Seismic Displacement Demands for Performance-Based Design and Rehabilitation of Structures in North America

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SUMMARY:
Application of displacement-based design and evaluation (DBDE) methods requires characterization of seismic displacement demands through site-specific displacement spectra. In this work, such demands in Eastern North America (ENA) and Western North America (WNA) are determined using: (i) available historical ground motions, (ii) site-specific simulated records, and (iii) ground motion prediction equations (GMPE). The obtained displacement spectra are examined to identify trends in regional spectral shapes as a function of magnitude, distance, and period range of interest. We demonstrate the differences between ENA and WNA displacement demands highlighting the impact on DBDE in these regions. The most recent ENA and WNA GMPEs are used to assess seismic displacement demands considering parameters including magnitude, shear wave velocity, period of vibration, and closest distance to fault. The results are confronted against those computed using historical and simulated records. Conclusions are formulated about the differences between seismic displacement demands in ENA and WNA.

Keywords: Displacement Spectra, Real and Simulated Ground-motions, Ground-motion Prediction Equations

1. INTRODUCTION

Displacement-based seismic design and evaluation methods are becoming increasingly popular as alternative approaches to more conventional prescriptive techniques. Application of displacement-based methods requires the characterization of seismic displacement demands through displacement spectra corresponding to site-specific seismic hazard (Kowalsky 2002; Priestley et al. 2007). Elastic and inelastic seismic displacement spectra, displacement-based seismic hazard maps, uniform hazard displacement spectra and damping modifying factors have been developed in Europe using ground motions from Europe and other regions (Tolis and Faccioli 1999; Borzi et al. 2001; Eurocode8 2003; Faccioli et al. 2004; Karakostas et al. 2007). Moreover, studies on displacement demands in this region having resulted in development of ground motion prediction equations for displacements can be found in the literature (Bommer and Elnashai 1999; Akkar and Bommer 2007; Cauzzi and Faccioli 2008).

The majority of the Canadian population lives in the eastern and western Canada usually concentrated in major cities. This implies a higher seismic risk in these two regions, to be linked to various structural vulnerability indices corresponding to a diversely built environment. A number of differences between earthquakes occurring in the east and the west have been reported in the literature. Seismic waves in ENA have a lower attenuation rate than their western counterparts (Atkinson and Boore, 2011). Therefore, they can be felt in longer distances from the epicenter. In contrast, western earthquakes usually attenuate quickly within 100 km from the epicenter. One other difference in the seismicity of these regions is the fault systems. The fault systems in WNA extend to the surface, while there is no evidence so far of surface faulting in ENA. Surface faulting generally results in more reliable seismic hazard evaluation in the west, while intra-plate seismicity such as in Quebec, Canada leaves seismologists with lots of unknowns. Finally, higher frequency content is associated with the ground motions recorded in ENA (Atkinson and Beresnev, 1998). Hypocentral (Focal) depth can be named as a similar characteristic between eastern and western earthquakes. The focal depth in both regions is approximately between surface and 30 km (Natural Resources Canada, 2011a; Natural Resources Canada, 2011b). This excludes the subduction zone in the west where much deeper focal points can be produced.

Most of the research related to seismic hazard in Canada has focused on the prediction of earthquake induced accelerations, leading to seismic hazard maps, site-specific uniform hazard acceleration spectra and their corresponding deaggregation data (NRCC 2005; NRCC 2010; Atkinson and Beresnev 1998; Adams and Atkinson 2003; Adams and Halchuk 2004; Atkinson 2009). Characterization of displacement demands in Canada is highly required in the context of displacement-based seismic design and evaluation (Bouaanani and Alexieva 2006; Humar et al. 2011). However, such a thorough characterization of displacements has not been addressed in the literature. The main objective of this paper is to provide a systematic investigation of seismic displacement demands in ENA and WNA through (i) available historical ground motions, (ii) site specific simulated records and (iii) ground motion prediction equations (GMPE). As widely known, computation of reliable displacement time-histories and spectra from recorded ground motions is usually associated with uncertainties related to several aspects of their processing such as base-line correction, filtering issues, long-period drift, and analog-to-digital conversion (Bommer and Elnashai 1999, Akkar and Boore 2009). This task is even more complicated by the scarcity of significant historical records in Canada, particularly in the East. Due to these considerations, it is inevitable to include the analysis of seismic displacement demands obtained from simulated ground motions reflecting most recent assessment of the Canadian seismic hazard. In addition, various ground-motion prediction equations specific to eastern and western North American seismic hazards have been developed (Boore et al. 1997; Atkinson and Boore 2006; Boore and Atkinson 2008; Atkinson 2008; Campbell and Bozorgnia 2008; Abrahamson and Silva 2008). Thus spectral displacements corresponding to recorded historical ground motions, two sets of simulated ground motions and two sets of GMPEs will be investigated to assess the differences between seismic displacement demands in ENA and WNA.

2. SEISMIC DISPLACEMENT DEMANDS FROM HISTORICAL RECORDS

2.1. Studied Historical Records

Eleven historical events which occurred between 1940 and 2010 form the historical database of this study. Table 2.1 contains the ENA and WNA historical ground motions studied in this paper. The accelerograms recorded during these events are frequently used by the structural engineering community for seismic performance assessment in the region. Most of these events caused only minor property damage, but they provided a wealth of information to characterize the corresponding seismic hazard. The acceleration time histories used in this study and the components defining instrument axes are obtained from the following references (Munro and Weichert 1989; Weichert et al. 1982; Weichert et al. 1986; Weichert et al. 2009; LDEO/NCEER 2007; PEER 2009).

Table 2.1. Selected ground motions for the historical database

Eastern Events			Western Events		
Earthquake name	Year	Magnitude	Earthquake name	Year	Magnitude
Miramichi	1982	5.0 M_b; 4.0 M_N	Imperial Valley	1940	6.9 M_W
Nahanni	1985	4.8 M_b; 5.4 M_b; 5.7 M_b	Parkfield	1966	6.1 M_W
Saguenay	1988	5.8 M_w	San Fernando	1971	6.6 M_W
Cap Rouge	1997	5.1 M_N	Loma Prieta	1989	7.0 M_W
Riviere du Loup	2005	5.4 M_N	Northridge	1994	6.7 M_W
Val des Bois	2010	5.0 M_W			

2.2. Seismic Displacement Demands

The 5%-damped displacement spectra of the horizontal historical records were generated. It was observed that considerably higher displacement demands were associated with records from WNA. In the East the induced displacements were generally low. However, ground motions with higher magnitudes (i.e. Saguenay and Nahanni) caused higher displacements. Considering several stations at which the Saguenay event was recorded, higher displacement demands were observed in hypocentral distances of approximately 90 km (e.g. Baie St. Paul). The displacements declined for both shorter and longer distances.

In the West, similar to the East, records of higher magnitudes resulted in higher displacements. The Parkfield event, having the lowest magnitude, demonstrates the lowest displacements. The displacement demand in the west in general, increases toward higher period ranges. On the contrary, in the East, where highest demands are mainly in the intermediate period range, only a few events demonstrated such a trend.

Studying all the spectra generated from the selected database of historical records, general trends can be associated with the spectral shapes in ENA and WNA. Three general spectral shapes are determined and presented in Fig. 2.1a for Eastern spectra.

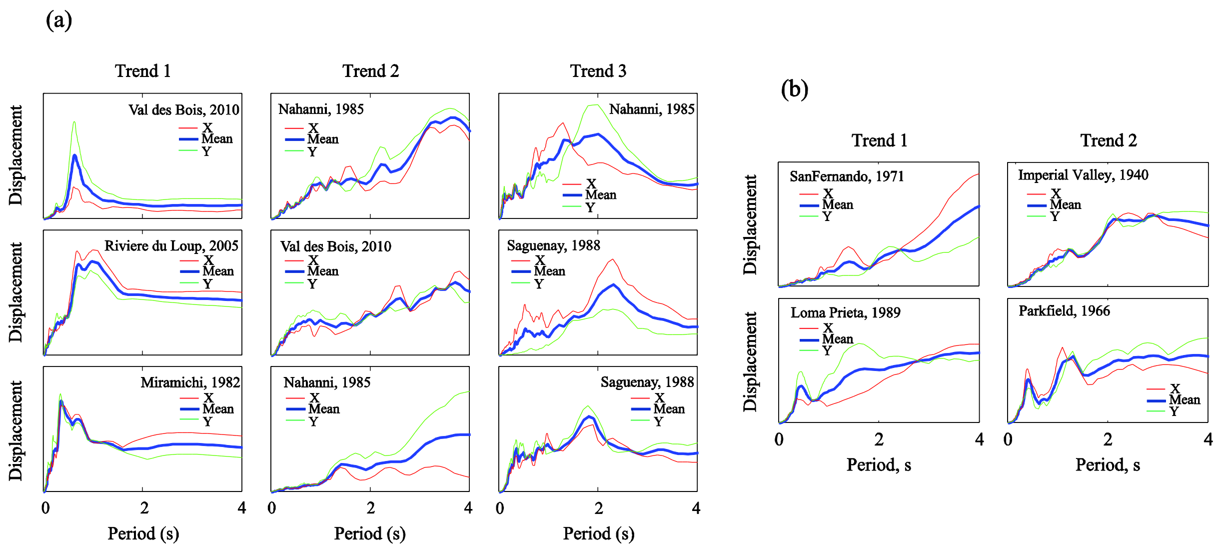

Figure 2.1. General trends identified in the historical records of (a) ENA and (b) WNA

The first trend shows the maximum displacement at short period range after which the demand declines and remains approximately constant towards longer periods. The second trend demonstrates an increase in the displacements towards longer periods. This type of spectral shape is similar to those in the WNA. The third trend exhibits a peak displacement in the intermediate period range with a gradual decline in the demands towards longer periods. Figure 2.1.b presents the two trends determined among the spectra of the West. The first trend shows an increase in the demand towards longer periods whereas the second trend demonstrates a local declination in the displacement demands in the intermediate period range followed by a plateau of the displacement amplitudes towards longer periods.

3. SEISMIC DISPLACEMENT DEMANDS FROM SIMULATED RECORDS

3.1. Studied Simulated Records

The seismic displacements from two sets of simulated ground motions corresponding to seismic hazard maps and uniform hazard spectra prescribed in the recent editions of the National Building

Code of Canada (NBCC 2005; NBCC 2010) were studied. These ground motions are frequently used by the structural engineering community for seismic performance assessment in Canada. In this work the two sets of simulated ground motions are referred to as data sets A and B.

3.1.1. Data set A

Data set A contains 32 simulated ground motions generated for firm-ground site conditions according to the procedure described by Atkinson and Beresnev (1998) using a stochastic point-source simulation approach for crustal earthquakes (Boore 1983; Atkinson and Boore 1995; Atkinson and Boore 1997). The accelerograms can be matched to the 2% in 50 years NBCC 2005 UHS at different Canadian cities using appropriate magnitude and hypocentral distance combinations and scaling factors (Tremblay and Atkinson 2001). The spectral period ranges and corresponding magnitudes and hypocentral distances of these ground motions are given in Table 3.1. The table also contains the magnitude-distance classification of the records into bins EA1 to EA4 for eastern Canada and WA1 to WA4 for western Canada.

Table 3.1. Specifications of the studied simulated records from data set A

	Eastern Canada				Western Canada			
	EA1	EA2	EA3	EA4	WA1	WA2	WA3	WA4
No. of Records	4	4	4	4	4	4	4	4
Mag. (M_W)	6.0	6.0	7.0	7.0	6.5	6.5	7.2	7.2
Hypocentral Dist. (km)	30.0	50.0	20.0	70.0	30.0	50.0	20.0	70.0

3.1.2. Data set B

Data set B contains 1440 simulated records generated by Atkinson (2009) using calibrated stochastic finite-fault models for eastern Canada (Atkinson and Boore 1995; Atkinson and Boore 2006) and crustal events in western Canada (Motazedian and Atkinson 2005). These accelerograms can be used to match seismic hazard maps in various eastern and western Canadian localities considering appropriate magnitude, hypocentral distance and fault distance combinations as well as site conditions including NBCC site classes A, C, D, and E. The spectral period ranges and corresponding magnitudes, hypocentral and fault distances of these ground motions are presented in Table 3.2. The magnitude-hypocentral distance classification of the records into bins EB1 to EB4 for ENA and WB1 to WB4 for WNA and the fault distance ranges for each bin are also included in the same table.

Table 3.2. Specifications of the studied simulated records from data set B

	Eastern Canada				Western Canada			
	EB1	EB2	EB3	EB4	WB1	WB2	WB3	WB4
No. of Records	45	45	45	45	45	45	45	45
Mag. (M_W)	6.0	6.0	7.0	7.0	6.5	6.5	7.5	7.5
Hypocentral Dist. (km)	15.0	30.0	25.0	100.0	12.0	30.0	25.0	100.0
Min. Fault Dist. (km)	10.7	16.9	13.8	41.6	8.4	13.2	10.2	30.2
Max. Fault Dist. (km)	17.0	30.7	25.8	100.2	13.0	31.1	26.3	100.4

3.2 Seismic Displacement Demands of Data Set A

The 5%-damped displacement spectra of the records were generated and the effects of variations in magnitude and distance on the spectral displacements were studied. Fig. 3.1a and b show the mean displacement spectra of each bin for ENA and WNA, respectively. Similar to the historical records, it is observed that higher displacement demands are induced in the West. Moreover, displacement spectra of the same magnitude cause lower displacement demands as the hypocentral distance increases (e.g. EA1 vs. EA2).

In the East, records of higher magnitude and shorter hypocentral distance (i.e. EA3) dominate the displacement demands in the region. The spectral shape of the mean demands in the East demonstrates that the displacements increase up to periods of approximately 1.5s to 2s and remain approximately constant in the higher period range.

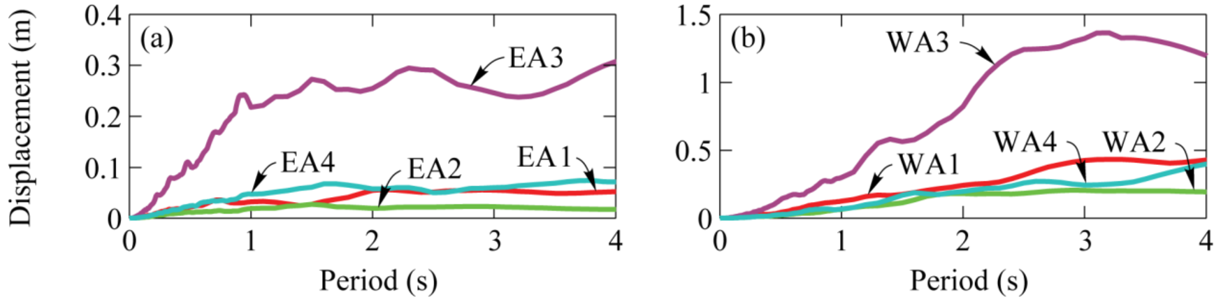

Figure 3.1. Mean displacement demands in (a) ENA and (b) WNA based on simulated records of set A

In the West, similar to ENA, the highest displacements are resulted from higher magnitude records from a shorter distance (i.e. WA3). The fairly constant displacement section of the spectra, however, is shifted towards longer periods (i.e. starting from 2s to 3s). The spectrum from bin WA4 demonstrates a different trend gradually rising beyond 4s.

3.3 Seismic Displacement Demands of Data Set B

A similar study was performed on the 5%-damped displacement spectra of data set B corresponding to soil type C (soft rock/very dense soil). Fig. 3.2 illustrates the mean displacement demands of each eastern and western bin.

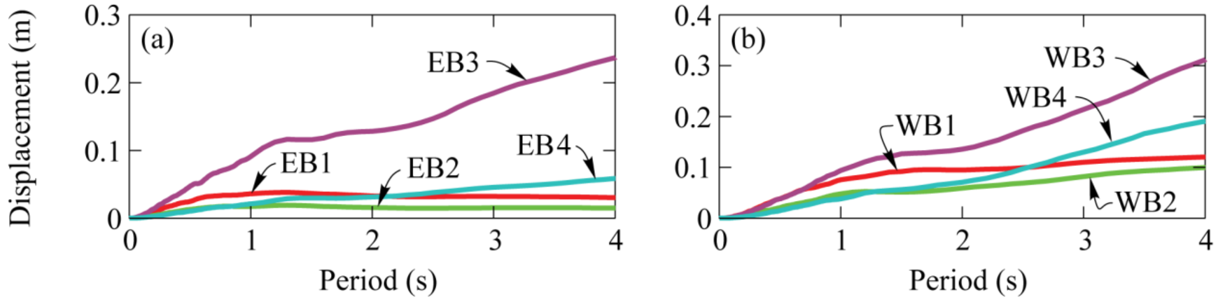

Figure 3.2. Mean displacement demands in (a) ENA and (b) WNA based on simulated records of set B

Fig. 3.2a compares the mean spectra from each eastern bin. These results show that high magnitude records dominate displacement demands in longer periods starting from 2s onward, and that this predominance covers even the entire investigated period range as hypocentral distances decrease, i.e. bin EB3. These trends emphasize that the high displacement demands of simulated ground motions with lower magnitudes and hypocentral distances, i.e. EB1 and EB2, is observable in the short period range. In contrast, the high displacement demands of records with larger magnitudes and hypocentral distances, i.e. EB3 and EB4, occur in the long period range. The results also illustrate the effect of hypocentral distance on displacement demands in ENA, indicating that among records of the same magnitude, the ones with shorter hypocentral distances produce higher spectral displacements.

Fig. 3.2b illustrates the mean displacement demands corresponding to bins WB1 to WB4. As expected, these results confirm that displacement demands in WNA are generally higher than in ENA. Similar to ENA, western ground motions with a higher magnitude and a shorter hypocentral distance, i.e. Bin WB3, induce higher displacement demands. However, records of lower magnitude and shorter hypocentral distances, i.e. Bin WSB1, exhibit a moderate increase in the short period range contrasting with the sharp rise highlighted previously for eastern records. We also observe that the subsequent approximate plateau in spectral displacements starts at periods larger than in the case of ENA. Similar to higher magnitude records from ENA, displacement demands in the west increase with larger periods. Fig. 3.2 confirms that higher spectral displacements are produced by records with shorter hypocentral distances. An overall comparison between the mean values of eastern and western displacement spectra shows that records of shorter distance induce peak displacement demands in the period range of 1s to 1.5s in the East and 3.5s to 4s in the West. As concerns records of higher magnitudes and longer distances, i.e. EB4 and WB4, the largest displacement demands correspond to periods larger than 4s in both ENA and WNA.

4. SEISMIC DISPLACEMENT DEMANDS FROM GMPES

Ground motion prediction equations (GMPE), also known as attenuation relationships, are of great importance in probabilistic seismic hazard analysis (PSHA). However, these relationships are among the main sources of uncertainty in the mentioned domain (Atkinson and Boore 2011) as new findings on this matter are presented from time to time through seismological studies which result in development of new GMPEs. Parameters related to ground motions such as spectral acceleration at each period, are obtained from GMPEs to be used in the related fields such as structural engineering.

4.1 Studied GMPEs

Several GMPEs have been proposed in the literature to simulate ground motions in ENA and WNA (Atkinson and Boore 1995; Boore et al. 1997; Campbell 2003; Atkinson and Boore 2006; Boore and Atkinson 2008; Pezeshk et al. 2011). In this study, two sets of GMPEs are selected to assess the displacement demands in ENA and WNA. These GMPEs are frequently referred to in the seismic hazard analysis of North America. The GMPEs of Atkinson and Boore (2006) and Boore and Atkinson (2008) are adopted for ENA and WNA respectively. For convenient reference, these two GMPEs are denoted as AB06 and BA08. The latest modifications to the mentioned equations, explained in detail in Atkinson and Boore (2011), were considered in this study.

4.1.1. AB06

Atkinson and Boore (2006) proposed a set of relationships to predict ENA ground motions using a stochastic finite fault model (Hanks and McGuire 1981; Boore 1983). A set of 38400 ground motions from 10 earthquakes with moment magnitudes (M_W) between 3.5 and 8 was simulated. Ground motions were simulated for 24 stations with fault distances ranging from 1km to 1000 km, located along 8 lines spreading out from the center of the top of the fault in equal azimuths. For each magnitude and station 20 random trials were considered. The 5%-damped acceleration spectra corresponding to the records were generated, and through regression analyses equations were proposed for pseudo-spectral acceleration amplitudes corresponding to ENA ground motions for rock and soil sites.

4.1.2. BA08

Boore and Atkinson (2008) presented a suite of GMPE equations corresponding to WNA derived by empirical regression of a collection of ground motions provided by Pacific Earthquake Engineering Research Center’s Next Generation Attenuation (PEER NGA). The analysis was performed on 1574 main shocks of distances up to 400km for periods shorter than 1s. The number of analyzed records decreased for longer periods. The proposed equations predict peak ground acceleration, peak ground velocity and 5%-damped spectral acceleration corresponding to a moment magnitude (M_W) range of between 5 to 8 for both rock and soil sites.

The specifications of the adopted GMPEs are provided in Table 4.1.

Table 4.1. Specifications of the studied GMPEs

	AB06	BA08
Earthquake Type	Shallow crustal earthquakes in eastern Canada	Shallow crustal earthquakes in western Canada
Variables	M_W, $R_{rupture}$, NEHRP site class (V_{s30})	M_W, $R_{Joyner\text{-}Boore}$, NEHRP site class (V_{s30})

4.2 Seismic Displacement Demands of GMPEs

The displacements predicted by GMPEs in North America have not been extensively discussed in the literature. Thus the predicted displacements by the selected GMPEs were studied to validate these relationships against the displacement demands induced by a selection of the historical ground motions in ENA and WNA. The spectral displacement predictions corresponding to the desired distance, magnitude, site class and period of vibration were calculated by multiplying the pseudo spectral acceleration predictions of each set of the GMPEs by $T^2/4\pi^2$.

4.2.1. AB06

The Saguenay and Val des Bois events (Table 2.1) were selected as the eastern historical records to validate the AB06 displacement predictions. Fig. 4.1a shows the predictions of AB06 for rock site and displacement amplitudes induced by the historical records at periods of 0.2, 1, 3 and 4s.

As can be seen, AB06 under predicts the displacements of Val des Bois earthquake at all the studied periods. However, the difference decreases at longer periods. It should be noted that the predictions of AB06 demonstrate a better agreement with the amplitudes of Val de Bois at distances longer than the distance range of interest of this study.

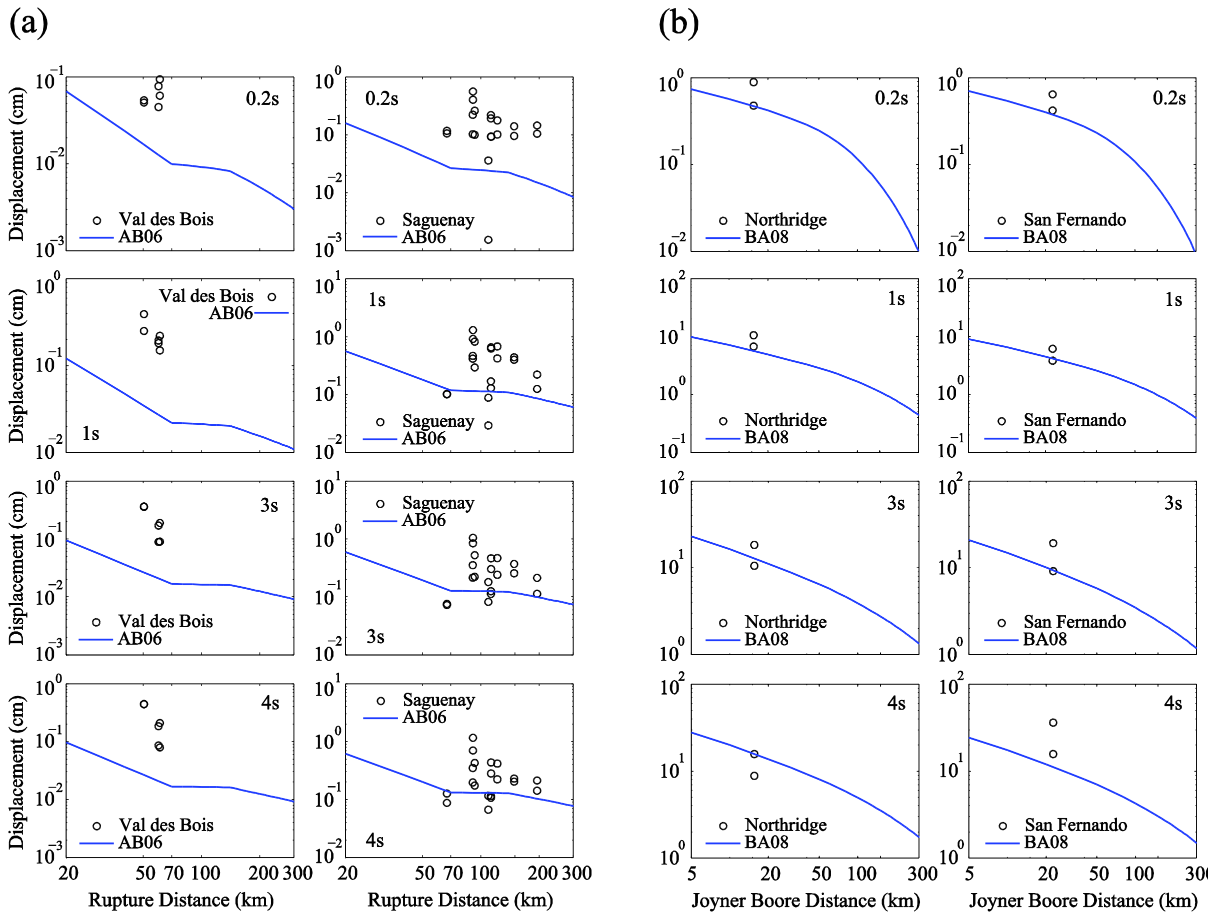

Figure 4.1. Comparison between the displacements from the GMPEs and the historical records in (a) ENA and (b) WNA

In contrast to Val des Bois, the AB06 equations provide a better prediction of displacements of Saguenay. Similar to Val des Bois, the agreement improves as the period increases. The AB06 predictions were also compared to the rest of the historical records mentioned in Table 2.1. The overall results showed an apparent improvement in the agreement between the predictions and the real amplitudes as the period increased. The same pattern was visible at longer distances. However, an over prediction of displacement amplitudes was observed at very short distances (≤ 5km).

4.2.2. BA08

The Northridge and San Fernando events (Table 2.1), as the western historical records, were compared to the predictions of AB08. Fig. 4.1b shows the predictions of BA08 for stiff soil site and displacement amplitudes induced by the historical records at periods of 0.2, 1, 3 and 4s.

It is observed that the BA08 equations slightly under predict the displacement demands at shorter periods in the case of Northridge. However, the equations demonstrate minor over-prediction of the displacement in very long periods (e.g. 4s). Nevertheless, the predicted distances are in acceptable agreement with the real displacements.

BA08 demonstrates a similar pattern of prediction in comparison to the records of San Fernando at short periods. The under prediction in this case is more pronounced than the displacements of Northridge. However, in the intermediate periods a better prediction is observed. In contrary to Northridge, the equations under predict the displacements at very long periods (e.g. 4s).

It has to be noted that generally the GMPEs are not derived to perfectly match individual records or events. These equations normally represent the median or the mean spectral values corresponding to the region under study. Thus presentation of a wide selection of records of similar specifications (magnitude, site condition, etc.) is needed to observe the validity of the predictions. For example, in the scale of this study, the events of San Fernando and Northridge are quite similar in magnitude ($6.6M_w$ and $6.7M_W$ respectively) and the site condition (stiff soil). If the right column of sub-figures in Fig. 4.1b is projected on the left one, the resulting figure shows an acceptable prediction of the corresponding displacements.

5. CONCLUSION

This paper presented a systematic study of the seismic displacement demands in ENA and WNA to provide an insight into one of the principal ingredients of displacement-based design and evaluation. A selection of historical ground motions, 11 events in total, two sets of simulated ground motions, 392 records in total, were studied and the effects of magnitude and hypocentral and fault distances representative of North American seismic hazard on the displacement demands were discussed. Three general trends in historical ground motions were determined in ENA and two such trends were observed in WNA. The general trends were also observed in the majority of the computed spectra of the simulated ground motions.

In general, higher seismic displacement demands were observed in the west with a monotonic increase up to 4s in some cases. The computed displacement spectra confirmed that displacement amplitudes decreased with larger hypocentral distances, while significantly higher displacement demands were generated by ground motions with higher magnitudes and shorter distances.

Two suites of ground motion prediction equations were studied to validate the applicability of the proposed equations to the displacement demands in North America. The predictions of displacement demands are acceptable in the period and distance range of study in comparison to the majority of the historical records.

This work provided a first thorough characterization of seismic demands in North America, and will serve as the basis for further research to reduce the uncertainties in the prediction of spectral displacements particularly for longer periods.

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