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GROUND MOTION SCALING/MATCHING FOR NONLINEAR DYNAMIC ANALYSIS OF BASEMENT WALLS

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ABSTRACT: This paper reports on specific component of an ongoing research at the University of British Columbia on seismic design of basement walls in British Columbia. Series of dynamic nonlinear soil-structure interaction analyses have been conducted to evaluate the seismic performance of a typical basement wall. The input motions for these analyses reflect three dominant seismic mechanisms in the Lower Mainland: shallow crustal earthquakes, deep subcrustal earthquakes and interface earthquakes from a Cascadia event. Exploratory analyses showed that the Cascadia motions had no significant effect on the walls. The crustal and subcrustal motions were scaled to the uniform hazard spectrum for Vancouver using both linear and spectral matching techniques. The spectrally matching method uses the wavelet algorithm to modify the spectral shape of the response spectrum to match the target demand. Also five different linear scaling approaches were used in this study without altering the frequency content of the ground motions: (1) scaling the spectral acceleration at PGA (2) scaling the spectral acceleration at the natural period of the soil-basement wall system, (3) scaling in a period range of 0.2T-1.5T, where T is the natural period of the system, as in this period range the integration of spectral accelerations become equal to the area under the target spectrum, (4) scaling the spectral accelerations of all selected motions following the recommendation of ASCE (2005, 2010) such that the average value of the 5 percent damped response spectra for the suite of motions is not less than the target response spectrum in the period range of 0.2T-1.5T, (5) scaling the ground motions based on minimizing the mean square error (MSE) between the spectral acceleration of the record and the target response in the period range of interest. The results of these analyses using the different scaling/matching techniques will be compared to facilitate a decision on the best technique to use for this problem.

1. Introduction

The Structural Engineers Association of British Columbia (SEABC) initiated a task force to review the current seismic design procedures for basement walls. The current state of practice for seismic design of basement walls in the United States (Lew et al. 2010; Lew 2012) as well as in British Columbia (DeVall et al. 2010) is based on the Mononobe–Okabe (M–O) method. In this limit-equilibrium force method, the earthquake thrust acting on the wall is a function of the Peak Ground Acceleration (PGA).

The National Building Code of Canada (NBCC) changed the seismic hazard level for the design of the buildings, from 10% in 50 years in NBCC1995 to 2% in 50 years in NBCC2005 and NBCC2010, which corresponds to doubling the PGA in Vancouver from 0.23g to 0.46g. In light of the fact that there is no evidence of any significant damage to basement walls during major earthquakes, SEABC became concerned about whether in adopting the 2005 and 2010 seismic hazard the walls were being grossly overdesigned using the new code mandate PGA. This led SEABC to initiate a task force to review current seismic design procedures for deep basement walls and the University of British Columbia was asked to carry out this research.

Series of nonlinear dynamic analysis have been conducted to evaluate the performance of the basement walls designed for different fractions of the code PGA. The main objective of this paper is to provide further evidence for evaluating the recommended fraction of code mandated PGA that be used with the M-O method to result in an acceptable seismic performance of basement walls (Taiebat et al., 2014). In order to carry out a nonlinear dynamic analysis, suite of accelerograms, which are representative of the seismic demand (e.g. the uniform hazard spectrum (UHS)) are required. There are two main options for scaling the ground motions: (1) adding wavelets in the time domain and modifying the spectral shape of the response spectrum to match the target demand or (2) linear scaling accelerogram without altering its spectral shape. There is a debate in literature about the use of the linearly scaled records versus the spectrally matched ground motions.

In our previous publications (Taiebat et al., 2013, 2014) the proposed fraction of the code PGA for design of the basement walls was based on the performance of the walls subjected to the suites of motions which were all spectrally matched to the UHS of Vancouver. In this paper the weakest wall, designed for 50% of NBCC 2010 PGA, has been studied and its performance in the form of drift ratio under a suits of crustal and subcrustal ground motions all scaled/matched to the seismic demand in Vancouver is investigated.

2. Numerical Model of the Basement Wall

A series of nonlinear two-dimensional finite difference analyses using FLAC 2D (Itasca 2012) have been conducted to model the seismic behavior of 4-level basement wall designed for 50% of NBCC2010 PGA for Vancouver. The description of the boundary condition, construction simulation, structural and interface elements can be found in the companion paper (Taiebat et al. 2014). The 2D model of the aforementioned 4-level basement wall is presented in Fig. 1.

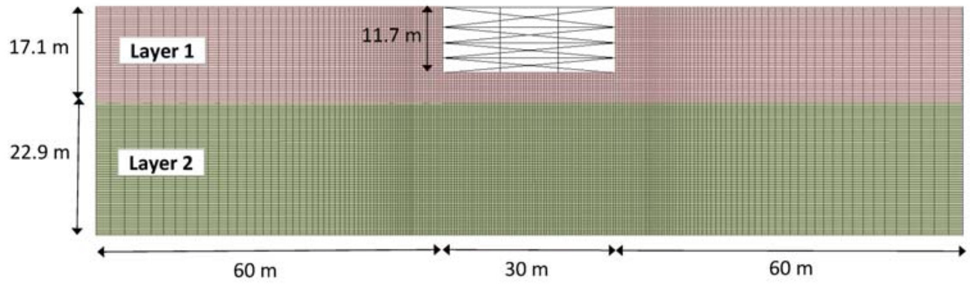


Fig. 1 - 4-level basement wall model in FLAC 2D

In consultation with geotechnical engineers, the soil properties listed in Table 1 are suggested for the two soil layers in Fig. 1. In this table V_{s1} is a normalized shear wave velocity (Robertson et al. 1992), which is a function of the effective overburden stress.

Table 1 - Soil layer material properties

Soil layer	Density (kg/m^3)	V_{s1} (m/s)	G_{max} (MPa)	Mohr-Coulomb				UBCHYST				
				υ	Coh. (kPa)	ϕ (°)	ψ (°)	hrm	hdfac	hrf	hn1	hn
1	1950	200	17-143	0.28	0	33	0	0.5	0	0.98	1.0	3.3
2	1950	400	580-885	0.28	20	40	0	0.5	0	0.85	1.5	2.0

Two layers of soil are modeled with UBCHYST soil model, which is a two dimensional nonlinear hysteretic model developed at the University of British Columbia by Naesgaard and Byrne (Naesgaard 2011) for dynamic analyses of silty non-liquefiable soils subjected to earthquake loading. Later on, this model was converted to DLL (Mikola and Sitar, 2012) in order to improve the efficiency of the code, which is used in this study.

In UBCHYST the tangent shear modulus (G_t) is a function of the peak shear modulus (G_{max}) times a reduction factors which are a function of the developed stress ratio which varies throughout the loading cycle to generate nonlinear hysteretic stress-strain loops. In this model, the magnitude of the stress ratio is limited by a Mohr-Coulomb failure envelope.

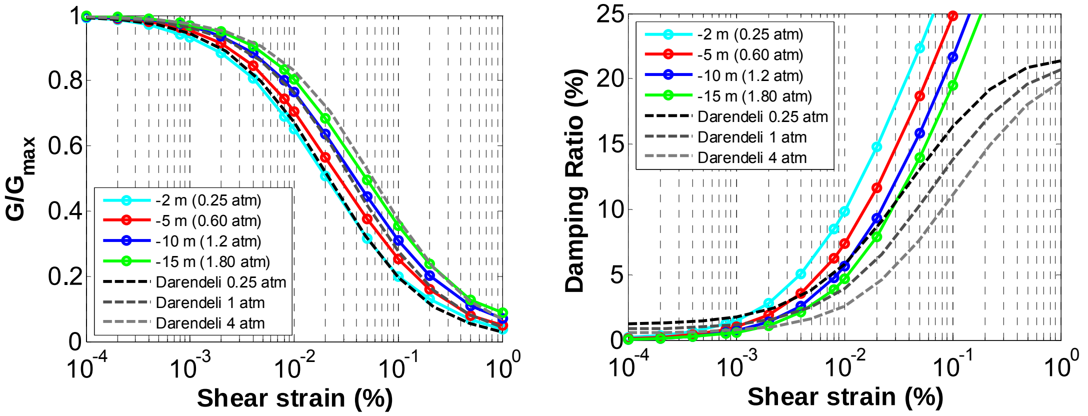


Fig. 2 - Modulus reduction and damping curves estimated by FLAC at different depth of the first layer of soil using UBCHYST model.

The UBCHYST model parameters are calibrated by comparing uniform cyclic response to that inferred from modulus reduction and damping curves published by Darendeli (2001). To this aim, for each layer of soil an initial estimate of values was made based on a sensitivity analysis. Then an element cyclic simple shear (CSS) test using UBCHYST constitutive model was conducted in FLAC at different depth of the model for fifteen shear strain values, ranging from 0.0001% to 1% to generate modulus and damping curves. The UBCHYST parameters were adjusted in a way to result the best match to the Darendeli modulus reduction and damping curves. Fig. 2 illustrates the modulus reduction and damping of the first soil layer at different confining pressures compared to the laboratory results of Darendeli. As it is shown in this figure the model overestimates the damping response at medium to large shear strains ($> 0.1\%$). Mikola and Sitar (2012) had drawn the same conclusion and related it to the width of the hysteresis loop in the UBCHYST model.

3. Selection of Ground Motion Records

The south-west of British Columbia has significant hazard contributions from crustal, subcrustal and subduction earthquakes. This fact is reflected in a calculation of uniform hazard spectrum, which envelops the spectral acceleration values from all three earthquake types and is the basis for the design response spectrum in the NBCC code. As the exploratory analyses showed that the Cascadia motions had no significant effect on the basement walls, these motions are excluded from this study. Following the recommendation of the NEHRP (2011) for selecting and scaling earthquake ground motions for performing response-history analyses, a suit of seven ground motions were selected for each crustal and subcrustal mechanism, as explained below.

The reference soil classification, Site Class C, proposed by the National Building Code of Canada (NBCC 2010) was selected as the fundamental site condition for this study. A Site Class-C site is defined by an average shear wave velocity in the upper 30 m, V_{s30}, between 360 m/s and 760 m/s, and is considered to be dense soil or soft rock.

Appropriate ranges of magnitudes and distances to earthquake sources were determined by de-aggregating the probabilistic seismic hazard in Vancouver reported by Pina et al. (2010). Based on the results of de-aggregation of the UHS of Vancouver, searching criteria for the crustal and subcrustal ground motions was set as the magnitude range of 6.5 to 7.5, with the closest distance of 10-30 km and 30-150 km of the causative fault plane from the earthquake sites for the crustal and subcrustal motions, respectively.

Table 2 - List of selected crustal ground motions.

No.	Event Name	Year	Station	Mag.	V_{s30} (m/s)	Direction
1	Friuli- Italy-01	1976	Tolmezzo	6.5	424.8	FN
2						FP
3	Tabas- Iran	1978	Dayhook	7.35	659.6	FN
4						FP
5	New Zealand-02	1987	Matahina Dam	6.6	424.8	FN
6						FP
7	Loma Prieta	1989	Coyote Lake Dam (SW Abut)	6.93	597.1	FN
8						FP
9	Loma Prieta	1989	San Jose - Santa Teresa Hills	6.93	671.8	FN
10						FP
11	Northridge-01	1994	LA - UCLA Grounds	6.69	398.4	FN
12						FP
13	Hector Mine	1999	Hector	7.13	684.9	FN
14						FP

Table 3 - List of selected subcrustal ground motions.

No.	Event Name	Year	Station	Mag.	V_{s30} (m/s)	Direction
1	Miyagi Oki, Japan	2005	MYG016	7.2	580	E-W
2						N-S
3			MY6014		706.2	E-W
4						N-S
5			FKS010		585.9	E-W
6						N-S
7			MYG013		535.5	E-W
8						N-S
9			IWT011		565.3	E-W
10						N-S
11	Nisqually, WA	2001	Olympia Residence	6.8	-	E-W
12						N-S
13	Michoacan, Mexico	1997	Villita Margen Derecha (VILE)	7.3	-	E-W
14						N-S

Crustal earthquakes were downloaded from the PEER-NGA database (Chiou et al. 2008). Selection of the candidate ground motions was done based on the best linearly matched motions to the UHS of Vancouver in the period range of 0.02-1.7 sec. In addition, in order to eliminate the potential bias towards one specific event, no more than two ground motions are selected from a single seismic event. Table 2 shows the list of the selected seven crustal ground motions. It should be mentioned that both Fault-Normal and Fault-Parallel components of each motion are used in this study (fourteen ground motions).

Subcrustal earthquakes were also selected based on the best linearly matched motions to the UHS of Vancouver and were mostly downloaded from the COSMOS database (Archuleta et al. 2006). Japanese earthquakes were directly downloaded from the K-NET (Kinoshita 1998) and KiK-net (Aoi et al. 2000) databases. The list of the selected seven subcrustal ground motions are presented in Table 3. Both components of E-W and N-S of each ground motion have been used in this paper (fourteen ground motions).

4. Ground Motion Linearly Scaling and Spectrally Matching Methods

For conducting a nonlinear dynamic analysis of basement walls, several methods of scaling/matching the input ground motions are chosen to modify accelerograms to become representative of the seismic demand. The premise to verify is to reduce the dispersion in the elastic response spectra of the input ground motion in order to reduce the variability in the output of nonlinear response history analyses. The selected crustal ground motions has been scaled and matched by using six different undermentioned methods, while in the case of subcrustal motions, just two of the following methods has been explored.

4.1. PGA scaling

One of the commonly used methods of scaling the time history to a target spectrum is the PGA scaling. In this method, the selected record is multiplied by a scalar coefficient in a way that the PGA of the scaled record becomes equal to the PGA of the target spectrum, which based on NBCC2010 for Vancouver is 0.46g. In this method the frequency content and spectral shape of the accelerogram are not taken into consideration and even though all PGA scaled ground motions all have the same PGA, their response spectrum fall in a very wide range throughout the different periods as is shown in Figure 3(a).

4.2. Sa(T_1) scaling

The objective of this option is to use a multiplier that scale the records so that the spectral acceleration at a fundamental period of the system matches the target spectral acceleration at that period. This method provides a set of scaled time series whose spectral acceleration of all are equal to the target spectrum at the fundamental period of the system. One of the main concerns in using this methodology is losing accuracy at higher modes of vibration due to yielding and nonlinear behavior which elongate the vibration periods (Kurama and Farrow, 2003). Moreover scaling the record just based on one specific period is not a good indicator of strength and frequency content of the ground motions. Figure 3(b) illustrates the spectral response of the time histories scaled using this method at T_1=0.4 sec which is the natural period of the system. The response spectrum of these scaled ground motions exhibits a wide range in spectral accelerations.

4.3. ASCE scaling

The procedures and criteria in IBC (International Building Code, 2006) and CBC (California Building Code, 2007) for the selection and scaling ground-motions for use in nonlinear response history analysis of structures are based on ASCE 7-05 and 7-10 provisions (ASCE, 2005, 2010).

The American Society of Civil Engineering (ASCE, 2005, 2010) recommends a method in which the ground motions are scaled in such a way that the average value of 5% damped response spectra for the suites of motions is not less than the design response spectrum in the period range of $0.2T_1$ to $1.5T_1$, where T_1 is the natural period of vibration of the system. This range is chosen due to inelastic behavior which results in higher fundamental periods to an effective value of $1.5T_1$ and on the other hand the mode transitional period which often falls between one-quarter and one-third of the fundamental period. The ASCE 7-05 and 7-10 scaling procedure does not insure a unique scaling factor for each record; obviously, various combinations of scaling factors can be defined to insure that the average spectrum of scaled records remains above the design spectrum. Figure 3(c) illustrates the results of this scaling method using T_1=0.4 sec as a fundamental period of the soil-wall system.

4.4. SIa scaling

In this method, the multiplier is applied to the accelerogram in a way that the area under the response spectrum becomes equal to the integration of spectral acceleration in the period range of interest $0.2T_1$ to $1.5T_1$. (Michaud and Léger, 2014)

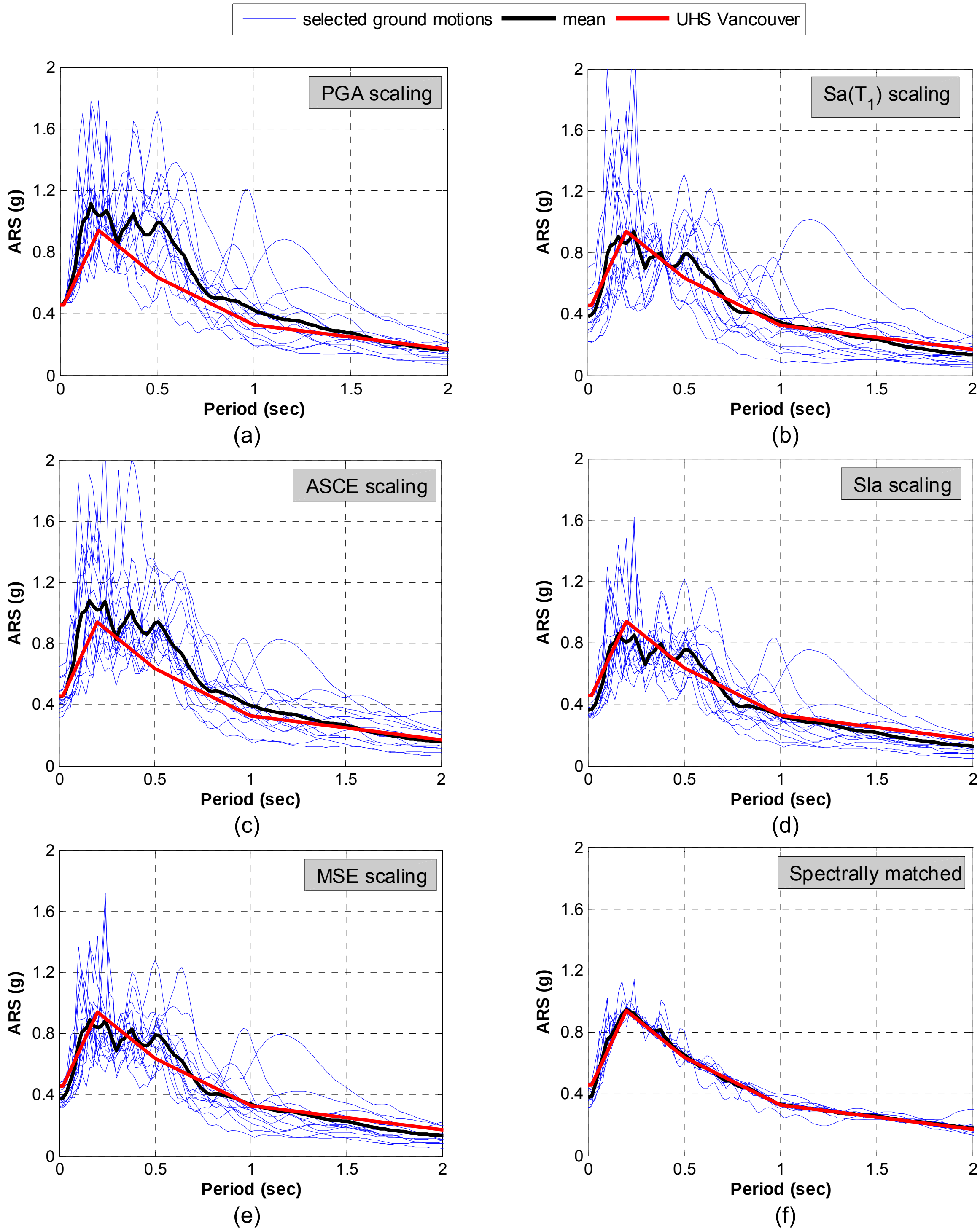


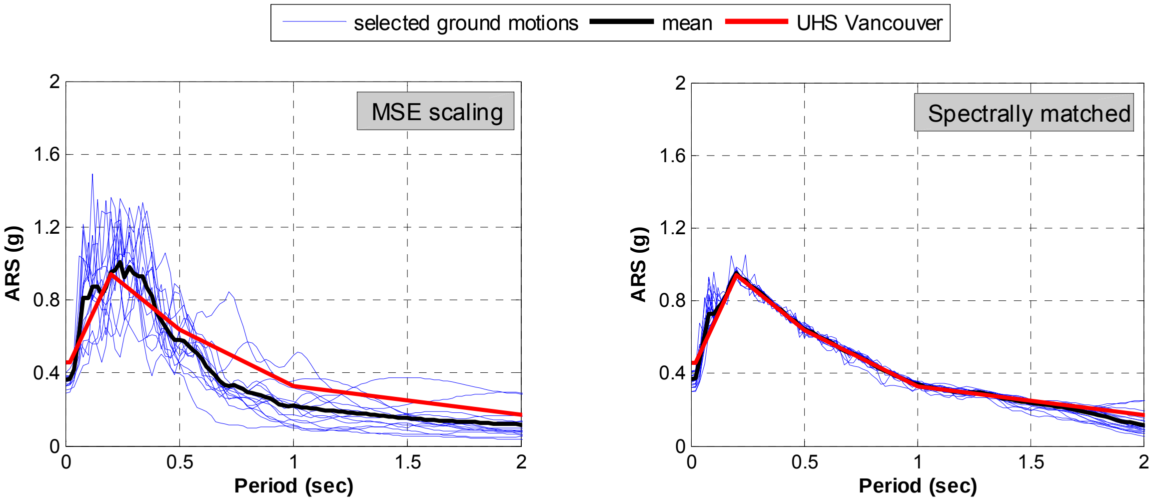
Fig. 3 – Mean acceleration spectra of the selected fourteen crustal input ground motions for the nonlinear dynamic analysis of basement walls using different methods of scaling/matching the ground motions to the target NBCC 2010 UHS of Vancouver.

4.5. MSE scaling

In this method a quantitative measure of the overall fit of the record to a target spectrum is the mean squared error (MSE) between the target spectrum and the response spectrum of a recorded time history. For this purpose the period range of interest ($0.2T_1$ to $1.5T_1$) is subdivided into a large number of points equally-spaced and the target and record response spectra are interpolated to provide spectral acceleration at each period, respectively. The MSE is then computed using the following equation over the user-specified period as:

$$MSE = \frac{\sum w(T_i)\{\ln[SA^{\text{target}}(T_i)] - \ln[f \times SA^{response}(T_i)]\}^2}{\sum w(T_i)} \tag{1}$$

In this equation, $SA^{\text{target}}(T_i)$ is the spectral acceleration of the target spectrum, $SA^{\text{response}}(T_i)$ is the spectral acceleration of the scaled ground motion, $w(T_i)$ is a weight function and f is a linear scale factor applied to the entire response spectrum of the recording, minimizing MSE between the target spectrum and the response spectrum. Figures 3(e) and 4(a) illustrate the spectral response of the time histories scaled using MSE method for a selected crustal and subcrustal ground motions, respectively.



(a) (b)

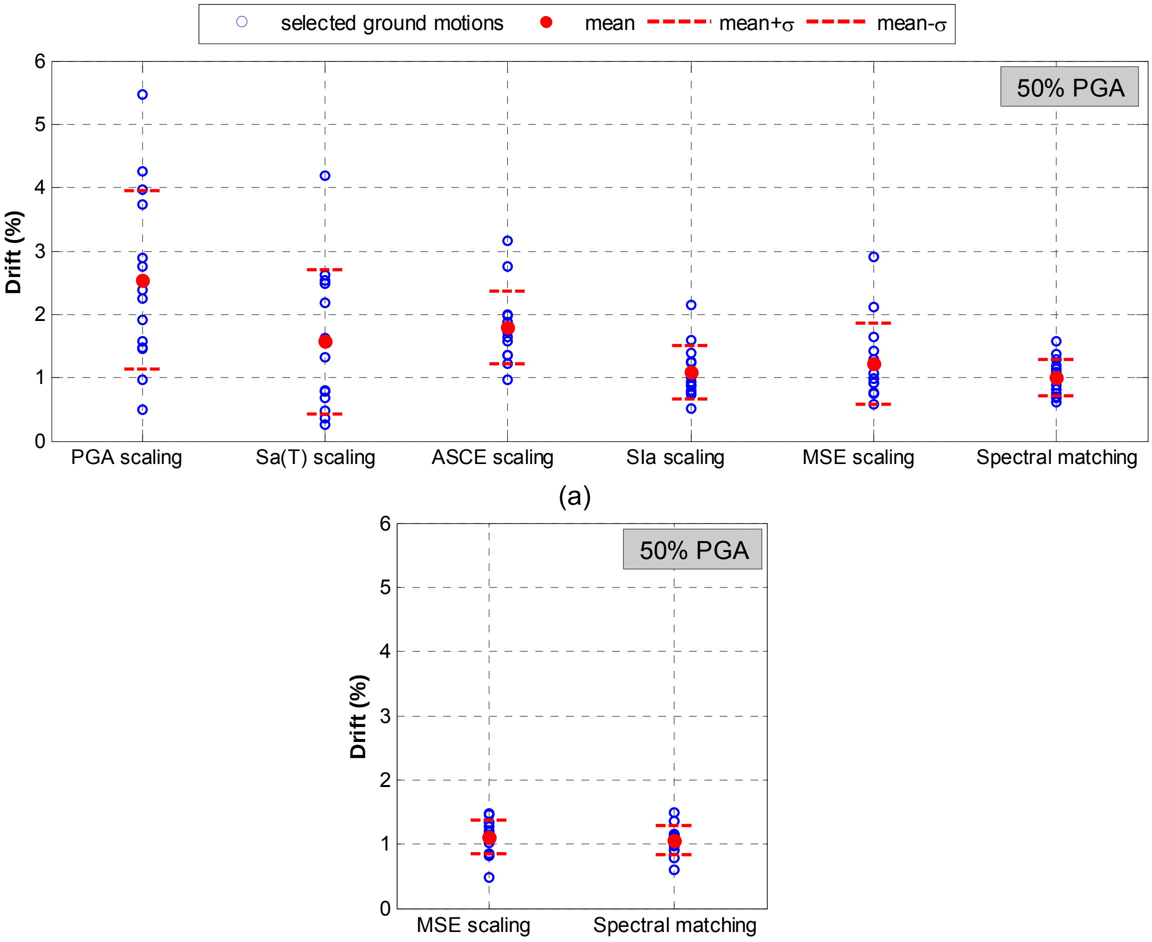
Fig. 4 – Mean acceleration spectra of the selected fourteen subcrustal input ground motions for the nonlinear dynamic analysis of basement walls using different methods of scaling/matching the ground motions to the target NBCC 2010 UHS of Vancouver.

4.6. Time domain spectral matching

The computer program, SeismoMatch (Seismosoft 2009) has been used to spectrally match the ground motions to the target spectrum. SeismoMatch is an application uses the wavelet algorithm proposed by Abrahamson (1992) and Hancock et al. (2006) to adjust earthquake ground motions and obtain a response spectrum with a close match to the target spectrum in a period range of interest. In this approach, carefully selected elementary wavelets are added and subtracted to the original record in a way that an extra displacement to the record will not be imposed. The basic characteristic of the original record with respect to the amplitude and frequency content of the record over the time history duration is preserved and a developed design time histories have a spectra similar to the a design spectra (NEHRP 2011). This procedure is popular in engineering practice because it reduces the variance of the structural responses due to variability of the earthquake records and provide a platform to estimate the mean response with fewer numbers of analyses (Seifried and Baker, 2014). The only argument that can be made is that although this method meets the target spectrum requirements adequately, but it does not produce ground motions representative of actual earthquake records.

5. Simulation Results

The maximum resultant drift ratio along the height of the wall is used to compare the response of the basement wall under the action of records selected and scaled using different methods. For this purpose, the recommendations of ASCE task committee on design of blast-resistant buildings in petrochemical (ASCE-TCBRD, 2010) is used as the performance standard. To the best knowledge of the authors, there is no other report on the acceptable drift ratios for constrained walls with distributed lateral loading. In this recommendation, the drift ratio of a basement wall at the middle of each storey is calculated as the difference between the displacement of the wall at that level and the average displacements of the wall at the top and bottom of the storey divided by half of the storey height. The committee specified a low response category as “Localized component damage with moderate cost of repairs”. The response limits associated with this category for the reinforced concrete wall panels (with no shear reinforcement) is 1.7% drift ratio.



(a)

(b)

Fig. 6 – The resultant maximum drift ratio of the basement wall designed for 50% of NBCC 2010 code PGA for Vancouver, subjected to fourteen (a) crustal (b) subcrustal ground motions scaled/matched using different methods.

Based on the recommendations of NEHRP (2011) and ASCE 7-05 and 7-10 (2005, 2010), the mean value of an engineering demand parameter (e.g. drift ratio) is taken as the design value over fourteen ground motions. Fig. 6 provides comparisons of the resultant maximum drift ratio along the height of the 4-level basement wall designed for 50% of code PGA, obtained from the suites of crustal and subcrustal records scaled/matched according to the various methods outlined in this paper. In these plots, the mean value corresponds to the average of the maximum drift ratio along the height of the wall subjected to fourteen seismic events for each case. Assuming normally distributed drift ratios, mean ± σ represents the first standard deviation with 68% chance that the mean falls within the range of standard error.

For the sake of comparison, the resultant drift ratio of the system subjected to the spectrally matched ground motions in figures 6a and 6b are defined as a “reference” value, to provide a basis for comparing the performance of the system subjected to the various methods outlined in this paper. Spectral matching reduce spectral variability within a suite of ground motions at a period range of interest and provide an estimation of mean response with a reasonable standard deviation.

It can be concluded from these figures that scaling the ground motion record at PGA does not return very good results in nonlinear dynamic analysis. This is due to the importance of spectral shape in nonlinear response, as PGA is not a good indicator of the strength and frequency content of the ground motion. Also scaling the ground motion at fundamental period of the system, $Sa(T_1)$, leads to the results with high dispersion. This is because of the lengthening of the apparent period of vibration due to yielding the structure. In contrast, using other scaling methods in which the suites of ground motions are scaled linearly in a period range instead of a single period, result in a lower standard deviation (dispersion) in a seismic response and thus more reliable mean value. This is due to consideration of the spectral shape and frequency content of each ground motion in the scaling factor calculation process.

Scaling the suites of ground motions based on SIa and MSE scaling methods results in a mean spectrum with an overall good match with the seismic demand (UHS) in a period range of interest (Fig. 3d,e and Fig. 4a) and results in a mean drift ratio in agreement with “reference” value and far below the acceptance criteria of 1.7%. Whereas ASCE scaling method generates stronger motions (Fig. 3c) and consequently larger drift ratios compare to the spectral matching method.

6. Conclusion

Different methods of ground motion scaling/matching to the uniform hazard spectrum of Vancouver with the 2% in 50 years hazard level were discussed and the seismic performance of the basement wall in the form of drift ratio is evaluated. The principal finding of this work is that the level of variability of the response in the form of standard deviation of the resultant drift ratios are reduced significantly as one moves from (1) linear scaling the records to match the target spectrum at PGA or the natural period of the system ($Sa(T_1)$), to (2) linear scaling the records to match the target spectrum over the period range using different methods such as ASCE, MSE and SIa scaling, to (3) spectrally matching the records in a time domain using the wavelet algorithm. The robust mean value of the drift ratio can be estimated by using the spectrally matched accelerograms. The result of this study showed that using the SIa and MSE linear scaling methods also lead to a mean drift ratio similar to the spectrally matched ground motions whereas ASCE scaling generates stronger motions and consequently larger drift ratios.

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