This is a preprint of an article accepted for publication in Journal of Earthquake Engineering on 17 November 2014. The published article is available online at
http://www.tandfonline.com/doi/abs/10.1080/13632469.2014.990654
To be cited as: Daneshvar P., Bouaanani N. 2015. Prediction of high-damping spectral displacements in Eastern North America. Journal of Earthquake Engineering, 19: 701-730.

Prediction of high-damping seismic demands in Eastern North America

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Abstract

This paper investigates high-damping seismic demands and associated damping reduction factors in Eastern North America (ENA). A database of hybrid empirical records with moment magnitudes $M \geq 6.0$ is first studied to evaluate 5%- to 30%-damped seismic demands. A new magnitude- and distance-based equation is proposed to predict ENA spectral displacements and then used to characterize their sensitivity to variations in period, magnitude, epicentral distance and site conditions. The proposed equation is also used to assess damping reduction factors in ENA. The results contribute to improved assessment of seismic demands in ENA while accounting for added-damping in structural seismic design.

Keywords: High-damping seismic demands, Damping reduction factors, ENA seismic hazard, Displacement spectra, Pseudo-acceleration spectra, Ground motion prediction equations.

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1. Introduction

Damage and loss caused by Loma Prieta (1989) and Northridge (1994) earthquakes promoted the application of energy dissipation systems to various structures (Ramirez et al. 2002) either as a retrofit strategy or as a measure to prevent or diminish damage to structural members. Utilization of simplified seismic design or evaluation methodologies incorporating added-damping effects of such systems requires the determination of spectral amplitudes associated with damping levels higher than the common 5% of critical. For example, high-damping displacement spectra are needed to determine the displacements across seismic isolation devices in bridge structures according to the simplified design methods prescribed in the Canadian Highway Bridge Design Code (CAN/CSA S6). High-damping seismic demands and damping modification factors corresponding to ground motions in various regions have been investigated by several researchers such as Newmark and Hall (1973, 1982), Tolis and Faccioli (1999), Borzi et al. (2001), Atkinson and Pierre (2004), Faccioli et al. (2004), Karakostas et al. (2007), and Faccioli and Villani (2009). Studies of seismic demands in Europe also resulted in ground motion prediction equations (GMPE) for displacements (Bommer and Elnashai 1999, Akkar and Bommer 2007, Cauzzi and Faccioli 2008).

Most of the research characterizing seismic hazard in Eastern North America (ENA), a zone with moderate to low seismic activity, has focused on the prediction of earthquake-induced pseudo-accelerations for a 5% critical damping level (Atkinson and Boore 1995, Somerville et al. 2001, Silva et al. 2002, Campbell 2003, Atkinson and Boore 2006, Campbell 2007, Atkinson 2008, Pezeshk et al. 2011). Some of these results have led to seismic hazard maps, site-specific uniform hazard pseudo-acceleration spectra and corresponding disaggregation data (NRCC 2005, NRCC 2010, ASCE7-10, USGS, Atkinson and Beresnev 1998, Hwang et al. 2001, Adams and Atkinson 2003, Adams and Halchuk 2004, Atkinson 2009, Shahjouei and Pezeshk 2013). Despite the increasing application of energy dissipating and seismic isolation devices to different types of structures, and the emergence of seismic design and evaluation methods which require spectral amplitudes at damping levels above 5% critical, little attention has been devoted to predicting seismic demands corresponding to high-damping levels in ENA. Furthermore, damping reduction factors corresponding to seismic hazard in this region have been rarely addressed. The main objective of this paper is to contribute to filling this gap by characterizing high-damping spectral displacements induced by ENA-type ground motions and developing magnitude- and distance-based equations to predict these seismic demands.

2. Records used

ENA records of significant magnitude are sparse and most of the available ground motions are of low magnitude or were recorded at relatively long distances. A large number of ENA records have been complied as part of the NGA-East project (Goulet et al. 2013). However, most of these records are from events of moment magnitudes M lower than 5.5 and far field epicentral distances *R* higher than 50 km (Goulet et al. 2013), which implies fairly low seismic amplitudes. One of the objectives of the present work is to characterize high-damping seismic demands and corresponding damping reduction factors for events with moment magnitudes larger than M = 6.0, which are of more interest to structural engineering applications. For this purpose, we investigate seismic demands corresponding to a set of hybrid empirical ground motions originally proposed by McGuire et al. (2001) to conduct seismic analyses in Central and Eastern United States (CEUS) or ENA.

The original data set covers a wide range of magnitudes and distances to compensate for the limited number of recorded ground motions in these regions. McGuire et al. (2001) generated this data set by applying a scaling process to ground motions recorded in seismically active regions including California, Montana, Italy, Uzbekistan, Mexico, Georgia, Taiwan, Turkey, Japan and Iran. The data set also includes records from Saguenay (1988) and Nahanni (1985) events which are typical of ENA seismic hazard. A single corner frequency point source model was adopted by McGuire et al. (2001) to determine transfer functions relating ground motions from seismically active regions to ENA ground motions of the same magnitude, distance and site condition. The resulting hybrid empirical records maintain realistic inter-component phase, amplitude relationships and frequency to frequency variability (McGuire et al. 2001). A total of 552 horizontal hybrid records provided for rock and soil sites are selected from this database for the purpose of the present work. The distinction between the site conditions is made through V_{s30}, the average shear-wave velocity in the uppermost 30 m, based on the NEHRP site classification. Records having a $V_{s30} \geq 360$ m/s are categorized as rock sites, i.e. NEHRP site classes A, B, and C, and those with a $V_{s30} < 360$ m/s are categorized as deep soil sites, i.e. NEHRP site classes D and E. The selected records cover a moment magnitude range of M = 6.0 to M = 7.6 and epicentral distances *R* from 1 to 250 km. Figure 1 shows the M-*R* distributions of the selected records.

As widely known, computation of reliable displacement time-histories and spectra from recorded ground motions is usually associated with difficulties related to their processing such as base-line correction, filtering issues (more pronounced effects on displacement spectra), long-period drift, and analog-to-digital conversion for data recorded decades ago using analog instruments (Bommer and Elnashai 1999, Boore 2005, Paolucci et al. 2008, Akkar and Boore 2009). Although detailed information about the processing of the above-described hybrid records was not provided by McGuire et al. (2001), it is assumed, according to an example given in the same reference, that casual four-pole Butterworth high-pass and low-pass filters were applied except for near source short duration records where acasual Butterworth filters were used. As high-pass filters can significantly affect the spectral displacements resulting from the processed records at long period ranges, the displacement spectrum corresponding to each record is not considered beyond the period at which the record is filtered. Figure 2 illustrates the range of applied high-pass filters for the selected records. Results are shown next for a period range up to 2.0 s to reinforce confidence in the predicted spectral amplitudes.

3. Target spectral pseudo-accelerations and spectral matching

The hybrid empirical records were originally developed to conduct seismic analyses after being scaled or matched to target spectral pseudo-accelerations of interest (McGuire et al. 2001). The aim of this work is to characterize seismic demands that are consistent with seismic hazard in ENA. Accordingly, we generate target spectral pseudo-accelerations using the new model underlying seismic hazard maps and uniform hazard spectra of the 2015 editions of the National Building Code of Canada (NBCC) and the Canadian Highway Bridge Design Code (CAN/CSA-S6). This model, developed by Atkinson and Adams (2013) and referred to as AA13 hereafter, consists of a central GMPE and upper and lower GMPEs to account for epistemic uncertainty about the central one. The central GMPE is determined by calculating the geometric mean of five peer reviewed mean GMPEs available in the literature. The geometric mean plus/minus (±) its standard deviation is considered as the upper/lower GMPE. The five GMPEs are SGD02SC (Silva, Gregor and Darragh 2002, the single corner model with variable stress), SGD02DC (Silva, Gregor and Darragh 2002, the double corner model with magnitude saturation), AB06 (Atkinson and Boore 2006, 2011), A08 (Atkinson

2008) and PZT11 (Pezeshk, Zandieh and Tavakoli 2011). The final predictions are provided in terms of moment magnitudes and epicentral distances for B/C site condition. The reader is referred to Atkinson and Adams (2013) for more details about the determination of the central, upper and lower GMPEs, distance metric conversions, and also conversion factors used to modify the predictions corresponding to different site conditions to represent those of B/C site condition. The spectral pseudo-accelerations provided by the central GMPE of the AA13 model for different moment magnitudes and epicentral distances are selected as target spectra for the purpose of the present study. To maintain compatibility between site conditions, conversion factors proposed by Atkinson and Adams (2013) and Atkinson and Boore (2011) are adopted to account for ground motions on rock, i.e. site class A (rock sites), and deep soil sites, i.e. site class D (soil sites). To be consistent with distance metrics used in the table of predictions provided by Atkinson and Adams (2013), the epicentral distances corresponding to the hybrid empirical record are taken from PEER Ground Motion Database (http://peer.berkeley.edu/nga). The computer program RSPMatch2005 (Abrahamson 1992, Hancock et al. 2006) is used to match the 5%-damped pseudo-acceleration response spectrum of each hybrid empirical record with a given moment magnitude M ($6.0 \leq \mathrm{M} \leq 7.6$) and epicentral distance R ($1 \leq R \leq 250$ km) to the AA13 target spectral pseudo-accelerations corresponding to the same M and R. Spectral matching is carried out over a period range up to 2.0 s using two passes considering a tolerance of 5%. This matching process resulted in a total of 523 acceptably matched hybrid records corresponding to rock and soil sites. The final selection consists of 244 records on rock sites, and 279 on soil sites.

4. 5%-damped seismic demands

The 5%-damped displacement spectra of the matched hybrid records described above are computed for periods up to T = 2.0 s and epicentral distances up to R = 250 km. The computed spectra are divided into two bins based on the corresponding site condition, i.e. rock or soil sites. Regression analyses using the least square approach are performed on the obtained 5%-damped spectral displacement ordinates of the records from each bin. To investigate the trends in each bin, we first propose a simple functional form which is linear in logarithmic scale with a minimum number of coefficients

$$\log_{10} S_{\mathrm{d}}(T) = a_1 + a_2 \mathrm{M} + a_3 \log_{10} R + a_4 R + a_5 S_{\mathrm{S}} \tag{1}$$

where $S_{\mathrm{d}}(T)$ is the spectral displacement (m) at a period T of a random horizontal component of a ground motion of moment magnitude M and epicentral distance R (km) and where a_1, a_2, a_3, a_4 and a_5 are coefficients determined by regression analyses. S_{S} in Eq. (1) is a dummy variable that takes a value of 0 when predicting displacements for rock sites and a value of 1 for soil sites. The adopted functional form satisfies the relationship between the logarithm of spectral ordinates and magnitude. It also takes account of inelastic and seismic wave geometric attenuation as a function of the distance from the source (Boore and Joyner 1982).

Comparisons between the predictions of Eq. (1) and the records in the database at different periods are illustrated in Figures 3(a) and (b). A very good agreement is observed between the predictions of the proposed equation and the spectral displacements from the matched hybrid records. The equation tends to slightly over predict a number of displacement amplitudes at very short distances. However, predictions improve as the distance increases. Figures 3(a) and (b) also illustrate the combined effect of magnitude and distance on displacements. The predicted displacements decrease with a steep slope towards longer distances, which illustrates the pronounced attenuating effect of increasing epicentral distance at intermediate and high magnitudes. It can be observed from Figures 3(a) and (b) that the difference between predictions corresponding to minimum and maximum considered magnitudes at a given period increases as the period lengthens. Figures 3(a) and (b) also clearly show that regardless of spectral displacement amplitudes, the studied seismic demands follow similar magnitude- and distance-based trends on both rock and soil sites.

The proposed functional form of Eq. (1) does not consider saturation effects, i.e. Spectral amplitudes from large earthquakes are relatively independent from magnitude (magnitude saturation) and/or distance (distance saturation) in the near field. These effects are however clearly seen in Figures 3(a) and 3(b). Therefore, a second functional form is proposed to consider such effects which generally result in more realistic predictions at shorter distances (Campbell 1981, Silva et al. 2002, Campbell and Bozorgnia 2008, Pezeshk et al. 2011)

$$\begin{aligned}\log_{10} S_{\mathrm{d}}(T) = {} & a_1 + a_2\mathrm{M} + a_3(\mathrm{M}-6)^2 + a_4\log_{10}\left(R + a_5\exp(\mathrm{M}-6)\right) \\ & + a_6\left(R + a_5\exp(\mathrm{M}-6)\right) + a_7 S_{\mathrm{S}}\end{aligned} \tag{2}$$

The saturation term in Eq. (2), i.e. $a_5\exp(\mathrm{M}-6)$, is adapted from the one originally proposed by Campbell (1981), i.e. $c_1\exp(c_2\mathrm{M})$. The added saturation term makes Eq. (2) a nonlinear model function and thus coefficients a_1, a_2, a_3, a_4, a_5, a_6 and a_7 are determined through nonlinear regression analyses.

Comparisons between the predictions of Eq. (2) and the records in the database at different periods are illustrated in Figures 4(a) and (b). Similar to Eq. (1), a very good agreement is observed between the predictions of Eq. (2) and the spectral displacements from the matched hybrid records. However, the effect of the added saturation term is now clearly seen. Both magnitude and distance saturations are observed in the predictions of Eq. (2) which are in agreement with the trends in the computed displacements from the records in the database. The pronounced attenuating effect corresponding to the increase in epicentral distance at intermediate and high magnitudes is also captured by the proposed equation. Observations of the relation between the considered maximum and minimum magnitudes and the studied period are akin to those of Eq. (1).

Figures 5 and 6 compare the 5%-damped predicted spectral pseudo-accelerations S_a from Eqs. (1) and (2), i.e. multiplication of S_{d} by $(4\pi^2)/T^2$ to obtain S_{a} at a given period *T*, to those obtained from the central and individual GMPEs of the AA13 model. These results clearly show that the 5%-damped spectral pseudo-accelerations and displacements provided by the proposed equations based on the selected hybrid records are in very good agreement with the predictions of the AA13 model for the considered rock and soil sites. However, Eq. (2) tends to under predict spectral pseudo-accelerations corresponding to magnitudes higher than M = 7.0 and distances up to approximately *R* = 30 km. This roots from the lack of records at these magnitude and distance ranges combined with the magnitude and distance saturation term introduced in the equation. Eq. (1) provides a better prediction at the same M-*R* combinations due to the linear continuous increase in the predictions towards shorter distances as a result of the absence of a magnitude and distance saturation term. This term is however to be included considering generally observed trends from other records (Campbell 1981, Silva et al. 2002, Campbell and Bozorgnia 2008, Pezeshk et al. 2011). For this reason, only Eq. (2) will be used next to determine higher damping seismic demands and associated damping reduction factors. The coefficients corresponding to Eq. (2) are provided in Table 1. We note that the spectral displacements predicted by Eq. (2) are the mean expected displacement amplitudes for the region as the underlying spectra have been spectrally matched to the central AA13 GMPE.

To show the goodness of fit of the predictions with respect to the spectra of the matched records, the mean values of the logarithm of the residuals corresponding to Eq. (2) are also provided in Table 1 for both site classes. As the spectra have been matched to AA13 central GMPE in the period range of study, the reader can refer to Atkinson and Adams (2013) for further information about the determination of upper and lower GMPEs and related standard deviations. Validation of the predictions of Eq. (2) against computed higher damping spectral displacements of the hybrid records will be presented in the next section.

5. High-damping seismic demands

The 10%-, 15%-, 20%-, 25%- and 30%-damped displacement response spectra of the hybrid records described previously are first computed. For each damping level, nonlinear regression analyses using the least square approach are performed on the obtained damped spectral ordinates. To maintain uniformity, the same functional form as in Eq. (2) is adopted for damping levels higher than 5%. Tables 2 to 6 list the coefficients and the mean values of the logarithm of residuals resulting from regression analyses. Figures 7 and 8 show the comparison between the computed spectral displacements and the predictions corresponding to damping levels of 15% and 30% at different periods. Trends similar to those observed for the 5%-damped predicted and computed spectral displacements are seen at higher damping levels for ground motions for both rock and soil sites.

Figures 9 and 10 show the spectral displacements generated using the functional form of Eq. (2) and the coefficients provided in Tables 1 to 6, corresponding to a number of magnitude-distance combinations at different damping levels. Figures 9 and 10 clearly demonstrate the expected effect of magnitude and distance on displacement demands through the studied period range, i.e. larger displacements correspond to higher magnitudes whereas an increase in epicentral distance has an opposite effect on seismic demands. It is also observed that the decline in the increasing branch of displacement demands disappears with increasing magnitude, a behavior that affects the definition of the control periods of displacement design spectra. Figures 9 and 10 also show that displacement spectral shapes tend to become smoother at higher damping ratios. This effect is more pronounced at lower magnitudes and shorter distances in particular, as the 5%-damped displacement spectra for rock and soil sites are smoother at higher magnitudes. As mentioned previously, it is suggested that the provided equation and coefficients corresponding to higher magnitudes, i.e. M > 7 and shorter distances, i.e. approximately $R < 30$ km, be used with caution due to the small number of near field hybrid records in the database. Finally, we note that the high damping spectral pseudo-accelerations at a given period T can be obtained from Eq. (2) and Tables 2 to 6 through multiplication of S_d by $(4\pi^2)/T^2$.

6. Application to assessment of damping reduction factors in ENA

Damping reduction factors, denoted hereafter as η, are commonly used to evaluate the effect of damping on seismic demands and are defined as the ratio between the 5%-damped displacement spectrum $S_\mathrm{d}(T, 5\%)$, respectively pseudo-acceleration $S_\mathrm{a}(T, 5\%)$, and displacement spectra $S_\mathrm{d}(T, \xi)$, resp. pseudo-acceleration $S_\mathrm{a}(T, \xi)$, for higher damping levels ξ at a period T

$$\eta(T,\xi) = \frac{S_\mathrm{d}(T,\xi)}{S_\mathrm{d}(T,5\%)} = \frac{S_\mathrm{a}(T,\xi)}{S_\mathrm{a}(T,5\%)} \tag{3}$$

To investigate the effects of moment magnitude and distance on η factors, the studied records are first classified into 8 bins for each site condition, i.e. rock or soil, as indicated in Table 7. The η factors corresponding to damping levels of 10%, 15%, 20%, 25% and 30% for each record of the 8 bins are then computed for periods up to 2.0 s. Figures 11 and 12 show the means of the η factors obtained for each bin. We note that the jagged curves of η factors from Bin IV for rock sites are due to the small number of records in this bin. The pronounced period dependency of computed η factors particularly at shorter distances, i.e. Bin I, mainly roots from the high frequency content of the ground motions in ENA. High-frequency ground motions expose a structure having a short vibration period to more cycles in comparison to a structure vibrating at a longer period and thus the effect of damping is more significant on short-period structures (Naeim and Kircher 2001). This results in relatively lower η factors in the short period range. High magnitude ground motions with epicenters at relatively longer distances have more pronounced effects on long-period structures. This explains the greater effect of damping at longer periods and thus observation of slightly lower η factors at longer periods for motions from farther distances. This trend can be observed in Figures 11 and 12 where the effect of distance on η factors for rock and soil sites is generally not significant at short periods, while it is more pronounced towards longer periods. At higher damping levels, this effect increases the difference between the η factors at longer periods as the ground motions in Bin I are not expected to significantly affect structures with vibration periods in this range and hence the larger corresponding η factors. Romero and Rix (2005) and Darragh and Shakal (1991) report ground motion amplifications on soil sites at longer periods which explains the observed effect of damping for soil sites even at longer periods, e.g. Figure 11(b). However, as magnitude increases, nonlinear soil behavior results more predominant damping effects at short periods while they decrease as period lengthens (Romero and Rix 2005), i.e. Figure 12(b). Figures 11 and 12 reveal that, for rock sites, magnitude has generally less significant effects on η factors than distance in the period range of study. Similar to magnitude, distance influences the η factors from soil sites more noticeably than those from rock sites for periods up to 2.0 s.

Several equations have been proposed in the literature to approximate η factors considering seismic hazard in different regions. Newmark and Hall (1973, 1982) [NH1973, NH1982], used the horizontal and vertical components of 14 pre-1973 California ground motions to determine maximum spectral amplitudes corresponding to damping levels lower than 20%. Considering the median values of the damped peak amplitudes, equations were proposed for displacement reduction factors. Bommer et al. (2000) [BEW2000], studied the damped displacement spectra of ground motion components from 43 shallow earthquakes recorded on rock, stiff soil and soft soil sites in Europe and the Middle East. They proposed an equation which was implemented in Eurocode 8 (2004). Lin and Chang (2003) [LC2003], proposed an equation for damping reduction factors based on the displacement responses of SDOF systems for periods between 0.01 and 10 s and damping ratios between 2% and 50%. The database of the studied records consisted of 1037 accelerograms recorded in the United States. The Chinese guidelines for seismically isolated structures (Zhou et al. 2003) [ZWX2003], propose a period independent equation. Atkinson and Pierre (2004) [AP2004], extended the simulations performed to develop the GMPE of Atkinson and Boore (1995) for moment magnitudes between 4 and 7.25 at hypocentral distances of 10 to 500 km. The 1%, 2% 3%, 5%, 7%, 10% and 15%-damped response spectra were computed and finally a magnitude and distance independent set of η factors were proposed for periods between 0.05 and 2.0 s, magnitudes greater than 5 and distances shorter than 150 km. AASHTO (2010) includes a simplified equation to obtain the damping reduction factor for damping levels up to 50%, while recommending caution with factors for damping ratios greater than 30% corresponding to hysteretically-damped isolation systems. The same η factors are prescribed by ASCE7-10 for isolated structures. ASCE7-10 also prescribes a set of damping modification factors for structural response which is slightly different from those prescribed for isolated systems particularly at higher damping levels.

Figure 13 compares the damping reduction factors determined using the proposed functional form of Eq. (2) and the coefficients provided in Tables 1 to 6 to predictions of the above-mentioned equations for records on rock and soil sites at damping levels of 10%, 20% and 30%. The results show that period-independent equations fail to appropriately predict variations of damping reduction factors particularly at longer periods where a constant increase in the η factors is observed. It is also seen that period-dependent damping reduction factors by Lin and Chang (2003) are not in good agreement with the computed η factors as they: (i) over-estimate η factors for periods up to between 1.5 and 1.7 s for both rock and soil sites, and (ii) under-estimate η factors for soil sites after these periods. We note that it is somehow expected that the above described period-independent equations as well as the period-dependent relationship proposed by Lin and Chang (2003) do not fully match η factors in ENA since they were developed using record databases mainly from other regions. Predictions by Atkinson and Pierre (2004) show relatively better agreement with the observed variation in η factors within their range of application, i.e. $\xi \leq 10\%$. Figure 13 also shows that the η factors predicted using the proposed functional form in Eq. (2) and the coefficients provided in Tables 1 to 6 are in good agreement with the computed η factors illustrated in Figures 11 and 12. These results verify the applicability of the proposed equation for different damping levels for horizontal motions on both rock and soil sites.

7. Summary and conclusions

This work aimed at assessing seismic demands and associated damping reduction factors corresponding to ENA horizontal ground motions with moment magnitudes larger than M = 6.0, which are of more interest to structural engineering applications. For this purpose, a database of 552 horizontal hybrid empirical records was first compiled to cover appropriate magnitude and epicentral distance ranges. Each selected record with a given moment magnitude M, with $6.0 \leq M \leq 7.6$, and epicentral distance R, with $1 \leq R \leq 250$ km, was then spectrally matched to the 5%-damped spectral pseudo-accelerations provided for the same M and R combination by GMPEs accounting for recent developments related to ENA seismic hazard. The matched records were used to compute 5%-, 10%-, 15%-, 20%-, 25%- and 30%-damped spectral displacements on which nonlinear regression analyses were conducted to obtain a magnitude- and distance-based prediction equation for periods up to 2.0 s. The majority of predicted displacement spectra followed a similar trend showing a shift in peak displacement amplitudes towards longer periods as moment magnitude increases. The results also confirmed the expected direct (respectively reciprocal) relation between displacement demands and magnitude (resp. distance). The proposed equation was also used to characterize damping reduction factors considering the effects of moment magnitude, epicentral distance and site condition. The period dependency of damping reduction factors, particularly at higher damping levels, was illustrated and discussed. The effect of distance and magnitude on damping reduction factors was found to be less significant than the effect of period particularly at shorter periods. We also observed that the effect of distance on damping reduction factors is more pronounced for soil sites as well as the effect of moment magnitude. The results of this work will contribute to an improved assessment of seismic demands considering the particularities of seismic hazard in ENA while accounting for added-damping in the design of structures equipped with energy dissipation systems. We finally mention that the results presented in this work focused on a period range up to 2.0 s and that further research is needed to assess ENA seismic demands at longer periods.

Acknowledgements

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canadian Seismic Research Network (CSRN).

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LIST OF TABLES

Table 1. Coefficients and mean values of the logarithm of residuals of Eq. (2) for 5% damping corresponding to horizontal motions on rock and soil sites

	Coefficients for Eq. (2) at 5% damping								
T (s)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Mean log. Residuals	
								Rock	Soil
0.040	-5.36409	0.51781	-0.02660	-1.20615	1.94522	-0.00121	0.01313	0.0033	0.0058
0.045	-5.42371	0.55313	-0.04709	-1.23885	2.10822	-0.00100	0.01815	0.0031	0.0059
0.050	-5.33824	0.54642	-0.04266	-1.18596	2.06082	-0.00140	0.01230	0.0026	0.0057
0.055	-5.28286	0.54342	-0.04673	-1.15881	1.84157	-0.00135	0.02520	0.0027	0.0058
0.060	-5.16751	0.52369	-0.03867	-1.10224	1.66305	-0.00159	0.04167	0.0023	0.0058
0.065	-5.08995	0.53142	-0.04033	-1.13928	1.99686	-0.00133	0.05548	0.0025	0.0059
0.070	-4.97158	0.51830	-0.03842	-1.12501	1.80661	-0.00130	0.07043	0.0030	0.0060
0.075	-4.99378	0.53163	-0.04731	-1.12641	1.81361	-0.00124	0.07912	0.0028	0.0062
0.080	-4.86016	0.51973	-0.03521	-1.13054	1.89214	-0.00125	0.08949	0.0028	0.0059
0.085	-4.88796	0.53059	-0.04180	-1.12555	1.88596	-0.00122	0.10247	0.0031	0.0062
0.090	-4.82748	0.53252	-0.04173	-1.14367	1.95553	-0.00109	0.11395	0.0031	0.0062
0.095	-4.88984	0.54414	-0.05079	-1.12032	1.91291	-0.00117	0.12638	0.0030	0.0061
0.100	-4.79011	0.53591	-0.04589	-1.12276	2.01155	-0.00118	0.13958	0.0031	0.0055
0.150	-4.72314	0.53814	-0.05641	-1.01085	1.33508	-0.00136	0.19303	0.0020	0.0050
0.200	-4.71125	0.56477	-0.07425	-1.01799	1.35031	-0.00111	0.24687	0.0019	0.0057
0.250	-4.73268	0.58048	-0.07845	-1.00088	1.28405	-0.00106	0.27791	0.0019	0.0059
0.300	-4.78418	0.60175	-0.08827	-1.00164	1.23008	-0.00092	0.31029	0.0020	0.0060
0.350	-4.85896	0.62287	-0.09375	-0.99904	1.23666	-0.00084	0.33681	0.0020	0.0060
0.400	-4.95961	0.64505	-0.10178	-0.98650	1.21224	-0.00082	0.35758	0.0020	0.0061
0.450	-5.00303	0.66312	-0.10666	-1.00062	1.26732	-0.00066	0.37279	0.0019	0.0066
0.500	-5.09159	0.68340	-0.11474	-0.99696	1.25255	-0.00059	0.39196	0.0020	0.0068
0.550	-5.09255	0.68860	-0.11181	-0.99826	1.24029	-0.00055	0.39540	0.0020	0.0065
0.600	-5.18577	0.70700	-0.11662	-0.99302	1.28346	-0.00056	0.39928	0.0019	0.0062
0.650	-5.23595	0.72093	-0.11951	-1.00186	1.30524	-0.00046	0.39672	0.0018	0.0062
0.700	-5.29120	0.73113	-0.12133	-0.99054	1.24791	-0.00048	0.39915	0.0018	0.0066
0.750	-5.32340	0.74316	-0.12322	-1.00360	1.32564	-0.00039	0.39993	0.0018	0.0069
0.800	-5.38102	0.75159	-0.12480	-0.98950	1.21633	-0.00040	0.40252	0.0019	0.0067
0.850	-5.41599	0.76176	-0.12733	-0.99280	1.28919	-0.00036	0.40417	0.0019	0.0063
0.900	-5.46825	0.77352	-0.12997	-0.99558	1.30281	-0.00032	0.40819	0.0019	0.0062
0.950	-5.54587	0.78384	-0.13369	-0.97408	1.21684	-0.00039	0.40753	0.0019	0.0057
1.000	-5.50090	0.78238	-0.12970	-0.98660	1.26435	-0.00031	0.40351	0.0019	0.0049
1.100	-5.58107	0.80263	-0.13285	-1.00070	1.33763	-0.00022	0.40118	0.0018	0.0047
1.200	-5.67449	0.81982	-0.13291	-0.99445	1.40916	-0.00024	0.40101	0.0018	0.0048
1.300	-5.81050	0.84640	-0.14105	-1.00010	1.44695	-0.00019	0.39926	0.0019	0.0046
1.400	-5.81590	0.85126	-0.13818	-1.00346	1.41810	-0.00015	0.39704	0.0018	0.0047
1.500	-5.88750	0.86567	-0.14122	-1.00596	1.42432	-0.00008	0.39808	0.0018	0.0048
1.600	-5.97837	0.88280	-0.14421	-1.00522	1.46054	-0.00006	0.39785	0.0020	0.0050
1.700	-6.07042	0.89791	-0.14751	-0.99618	1.40383	-0.00009	0.39653	0.0020	0.0050
1.800	-6.05388	0.89796	-0.14191	-0.99756	1.41574	-0.00006	0.39542	0.0019	0.0055
1.900	-6.09457	0.91018	-0.14246	-1.00899	1.52445	-0.00004	0.39470	0.0019	0.0055
2.000	-6.00353	0.90184	-0.13388	-1.02178	1.47770	0.00005	0.39183	0.0020	0.0060

Table 2. Coefficients and mean values of the logarithm of residuals of Eq. (2) for 10% damping corresponding to horizontal motions on rock and soil sites

	Coefficients for Eq. (2) at 10% damping								
T (s)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Mean log. Residuals	
								Rock	Soil
0.040	-5.56486	0.53818	-0.04010	-1.21183	1.98772	-0.00126	0.02677	0.0049	0.0087
0.045	-5.53269	0.54962	-0.04266	-1.21172	2.17812	-0.00131	0.04040	0.0043	0.0069
0.050	-5.52004	0.57044	-0.04990	-1.24616	2.33246	-0.00109	0.04322	0.0046	0.0071
0.055	-5.24699	0.51772	-0.02924	-1.15273	1.71609	-0.00148	0.05358	0.0041	0.0068
0.060	-5.24915	0.52740	-0.04035	-1.14854	1.61865	-0.00129	0.06567	0.0048	0.0072
0.065	-5.20871	0.52879	-0.04356	-1.13179	1.68188	-0.00137	0.08147	0.0045	0.0072
0.070	-5.10274	0.53017	-0.04128	-1.16590	1.93074	-0.00117	0.09179	0.0045	0.0075
0.075	-5.01567	0.52373	-0.03713	-1.15622	1.93405	-0.00118	0.09683	0.0042	0.0072
0.080	-4.96694	0.52469	-0.03386	-1.15756	1.99910	-0.00120	0.10665	0.0044	0.0070
0.085	-5.12303	0.55709	-0.05335	-1.15619	1.98023	-0.00115	0.11465	0.0044	0.0072
0.090	-5.04161	0.55064	-0.05280	-1.15030	1.94404	-0.00119	0.12526	0.0041	0.0076
0.095	-5.00430	0.54789	-0.05206	-1.13810	1.88925	-0.00121	0.13821	0.0043	0.0073
0.100	-4.96123	0.54190	-0.05403	-1.11763	1.82023	-0.00123	0.14857	0.0043	0.0071
0.150	-4.78224	0.53497	-0.04464	-1.04120	1.52143	-0.00145	0.20171	0.0038	0.0064
0.200	-4.60368	0.53339	-0.05388	-1.04310	1.46014	-0.00111	0.24767	0.0038	0.0070
0.250	-4.71279	0.55474	-0.06203	-0.99079	1.16301	-0.00119	0.27564	0.0031	0.0074
0.300	-4.69187	0.56608	-0.06786	-0.99118	1.19800	-0.00110	0.30716	0.0033	0.0072
0.350	-4.83819	0.59646	-0.08441	-0.98253	1.09643	-0.00093	0.33537	0.0036	0.0071
0.400	-4.88727	0.61126	-0.08508	-0.97265	1.09569	-0.00094	0.35383	0.0034	0.0073
0.450	-5.03447	0.64964	-0.10127	-0.99986	1.19852	-0.00074	0.36733	0.0033	0.0076
0.500	-5.17844	0.67513	-0.11230	-0.98384	1.07042	-0.00077	0.38333	0.0038	0.0076
0.550	-5.36829	0.71281	-0.12859	-0.99449	1.12811	-0.00064	0.39040	0.0037	0.0079
0.600	-5.27946	0.70810	-0.11883	-1.01564	1.25097	-0.00049	0.39362	0.0034	0.0075
0.650	-5.38741	0.73105	-0.12763	-1.01697	1.31240	-0.00048	0.39219	0.0032	0.0072
0.700	-5.38383	0.73206	-0.12361	-1.00727	1.27830	-0.00047	0.39363	0.0033	0.0074
0.750	-5.41883	0.74157	-0.12063	-1.00374	1.44286	-0.00056	0.39627	0.0035	0.0073
0.800	-5.49441	0.75608	-0.12606	-1.00227	1.32213	-0.00048	0.39507	0.0038	0.0075
0.850	-5.60347	0.77212	-0.13405	-0.98356	1.17878	-0.00050	0.39468	0.0038	0.0076
0.900	-5.63486	0.77934	-0.13612	-0.98073	1.10627	-0.00045	0.39581	0.0033	0.0073
0.950	-5.68186	0.78777	-0.13988	-0.97336	1.06271	-0.00041	0.39754	0.0031	0.0073
1.000	-5.66207	0.79198	-0.13677	-0.99196	1.21440	-0.00034	0.39776	0.0031	0.0068
1.100	-5.70892	0.81173	-0.13878	-1.02373	1.43229	-0.00022	0.39953	0.0030	0.0065
1.200	-5.76802	0.82145	-0.13684	-1.01092	1.39909	-0.00022	0.40079	0.0030	0.0063
1.300	-5.89832	0.84233	-0.14248	-0.99777	1.31651	-0.00025	0.39948	0.0031	0.0064
1.400	-5.81453	0.83731	-0.13088	-1.01972	1.29801	-0.00011	0.39569	0.0029	0.0065
1.500	-5.85804	0.84912	-0.13045	-1.02890	1.32973	-0.00001	0.39823	0.0030	0.0067
1.600	-5.92241	0.86538	-0.13240	-1.03799	1.44684	0.00000	0.39858	0.0035	0.0072
1.700	-5.93928	0.87038	-0.12882	-1.03341	1.39103	-0.00002	0.39418	0.0035	0.0072
1.800	-5.91084	0.87118	-0.12182	-1.04327	1.41387	0.00001	0.39306	0.0034	0.0079
1.900	-5.83344	0.86746	-0.11493	-1.06411	1.47658	0.00013	0.39155	0.0038	0.0092
2.000	-5.80885	0.87464	-0.11250	-1.09224	1.55209	0.00025	0.39158	0.0050	0.0116

Table 3. Coefficients and mean values of the logarithm of residuals of Eq. (2) for 15% damping corresponding to horizontal motions on rock and soil sites

	Coefficients for Eq. (2) at 15% damping								
T (s)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Mean log. Residuals	
								Rock	Soil
0.040	-5.53092	0.51247	-0.03590	-1.15720	1.78766	-0.00147	0.03143	0.0064	0.0095
0.045	-5.67836	0.56397	-0.05444	-1.22023	2.05964	-0.00114	0.05891	0.0056	0.0082
0.050	-5.37282	0.52612	-0.03762	-1.20899	1.89025	-0.00103	0.06199	0.0062	0.0084
0.055	-5.42431	0.54137	-0.04699	-1.18436	1.73824	-0.00113	0.06794	0.0058	0.0082
0.060	-5.27918	0.53489	-0.03663	-1.20305	1.91677	-0.00114	0.08371	0.0061	0.0080
0.065	-5.20262	0.52933	-0.04057	-1.18759	1.86023	-0.00109	0.09539	0.0060	0.0085
0.070	-5.15385	0.52993	-0.04119	-1.18078	1.91366	-0.00107	0.10329	0.0055	0.0087
0.075	-5.07409	0.53003	-0.03608	-1.19395	2.08176	-0.00106	0.11159	0.0055	0.0085
0.080	-5.10417	0.53845	-0.03891	-1.17159	2.02567	-0.00123	0.11987	0.0056	0.0082
0.085	-5.18997	0.55444	-0.05308	-1.15063	1.89390	-0.00121	0.12715	0.0055	0.0082
0.090	-5.15803	0.55519	-0.05336	-1.14357	1.88956	-0.00128	0.13667	0.0052	0.0082
0.095	-5.16017	0.55766	-0.06152	-1.13165	1.72084	-0.00118	0.14712	0.0054	0.0086
0.100	-5.09674	0.54861	-0.05875	-1.11135	1.67031	-0.00127	0.15629	0.0054	0.0082
0.150	-4.86042	0.53523	-0.04413	-1.04259	1.51841	-0.00150	0.20877	0.0050	0.0076
0.200	-4.63856	0.52423	-0.04541	-1.03636	1.46987	-0.00120	0.24836	0.0049	0.0083
0.250	-4.74970	0.54656	-0.05542	-0.98385	1.12542	-0.00131	0.27926	0.0039	0.0084
0.300	-4.64445	0.54672	-0.05600	-0.99617	1.19673	-0.00111	0.30993	0.0045	0.0083
0.350	-4.84676	0.58181	-0.07702	-0.96841	0.98882	-0.00102	0.33464	0.0048	0.0084
0.400	-4.92342	0.59909	-0.07869	-0.95228	0.95379	-0.00104	0.35415	0.0046	0.0085
0.450	-5.11198	0.64787	-0.09929	-0.99247	1.16901	-0.00084	0.36632	0.0047	0.0085
0.500	-5.27754	0.67556	-0.11134	-0.97291	0.98782	-0.00086	0.37866	0.0053	0.0083
0.550	-5.44621	0.70924	-0.12582	-0.98119	0.99268	-0.00071	0.38587	0.0051	0.0087
0.600	-5.41528	0.71857	-0.12277	-1.02198	1.23359	-0.00048	0.39117	0.0047	0.0084
0.650	-5.43323	0.72821	-0.12354	-1.02776	1.35300	-0.00044	0.39198	0.0046	0.0081
0.700	-5.46552	0.73580	-0.12470	-1.01751	1.37829	-0.00046	0.39305	0.0043	0.0082
0.750	-5.48663	0.74190	-0.12192	-1.01129	1.42332	-0.00051	0.39463	0.0047	0.0084
0.800	-5.53757	0.75122	-0.12465	-1.00371	1.30073	-0.00046	0.39361	0.0050	0.0085
0.850	-5.64526	0.76937	-0.13232	-0.99633	1.18824	-0.00042	0.39301	0.0050	0.0088
0.900	-5.70040	0.77989	-0.13571	-0.98978	1.11562	-0.00042	0.39357	0.0044	0.0088
0.950	-5.72828	0.78582	-0.13791	-0.98281	1.05580	-0.00040	0.39220	0.0040	0.0089
1.000	-5.73636	0.79261	-0.13827	-0.99570	1.11617	-0.00033	0.39509	0.0041	0.0087
1.100	-5.73450	0.80722	-0.13480	-1.03681	1.46522	-0.00019	0.39941	0.0041	0.0080
1.200	-5.70938	0.80303	-0.12632	-1.02222	1.31787	-0.00020	0.40090	0.0041	0.0081
1.300	-5.79810	0.82032	-0.12820	-1.01989	1.30181	-0.00018	0.39879	0.0040	0.0080
1.400	-5.79206	0.82665	-0.12281	-1.03933	1.28655	-0.00001	0.39763	0.0040	0.0082
1.500	-5.79483	0.83310	-0.12030	-1.05100	1.29875	0.00009	0.39845	0.0044	0.0087
1.600	-5.82471	0.84487	-0.11743	-1.06277	1.42981	0.00008	0.39791	0.0051	0.0093
1.700	-5.84413	0.85237	-0.11545	-1.06253	1.41542	0.00003	0.39286	0.0053	0.0100
1.800	-5.77520	0.84941	-0.10700	-1.07797	1.49784	0.00006	0.39065	0.0056	0.0110
1.900	-5.68546	0.84414	-0.09816	-1.09966	1.53857	0.00017	0.38935	0.0064	0.0133
2.000	-5.66296	0.85807	-0.09653	-1.15608	1.76974	0.00041	0.39261	0.0085	0.0167

Table 4. Coefficients and mean values of the logarithm of residuals of Eq. (2) for 20% damping corresponding to horizontal motions on rock and soil sites

	Coefficients for Eq. (2) at 20% damping								
T (s)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Mean log. Residuals	
								Rock	Soil
0.040	-5.65323	0.51530	-0.04781	-1.12139	1.47411	-0.00145	0.04377	0.0082	0.0106
0.045	-5.52186	0.52959	-0.03796	-1.21404	1.91973	-0.00104	0.06529	0.0070	0.0093
0.050	-5.42090	0.52876	-0.02981	-1.21523	2.05088	-0.00116	0.07587	0.0071	0.0091
0.055	-5.43668	0.53711	-0.04375	-1.18963	1.81154	-0.00113	0.08450	0.0069	0.0086
0.060	-5.33418	0.53186	-0.03912	-1.18646	1.85577	-0.00116	0.09529	0.0066	0.0089
0.065	-5.10337	0.50540	-0.02189	-1.18322	1.94614	-0.00121	0.10364	0.0064	0.0089
0.070	-5.13923	0.52296	-0.03199	-1.19513	2.01827	-0.00108	0.11447	0.0068	0.0093
0.075	-5.15033	0.52892	-0.04023	-1.17663	1.90758	-0.00108	0.12198	0.0065	0.0094
0.080	-5.17183	0.53729	-0.04443	-1.16078	1.89563	-0.00118	0.13075	0.0064	0.0090
0.085	-5.22729	0.54898	-0.05151	-1.14067	1.83840	-0.00129	0.13977	0.0064	0.0088
0.090	-5.25491	0.55857	-0.06113	-1.13691	1.75755	-0.00119	0.14692	0.0063	0.0092
0.095	-5.17386	0.54645	-0.05690	-1.11396	1.63430	-0.00129	0.15444	0.0062	0.0091
0.100	-5.11482	0.54360	-0.05564	-1.11730	1.69424	-0.00126	0.16265	0.0062	0.0089
0.150	-4.96640	0.54269	-0.04811	-1.04109	1.55637	-0.00155	0.21462	0.0058	0.0082
0.200	-4.73040	0.52842	-0.04468	-1.03586	1.43347	-0.00125	0.25227	0.0056	0.0091
0.250	-4.76928	0.54113	-0.04931	-0.98951	1.15096	-0.00133	0.28498	0.0046	0.0089
0.300	-4.67209	0.53992	-0.05089	-0.99321	1.12781	-0.00111	0.31313	0.0051	0.0092
0.350	-4.82818	0.56771	-0.06777	-0.96396	0.93782	-0.00104	0.33547	0.0055	0.0093
0.400	-4.98186	0.59601	-0.07712	-0.94198	0.86443	-0.00108	0.35378	0.0055	0.0093
0.450	-5.18299	0.64734	-0.09713	-0.98504	1.13130	-0.00089	0.36605	0.0056	0.0090
0.500	-5.34403	0.67526	-0.10908	-0.96942	0.96884	-0.00089	0.37743	0.0062	0.0088
0.550	-5.42796	0.69694	-0.11671	-0.98244	0.99155	-0.00074	0.38421	0.0060	0.0089
0.600	-5.50732	0.72495	-0.12354	-1.02770	1.25279	-0.00046	0.38863	0.0055	0.0090
0.650	-5.49757	0.73007	-0.12257	-1.03447	1.38100	-0.00038	0.39088	0.0054	0.0089
0.700	-5.52219	0.73697	-0.12423	-1.02544	1.42525	-0.00040	0.39228	0.0053	0.0092
0.750	-5.55657	0.74236	-0.12360	-1.00848	1.35005	-0.00046	0.39336	0.0054	0.0094
0.800	-5.59020	0.75003	-0.12428	-1.00511	1.25267	-0.00041	0.39303	0.0055	0.0096
0.850	-5.67483	0.76674	-0.13002	-1.00650	1.19707	-0.00035	0.39344	0.0054	0.0098
0.900	-5.73103	0.77680	-0.13335	-0.99665	1.10526	-0.00037	0.39229	0.0048	0.0099
0.950	-5.76376	0.78405	-0.13590	-0.99142	1.05329	-0.00037	0.39228	0.0046	0.0100
1.000	-5.77756	0.79141	-0.13568	-1.00177	1.11689	-0.00032	0.39343	0.0046	0.0100
1.100	-5.79287	0.80695	-0.13205	-1.03615	1.40650	-0.00019	0.39813	0.0048	0.0094
1.200	-5.73590	0.80039	-0.12137	-1.03106	1.30655	-0.00018	0.39984	0.0050	0.0095
1.300	-5.78209	0.81452	-0.12095	-1.04507	1.31437	-0.00005	0.39880	0.0048	0.0095
1.400	-5.77589	0.81987	-0.11638	-1.05743	1.30760	0.00006	0.39792	0.0050	0.0098
1.500	-5.78338	0.82784	-0.11489	-1.07073	1.32809	0.00015	0.39737	0.0057	0.0107
1.600	-5.80082	0.83905	-0.11135	-1.08759	1.44882	0.00016	0.39569	0.0065	0.0113
1.700	-5.80075	0.84523	-0.10926	-1.09355	1.46758	0.00015	0.39115	0.0071	0.0125
1.800	-5.74528	0.84463	-0.10185	-1.10856	1.52692	0.00017	0.38900	0.0078	0.0142
1.900	-5.65656	0.84336	-0.09336	-1.14528	1.67288	0.00032	0.38980	0.0092	0.0170
2.000	-5.64087	0.85701	-0.09304	-1.19525	1.86684	0.00052	0.39254	0.0116	0.0209

Table 5. Coefficients and mean values of the logarithm of residuals of Eq. (2) for 25% damping corresponding to horizontal motions on rock and soil sites

	Coefficients for Eq. (2) at 25% damping								
T (s)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Mean log. Residuals	
								Rock	Soil
0.040	-5.63047	0.50972	-0.03979	-1.12797	1.62898	-0.00157	0.05601	0.0084	0.0104
0.045	-5.52618	0.52720	-0.04265	-1.22626	1.93124	-0.00081	0.07746	0.0074	0.0103
0.050	-5.37031	0.50278	-0.02369	-1.15922	1.82860	-0.00143	0.08742	0.0073	0.0098
0.055	-5.51924	0.54363	-0.04826	-1.18517	1.87722	-0.00113	0.09716	0.0077	0.0093
0.060	-5.27149	0.51702	-0.03318	-1.19410	1.89067	-0.00103	0.10537	0.0074	0.0097
0.065	-5.23833	0.52217	-0.03133	-1.19434	1.99253	-0.00106	0.11487	0.0072	0.0093
0.070	-5.22494	0.52580	-0.03682	-1.18146	1.91514	-0.00103	0.12254	0.0075	0.0098
0.075	-5.13661	0.52232	-0.03266	-1.18539	2.02607	-0.00111	0.13269	0.0071	0.0095
0.080	-5.19611	0.52960	-0.04261	-1.14328	1.81366	-0.00124	0.14123	0.0070	0.0094
0.085	-5.28379	0.54975	-0.05660	-1.14159	1.76942	-0.00115	0.14843	0.0071	0.0096
0.090	-5.26868	0.54951	-0.05533	-1.11795	1.74981	-0.00136	0.15586	0.0066	0.0094
0.095	-5.21841	0.54893	-0.05835	-1.12668	1.72065	-0.00121	0.16248	0.0067	0.0095
0.100	-5.17007	0.54399	-0.05334	-1.11179	1.73394	-0.00136	0.16948	0.0065	0.0093
0.150	-5.04338	0.54643	-0.05110	-1.03643	1.55822	-0.00159	0.21999	0.0063	0.0087
0.200	-4.85396	0.53615	-0.04710	-1.02135	1.33106	-0.00132	0.25662	0.0060	0.0092
0.250	-4.80014	0.53942	-0.04637	-0.99489	1.19616	-0.00134	0.28932	0.0050	0.0092
0.300	-4.69647	0.53613	-0.04780	-0.99584	1.08458	-0.00109	0.31415	0.0054	0.0099
0.350	-4.87336	0.56663	-0.06578	-0.96403	0.89473	-0.00104	0.33653	0.0059	0.0100
0.400	-5.04583	0.59815	-0.07666	-0.94128	0.87324	-0.00110	0.35369	0.0061	0.0099
0.450	-5.26194	0.64889	-0.09706	-0.97343	1.06300	-0.00094	0.36599	0.0062	0.0094
0.500	-5.40316	0.67525	-0.10749	-0.96452	0.94281	-0.00091	0.37675	0.0067	0.0092
0.550	-5.45721	0.69315	-0.11317	-0.98113	0.98469	-0.00073	0.38305	0.0065	0.0093
0.600	-5.54561	0.72079	-0.12073	-1.01787	1.19742	-0.00049	0.38678	0.0060	0.0094
0.650	-5.54250	0.72769	-0.12042	-1.02804	1.32548	-0.00040	0.38944	0.0060	0.0095
0.700	-5.57717	0.73740	-0.12400	-1.02593	1.37141	-0.00036	0.39167	0.0059	0.0099
0.750	-5.60287	0.74222	-0.12303	-1.01181	1.31911	-0.00039	0.39173	0.0058	0.0102
0.800	-5.65072	0.75216	-0.12499	-1.00711	1.22651	-0.00037	0.39199	0.0057	0.0104
0.850	-5.72137	0.76690	-0.12886	-1.00895	1.19666	-0.00032	0.39280	0.0056	0.0106
0.900	-5.75742	0.77492	-0.13100	-1.00382	1.13231	-0.00033	0.39248	0.0051	0.0107
0.950	-5.79007	0.78303	-0.13346	-1.00240	1.09699	-0.00031	0.39221	0.0050	0.0109
1.000	-5.79364	0.78859	-0.13112	-1.01161	1.15658	-0.00027	0.39236	0.0049	0.0109
1.100	-5.81882	0.80348	-0.12796	-1.03719	1.34490	-0.00017	0.39747	0.0054	0.0107
1.200	-5.76901	0.80260	-0.11962	-1.05134	1.32861	-0.00005	0.40002	0.0057	0.0108
1.300	-5.79086	0.81258	-0.11661	-1.06177	1.31710	0.00003	0.39812	0.0056	0.0110
1.400	-5.77811	0.81612	-0.11169	-1.06909	1.30204	0.00010	0.39648	0.0061	0.0115
1.500	-5.78378	0.82507	-0.11022	-1.08604	1.34980	0.00018	0.39598	0.0069	0.0124
1.600	-5.81541	0.84023	-0.11044	-1.10929	1.47082	0.00024	0.39425	0.0079	0.0134
1.700	-5.77805	0.84196	-0.10584	-1.12166	1.50151	0.00027	0.39034	0.0089	0.0152
1.800	-5.73002	0.84371	-0.09922	-1.14140	1.58721	0.00032	0.38837	0.0099	0.0173
1.900	-5.68069	0.84971	-0.09356	-1.18048	1.78511	0.00043	0.39044	0.0116	0.0201
2.000	-5.69845	0.86601	-0.09679	-1.21887	1.90194	0.00059	0.39050	0.0142	0.0242

Table 6. Coefficients and mean values of the logarithm of residuals of Eq. (2) for 30% damping corresponding to horizontal motions on rock and soil sites

	Coefficients for Eq. (2) at 30% damping								
T (s)	a_1	a_2	a_3	a_4	a_5	a_6	a_7	Mean log. Residuals	
								Rock	Soil
0.040	-5.52826	0.49986	-0.02515	-1.17712	1.88581	-0.00137	0.06894	0.0097	0.0105
0.045	-5.71865	0.55398	-0.05582	-1.22526	2.02947	-0.00090	0.08901	0.0087	0.0106
0.050	-5.49173	0.51813	-0.03413	-1.16255	1.89913	-0.00132	0.09776	0.0073	0.0101
0.055	-5.47982	0.54043	-0.03659	-1.21296	2.22508	-0.00115	0.10635	0.0079	0.0094
0.060	-5.32630	0.51624	-0.03298	-1.16982	1.93811	-0.00120	0.11362	0.0075	0.0097
0.065	-5.30184	0.52219	-0.03437	-1.17175	1.94976	-0.00119	0.12562	0.0075	0.0100
0.070	-5.20463	0.51429	-0.02994	-1.16541	1.95422	-0.00118	0.13108	0.0075	0.0097
0.075	-5.18559	0.51269	-0.03504	-1.13457	1.80773	-0.00129	0.14027	0.0075	0.0096
0.080	-5.22197	0.52672	-0.04067	-1.13734	1.85731	-0.00129	0.14895	0.0074	0.0095
0.085	-5.23440	0.53302	-0.04771	-1.12815	1.75310	-0.00127	0.15671	0.0074	0.0096
0.090	-5.23311	0.53851	-0.05144	-1.12256	1.77533	-0.00128	0.16239	0.0070	0.0097
0.095	-5.27215	0.55062	-0.05679	-1.12178	1.80136	-0.00130	0.16988	0.0068	0.0095
0.100	-5.24532	0.54884	-0.05819	-1.10812	1.74323	-0.00135	0.17643	0.0067	0.0096
0.150	-5.12707	0.55226	-0.05628	-1.03377	1.51668	-0.00156	0.22503	0.0065	0.0089
0.200	-4.97954	0.54691	-0.05078	-1.01168	1.27626	-0.00140	0.26139	0.0063	0.0092
0.250	-4.87547	0.54679	-0.05002	-1.00511	1.22219	-0.00127	0.29205	0.0053	0.0095
0.300	-4.78704	0.54371	-0.05202	-0.99619	1.06027	-0.00107	0.31572	0.0055	0.0103
0.350	-4.91450	0.56612	-0.06358	-0.96309	0.87703	-0.00104	0.33621	0.0061	0.0104
0.400	-5.11853	0.60363	-0.07711	-0.94311	0.91676	-0.00111	0.35294	0.0066	0.0102
0.450	-5.31225	0.64687	-0.09555	-0.96076	0.97647	-0.00099	0.36539	0.0065	0.0097
0.500	-5.46663	0.67744	-0.10795	-0.95954	0.92801	-0.00092	0.37483	0.0068	0.0096
0.550	-5.49023	0.69116	-0.11036	-0.97905	0.99798	-0.00074	0.38173	0.0067	0.0096
0.600	-5.55976	0.71359	-0.11631	-1.00670	1.13920	-0.00053	0.38492	0.0064	0.0098
0.650	-5.56359	0.72233	-0.11745	-1.02054	1.25553	-0.00040	0.38750	0.0064	0.0101
0.700	-5.61287	0.73529	-0.12163	-1.02225	1.32565	-0.00036	0.39033	0.0063	0.0104
0.750	-5.65927	0.74625	-0.12305	-1.01924	1.33267	-0.00035	0.39024	0.0059	0.0107
0.800	-5.70357	0.75545	-0.12493	-1.01417	1.23385	-0.00032	0.39062	0.0058	0.0110
0.850	-5.73434	0.76407	-0.12517	-1.01528	1.21861	-0.00031	0.39202	0.0057	0.0111
0.900	-5.74357	0.76842	-0.12499	-1.01288	1.17365	-0.00030	0.39235	0.0054	0.0112
0.950	-5.77636	0.77634	-0.12624	-1.01115	1.14910	-0.00028	0.39233	0.0053	0.0113
1.000	-5.78343	0.78269	-0.12494	-1.02180	1.20504	-0.00022	0.39370	0.0054	0.0116
1.100	-5.81676	0.79767	-0.12335	-1.04302	1.29565	-0.00011	0.39749	0.0060	0.0118
1.200	-5.80140	0.80444	-0.11753	-1.06565	1.32062	0.00003	0.40018	0.0063	0.0120
1.300	-5.81801	0.81409	-0.11424	-1.07653	1.33578	0.00009	0.39874	0.0065	0.0123
1.400	-5.80183	0.81781	-0.11021	-1.08416	1.33504	0.00014	0.39576	0.0071	0.0131
1.500	-5.81130	0.82846	-0.10907	-1.10334	1.40209	0.00021	0.39428	0.0081	0.0140
1.600	-5.85601	0.84517	-0.11119	-1.12484	1.48494	0.00028	0.39277	0.0093	0.0156
1.700	-5.80101	0.84679	-0.10574	-1.14823	1.57704	0.00036	0.38971	0.0105	0.0177
1.800	-5.75548	0.84987	-0.09997	-1.17170	1.67444	0.00042	0.38819	0.0118	0.0200
1.900	-5.72278	0.85715	-0.09649	-1.20542	1.81429	0.00052	0.38939	0.0138	0.0229
2.000	-5.72096	0.86962	-0.09837	-1.23996	1.93500	0.00064	0.38962	0.0163	0.0269

Table 7. Magnitude-distance classification of the records in the database

Bin	Moment Magnitude M	Epicentral Distance R (km)	Number of Records	
			Rock Sites	Soil Sites
I	$6.0 \leq M < 7.0$	$1 \leq R \leq 50$	74	90
II	$6.0 \leq M < 7.0$	$50 < R \leq 100$	60	44
III	$6.0 \leq M < 7.0$	$100 < R \leq 150$	16	18
IV	$6.0 \leq M < 7.0$	$150 < R \leq 250$	2	9
V	$M \geq 7.0$	$1 \leq R \leq 50$	22	40
VI	$M \geq 7.0$	$50 < R \leq 100$	26	41
VII	$M \geq 7.0$	$100 < R \leq 150$	24	21
VIII	$M \geq 7.0$	$150 < R \leq 250$	20	16

LIST OF FIGURES

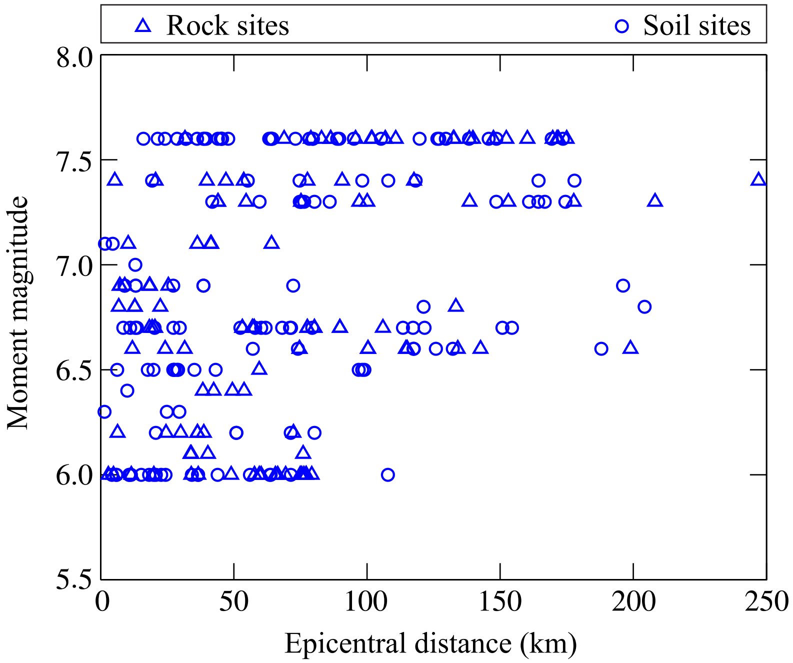

Figure 1. Magnitude and distance distributions of the records used in this study for rock and soil sites.

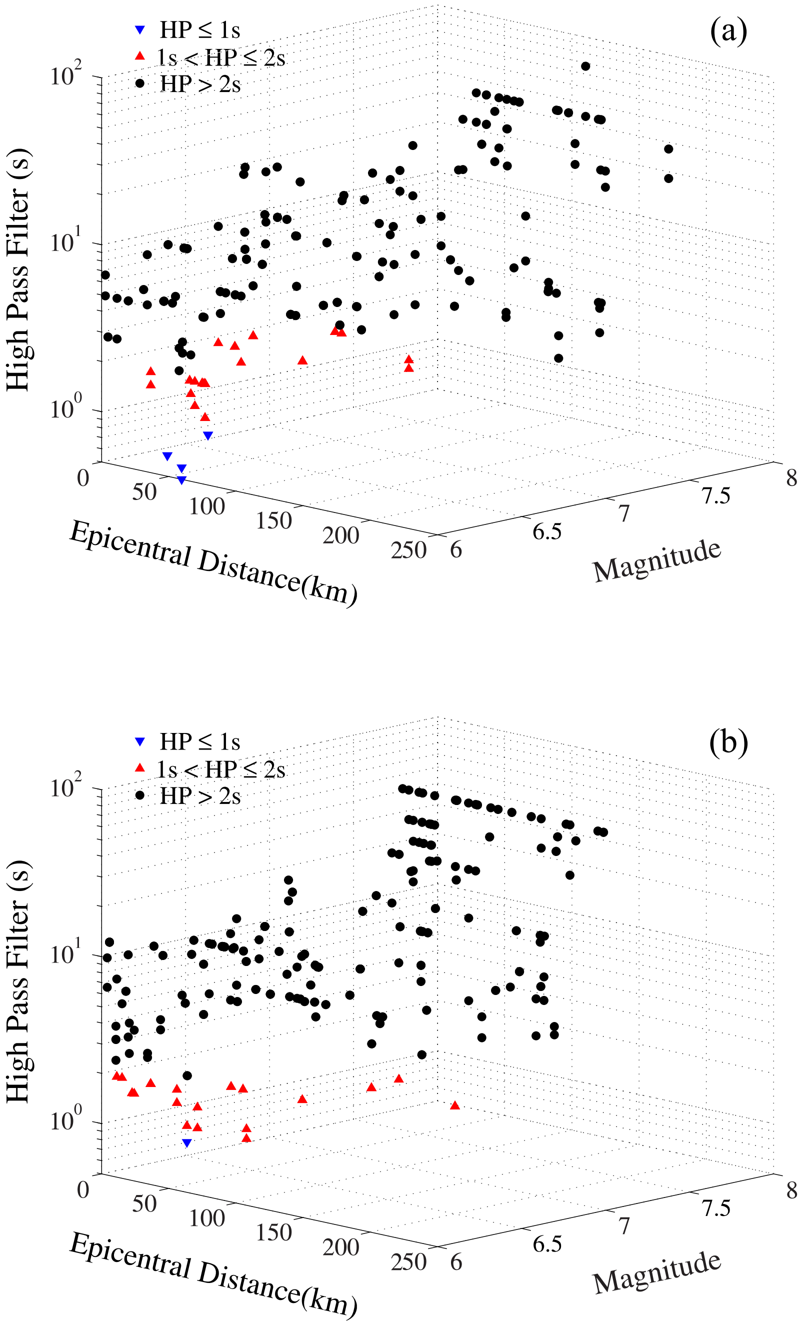

Figure 2. Distribution of the records used in this study based on the applied high pass filter (HP): (a) Rock sites; (b) Soil sites.

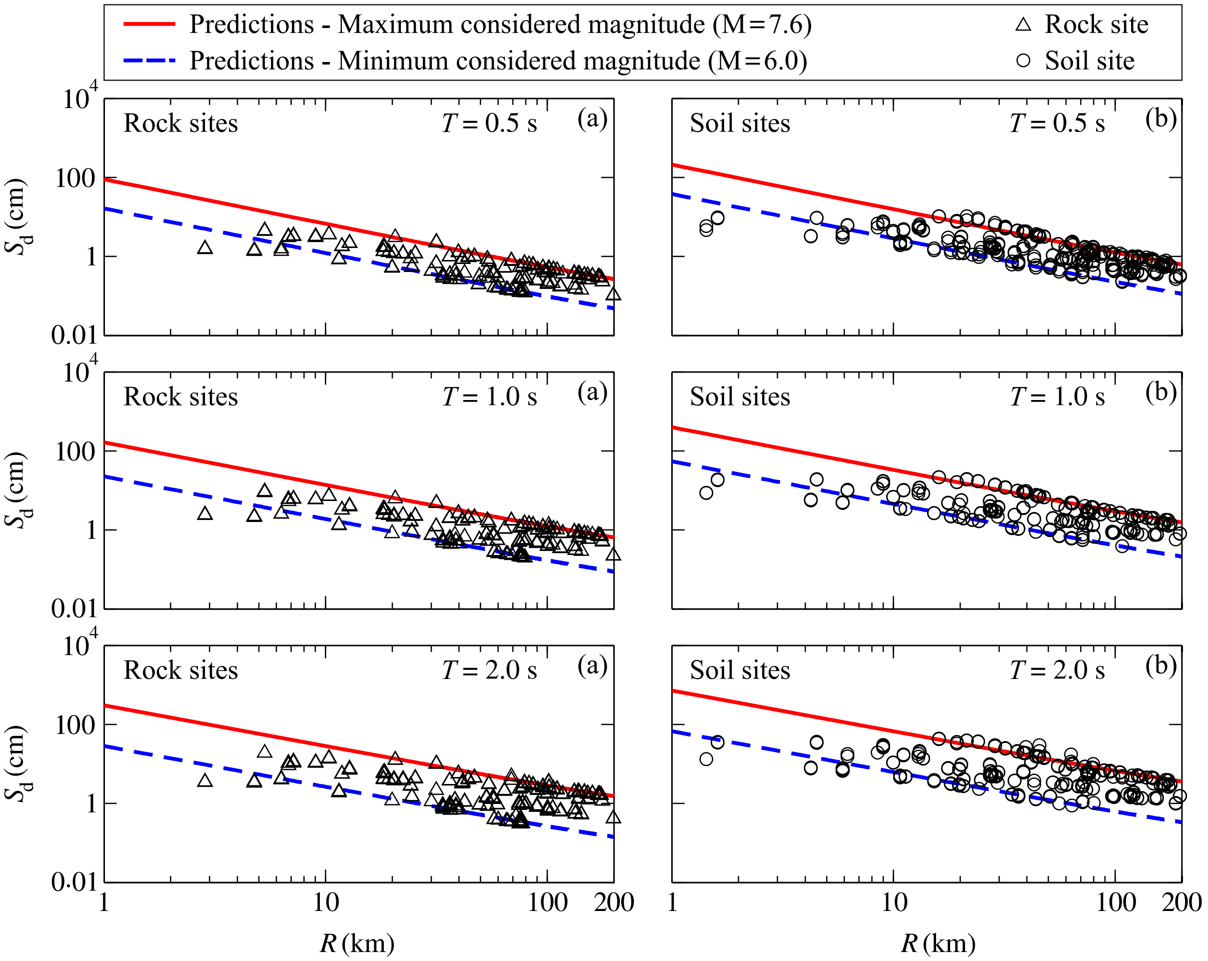

Figure 3. Comparison between 5%-damped spectral displacements predicted using Eq. (1) developed in this study and those computed from the data set of hybrid empirical records for magnitudes between M = 6.0 and M = 7.6 and periods of 0.5, 1.0 and 2.0 s: (a) Rock sites; and (b) Soil sites.

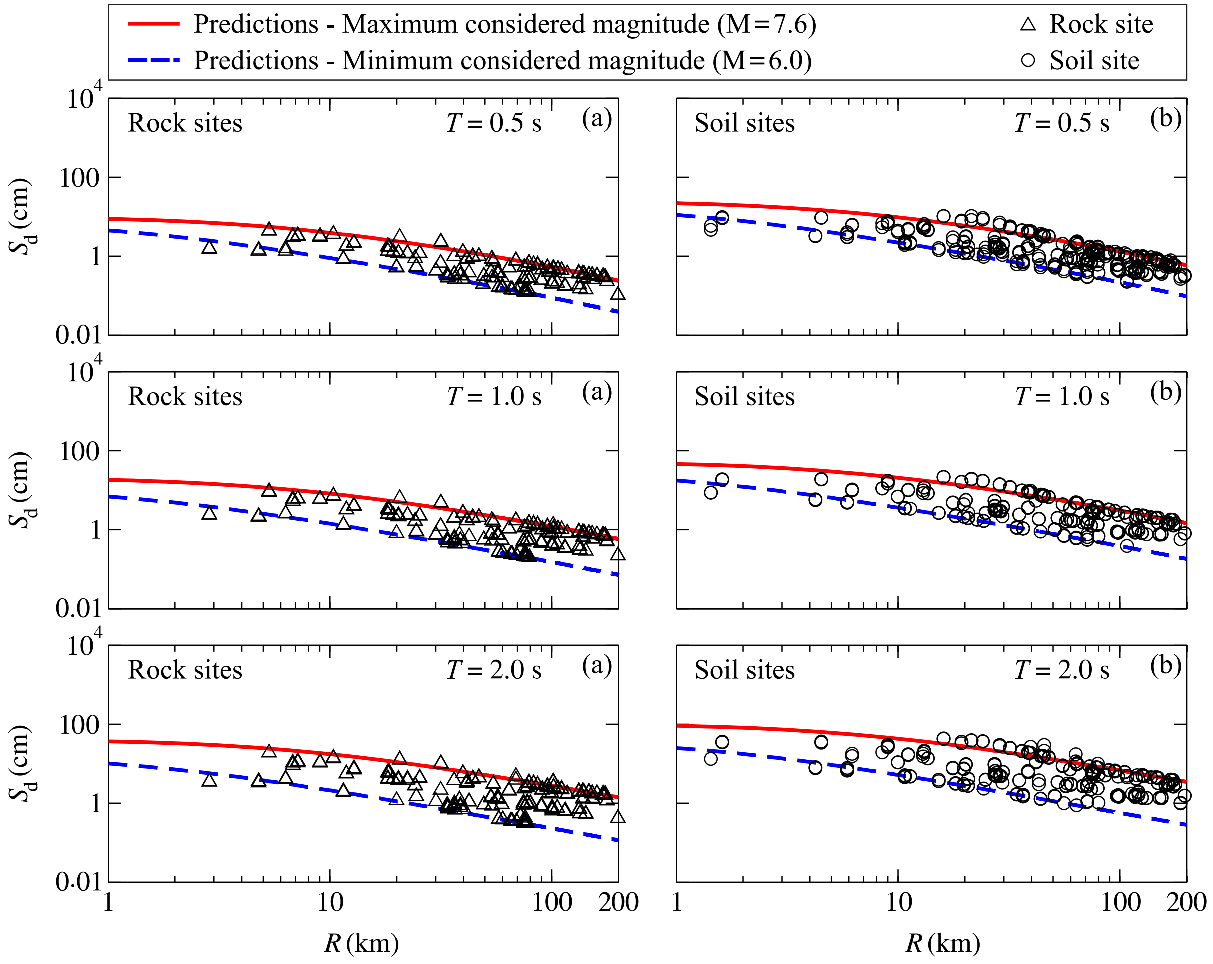

Figure 4. Comparison between 5%-damped spectral displacements predicted using Eq. (2) developed in this study and those computed from the data set of hybrid empirical records for magnitudes between M = 6.0 and M = 7.6 and periods of 0.5, 1.0 and 2.0 s: (a) Rock sites; and (b) Soil sites.

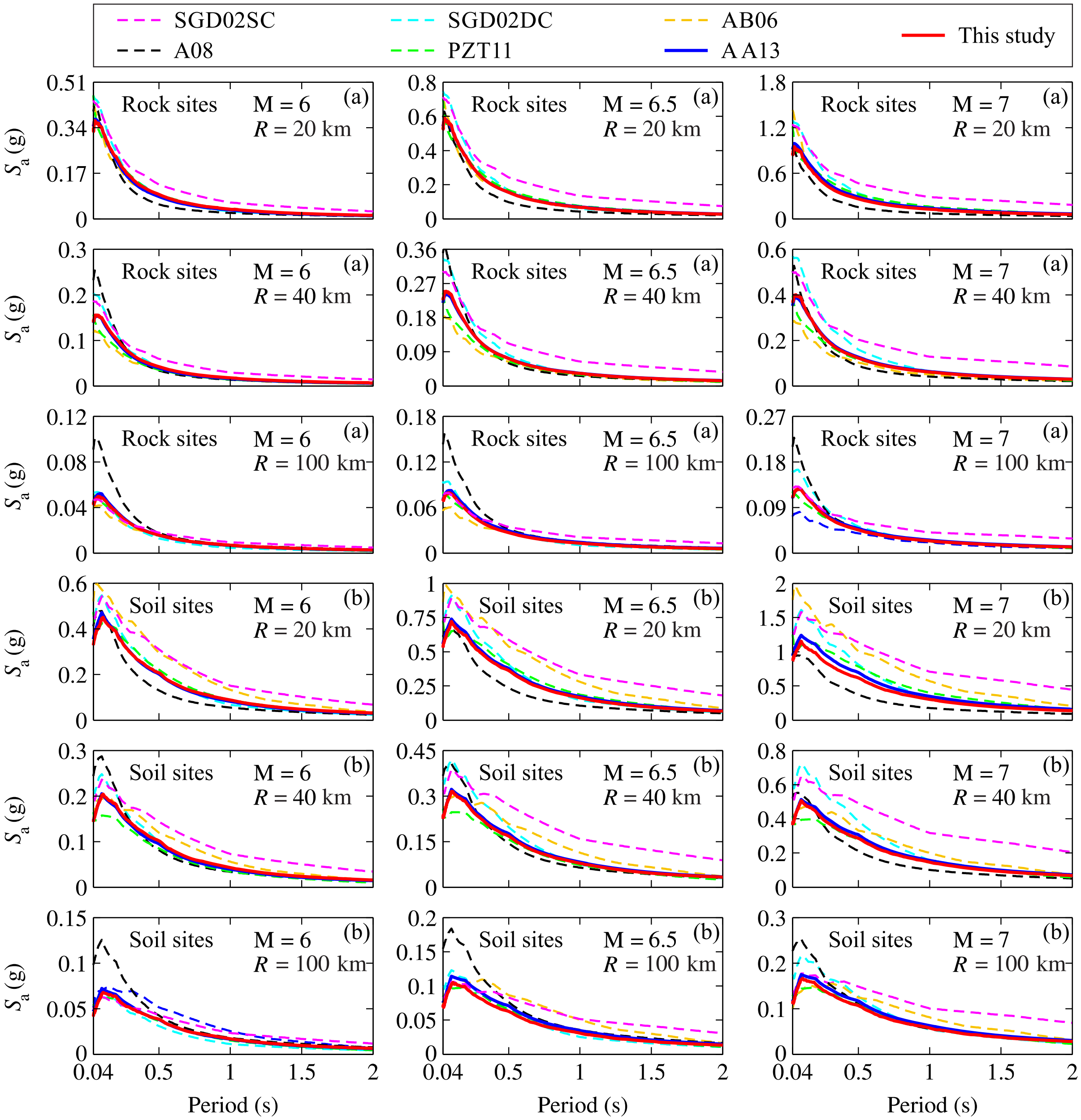

Figure 5. Comparison between 5%-damped spectral pseudo-acceleration predictions of the central GMPE proposed by Atkinson and Adams (2013) and those from Eq. (1) developed in this study: (a) Rock sites; and (b) Soil sites.

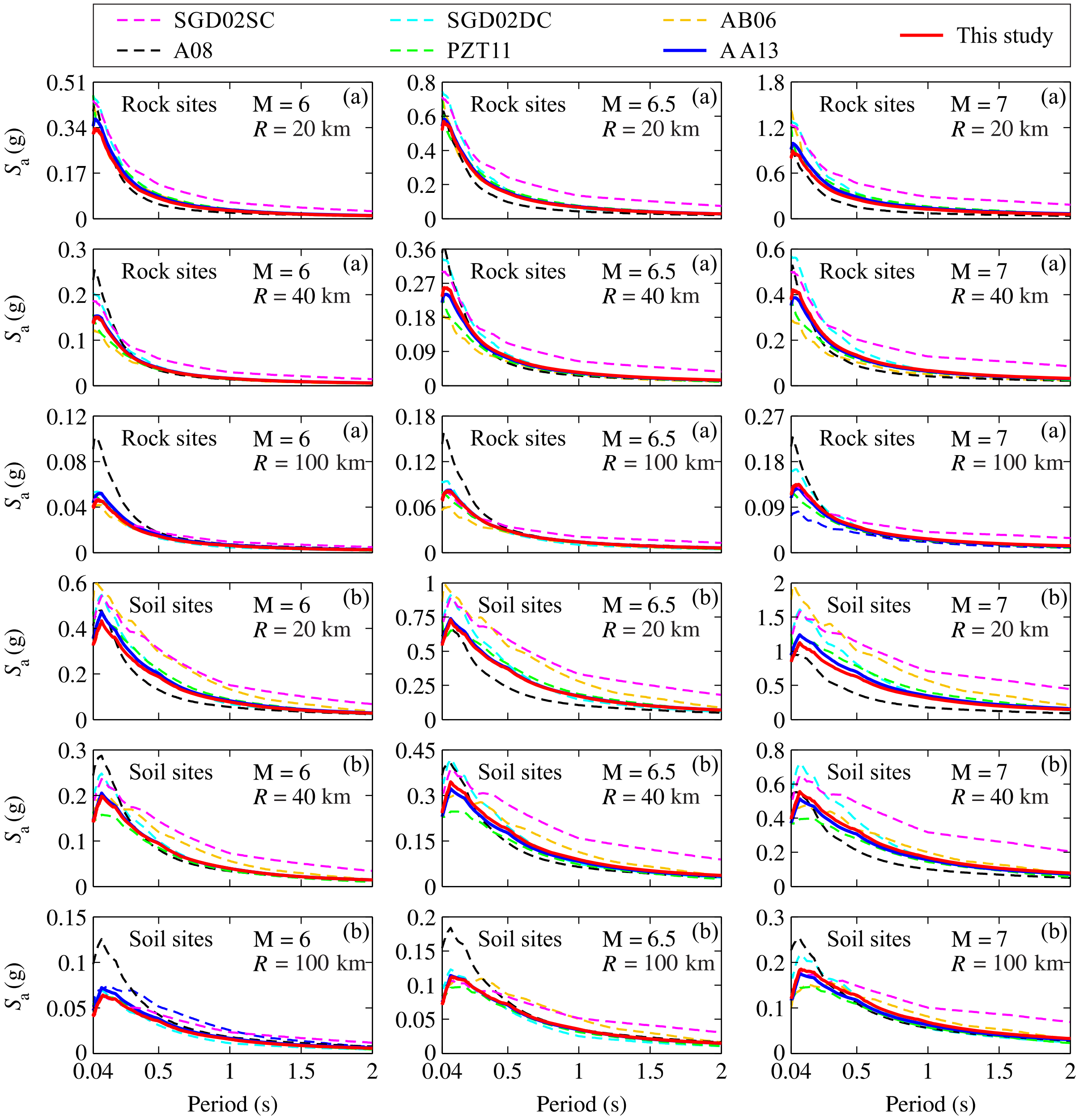

Figure 6. Comparison between 5%-damped spectral pseudo-acceleration predictions of the central GMPE proposed by Atkinson and Adams (2013) and those from Eq. (2) developed in this study: (a) Rock sites; and (b) Soil sites.

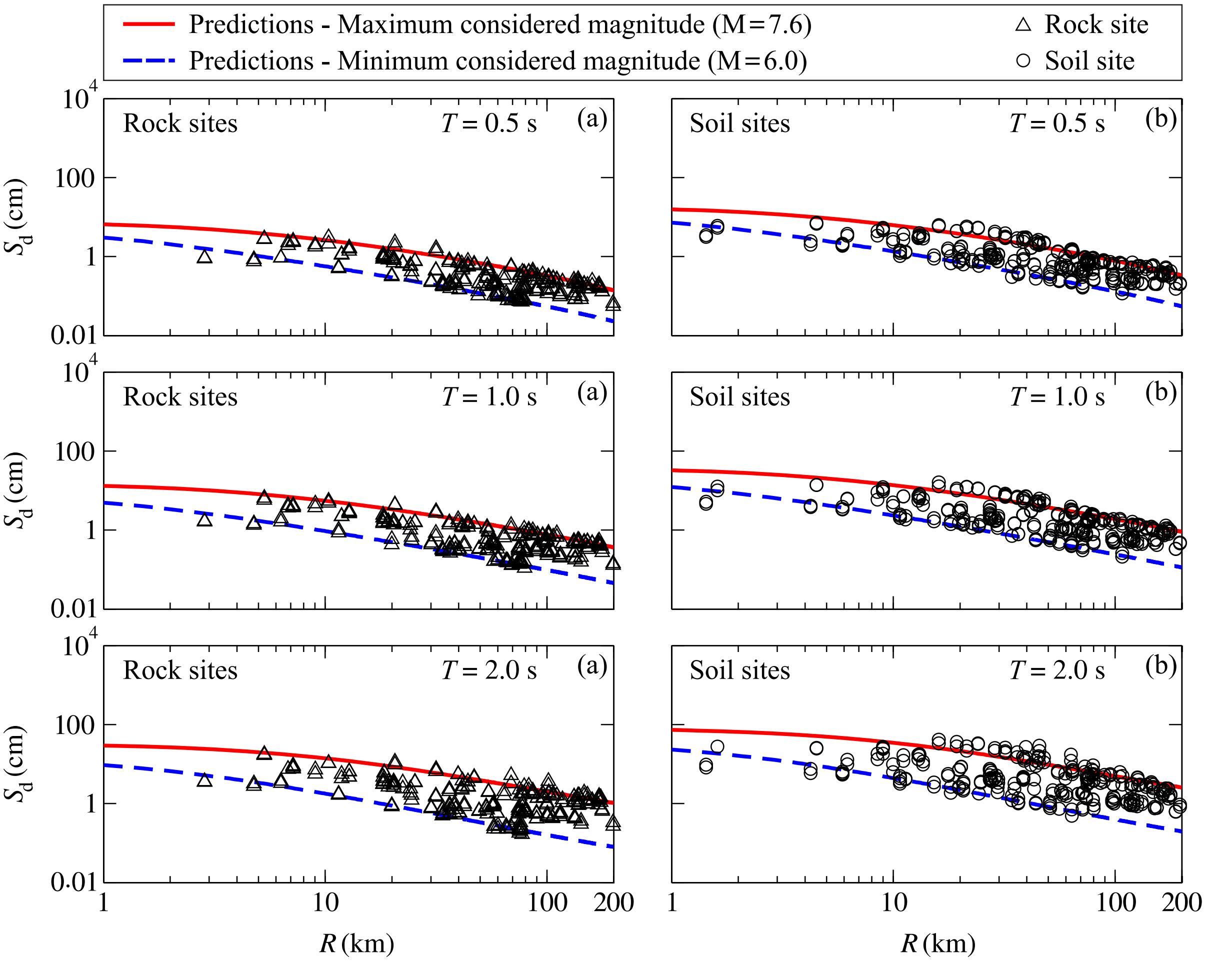

Figure 7. Comparison between 15%-damped spectral displacements predicted using Eq. (2) developed in this study and those computed from the data set of hybrid empirical records for magnitudes between M = 6.0 and M = 7.6 and periods of 0.5, 1.0 and 2.0 s: (a) Rock sites; and (b) Soil sites.

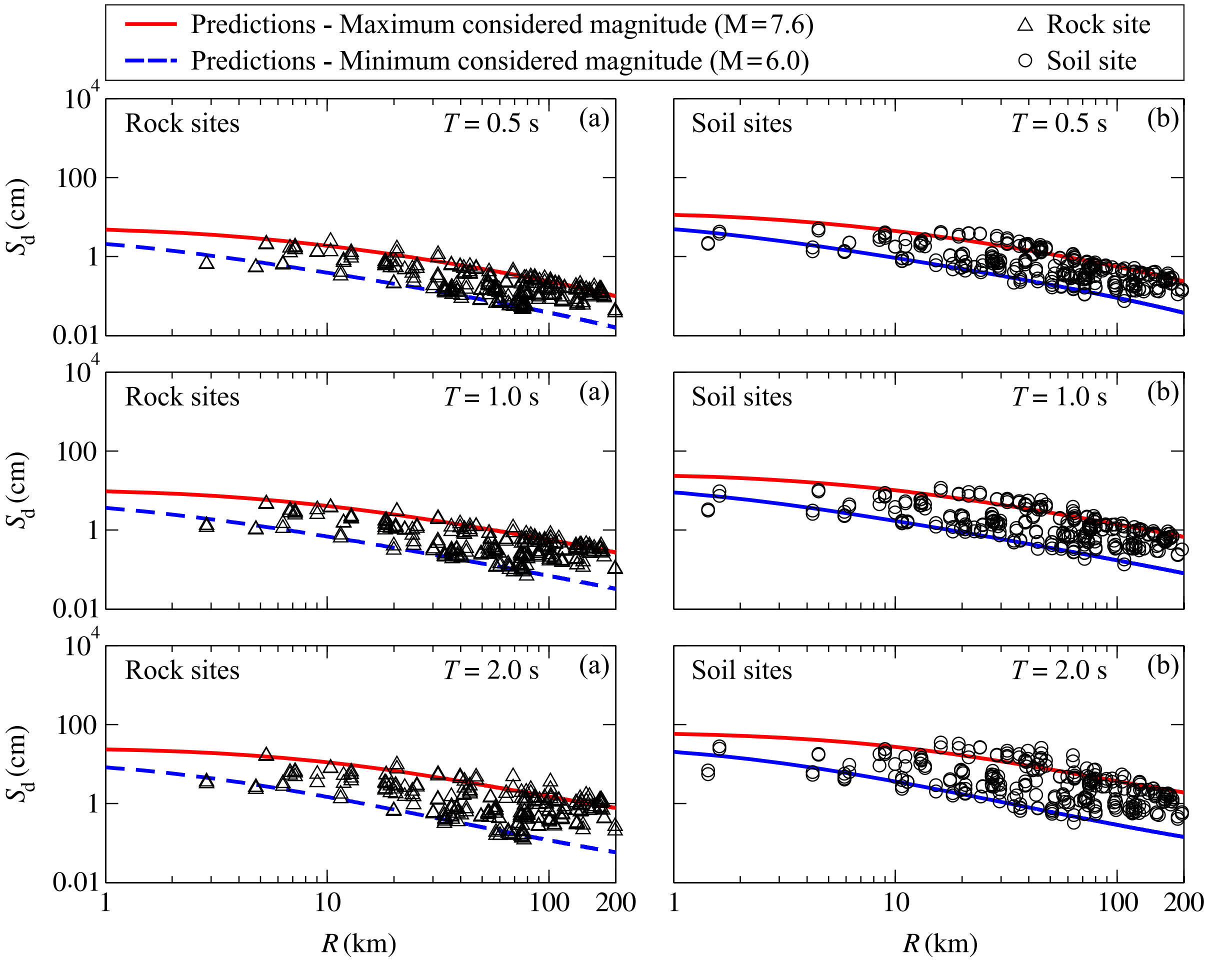

Figure 8. Comparison between 30%-damped spectral displacements predicted using Eq. (2) developed in this study and those computed from the data set of hybrid empirical records for magnitudes between M = 6.0 and M = 7.6 and periods of 0.5, 1.0 and 2.0 s: (a) Rock sites; and (b) Soil sites.

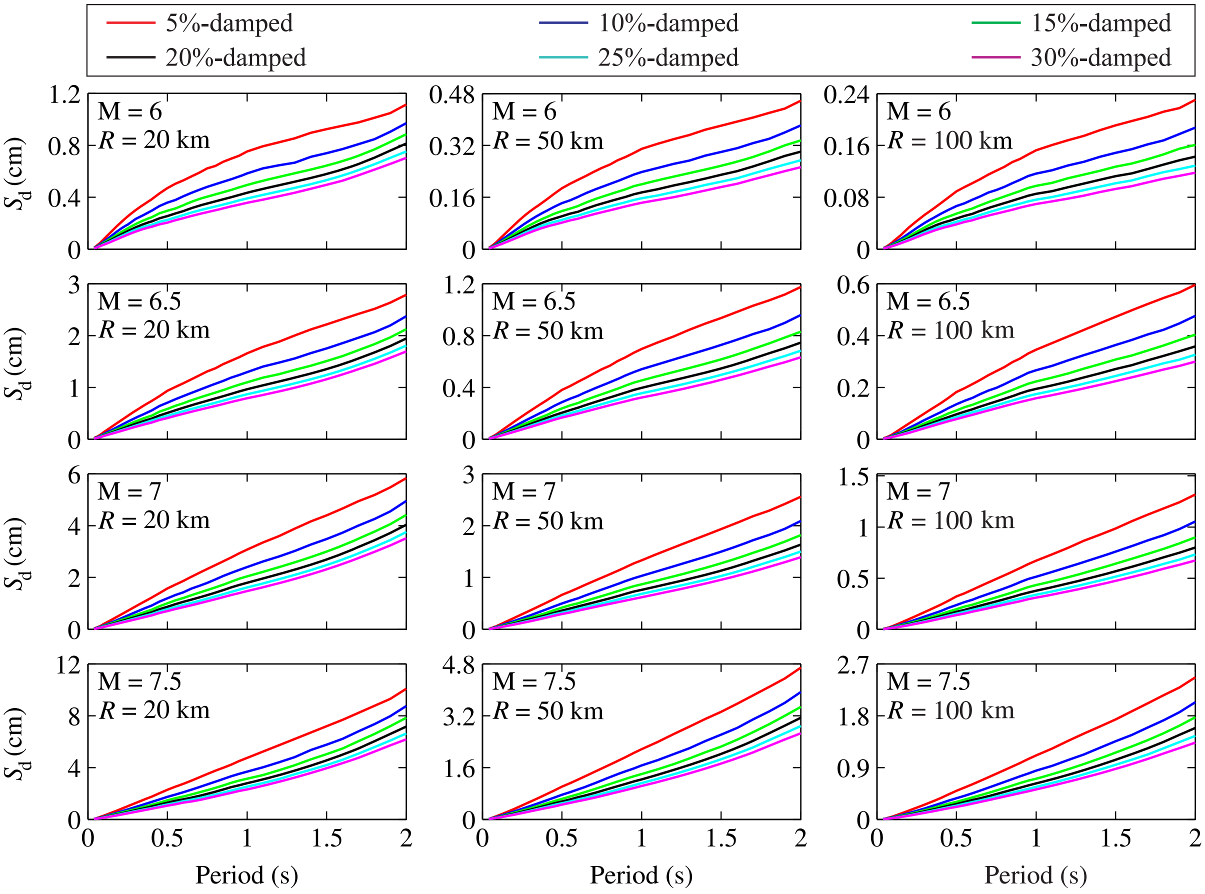

Figure 9. Displacement spectra at different damping levels for selected magnitudes and distances computed using Eq. (2) developed in this study for rock sites.

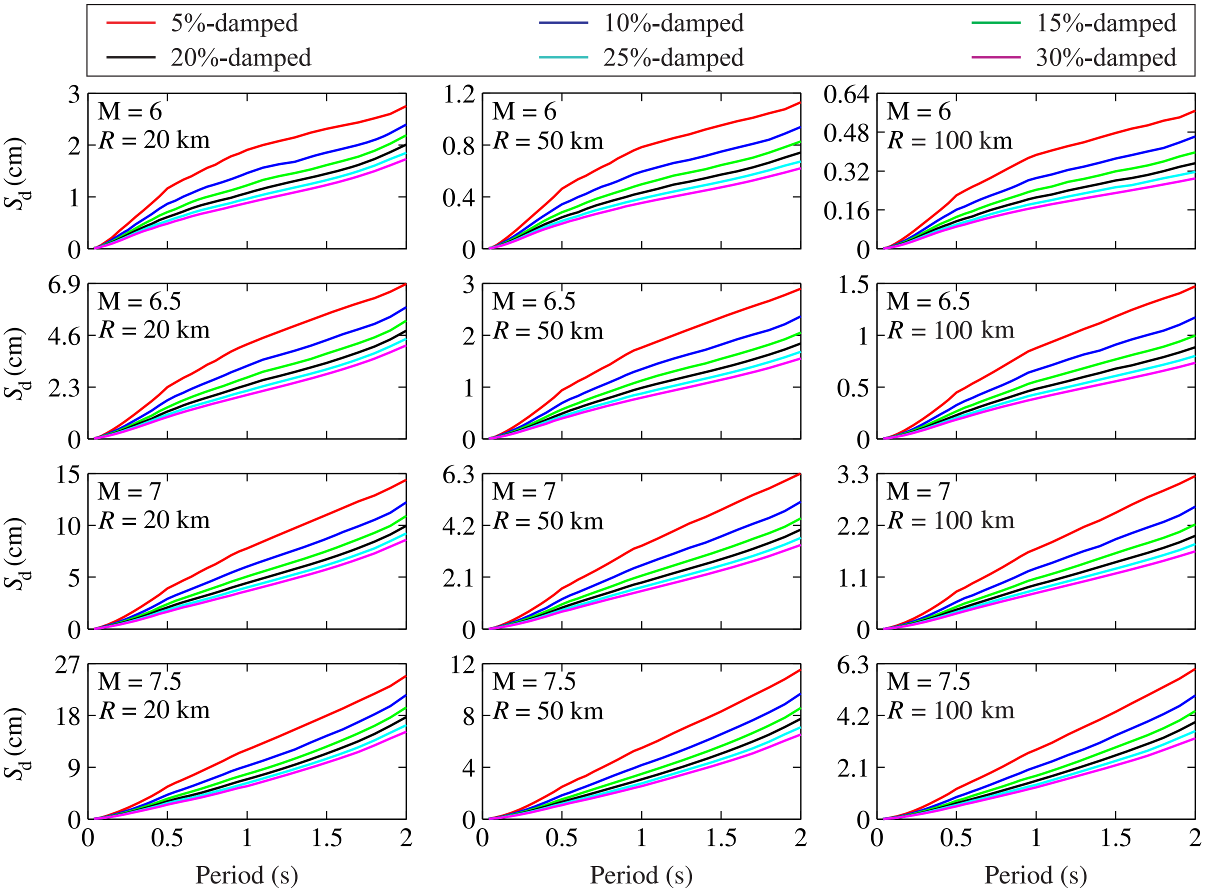

Figure 10. Displacement spectra at different damping levels for selected magnitudes and distances computed using Eq. (2) developed in this study for soil sites.

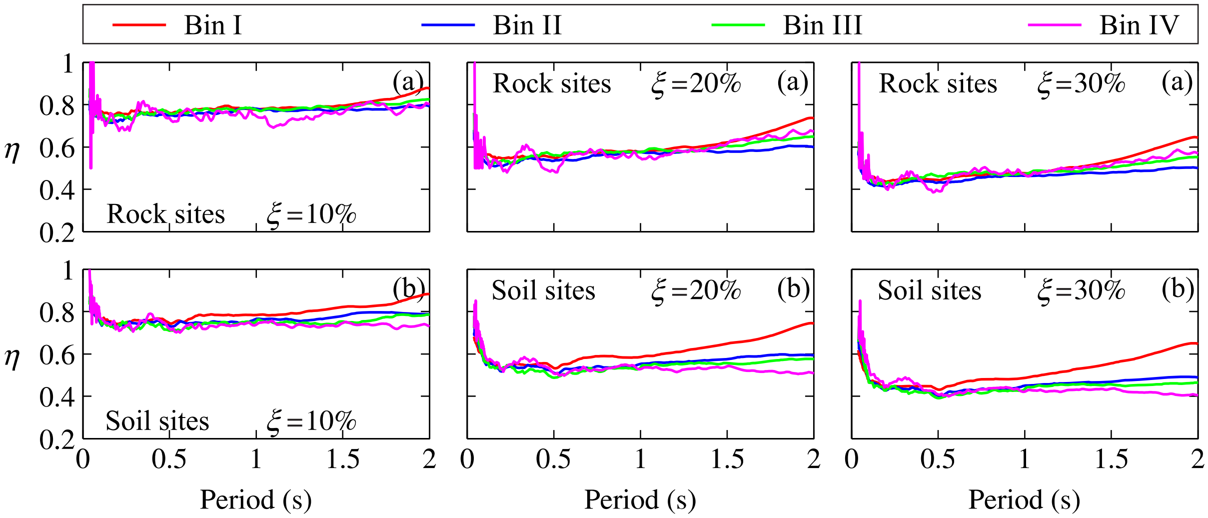

Figure 11. Damping reduction factors computed for ground motions in Bins I to IV: (a) Rock sites; and (b) Soil sites.

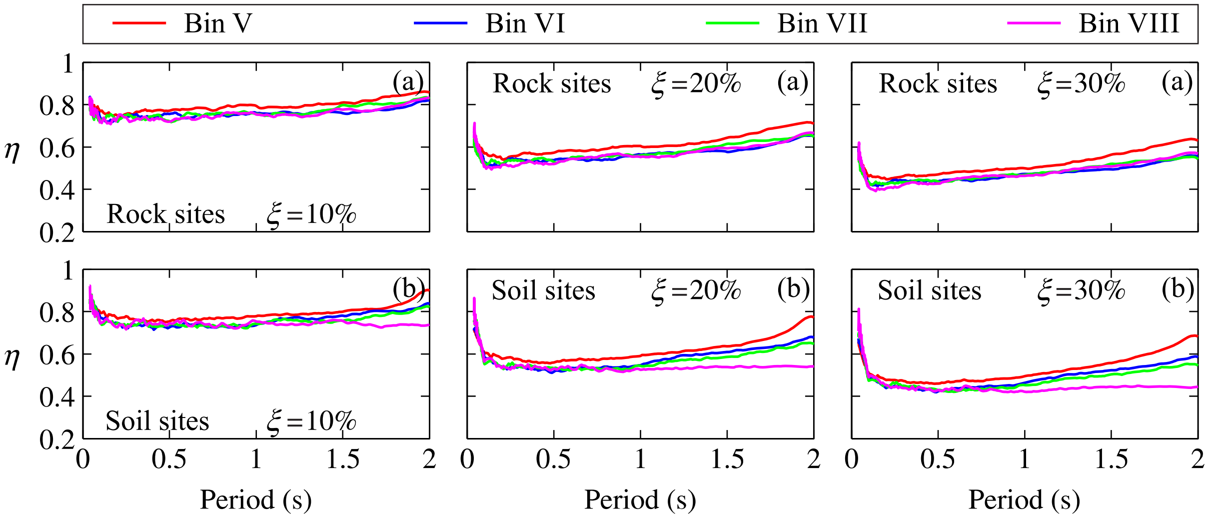

Figure 12. Damping reduction factors computed for ground motions in Bins V to VIII: (a) Rock sites; and (b) Soil sites.

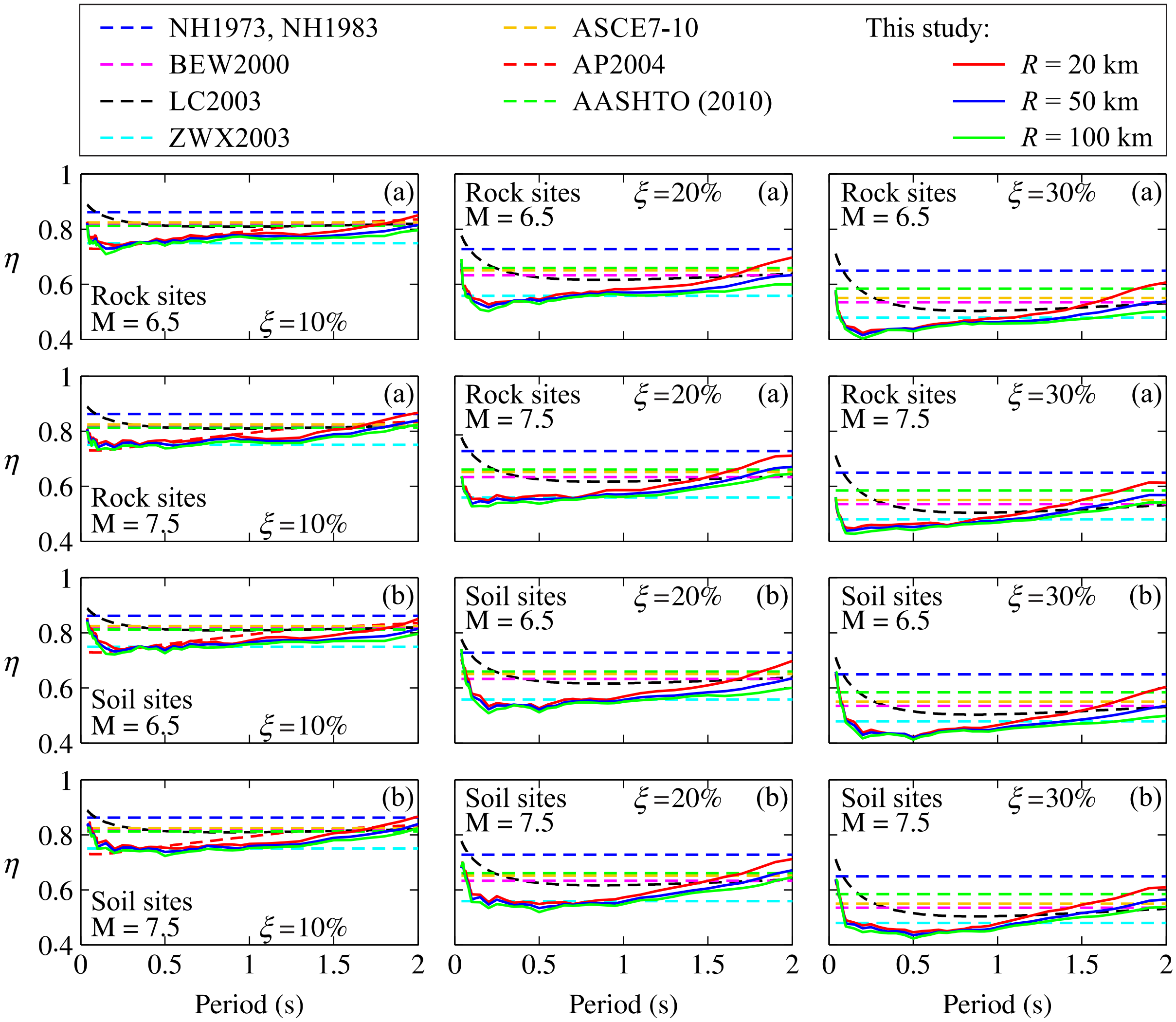

Figure 13. Comparison between damping reduction factors computed using Eq. (2) developed in this study and predictions of relationships available in the literature: (a) Rock sites; and (b) Soil sites.