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Proposed Seismic Signals Generated Compatible to CNBC 2005 Design Spectra

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Abstract

The National Building Code of Canada 2005 (NBCC-05) recommends the use of dynamic methods for the analysis of seismic resistant systems (SRS). In this context, when time history analysis is used, according to the NBCC, the selected seismic records should meet the following requirements: (i) be representative of the seismic hazard; (ii) have an acceleration spectrum compatible with the targeted design spectrum; and (iii) be sufficiently numerous. This paper presents seismic signals that were generated compatible to the design spectra from records that are representative of the seismic risk for Canadian seismic zones. The compatibility of these signals is complete because it is obtained by spectral calibration over the whole range of significant frequencies. The resulting calibrated seismic signals are readily available for use and are not specific to a particular SRS, but are applicable to any structural analysis regardless of the predominant vibration modes of the system analyzed. Using this method, seismic signals compatible with NBCC-05 design spectra have been developed for the Montreal (representative of the East) and Vancouver (representative of the West) regions and presented for soil classes A to E. Finally, a numerical example is provided to demonstrate the efficiency of the approach.

Introduction

Most modern seismic codes, including NBCC–05, recommend the use of dynamic methods for the seismic analysis of structures. To this end, two methods can generally be used: (a) modal analysis, which is based on superposition of the spectral responses of the natural vibration modes, or (b) time history analysis, the so-called "step-by-step" method, which is based on numerical integration of the equilibrium equation of the applied dynamic forces.

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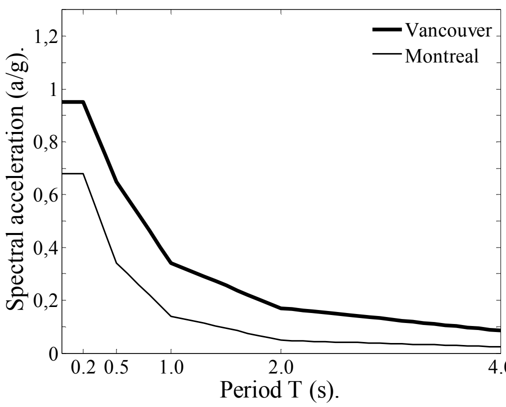

Figure 1. Uniform hazard spectrum.

When modal analysis is used, the solution is straightforward and is obtained from the design acceleration spectra defined in clause 4.1.8.4 of the NBCC-05 standard. In fact, according to the new Canadian seismic map, each Canadian city is identified by its so-called UHS, or *uniform hazard spectrum* (Fig. 1). The design spectra of five soil classes, A to E, ranging from hard rock to soft soil (see Table 4.1.8.4.A in NBCC-05), can be obtained by spectral adjustment of the UHS of each city using the soil coefficients F_a and F_v (Finn & Wightman, 2003) (Fig. 2).

a) **b)**

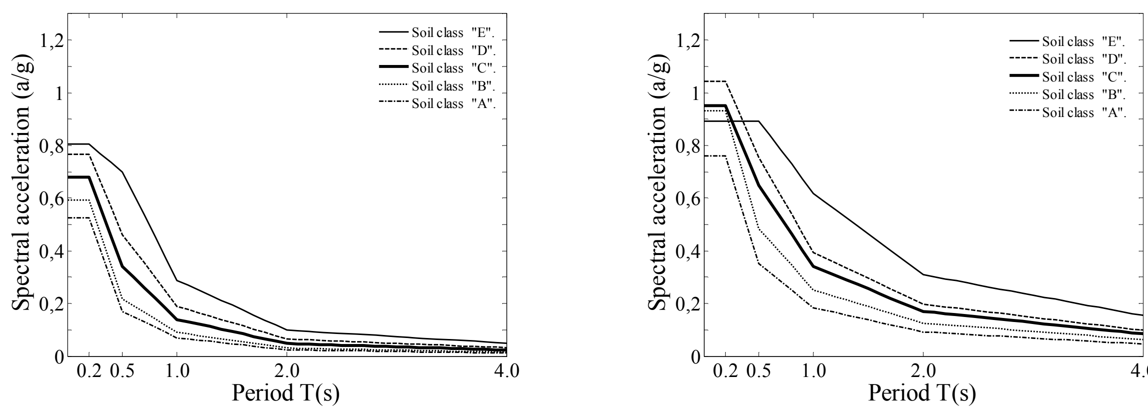

Figure 2. Design spectra for soil classes A, B, C, D, and E: **a)** Montreal; **b)** Vancouver.

On the other hand, when step-by-step time history analysis is used, the seismic records should be not only representative of the seismic hazard of the city under consideration, but also compatible with the target design spectrum (commentary J-183, NBCC-05). However, given the very limited number of historical seismic records for most Canadian cities, the synthetic signals developed by Atkinson and Beresnev (1998) offer an interesting alternative solution. This is particularly true when it is known that for most soil classes other than the reference soil (class C), there are no signals available, synthetic or historic, except for very few cities. However, although specifically generated for the seismic hazard of the reference Canadian soils (soils of class C), these synthetic signals fail to meet the compatibility criteria as defined in NBCC-05. The alternative is therefore to modify these signals so that they meet the spectral compatibility requirements, i.e., they exhibit a sufficient degree of similarity of the signal spectrum to the target design spectrum (commentary J-183, NBCC-05). This modification can be accomplished by a) a vertical shift of the acceleration spectrum (representing an amplification or attenuation of the seismic signal) or b) a calibration of the spectrum at each period of the modes which contribute most to the dynamic response of the SRS under consideration. The latter method is thought to be more appropriate because on the one hand, it meets the NBCC-05 requirements, and on the other hand, it generates step-by-step dynamic analysis results comparable to those from reference spectral analyses. However, although attractive, this solution is not practical for the structural engineer because it has to be repeated for each of the SRS under consideration, even if they are located in the same city and therefore are analyzed with reference to the same target design spectrum. The generalization of such an approach to the whole range of periods of NBCC-05 target design spectra will make it possible to generate seismic signals that are compatible and readily available for use.

Spectral Compatibility of a Seismic Signal with a Target Design Spectrum

The spectral compatibility of a seismic signal with a target design spectrum must be verified for the whole range of periods of the vibration modes that contribute most to the dynamic response of the SRS under consideration. The ordinates of the spectral accelerations must then be at least equal to the corresponding ordinates of the target spectrum.

One-Degree-of-Freedom System

When the structure is a one-degree-of-freedom system or responds principally in its fundamental mode, spectral compatibility can easily be achieved by amplifying the seismic signal by the shift ratio γ (Eq. 1) calculated at the period of the fundamental vibration mode as follows:

$$\gamma \geq \frac{S_{\text{target}}(T_1)}{S(T_1)}, \tag{1}$$

where $S_{\text{target}}(T_1)$, $S(T_1)$, and T_1 are respectively the target design spectral acceleration, the spectral acceleration of the seismic signal, and the period of the fundamental vibration mode of the structure being analyzed (see Fig. 3a, Table 2).

Multi-Degree-of-Freedom System

For a multi-degree-of-freedom system, spectral compatibility must be verified for the point corresponding to the fundamental period as well as for the periods of higher vibration modes (commentary J-183, NBCC-05). To this end, two calibration methods may be used, as described below.

Spectral Compatibility by Vertical Shift of the Seismic Acceleration Spectrum

Spectral compatibility can be achieved by a vertical shift (Eq. 2) of the acceleration spectrum (representing an amplification or attenuation of the seismic signal). This translation is then adjusted to coincide with the target design spectrum at the ordinate corresponding to the period of the fundamental vibration mode of the SRS being analyzed. However, the spectral accelerations of the seismic signal thus calibrated must be at least equal to the spectral acceleration of the target design spectrum for the periods of the higher vibration modes of the SRS being analyzed (Fig. 3b). If they are not, then the seismic signal must be amplified or attenuated using the maximum shift ratio calculated over the range of these periods:

$$\gamma \geq \max_{i=1}^{n}\left(\frac{S_{\text{target}}\left(T_i\right)}{S\left(T_i\right)}\right), \tag{2}$$

where *i* designates the vibration mode considered and *n* the total number of modes considered for the modal analysis. However, this approach, although simple, often leads to overdesign. With reference to Fig. 3, Table 2, and the results of the numerical example described below, it can be seen that for the fundamental mode, spectral compatibility requires a seismic signal attenuation of approximately 30% (Fig. 3a). However, this same signal must be amplified by more than 40% to achieve spectral compatibility for higher modes (Fig. 3b), resulting in a cumulative amplification of almost 70% at the period of the fundamental mode.

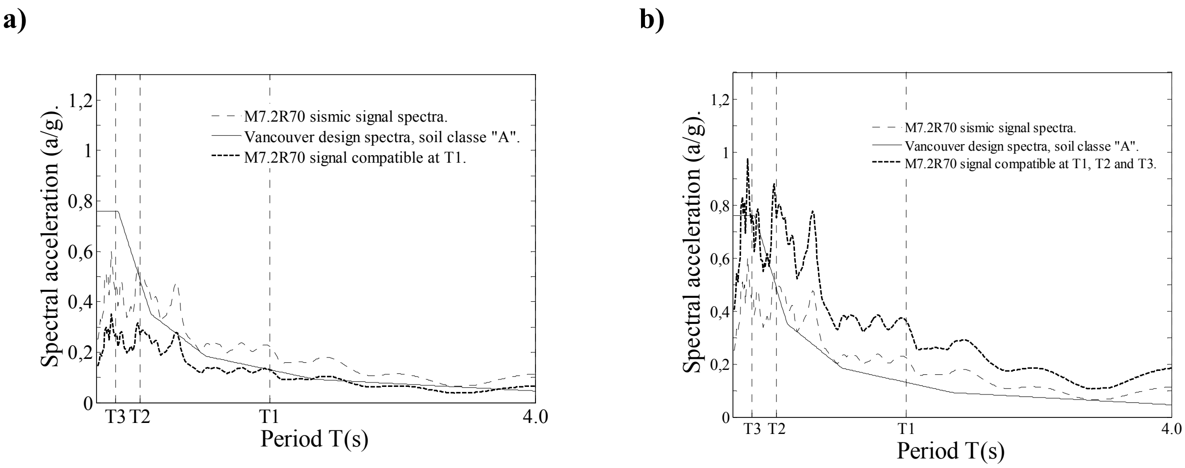

Figure 3. Spectral adjustment by vertical shift: a) at the fundamental mode period; b) at a higher mode period.

Spectral Compatibility by Multi-Ratio Calibration

When after spectral adjustment of a seismic signal at the period corresponding to its fundamental vibration mode, compatibility of the seismic signal spectrum with the target design spectrum is not achieved over the range of higher mode periods, the code permits modification of the seismic signal to meet code requirements (commentary J-184, NBCC-05). Spectral compatibility can then be obtained using a multi-ratio calibration. This approach, which is more refined than that described earlier, allows the seismic signal spectrum to converge toward the target design spectrum through a step-by-step procedure. At each step *m*, the seismic signal declined in the frequency domain is corrected using spectral ratios (Eq. 3) calculated at frequencies corresponding to the periods T_j of the vibration modes under consideration:

$$\gamma_{m_j} = \frac{S_{target}\left(T_j\right)}{S_{m-1}\left(T_j\right)} \quad \left(j = 1, 2.....n\right). \tag{3}$$

Spectral compatibility can be considered to be achieved when at step *m*, the spectra are sufficiently close to each other at the calibration points. At each of these points, the maximum spectral ratio must be close to unity, as defined by the tolerance limit ε used:

$$\max\left(\left|\frac{\gamma_{m_j}-1}{\gamma_{m_j}}\right|\right)\leq\varepsilon\quad\left(j=1,2.....n\right). \tag{4}$$

Spectral Compatibility over a Range of Design Spectrum Periods

Note that the exercise described above is to be repeated for each of the SRS under consideration, even if each system is analyzed with reference to the same target design spectrum. This is because the periods of the contributing modes can vary considerably from one structural system to another. Therefore, generalization of this approach for all design spectrum periods will make it possible to generate compatible seismic signals ready for use, as described elsewhere (Benazza & Chaallal, 2009). Such calibrated signals are not specific to one particular SRS, but are applicable to any structural analysis, regardless of the predominant vibration modes of the SRS under consideration (Fig. 4).

a) **b)**

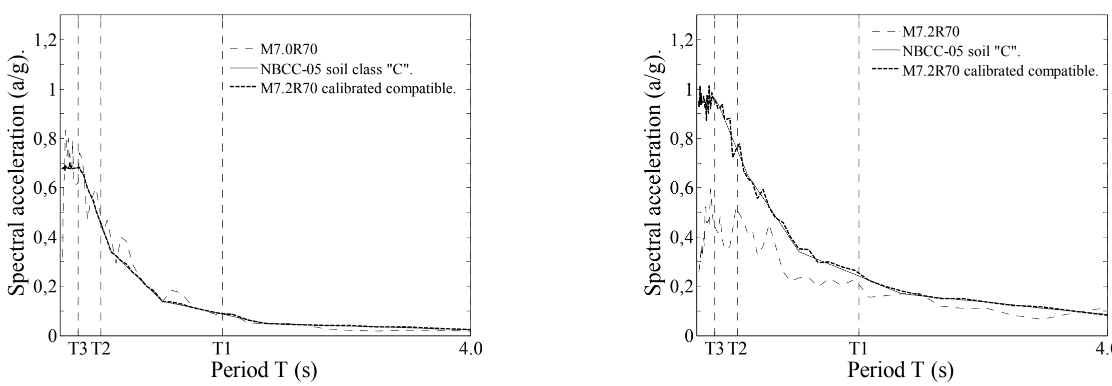

Figure 4. Response spectra of seismic signal (Atkinson and Beresnev, 1998), calibrated to be compatible to NBCC-05 design code spectra: **a)** Montreal; **b)** Vancouver.

Application to Seismic Analysis of Coupled Shear Walls

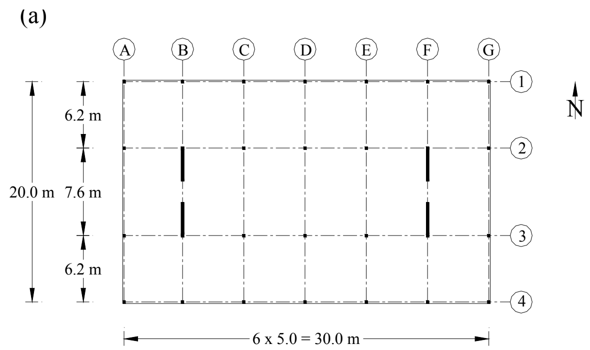

Figure 5. Plan view of coupled shear walls.

To demonstrate the efficiency of the generation of compatible seismic signals (Benazza & Chaallal, 2009) with respect to those obtained by the vertical shift approach, results from linear dynamic analyses (spectral versus time history) carried out on coupled shear walls (CSW) are compared in Table 3. The CSW are part of an SRS for a ten-story building located in Vancouver on soil classes A, C, and E (Fig. 5). The spectral analyses used the design spectra corresponding to the city of Vancouver, whereas the time history analyses used calibrated versions of the M7.2R70 synthetic seismic signal (Atkinson & Beresnev, 1998), which is representative of the seismicity of Vancouver. For each of the soil classes, analyses were performed for the following three forms: (i) M7.2R70 with no modification; (ii) M7.2R70 generated compatible to the target spectrum over the whole range of periods; (iii) M7.2R70 adjusted to the target spectrum by vertical shift.

Table 1. Relative modal periods and weights.

Mode	Period	W_i (%)	ΣW_i (%)
1	1.576	71	71
2	0.404	16	87
3	**0.182**	**5**	**92**
4	0.106	3	95
5	0.070	2	97

For the spectral analyses, the representativity of the dynamic response of the CSW corresponding to the first three modes is acceptable because together these modes represent 90% of the total modal weight (Table 1). Consequently, the periods corresponding to the first three modes are sufficient to verify the spectral compatibility of M7.2R70 obtained by the vertical shift approach. The acceleration spectra of M7.2R70 which are respectively compatible to the design spectra for soil classes A, C, and E are presented in Fig. 6. The vertical shift ratios used to obtain spectral compatibility by vertical shift are given in Table 2. Note that these coefficients can be high if compatibility over the whole range of intermediate periods between the lowest and the highest (see the fifth row of Table 2) is desired. Note also that the spectral accelerations obtained, which were made compatible by successive spectral calibrations using wavelet transformations (Mallat, 2000; Suares & Montejo, 2005) were determined using a procedure described elsewhere (Benazza & Chaallal, 2009). All

Table 2. Shift ratios for M7.2R70 synthetic seismic signal.

Mode	Soil Class		
	A	C	E
1	0.585	1.081	1.967
2	1.053	1.621	1.930
3	1.624	2.030	1.908
max (1, 2,3)	**1.624**	**2.030**	**1.967**
1 to 3	1.983	2.581	3.175

ordinates of these spectra feature a spectral deviation ratio—M7.2R70 generated compatible spectrum versus target spectrum—of less than 10% (see Eq. 4 and Fig. 6). The results of the dynamic analyses are summarized in Table 3, where Δ, M, and T are respectively the top displacement of the CSW, the bending moment, and the base shear force in each of the wall segments and α is the deviation ratio with respect to the spectral solution.

Table 3. Results of dynamic analyses: spectral versus time history.

		Δ (m)						M (kN.m)						T (kN)					
		Soil class						Soil class						Soil class					
		A		C		E		A		C		E		A		C		E	
		value	α (%)	value	α (%)	value	α (%)	value	α (%)	value	α (%)	value	α (%)	value	α (%)	value	α (%)	value	α (%)
Modal-Spectral analysis		0.118		0.217		0.394		466		820		1402		79		131		209	
	1	0.204	42	0.204	-6	0.204	-93	693	33	693	-18	693	-102	103	23	103	-27	103	-103
Temporal analysis	2	0.125	**6**	0.231	**6**	0.409	**4**	487	**4**	872	**6**	1459	**4**	75	**-5**	132	**1**	213	**2**
	3	0.331	64	0.414	48	0.401	2	1125	59	1407	42	1363	-3	128	38	209	37	203	-3

α: Deviation ratio between spectral and time history analyses.
1- Seismic signal M7.2R70 with no modification.
2- Seismic signal M7.2R70 generated to be compatible with the target spectrum over the whole range of periods.
3- Seismic signal adjusted to the target spectrum by vertical shift.

Conclusions

This paper has shown that seismic signals generated to be compatible with a target design spectrum using a generalized multi-factor point-by-point calibration method are adequate and can be used for step-by-step dynamic analyses. They yield time history analysis results comparable to those from reference spectral analysis. In addition, these signals are not specific to one particular SRS, but are applicable to any structural analysis, regardless of the predominant vibration modes of the SRS under consideration. The spectra of these signals are close, within ±10%, to the target design spectrum. They are obtained to be compatible to the design spectra for soil classes A to E in the same way that the design spectra are obtained by spectral calibration of the UHS corresponding to the city under consideration. This contrasts with the results obtained using the vertical shift technique with a unique shift ratio, which can grossly and unduly lead to overdesign.

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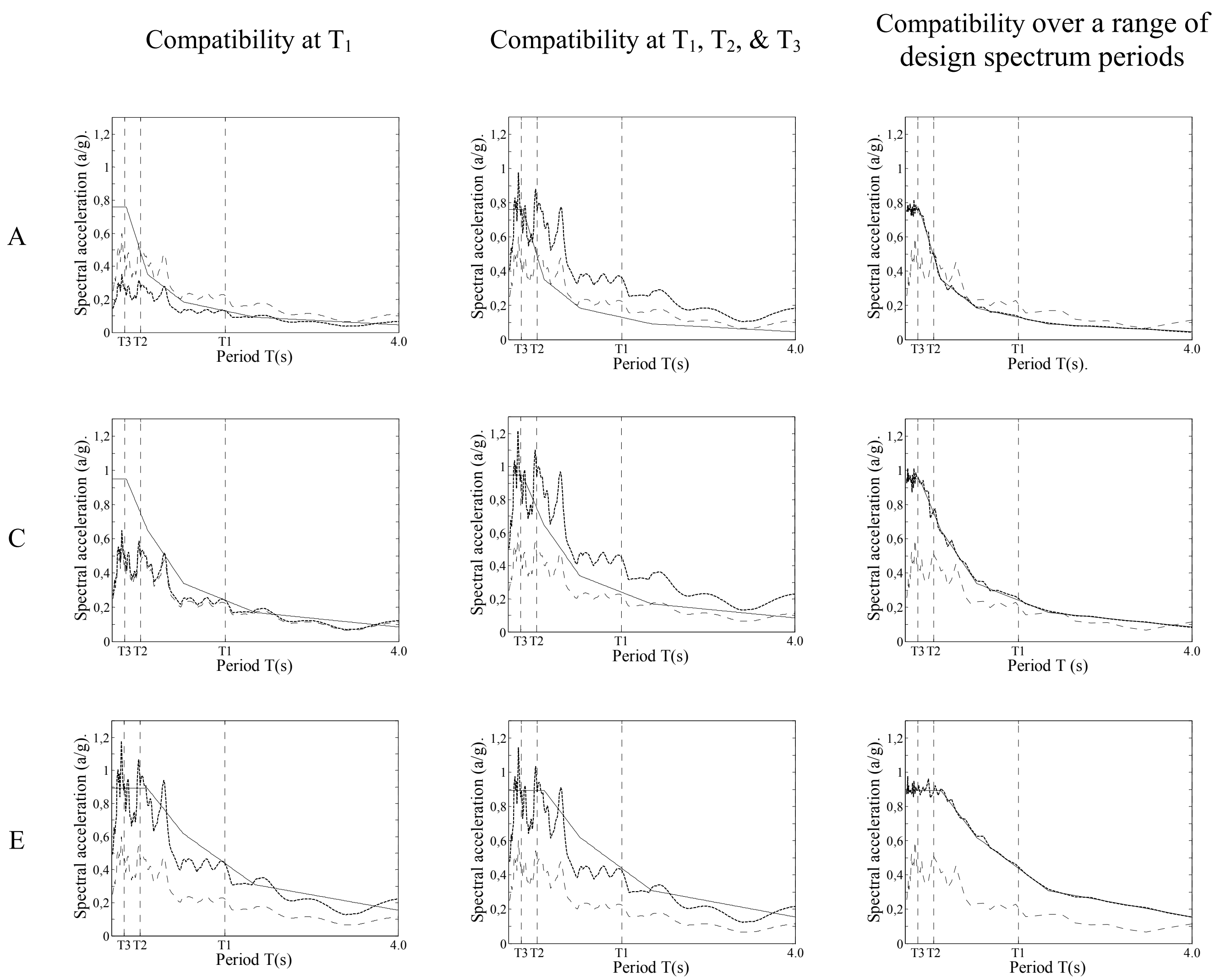

Figure 6. Spectrum compatibility for design soil classes A, C, and E: a) Vancouver design spectrum; b) M7.2R70 seismic design spectrum; c) M7.2R70 calibrated to be compatible with the design spectrum.

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