Modification of Ground Motions for Hazard Consistent Seismic Response Analysis

W.D. Liam Finn & Yuxin Pan
Department of Civil Engineering – University of British Columbia, Vancouver, BC, Canada.

Francisco Ruz
RyV Ingenieros, Santiago, RM, Chile

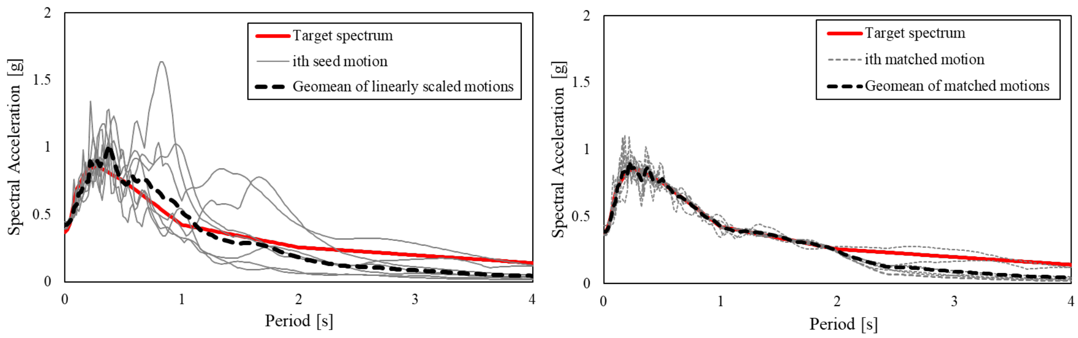
ABSTRACT: Linear scaling and spectrum matching are the two approaches that are widely used in practice for developing ground motions of appropriate intensity for dynamic analysis. Guidelines on the use of these procedures in various applications are given in NIST (2011). These guidelines envisage one type of seismic source, typically crustal earthquakes. This paper presents an application in a region with a more complex source system, the tri-source hazard Cascadia region of South-western British Columbia. Here the hazard is determined by crustal, sub-crustal and subduction earthquakes, each of which dominates a different period range of the design spectrum. There are no formal guidelines governing this case. Finally, the paper presents a new method, the Variable Target Spectrum, developed at Stanford University, that involves both linear scaling and spectral matching. It is particularly effective in tuning ground motions to hard rock spectra because there are few hard rock motions in available databases and so it is very difficult to get a good fit by linear scaling and consequently the demands on subsequent spectral matching are severe.

1 INTRODUCTION

Performance evaluation of the seismic design of critical structures is typically done by conducting nonlinear seismic response analyses to check that performance criteria are met. The input motions for analysis are selected from appropriate databases according to seismic metadata specifications such as magnitude, distance, spectral shape and site conditions. These motions are then either linearly scaled or spectrally matched to a target spectrum that represents the seismic hazard of the site. Detailed guidelines for scaling and matching are available from US sources (NIST 2011) but they all relate to hazard due to a single type of earthquake source. In British Columbia, the seismic environment is much more complex. The hazard is defined by the combined simultaneous contributions of three different types of seismic sources, crustal, subcrustal (in slab earthquakes), and subduction (interface) earthquakes. There are no specific guidelines available for the modification of selected motions that take into account this complex situation. A tentative procedure, proposed for dealing with this challenge, is described in Commentary J of the National Building Code for Canada (NBCC 2015), and is presented later. A difficult problem arises when the target spectrum is being used for hard rock conditions with a shear wave velocity of Vs = 2,500m/s. The databases have very few hard rock motions and therefore it is difficult to get a good spectral fit by linear scaling and necessary adjustments by spectral matching are likely to be severe. For this condition, the Variable Target Spectrum (VST) approach, recently developed at Stanford University by Seifried (2013) is very effective in generating appropriate ground motions as shown by examples presented herein. The VST method is now beginning to be used in practice for critical structures.

2 MODIFICATION OF GROUND MOTIONS IN PRACTICE

Both linear scaling and spectral matching are widely used in practice to modify ground motions to a target spectrum. Frequently spectral matching is applied after linear scaling to reduce the adjustment demand on spectral matching. There is no criticism of linear scaling but there is a strong body of opinion that spectral matching should not be used at all. The opinion is based on the findings of a number of studies (Bazzurro and Luco 2006; Carballo and Cornell 2000; Iervolino and De Luca 2010; Huang et al. 2011 and Seifried 2013) that show that nonlinear seismic response analyses using spectrally matched motions consistently yield unconservative results when compared to linear scaled results. However, there is a fundamental assumption implicit in this judgmental conclusion that the results from spectral matching are unconservative. This assumption is that linear scaling gives the 'correct' results. The basis for this assumption is not evident. A number of equally credible studies did not find any significant bias (Hancock et al. 2008; Heo et al. 2010; Huang et al. 2011 and Grant and Diaferia 2013). In both sets of studies the median (mean) spectra for both the linear and spectrally matched motions were close matches to the target spectrum. The differences in response is directly attributable to the greater dispersion in the linear scaled set of motions as shown in Figure 1. The period range of interest is 0.02-2.0s.



(a) (b)

Figure 1. Linear scaling (a) and matching (b) of ground motion

The spectrally matched motions are a very tight fit to the target spectrum and, therefore, it is reasonable to assume that they generate mean structural response parameters consistent with the intensity of shaking implied by the target spectrum. The same cannot be said about the linear scaled motions, even though the mean of the linear spectra is close to the target spectrum. The individual spectral peaks above the target spectrum represent seismic demands greater than implied by the target spectrum that are not counteracted by spectra below the target level because of the asymmetric nature of the nonlinear response. This results in greater mean response for linear scaling than that given by the spectrally matched motions. This is hardly a basis for asserting that spectral matching is conservative. The two procedures simply give different mean responses for obvious reasons but spectral matching gives a better fit to the target hazard.

3 MODIFICATION OF MOTIONS FROM TRI-HAZARD TYPE SOURCES

The Cascadia region of South-Western British Columbia is a very complex hazard environment. Here the hazard is determined by crustal, subcrustal and subduction earthquakes, each of which dominates a different period range of the design spectrum. The different sources as shown in Figure 2 and the applicable period range for each source type is shown in Figure 3.

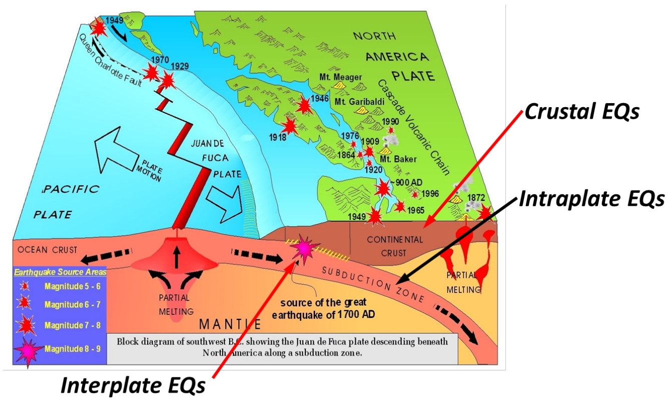


Figure 2. Earthquakes types in Cascadia subduction zone.

There are no formal guidelines governing the process of ground motion modification for these conditions. The Standard Committee on Seismic Design (SCED) who advise on the seismic provisions of the National Building Code of Canada (NBCC) recommended a tentative interim procedure for handling ground motion modification in the Cascadia region. This procedure may be found in Commentary J (pages J105-J112) of NBCC (2015) and is illustrated in Figure 3 taken from Commentary J. The example is for linear scaling over the stated period ranges.

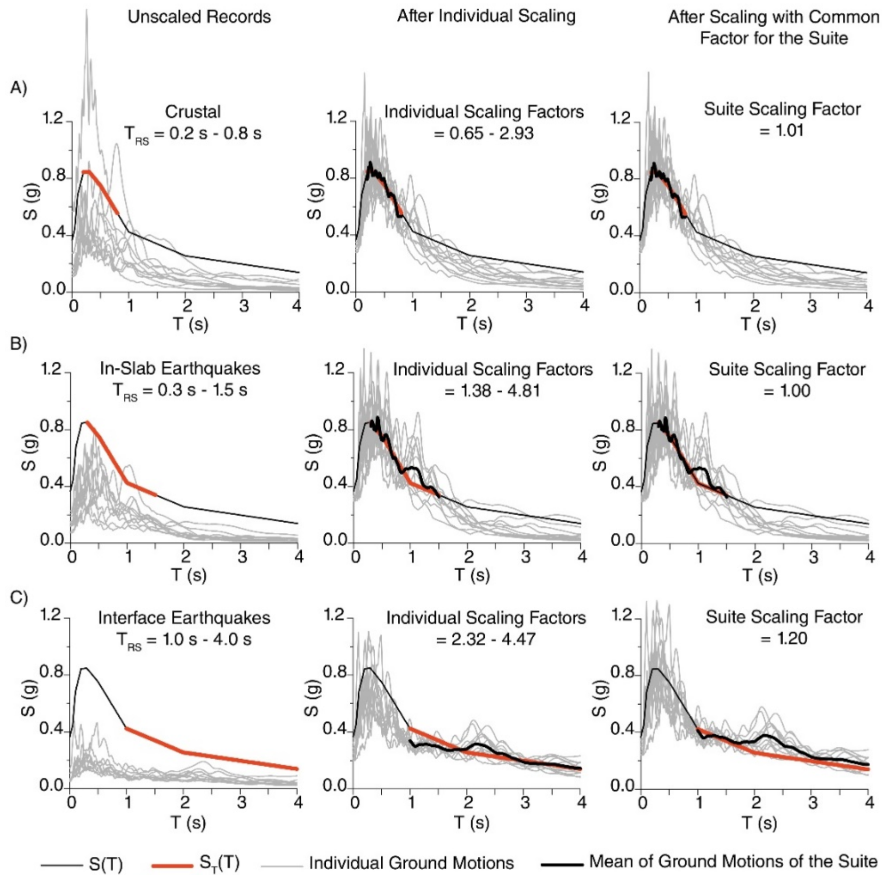


Figure 3. Scaling of ground motion records for a class C site in Vancouver (after NBCC (2015) Code Commentary J).

4 MODIFICATION OF GROUND MOTIONS BY VARIABLE TARGET SPECTRUM APPROACH (VST)

The success of linear scaling in modifying seismic records to conform to a target design spectrum depends on the availability of a large database of candidate motions with spectral shapes reasonably compatible with the shape of the target spectrum. For example, the PEER strong motion database contains a very large number of recorded motions on sites with time-averaged shear wave velocity, V_{s30} in the range 760-180m/s. In the case of a hard rock site, with shear wave velocity V_s = 2,500m/s, the design spectrum will contain much higher frequencies than the spectra on the sites with V_{s30} in the range 760-180m/s. Very few spectra are available in the database that can effect a reasonable match with a hard rock spectrum. Seifried (2013) developed a new approach that solves the problems caused by incompatible spectral shapes called the Variable Target Spectrum (VTS) Method. VTS is explained by means of two examples.

4.1 *Example 1: VST applied to Site Class C site*

The first step is to linearly scale a suite of motions to the target spectrum and calculate the mean spectral shape. The mean spectrum is a good but not a perfect match to the target spectrum as shown in Figure 4(a). Period dependent adjustment factors are calculated to ensure a perfect match. The distribution of adjustment factors with period Ti is called the Factor Function (Ti).

For a given period T_i, the Factor Function, $FF(T_i)$ is given by

$$FF(T_i) = \frac{Sa(T_i)_{target}}{Sa(T_i)_{seed}} \quad (1)$$

where $Sa(T_i)_{target}$ is the spectral ordinate at period Ti corresponding to the target spectrum and $Sa(T_i)_{seed}$ is the corresponding spectral ordinate of the seed motions. The resulting FF(TI) is shown in Figure 5(b).

A unique target spectrum for each seed motion is developed that is the product of the seed response spectrum and the factor function, or

$$Sa(T_i)_{new\ individual\ target} = FF(T_i) \cdot Sa(T_i)_{seed\ spectrum} \quad (2)$$

for all Ti to be spectrum matched, where $Sa(T_i)_{seed\ spectrum}$ is the actual spectral ordinate of the seed ground motion at period Ti. The improved match of the mean of the modified spectra to the target spectrum is shown in Figure 4(c). Each seed motion is now matched to its own unique factor adjusted spectrum. The mean spectrum of these matched motions is shown in Figure 4(d). Note that the mean of the matched spectra is still almost a perfect fit to the target spectrum in the period range of interest, 0.02 – 0.5s.

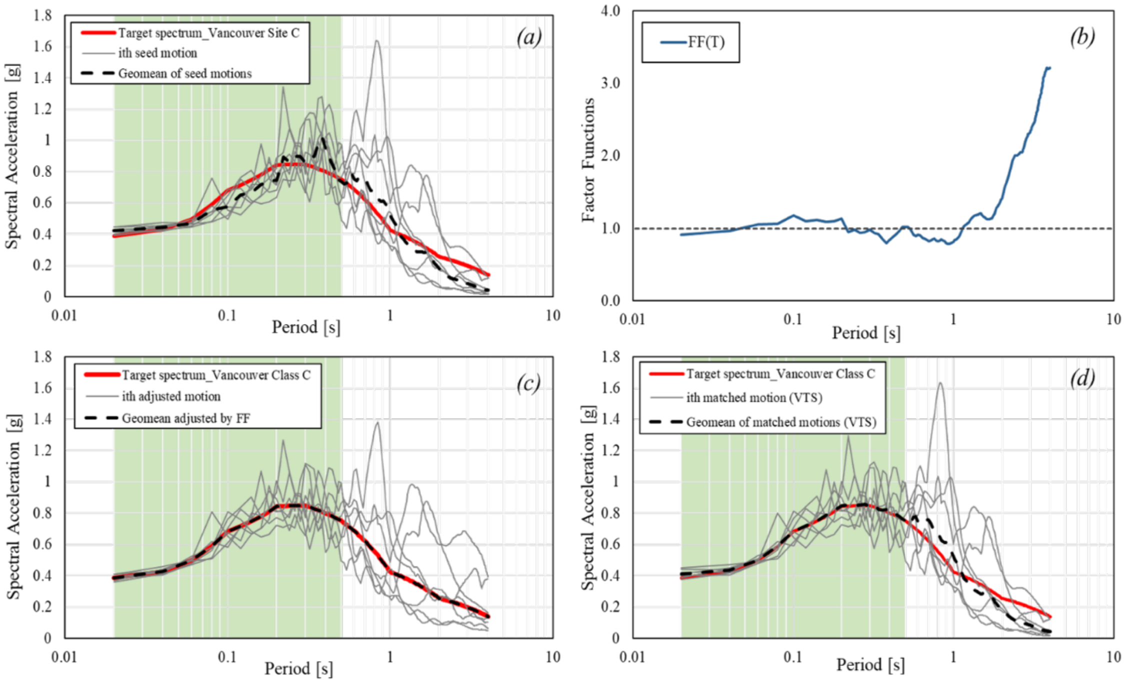


Figure 4. VTS matching for crustal motions for a Site class C site in Vancouver: (a) initial linear scaling, (b) factor function (FF), (c) adjusted individual target spectra, (d) motions matched to their own individual spectra. Period range of interest shown in green.

4.2 *Example 2: VTS applied to a hard rock site using subduction seed motions*

The same procedure is followed for scaling and matching seed motions to hard rock spectra. For this case subduction motions were selected as seed motions. The database for subduction motions is fairly limited and is associated with a narrow range in magnitudes Mw = 8-9.5. This makes it more difficult to get a good linear scaled match to the target spectrum.

The combined effects of hard rock spectral shape and the subduction motions on linear scaling are shown in Figure 5(a) for a period range of interest 0.02-0.5s. There is a much poorer match between the mean spectrum of the linearly scaled seed motions and the target spectrum than in the case of the Site Class C site where the seed motions were selected from a huge database. The difference shows up very clearly when the Function Factors for the two cases given in Figure 4b and Figure 5b are compared. Substantial function factors were realized over the entire period range for the hard rock site but only minor adjustments were required in the period range of interest for the Site Class C site. Figure 5(c) shows a very close fit of the mean spectrum of the modified spectra to the target spectrum. The results of matching each seed motion to its own unique modified spectrum are shown in Figure 5(d). There is a very good fit to the target in the period range of interest.

The most important aspect of the VTS method is the ability to develop appropriate motions for structural analysis that match a specified target spectrum in the absence of compatible seed motions. A second attractive aspect of the method is that it results in spectra that have the peaks and troughs like recorded motions. This latter aspect results in the matched motions retaining much of the dispersion of the initial seed motions. Seifried (2013) conducted nonlinear response analyses on a variety of degrading and non-degrading models and found that the VTS matched motions showed no bias relative to the original seed motions. This finding supports the opinion expressed in Section 2.0 that the difference between the mean response results for linear scaled motions and spectrally matched motions is due to the dispersion of the linear scaled motions and not to some intrinsic defect in the spectrally matched motions.

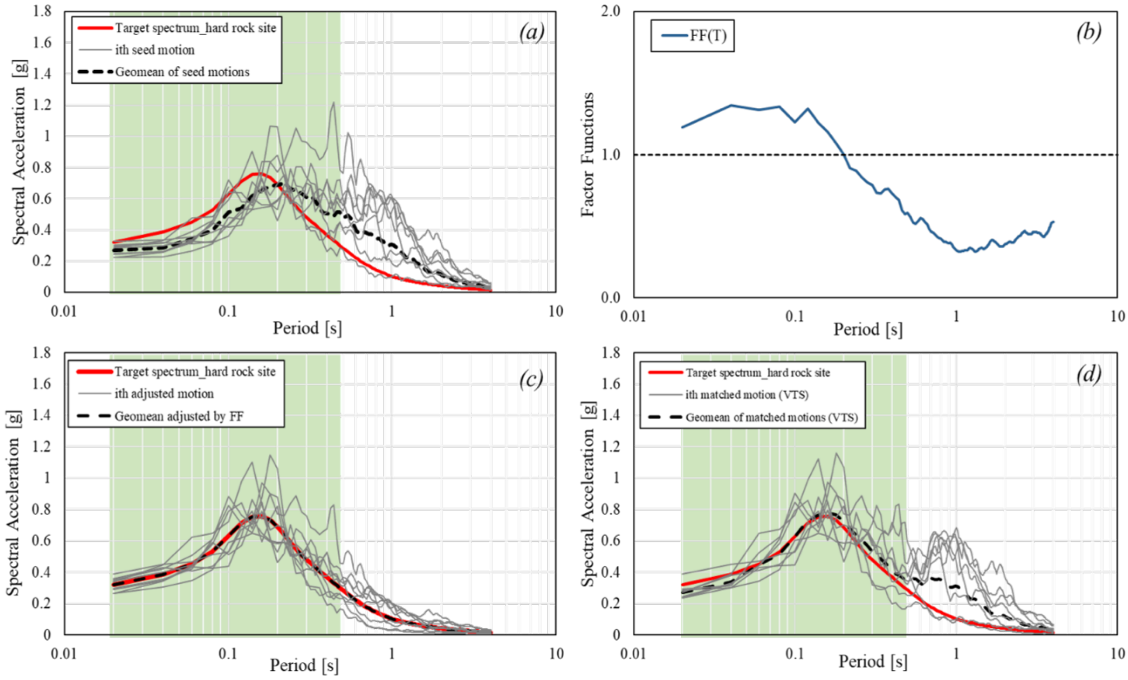


Figure 5. VTS matching for subduction motions for a hard rock site: (a) initial linear scaling, (b) factor function (FF), (c) adjusted individual target spectra, (d) motions matched to their own individual spectra. Period range of interest shown in green.

5 CHANGES IN MOTION CHARACTERISTICS DUE TO VTS

The changes induced in some key ground motion parameters of the seed motions such as dominant period and Arias Intensity by spectral matching and VTS matching are shown in Tables 1 thru 4.

Table 1. Changes of predominant periods of crustal motions after matching

Record	Change in Predominant Period [s]		
	Scaled seed motions	Matched motions	
		VTS method	Spectral matching
RSN1012	0.32	0.30	0.32
RSN2490	0.82	0.82	0.24
RSN2661	0.32	0.32	0.30
RSN4392	0.22	0.22	0.22
RSN4846	0.42	0.42	0.28
RSN4850	0.38	0.36	0.96
RSN4858	0.36	0.48	0.26

Table 2. Changes of Arias Intensity of crustal motions after matching

Record	Change in Arias Intensity [m/s]		
	Scaled seed motions	Matched motions	
		VTS method	Spectral matching
RSN1012	1.13	1.11	1.24
RSN2490	3.15	3.11	2.04
RSN2661	2.48	2.44	2.24
RSN4392	2.08	2.02	1.89
RSN4846	1.38	1.34	1.25
RSN4850	1.65	1.58	1.55
RSN4858	1.44	1.39	1.46

Table 3. Changes of predominant periods of subduction motions after matching

Record	Change in Predominant Period [s]		
	Scaled seed motions	Matched motions	
		VTS method	Spectral matching
Maule_(LACH1)	0.28	0.26	0.28
Maule_(LACH2)	0.44	0.16	0.26
Maule_(SJCH)	0.16	0.12	0.16
Maule_(STL)	0.24	0.16	0.24
Tohoku_(IWT)	0.18	0.18	0.20
Tohoku_(FKS)	0.20	0.18	0.20
Tohoku_(MYG)	0.14	0.14	0.16

Table 4. Changes of Arias Intensity of subduction motions after matching

Record	Change in Arias Intensity [m/s]		
	Scaled seed motions	Matched motions	
		VTS method	Spectral matching
Maule_(LACH1)	3.06	3.23	2.87
Maule_(LACH2)	3.84	4.46	3.23
Maule_(SJCH)	1.95	2.03	1.90
Maule_(STL)	2.60	2.50	2.08
Tohoku_(IWT)	3.69	3.66	3.59
Tohoku_(FKS)	1.47	1.80	1.74
Tohoku_(MYG)	3.81	3.69	3.26

6 SUMMARY AND CONCLUSIONS

The current state of practice for modification of ground motions to be consistent with a specified target spectrum by linear scaling or spectral matching is reviewed. The assertion that spectral matching shows an unconservative bias in mean response estimates in comparison with linear scaling estimates is critically examined. Linear scaling results in higher mean estimates of response because of the interaction between the asymmetric nature of nonlinear response and the dispersion of the linear scaled spectra. During nonlinear response, the effects of spectral excursions above the target spectrum will be larger than excursions below leading to greater mean response than with tight spectrally matched motions. This finding leads to the conclusion that spectral matching leads to unconservative results only if it is assumed that linear scaling is the correct method.

There are no guidelines for motion modification in the case of subduction regions such as the Cascadia region of South-Western British Columbia where three types of earthquakes crustal, in-slab and interface earthquakes contribute to hazard. Tentative guidelines in the National Building Code for Canada NBCC (2015) are presented for consideration. A new method, the Variable Target Spectrum (VTS) method is presented that has the ability to develop appropriate motions for structural analysis that match a specified target spectrum in the absence of shape compatible seed motions. The method results in spectra that have the peaks and troughs like recorded motions.

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