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SELECTION, SCALING AND APPLICATION OF GROUND MOTION RECORDS TO ASSESS THE NONLINEAR SEISMIC PERFORMANCE OF BUILDINGS LOCATED IN EASTERN NORTH AMERICA

Pierre Luabeya MUKENDI
Graduate Researcher, Polytechnique Montreal, Canada
pierre.luabeya-mukendi@polymtl.ca

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

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

ABSTRACT: This paper describes an application of the *CSRN Guidelines* for the selection and scaling of ground motion time histories for the seismic analysis of a structure located on a class C site in Montreal, Quebec. Two methods proposed in the *CSRN Guidelines* were used to select and scale the ground motions: Method A where the target response spectrum (TRS) is the design spectrum and Method B where four M-R scenario-specific TRSs are used to cover the period range of interest. For the latter, TRSs were obtained from a compatible ground motion prediction equation. Ensembles of 12 ground motion time histories were generated using the two methods and nonlinear response history analysis of a 4-storey shear building was performed using each ensemble. Method A resulted in more consistent ground motion spectral accelerations over the period range. Both methods resulted in similar mean, median, and 84th percentile storey drift demand for the studied building; however, higher demand was obtained from Method B when the demand was determined based on the most critical suite of ground motions or most critical ground motions. Variability associated to Method B can be induced by improper scaling of TRSs to the DS and selection of ground motions having inadequate spectral shapes.

1. Introduction

Guidelines for the selection and scaling ground motion time histories for seismic analysis of structures have been developed for possible implementation for the upcoming 2015 edition of the National Building Code of Canada (Atkinson et al., 2015). This development work was conducted within the Canadian Seismic Research Network (CSRN) and the Guidelines are referred to herein as the *CSRN Guidelines*. In the development process, trial examples were performed to verify the application of the procedure. This article presents an example that was examined for a hypothetical structure built on a class C site in Montreal, Quebec. The procedure was applied for the selection and scaling of individual horizontal ground motion components only. The selected site is located in a moderate seismic area typical of the eastern seismic region of Canada. Two different approaches permitted in the *CSRN Guidelines* were used to select and scale the ground motion time histories: method A where a single target response spectrum (TRS) corresponding to the design spectrum at the site was considered, and method B where the TRS was defined using 4 site-specific scenario response spectra that covered the period range of interest. The two methods resulted in two different ensembles of scaled ground motion time histories. Both ensembles were then used to perform nonlinear response history analysis of a 4-storey frame structure designed according to code provisions. Seismic demands imposed on the structure by the two ensembles are examined and compared.

The example was prepared using a draft version of the *CSRN Guidelines* available at the time of the study (Atkinson et al. 2012). Changes have been introduced since then in subsequent versions of the *CSRN Guidelines* but those are minor and do not affect the procedure as illustrated in this article. Similarly, the seismic data for the upcoming 2015 edition of the National Building Code of Canada (NBCC) was not available when preparing the example and the study was completed using the seismic data specified in the 2010 NBCC (NRCC). Using the more recent (2015) seismic data for the site would likely affect the results but the procedure and the main conclusions are expected to remain essentially the same. Further detail on the study can be found in Mukendi (2015).

2. Selection and Scaling of Ground Motions

2.1. Design Spectrum

In the 2010 NBCC, the design spectrum (DS), S(T), is obtained from uniform hazard spectral ordinates calculated for a probability of exceedance of 2% in 50 years at periods of 0.2, 0.5, 1.0 and 2.0 s. For a site class C in Montreal, QC, these values are respectively equal to 0.64, 0.31, 0.14 and 0.048. For periods shorter than 0.2 s, S(T) is equal to S(0.2 s). For periods equal to or longer than 4.0 s, S(T0 is equal to 0.5 times S(2.0 s). Values of S for intermediate periods between 0.2 and 4.0 s are obtained using linear interpolation. For the site studied, the peak ground acceleration for 2% in 50 years probability of exceedance is 0.33 g.

In the *CSRN Guidelines*, it is permitted to modify the shorter portion of the design spectrum to reflect better the actual seismic demand in that period range. Values were obtained from the Geological Survey of Canada for periods of 0.01 0.05, 0.1, and 0.3 s. Values were also provided at periods of 0.2, 0.5, 1.0, and 2.0 s. The data is given in Table 1 and the resulting design spectrum is plotted in Fig. 1.

Table 1 – Design spectrum adopted for site class C in Montreal, QC.

T (s)	**S (g)**
≤ 0.01	0.327
0.05	0.545
0.1	0.545
0.2	0.641
0.3	0.469
0.5	0.313
1.0	0.138
2.0	0.047
≥ 4.0	0.024

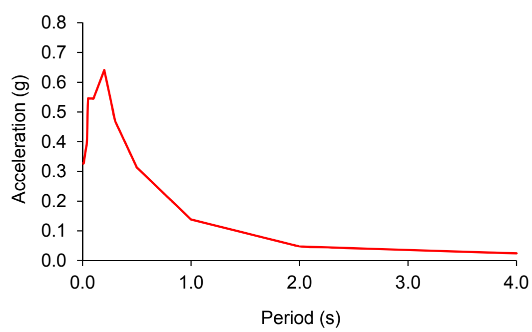

Fig. 1 - Design spectrum adopted for site class C in Montreal, QC.

2.2. Period Range

According to the *CSRN Guidelines*, selection and scaling of ground motion time histories must be performed with consideration of the design spectrum over a range of periods that extends from a period equal to the smaller of 0.2 times the structure first mode period and the period of the highest mode required to achieve 90% mass participation, to the longer of twice the first mode period and a period of 1.5 s. The four-storey structure examined in this study is described in Section 3. The periods in the first three modes of vibrations are respectively equal to 1.0, 0.40 and 0.26 s, and the corresponding cumulated participating masses are equal to 83, 94 and 98% of the total structure mass.

The lower bound of the period range is then equal to 0.20 s, i.e. the smaller of 0.2 x T_1 and the second mode period (0.40 s). The upper limit is taken equal to 2.0 s, i.e. the larger of 2 x T_1 and 1.5 s.

2.3. Selection and Scaling According to Method A

In Method A, the Target Response Spectrum (TRS) corresponds to the design spectrum S(T) within the period range of interest (0.2 s to 2.0 s). De-aggregation of the seismic hazard was examined to determine the dominant magnitude-distance (M-R) scenarios at the site. For Montreal, contributions to the spectral ordinates at periods of 0.2, 0.5, 1.0 and 2.0 s are all single mode with modal magnitudes M6.375 for T = 0.2 s, M6.625 for T = 0.5 s, and M6.875 for T = 1.0 and 2.0 s. In all cases, the modal distance is 30 km. Atkinson (2009) suggested that M6.0 earthquakes could be used for periods shorter than 0.5 s whereas M7.0 events would be necessary for longer periods. Based on this information, two M-R scenarios were defined together with corresponding scenario-specific period ranges as described in Table 2.

Table 1 – Selected M-R scenarios and corresponding scenario-specific period ranges.

Scenario	**Scenario–Specific Period Range (s)**	***M***	***R* (km)**
A	0.2 ≤ T ≤ 0.5	6.4	30
B	0.5 ≤ T ≤ 2.0	6.9	30

Ground motion time histories were selected from events having a magnitude within ±0.5 from the target magnitudes and recorded at stations located within ±30% from the target distances and where the average shear wave velocity was comprised between 360 and 760 m/s. In total, 12 ground motion time histories recorded during past earthquakes were selected, six for each scenario-specific period range. An ensemble of records selected for a scenario-specific period range is referred to as a suite. This selection satisfies the minimum requirements specified in the *CSRN Guidelines*: minimum of 11 ground motions for the entire ensemble, with a minimum of five records for each suite. The computed 5% damped acceleration response spectra of the individual selected records are plotted in Fig. 2.

One of the objectives of this project was to examine the applicability of the *CSRN Guidelines* when using actual ground motion data from past earthquakes. Due to the lack of records from historical events of the required magnitude that would be representative of eastern North America seismic conditions, the records in this example were extracted from the PEER database (PEER, 2010), a comprehensive database that contains recordings from shallow crustal earthquakes from worldwide active tectonic regions. In practice, a user could have used time histories simulated for eastern Canada, such as those available in the Engineering Seismic Toolbox (Atkinson, 2009, 2015). Nowadays, one can also search ground motion time histories from the stable continental regions of eastern North America in the recently developed NGA-East PEER database (PEER 2015).

Scaling of the records was performed in two steps. A first scaling factor, k_1, was determined for each record such that the area under the 5% damped acceleration spectrum of the record became equal to the area under the TRS over its scenario-specific period range. The computed k_1 factors varied between 0.95 and 2.61, with an average value of 1.68, and the resulting mean response spectra for each suite of six records are plotted in Fig. 3. For each scenario-specific period segment, a unique second scaling factor, k_2, was applied to all records of the suite such that the mean response spectra for the suite of records did not fall more than 10% below the TRS in the period segment. This criterion is a minimum requirement prescribed in the *CSRN Guidelines*. Figure 4 shows the error between mean response spectra and TRS before application of the k_2 factor. For both period segments, the criterion was nearly met and k_2 factors equal to 1.01 only were needed to satisfy the prescribed minimum limit.

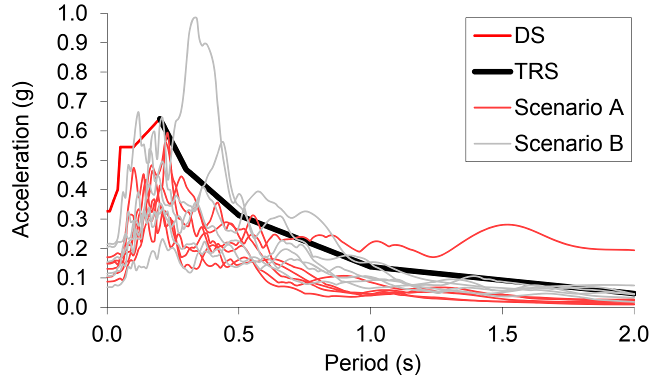

Fig. 2 – 5% damped acceleration spectra of the individual selected records before scaling.

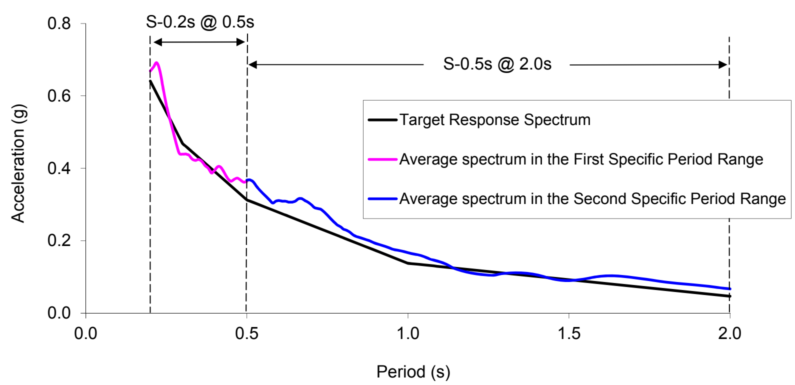

Fig. 3 – Target response spectrum and mean response spectra for each suite of 6 records scaled using k_1 factors.

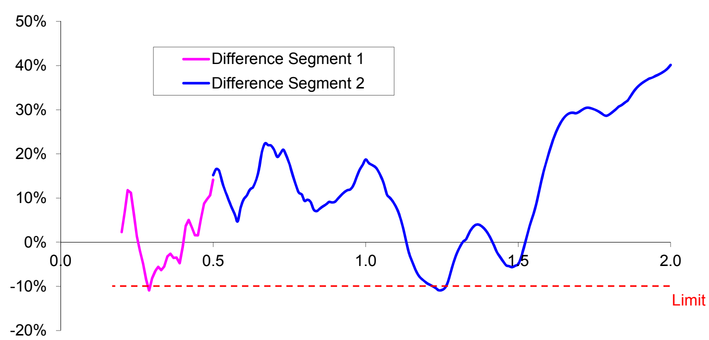

Fig. 4 – Difference between mean response spectra and the target response spectrum before application of the k_2 factor.

2.4. Selection and Scaling According to Method B

In Method B, the TRS is defined using a number of site-specific response spectra that cover portions of the period range of interest. The *CSRN Guidelines* do not specify the method to develop the TRS. This is left to the user. However, it is indicated that spectra should be develop to represent the dominant M-R scenarios contributing to the hazard over the period range of interest. In this study, four TRSs were used, one for each spectral ordinate of the DS for which de-aggregation results were available within the 0.2-2.0 s period range, i.e. at periods of 0.2, 0.5, 1.0 and 2.0 s. For each of these specific periods, an M-R scenario was defined that corresponded to the modal magnitude and distance of the contributions to the hazard at that period. For each scenario, a scenario-specific period range was then defined to cover the entire period range of interest. The characteristics of the four scenarios are summarized in Table 3. The TRS for each M-R scenario was established using the ground motion prediction equation (GMPE) developed by Atkinson and Boore (2006) for eastern North America. The calculations were performed using the SHAKE2000 program (GeoMotions, 2013).

Table 3 – TRS and Scenario-specific period ranges.

Scenario	Specific Period (s)	Scenario–Specific Period Range (s)	M	R (km)	TRS	Scale Factor
A	0.2	0.2 ≤ T ≤ 0.35	6.375	30	TRS-0.2s	3.71
B	0.5	0.35 ≤ T ≤ 0.75	6.625	30	TRS-0.5s	2.75
C	1.0	0.75 ≤ T ≤ 1.5	6.875	30	TRS-1.0s	1.75
D	2.0	1.5 ≤ T ≤ 2.0	6.875	30	TRS-2.0s	1.53

The TRSs were then individually scaled linearly so that they matched the design spectrum (DS) at their respective specific periods. The required scaling factors are given in Table 3 and the resulting scaled TRSs are plotted in Fig. 5. In the *CSRN Guidelines*, it is required that the TRS be nowhere less than 75 percent of the design spectrum within their respective specific period ranges. This verification is illustrated in Fig. 6. All TRSs were above the 75% DS lower limit and no further adjustment was needed to satisfy this criterion. The figure shows that, for this example, just satisfying this 25% tolerance on TRS matching can result in non-uniform TRS-DS ratios between the scenario-specific period ranges, as well as discontinuities between the TRSs. Possible impacts of this result is discussed later.

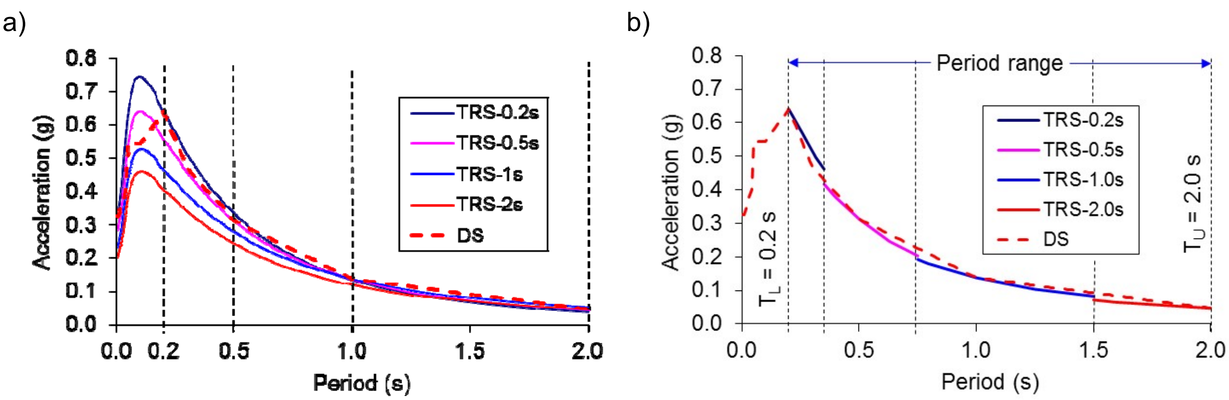

Fig. 5 – Scaled scenario-specific Target Response Spectra plotted over: a) Entire period range of interest; b) Respective scenario-specific period ranges.

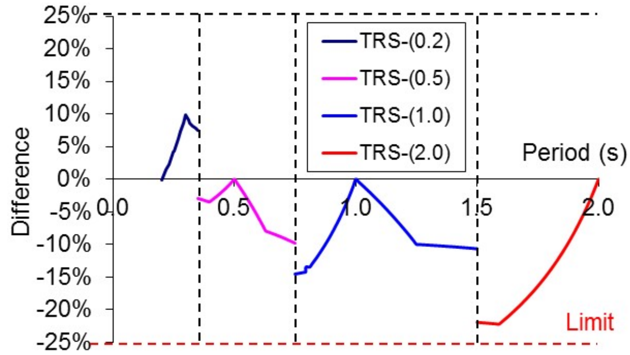

Fig. 6 – Differences between the TRS and DS in each scenario-specific period range.

The selection of the ground motion time histories was performed as in Method A, except that four M-R scenarios corresponding to the four TRSs were considered. Hence, only stations on class C sites were retained, however, the target magnitudes were rounded up to the first decimal and magnitudes within ±0.5 from the target M and distances within ±30% from the target R were considered acceptable for selection. For each TRS, a suite of three records selected from the PEER database was constructed to form an ensemble of 12 records. In later versions of the *CSRN Guidelines*, the minimum of records per suite was increased from three to five to achieve minimum robustness for each of the time history suites representing the main contributing M-R scenarios. In Fig. 7, the spectra of the unscaled records are plotted along with the scaled TRSs.

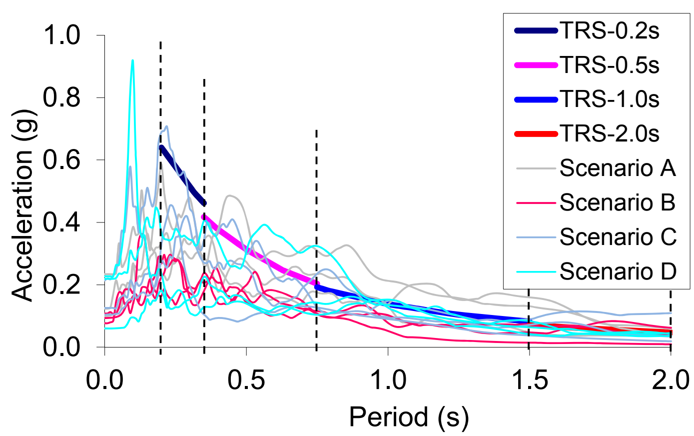

Fig. 7 – 5% damped acceleration response spectra of the selected individual records.

As in Method A, the records were first scaled individually to reach equal area under their spectra and the TRS over their respective scenario-specific period ranges. The required scaling factors k_1 varied from 0.96 to 2.26 with an average of 1.58. Errors between the mean spectrum of each suite and the corresponding TRS are shown in Fig. 8a. As in Method A, a second scaling factor k_2 was applied to the all records of each suite such that the mean spectrum of the suite does not fall more than 10% below the TRS. This correction was required for TRS-(0.2), TRS-(0.5), and TRS-(1.0) with values of k_2 = 1.02, 1.03 and 1.07. Mean spectra in each scenario-specific after application of the k_2 factors are compared to the TRSs in Fig. 8b.

a) b)

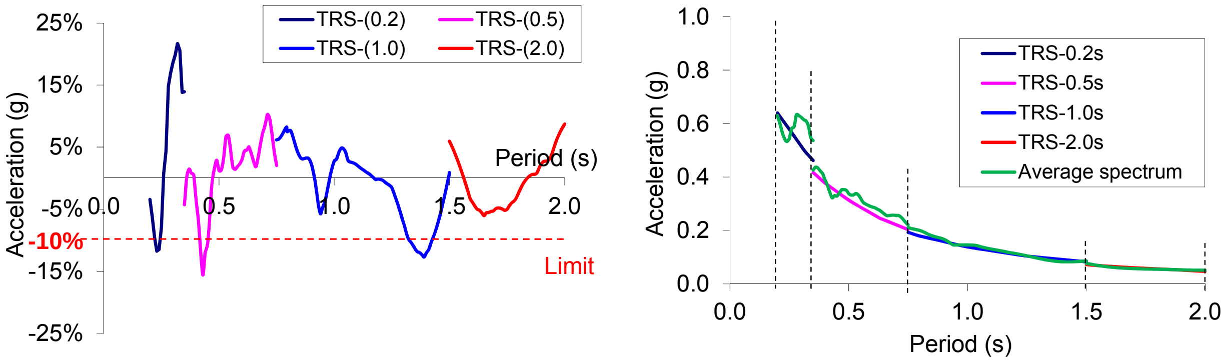

Fig. 8 – a) Differences between mean spectra of the scenario-specific suites of records and TRSs after application of factor k_1; b) Mean spectra of the scenario-specific suites of records after application of the k_2 factor.

2.5. Discussion on the results

In Fig. 9, the mean response spectra for the entire ensembles of 12 scaled ground motion time histories are compared for each method to the mean spectra of the scenario-specific suites. For Method A, the spectra of the entire ensemble is close to the site-specific spectra in both scenarios. This suggests that the time histories selected for anyone of the two M-R scenarios have spectral shapes similar to that of the design spectrum for the entire period range of interest. For this particular site, similar selection and scaling results would have likely been obtained using only one scenario. Conversely, in Fig. 9b, the motions selected and scaled in accordance with Method B have dissimilar spectra, which results in marked differences between the mean spectra of the 12 record time histories and the mean spectra of the scenario-specific suites of records. This is mainly attributed to the fact that selection and scaling of the ground motion records were performed in isolation for each scenario-specific period range. The consequences are illustrated in Fig. 10a, where the mean spectrum of each suite is compared to the DS over the entire 0.2-2.0 s period range. As shown, the records selected for TRS-0.2 produce spectral accelerations much higher than the DS at periods longer than 0.375 s. Conversely, the mean spectra of the records associated to TRS-2.0 is lower than the DS in the short period range. Another factor likely contributed to the differences observed for Method B between mean and DS spectra in Figs. 9b and 10a: in the method, the TRSs were linearly scaled to match the DS only up to the point where the 25% tolerance permitted in the *CSRN Guidelines* was satisfied. A tighter adjustment of the TRS against the DS at that stage (e.g., equal area under TRS and DS over the scenario specific ranges) would probably have led to more consistent ground motion demands.

a) b)

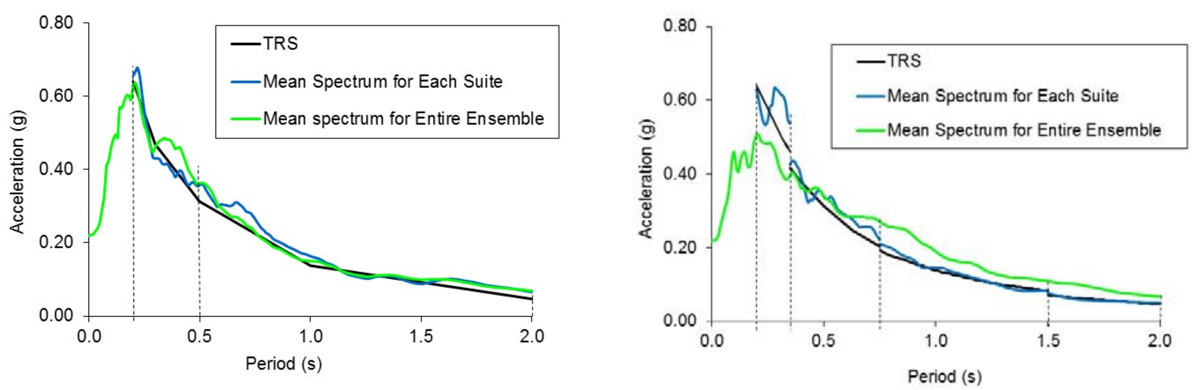

Fig. 9 – Comparison between mean spectra of the entire ensembles and mean spectra of the scenario-specific suites for: a) Method A; b) Method B.

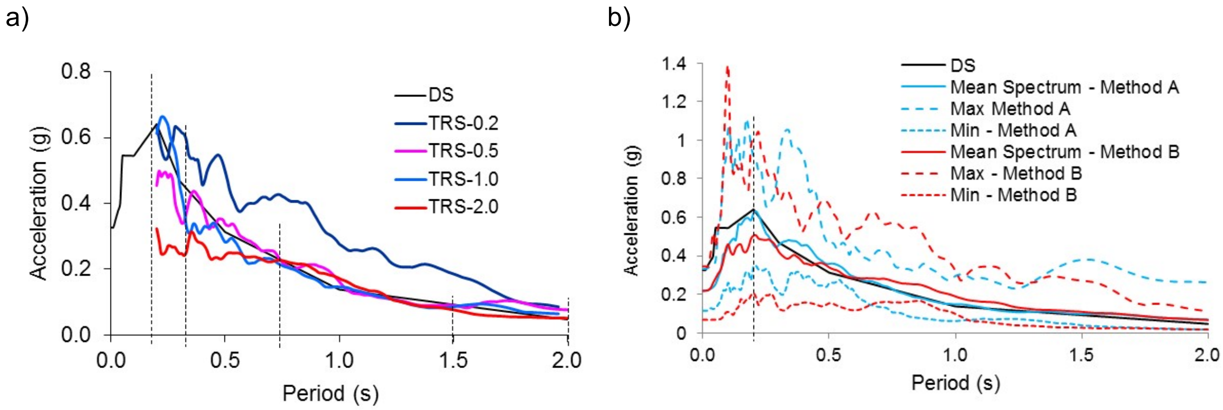

Fig. 10 – a) Comparison between ground motion spectra and DS: a) Mean spectra of the suites of Method B; b) Mean, maximum and minimum spectra of the entire ensembles.

Mean spectra and envelopes of the 12 ground motion time histories of each ensemble are compared to the DS in Fig. 10b. For Method A, since the TRS corresponds to the DS, the comparison between the mean spectrum and the DS is same as with the TRS in Fig. 9a. Hence, good match is obtained for the entire period range with mean spectral ordinates fluctuating between 0.9 to 1.19 times DS values in the 0.2-1.5 s range and increasing gradually from 1.06 to 1.46 DS for periods between 1.5 and 2.0 s. As expected from Fig. 10a, the mean spectrum from Method B is lower than the DS for short periods, with values ranging from 0.79 to 1.0 times DS values periods of 0.2 to 0.45 s. For longer periods, the mean spectrum exceeds the DS with peak ratios between the two spectra of 1.37 at T = 1.0 s and 1.44 at T = 2.0 s. Examination of the upper and lower bounds for both ensembles shows that both methods resulted in comparable dispersions. On average for all periods between 0.2 and 2.0 s, the differences between maximum and minimum spectral ordinates are 10% larger with Method B. As observed for the mean spectra, Method A results in higher demand for short periods while Method B is generally more severe in the medium (0.75-1.25 s) period range.

3. Nonlinear Response Analysis of the Prototype Structure

3.1. Structure Studied

The prototype structure is a 4-storey shear-type building structure. The seismic design was performed in accordance with the 2010 NBCC provisions using a ductility-related force modification factor R_d = 4.0. This value is typical of ductile steel seismic force resisting system such as buckling restrained braced frames. An overstrength-related force modification factor R_o of 1.0 was considered to obtain the probable structural lateral resistance to be specified to the numerical model. Nonlinear response analysis was performed using the SAP2000 computer program (CSI 2014). A bilinear storey shear-storey drift hysteretic response was specified for each storey of the structure. At each level, the post-elastic stiffness was adjusted to obtain strain hardening of 15% at a storey drift of 2%, which is typical of ductile steel frames. In the analyses, Rayleigh damping was specified with 5% of critical damping in the first two modes of vibration of the structure.

3.2. Nonlinear Seismic Response

Peak storey drift demand at every level is examined herein. For each ground motion ensemble, the following drift estimates were computed:

- A: Mean value from the 12 ground motion ensemble;
- B & C: 50^{th} and 84^{th} percentile values from the 12 ground motion ensemble;

- D: Maximum of the mean values from all scenario-specific suites; and
- E: Mean value of the n largest values from the 12 ground motion ensemble (n = size of scenario-specific suites).

The results are plotted in Fig. 11. As shown, both methods resulted in comparable mean values and vertical distributions of peak storey drifts (Line A). For both methods, mean values are also close to median (50th percentile) estimates, except at levels where greater dispersion exists in the results. In such cases, median drifts are smaller as they are less affected by extreme values. For this structure, the 84th percentile drift estimates from Methods A and B are comparable. For drift estimates D, the mean peak storey drift value was calculated for each suite of records and the largest mean value of all suites was retained. For Method A, this approach resulted in drift estimates close to the mean values. Much larger drifts were obtained under Method B ground motions because the critical suite was the one created with TRS-0.2, the records producing excessive demand at periods close to the structure period (Fig. 10). When using Method A, drift estimates E are equal to the mean value of the largest six drift results induced by the 12 ground motions. As shown, this prediction is comparable to the 84th percentile estimates. For Method B, the largest three drift results were considered to calculate drift estimates E. As expected from previous observations, the demand was dominated by the records from the TRS-0.2 suite, which led to values similar to drift estimates D.

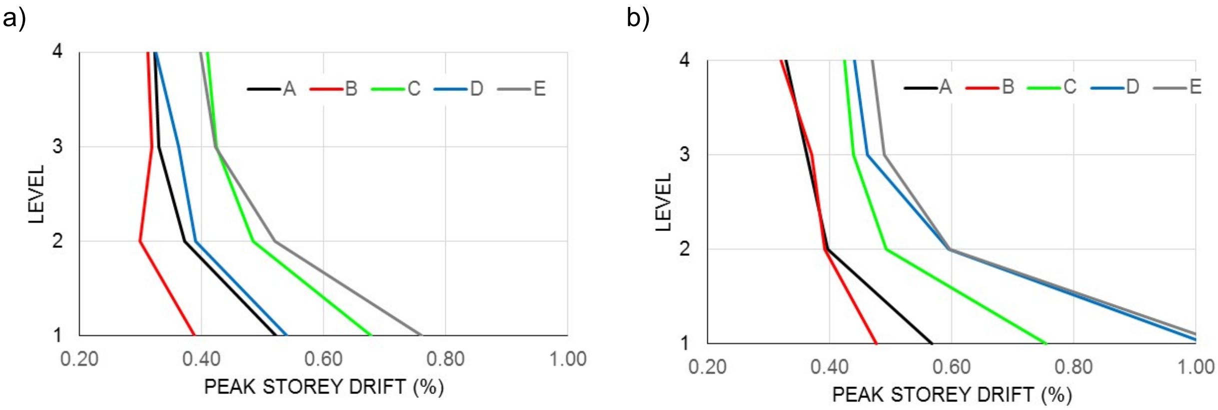

Fig. 11 – Statistics of peak response parameters: a) Method A; b) Method B.

4. Conclusions

Selection and scaling of ground motion time histories for the seismic analysis of a 4-storey structure located on a class C site in Montréal, QC, was performed in accordance with the two methods proposed in the recently developed *CSRN Guidelines*. A period range spanning from 0.2 to 2.0 s was considered for the structure studied. Method A, where the TRS is taken equal to the DS, resulted in more consistent ground motion demands over the period range compared to Method B where TRSs are defined for four M-R scenario-specific period ranges using a site compatible ground motion prediction equation. In Method B, suites of ground motions are selected and scaled independently for each of the four TRSs, which led to greater variability in ground motion spectral accelerations.

For the 4-storey building examined, the ground motion ensembles from the two methods induced similar mean, median, and 84th percentile peak storey drift estimates. Method B imposed higher drift demands than Method A when only Using method A, drift estimates determined from the most critical suite of time histories and from subsets of the most critical time histories respectively corresponded to the mean and 84th percentile values of the entire ground motion ensemble. These drift estimates were higher when Method B was adopted, which was attributed to the higher variability in ground motion demand resulting from the method. This variability can be induced by improper scaling of the TRSs to the DS and selecting ground motions having inadequate spectral shapes.

Application of Method A is simpler and is appropriate for sites where one or a few M-R scenarios contribute to the seismic hazard and when ground motion time histories with suitable spectral shapes are available. Acknowledgements

5. Acknowledgements

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