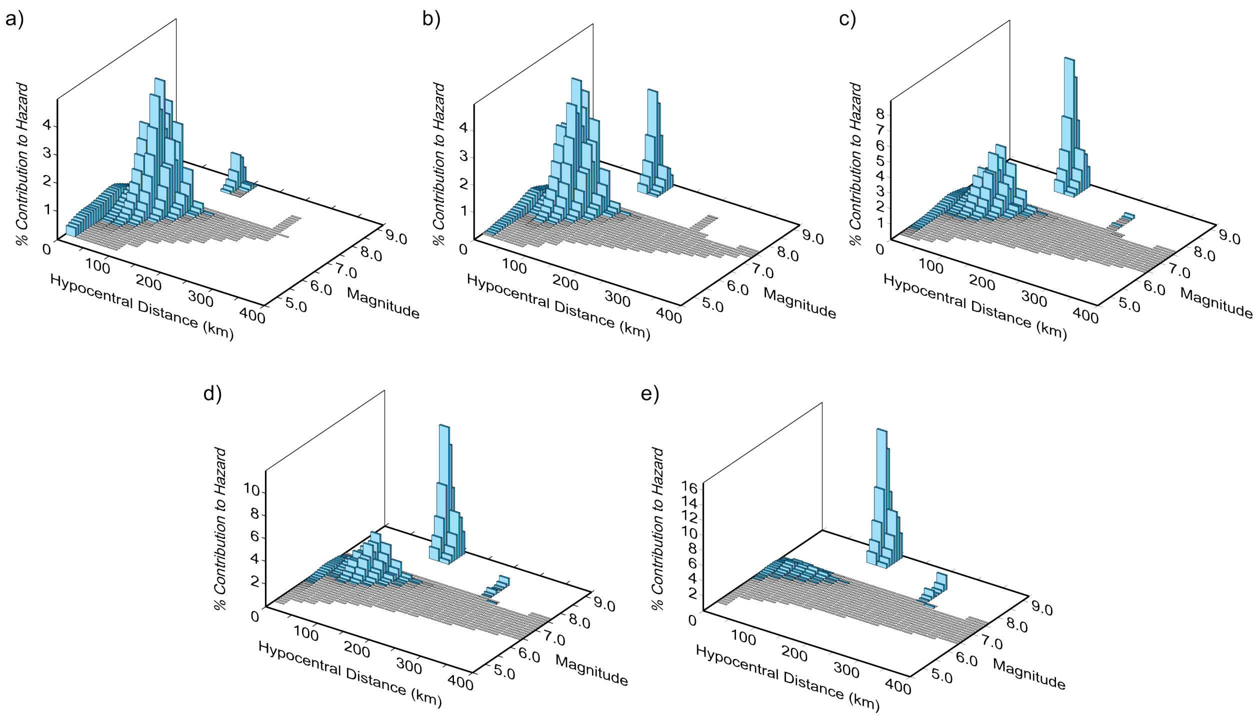

Fig. 7 – Seismic hazard deaggregations for Vancouver, BC, at periods of: a) 0.2, b) 0.5, c) 1.0, d) 2.0 s, and e) 5.0 s.

Table 1 – Mean magnitude and distances from deaggregation results for each event type (scenarios with underlined M-R values were used for ground motion selection).

	T = 0.2 s		T = 0.5 s		T = 1.0 s		T = 2.0 s	
Event Type	**M**	**R (km)**	**M**	**R (km)**	**M**	**R (km)**	**M**	**R (km)**
Crustal	6.5	14	**<u>6.7</u>**	**<u>14</u>**	6.8	18	7.0	15
In-slab	6.9	61	7.0	56	**<u>7.0</u>**	**<u>52</u>**	7.1	51
Interface	8.6	142	8.7	142	8.6	141	**<u>8.6</u>**	**<u>141</u>**

Step 3: Scaling of the ground motions

For each selected ground motion, the scaling factor was taken equal to the mean $S_T(T)/S_g(T)$ computed over the applicable period ranges T_{RS1}, T_{RS2}, and T_{RS3}. The spectra of the individual selected and scaled ground motions for each earthquake type are shown in Figs. 8a to 8c, and the corresponding mean spectra are plotted in Fig. 8d. Errors between mean and target spectra over each period range are plotted in Fig. 9a. As shown, the 10% matching criteria is not satisfied for any of the suites of ground motions. A second series of scaling factors equal to 1.03, 1.02, and 1.14 had to be applied to all motions of the suites of crustal, in-slab and interface event motions, respectively. The errors between the final mean and target spectra over each period range are illustrated in Fig. 9b.

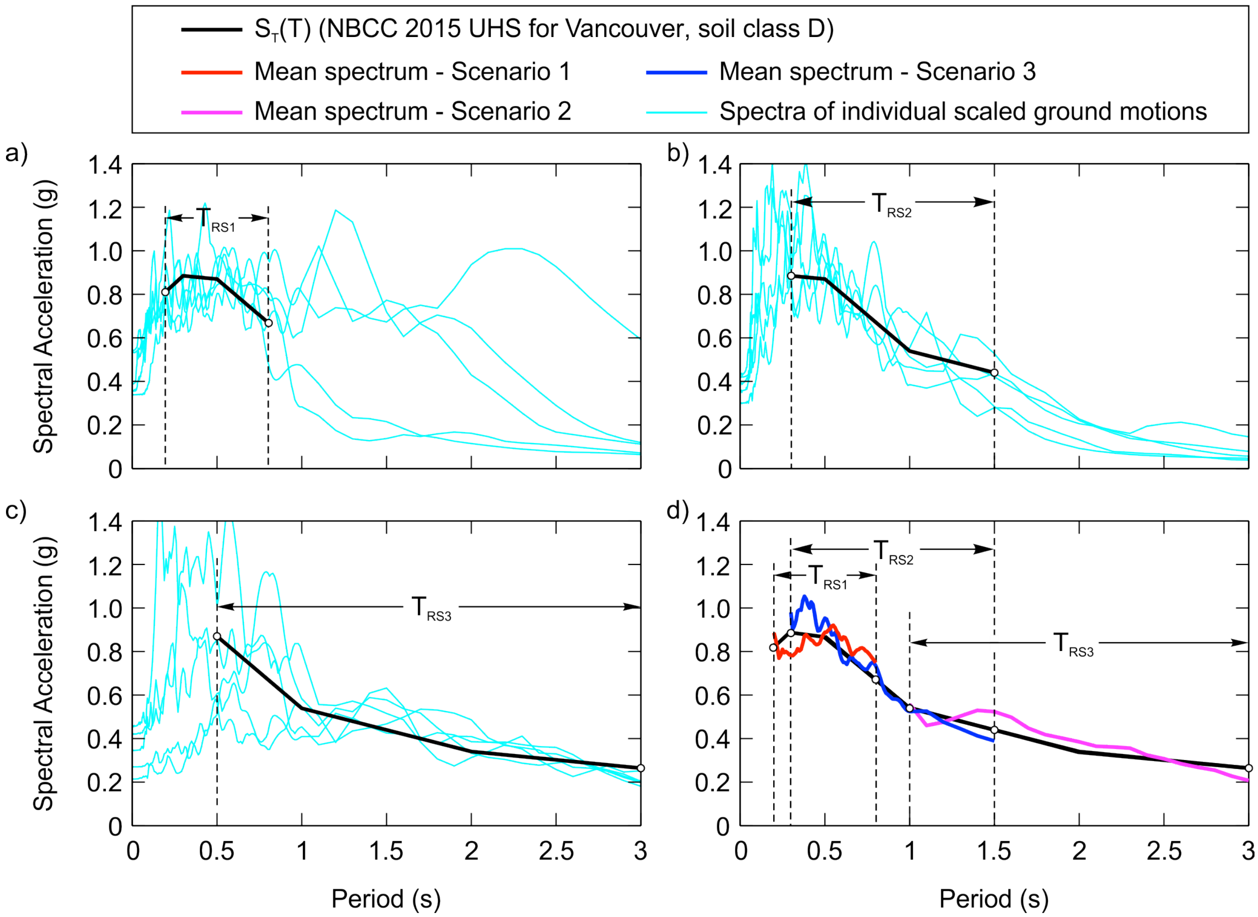

Fig. 8 – a) to c) Spectra of the selected and scaled individual ground motion time histories of Scenarios 1 to 3; and d) Mean spectra for the three scenarios.

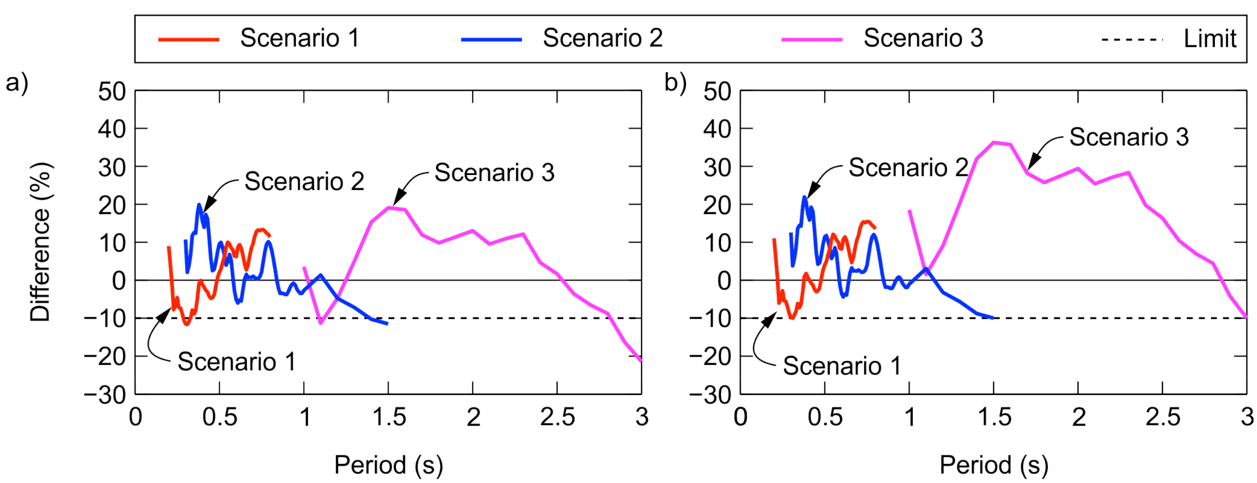

Fig. 9 – Differences between the mean $S_g(T)$ of the scaled records and $S_T(T)$ within each scenario-specific period range after the: a) first scaling factors; and b) second scaling factors.

4. Conclusions

The paper described the guidelines that are proposed for the selection and scaling of seismic ground motions for response history dynamic analysis of building structures in accordance with the upcoming NBCC 2015. The *NBCC Guidelines* include the following main steps:

1. Definition of a design spectrum corresponding to the NBCC S(T) with modifications in the short-period range.
2. Definition of a period range of interest, T_R, essentially based on the structure dynamic properties.
3. Definition of a target spectrum $S_T(T)$ over the period range T_R. Two methods are proposed: one where $S_T(T)$ is taken equal to S(T) and one where $S_T(T)$ is formed of one or more scenario-specific spectra reflecting the demand expected from the M-R scenarios and fault mechanisms dominating the hazard at the site.
4. Selection of appropriate ground motion time histories for each of the dominant M-R scenarios and fault mechanisms. The selected records must also be compatible with local soil conditions at the site.
5. Scaling of the selected records with respect to the target spectrum $S_T(T)$.

The *NBCC Guidelines* also provide information on acceptance criteria to be used for determining structural response parameters. The application of the *NBCC Guidelines* for selection and scaling of ground motions was illustrated by means of two examples.

5. Acknowledgements

Funding from the Canadian Seismic Research Network (CSRN) of the Natural Sciences and Engineering Research Council (NSERC) of Canada and the Strategic Network Program is acknowledged. The authors wish to express their appreciation to members of the Standing Committee on Earthquake Design (SCED) of the National Building Code of Canada and members of the Sub-Committee on Section 4 (Seismic Design) of CSA S6 Code for the Design of Highway Bridge Structures for their most valuable input.

6. References

ANCHETA, Timothy D., DARRAGH, Robert B., STEWART, Jonathan P., SEYHAN, Emel, SILVA, Walter J., CHIOU, Brian S.J., WOODDELL, Katie E., GRAVES, Robert W., KOTTKE, Albert R., BOORE, David M., KISHIDA, Tadahiro, and DONAHUE, Jennifer L., *PEER NGA-West2 Database*, PEER Report 2013/03, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA. 2013.

ATKINSON, Gail M., “Earthquake time histories compatible with the 2005 National building code of Canada uniform hazard spectrum”, *Canadian Journal of Civil Engineering,* Vol. 36, No. 6, June 2009, pp. 991-1000.

ATKINSON, Gail M., and ADAMS, John, “Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps”, *Canadian Journal of Civil Engineering*, Vol. 40, No. 10, 2013, pp. 988–998.

ATKINSON, Gail M., and BERESNEV, Igor A., “Compatible ground-motion time histories for new national seismic hazard maps”, *Canadian Journal of Civil Engineering*, Vol. 25, no. 2, 1998, pp. 305-318.

BAKER, Jack W., “Conditional Mean Spectrum: Tool for Ground-Motion Selection”, *Journal of Structural Engineering*, ASCE, Vol. 137, No. 3, SPECIAL ISSUE: Earthquake Ground Motion Selection and Modification for Nonlinear Dynamic Analysis of Structures, 2011, pp. 322–331.

BRADLEY, Brendon A., "A generalized conditional intensity measure approach and holistic ground-motion selection," *Earthquake Engineering & Structural Dynamics*, Vol. 39, No. 12, 2010, pp. 1321-1342.

BRADLEY, Brendon A., "A ground motion selection algorithm based on the generalized conditional intensity measure approach," *Soil Dynamics and Earthquake Engineering*, Vol. 40, 2012, pp. 48-61.

CCBFC. *Proposed Change 862 to NBC10*, Canadian Commission Building and Fire Codes, Ottawa, ON, 2014.

DANESHVAR, Poulad, BOUAANANI, Najib, and LÉGER, Pierre, "Application of conditional mean spectra for evaluation of a building's seismic response in Eastern Canada", *Canadian Journal of Civil Engineering*, Vol. 41, No. 8, 2014, pp. 769-773.

DANESHVAR, Poulad, BOUAANANI, Najib, GODA, Katsuichiro, ATKINSON, Gail M., "Damping Reduction Factors for Crustal, Inslab and Interface Earthquakes Characterizing Seismic Hazard in South-Western British Columbia, Canada", *Earthquake Spectra,* 2015a, doi: http://dx.doi.org/10.1193/061414EQS086M.

DANESHVAR, Poulad, BOUAANANI, Najib, and GODIA, Audrey, "On computation of conditional mean spectrum in Eastern Canada". *Journal of Seismology*, Vol. 19, No. 2, 2015b, pp. 443-467.

DEHGHANI, Morteza, and TREMBLAY, Robert, "Robust Period-Independent Ground Motion Selection and Scaling for Effective Seismic Design and Assessment", *Journal of Earthquake Engineering*, 2015, in press.

GODA, Katsuichiro, and ATKINSON, Gail M., "Seismic Performance of Wood-Frame House in South-Western British Columbia", *Earthquake Engineering and Structural Dynamics,* Vol. 40, No. 8, July 2011, pp. 903-924.

GOULET, Christine A., KISHIDA, Tadahiro, ANCHETA, Timothy D., CRAMER, Chris H., DARRAGH, Robert B., SILVA, Walter J., HASHASH, Youssef M.A., HARMON, Joseph, STEWART, Jonathan P., WOODDELL, Katie E., and YOUNGS, Robert, R., *PEER NGA-East Database*. PEER Report 2014/17, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, 2014.

HALCHUK, Stephen, ADAMS, John, and ANGLIN, Frank, "Revised deaggregation of seismic hazard for selected Canadian cities", *Proceedings of the 9th Canadian Conference on Earthquake Engineering*, Ottawa, ON, June, 2007, Paper No. 1188, pp. 420-432.

HALCHUK, Stephen, ALLEN, Trevor, ADAMS, John, and ROGERS, Garry, "*Fifth Generation Seismic Hazard Model Input Files as Proposed to Produce Values for the 2015 National Building Code of Canada*", Geological Survey of Canada, Open File 7576, 2014.

HASELTON, Curt B., FRY, Andy, BAKER, Jack W., HAMBURGER, Ron O., WHITTAKER, Andrew S., STEWART, Jonathan P., ELWOOD, Kenneth J., LUCO, Nicolas, HOOPER, John D., CHARNEY, Finley A., ZIMMERMAN, Reid B., and PEKELNICKY, Robert G., "Response-History Analysis for the Design of New Buildings: A Fully Revised Chapter 16 Methodology Proposed for the 2015 NEHRP Provisions and the ASCE/SEI 7-16 Standard", *Proceeding 10th U.S. National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, August 2014.

KOBOEVIC, Sanda, GUILINI-CHARETTE, Kim, CASTONGUAY, Pierre, and TREMBLAY, Robert, "Selection and scaling of NBCC 2005 compatible ground motions for nonlinear seismic analysis of building structures", *Canadian Journal of Civil Engineering*, Vol. 38, No. 12, 2011, pp. 1391-1403.

LIN, Lan, NAUMOSKI, Nove, SAATCIOGLU, Murat, FOO, Simon, BOOTH, Edmund, and GAO, Yuling, "Selection of Seismic Excitations for Nonlinear Analysis of Reinforced Concrete Frame Buildings," *Canadian Journal of Civil Engineering*, Vol. 40, no. 5, 2013, pp. 411-426.

MICHAUD, Dominic, and LÉGER, Pierre, "Ground motions selection and scaling for nonlinear dynamic analysis of structures located in Eastern North America," *Canadian Journal of Civil Engineering*, Vol. 41, no. 3, 2014, pp. 232-244.

NEHRP, *Selecting and Scaling Earthquake Ground Motions for Performing Response History Analysis*. Report No. NIST/GCR 11-917-15, prepared by the NEHRP Consultants Joint Venture for the National Institute of Standards and Technology, Gaithersburg, MA, November 2011.

PEER, *NGA-East: Median Ground-Motion Models for the Central and Eastern North America Region,* PEER Report 2014/17, Pacific Earthquake Engineering Research Center, Headquarters at the University of California, Berkeley, CA. 2015.