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DAMPING MODIFICATION FACTORS FOR DEEP INSLAB AND INTERFACE SUBDUCTION EARTHQUAKES

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Abstract

High-damping spectral amplitudes and corresponding damping reduction factors (η) are key parameters for seismic design and analysis of structures equipped with seismic protection systems, as well as for displacement-based design methodologies. In addition, spectral amplitudes at damping levels lower than 5% are important for design and safety evaluation of lightly damped structures such as transmission lines. Although various expressions for η factors are proposed in the literature, they were mainly developed based on shallow crustal ground motions. However, seismically-active regions such as Japan or south-western British Columbia experience different types of ground motions, such as deep inslab and interface subduction earthquakes. To fill this gap, η factors corresponding to these types of events are investigated in this paper. The developed η factors are based on a large and comprehensive database including records from relevant earthquakes, such as the 2011 Tohoku event. For comparison purposes, η factors corresponding to shallow crustal events are also proposed. The dependency of damping modification factors on soil class and the period at which probabilistic seismic hazard analysis is conducted is shown negligible. We illustrate the dependency of η factors on period, particularly for inslab events. Period-dependent equations are proposed to predict the η factors for damping ratios between 1% and 30% corresponding to deep inslab and interface subduction earthquakes, as well as shallow crustal events.

Keywords: damping modification factors; inslab earthquakes; interface earthquakes; crustal earthquakes, spectral displacements.

1. Introduction

Elastic displacement spectra associated with damping levels higher than the conventional 5% critical damping are important in the seismic design and evaluation of structures equipped with seismic protection systems. High-damping displacement spectra are also required for displacement-based design and evaluation techniques, such as direct displacement-based design [1, 2]. In addition, spectral amplitudes at damping levels lower than 5% are important for design and safety evaluation of lightly damped structures such as transmission lines. One popular approach among guidelines and building codes, [e.g. 3, 4], to determine such displacement spectra is using damping modification factors, denoted hereafter by η, the ratio between the 5%-damped displacement spectrum $S_d(T,5\%)$ and the displacement spectra $S_d(T,\xi)$ for other damping levels ξ at a period T:

$$\eta(T,\xi)=\frac{S_d(T,\xi)}{S_d(T,5\%)} \tag{1}$$

Various equations predicting η factors have been proposed in the literature. Newmark and Hall [5, 6] used the horizontal and vertical components of 14 pre-1973 California ground motions to propose damping reduction factors corresponding to damping levels lower than 20%. Bommer et al. [7] studied the damped displacement spectra of 183 ground motion components from 43 shallow earthquakes recorded on rock and stiff and soft soil sites in Europe and the Middle East. They proposed an equation that was implemented in Eurocode 8 [8]. The Chinese guidelines for seismically isolated structures include a period-independent equation for damping reduction factors [9]. Lin and Chang [10] studied 1,037 accelerograms recorded in the United States to propose period-dependent damping reduction factors for periods between 0.1 s and 6 s and damping ratios between 2% and 50%. Atkinson and Pierre [11] extended the simulations performed to generate a data set of synthetic records that was used in developing the GMPE of Atkinson and Boore [12] for scenarios between **M**4.0 and **M**7.25 at hypocentral distances of 10 km to 500 km. The 1%, 2% 3%, 5%, 7%, 10%, and 15%-damped response spectra were computed and a magnitude-distance–independent set of η factors was proposed for periods between 0.05 s and 2 s, magnitudes greater than 5, and distances shorter than 150 km. Cameron and Green [13] proposed a set of η factors for damping levels between 1% and 50% for magnitude-binned ground motion records from shallow crustal events. Ground motion duration was shown to highly influence η factors, whereas site conditions were found to have minor effect on these factors. AASHTO [14] reported a simplified equation to obtain damping reduction factors for damping levels up to 50%, but suggested caution regarding its use for damping ratios greater than 30%. Rezaeian et al. [15] studied a database of 2,250 records from shallow crustal ground motions and developed a magnitude- and distance-based model to predict damping modification factors for the average horizontal component of ground motion and damping levels between 0.5% and 30%. They observed the period dependency of the damping modification factors and reported a strong dependency of these factors on ground motion duration. An investigation of several period-dependent and period-independent η factors by Cardone et al. [16] showed that period-dependent models provide the most accurate predictions of computed displacement spectra. Furthermore, Bradley [17] reiterated the period and duration dependency of η factors while questioning the accuracy of a number of proposed equations, namely the one prescribed by [8], where response amplification is characterized in terms of source- and site-specific effects. We note that older equations are based on studies that may have lacked adequate record processing of the used accelerograms (such as filtering and zero padding) and therefore might not be suitable for long period ranges.

The majority of previous studies focused on shallow crustal earthquakes. However, seismically-active regions such as Japan or south-western British Columbia experience different types of ground motions, such as deep inslab and interface subduction earthquakes. Such recorded events were shown to have distinctive characteristics in terms of frequency content and duration [e.g. 18]. The effects of these differences on η factors were not comprehensively investigated in the literature. To fill this gap, this paper focuses on developing η factors corresponding to inslab and interface earthquakes. η factors corresponding to shallow crustal events are also developed for comparison purposes. A model equation to predict median η factors as a function of damping ratio, period and soil class is proposed for the three types of events studied. For illustration purposes, ground motions characterizing seismic hazard in south-western British Columbia are investigated. Vancouver is selected for the probabilistic seismic hazard analysis (PSHA) and site conditions corresponding to soft rock and soft soil sites are considered.

2. Record Selection

The records used in this study are selected from the K-NET, KiK-net [19], and SKnet [20] databases, to represent inslab and interface events, and from the PEER-NGA database [21], to represent shallow crustal events. First, a preliminary combined dataset of Japanese records was formed. The selection criteria included maximum limits on depth and hypocentral distances as well as minimum values for magnitude, PGA, PGV and number of available records per event. This resulted in 555,750 records from 6,261 earthquakes. To emphasize the important characteristics of damaging earthquakes in terms of amplitude, spectral content and duration, the combination of the preliminary dataset and the records from PEER-NGA were further refined using various preliminary selection criteria among which were: (i) a minimum moment magnitude of **M**6.0, and (ii) average shear wave velocity in the uppermost 30 m V_{S30} between 180 m/s and 760 m/s representing soil classes C and D of the National Building Code of Canada (NBCC) [22]. The refined selection criteria resulted in a total of 2,302 horizontal accelerograms.

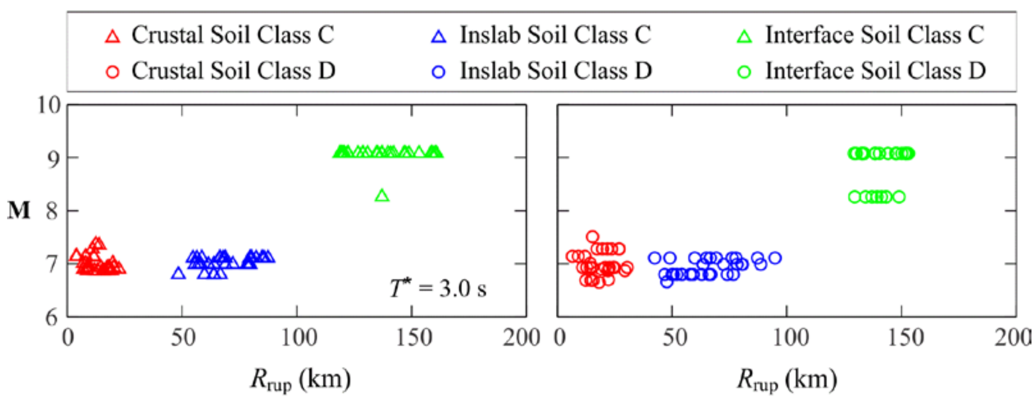

Fig. 1 – Magnitude-distance distribution of the selected records at period T^* = 3.0 s

PSHA considering a 2% in 50 years probability of exceedance, using the model developed by Atkinson and Goda for Vancouver [23], is conducted at different periods T^* = 0.2 s, 0.5 s, 1.0 s, 2.0 s, and 3.0 s to investigate the effects η factors. The deaggregation results are shown in Table 1 in terms of mean moment magnitude **M** and mean rupture distance $R_{rup.}$ The deaggregation results are found to be insensitive to soil class for all three event types. Crustal and inslab deaggregation results are affected by the choice of T^*. However, this is not the case for interface events in the considered period range, i.e. $T^* \leq 3.0$ s. The final step in the scenario-based record selection was to identify a set of records representing each event type and the corresponding mean **M** and mean R_{rup} obtained from deaggregation. A **M**-R_{rup} trade-off of 40 km, 60 km, and 60 km is adopted for crustal, inslab, and interface events, respectively. This suggested that, for example, a crustal record having a magnitude of one unit lower than the mean **M** obtained from deaggregation would be selected provided that it had a R_{rup} 40 km shorter than the mean R_{rup} obtained from deaggregation. The final selection consisted of 60 horizontal accelerograms for each combination of event type and soil class, i.e. 360 horizontal accelerograms for each T^*. As an example, Fig. 1 shows the **M**-R_{rup} distribution for T^* = 3.0 s. The reader is referred to the work of Daneshvar et al. [24] for the details regarding the selection process.

Table 1 – Magnitude-distance criteria for the selected records based on deaggregation results

Event Type	Soil class	T^* = 0.2 s		T^* = 0.5 s		T^* = 1.0 s		T^* = 2.0 s		T^* = 3.0 s	
		M	R_{rup}	**M**	R_{rup}	**M**	R_{rup}	**M**	R_{rup}	**M**	R_{rup}
Crustal	C	6.5	11	6.7	13	6.8	15	7.0	15	7.1	15
	D	6.5	14	6.7	14	6.8	18	7.0	15	7.1	17
Inslab	C	6.8	62	7.0	55	7.0	54	7.1	54	7.2	58
	D	6.9	61	7.0	56	7.0	52	7.1	51	7.2	53
Interface	C	8.6	141	8.6	141	8.6	142	8.6	142	8.6	141
	D	8.6	142	8.7	142	8.6	141	8.6	141	8.6	141

3. Computed Damping Modification Factors

The η factors corresponding to the selected records are computed using Eq. (1) at different damping levels ξ = 1%, 2%, 3%, 4%, 10%, 15%, 20%, 25%, and 30%. The correlation between computed η factors, damping ratios, and T^* is then studied based on the median η factors corresponding to each damping ratio, ground motion event and soil class. Figures 2 and 3 illustrate a selection of the results for soil classes C and D, respectively. As expected, the dependency of η factors on damping ratio is clearly shown. At higher damping levels, the steady state is reached after fewer cycles, resulting in considerably lower spectral displacements, hence the smaller η factors. Figures 2 and 3 also show the dependency of η factors on period T in the period range of interest in this study, i.e. $0 \leq T \leq 3.0$ s. Slight period dependency is observed for the η factors from crustal records with the increase in the η factors toward longer periods. On the contrary, the period dependency of η factors from inslab records is evident over the entire period range of interest. Despite the minor period dependency at very short periods and at longer periods $2.5 \text{ s} \leq T \leq 3.0$ s, η factors from interface records do not show a significant period dependency. The minor local variations in η factors are due to the presence of wave packets in specific segments of the ground motion records, having a narrow frequency bandwidth. This created local spectral peaks in low damping spectra ξ = 5 %, resulting in relatively smaller η factors at higher damping levels for which the wider frequency bandwidth produced smoother spectra [17].

To have a better grasp of the ground-motion-type-dependency of the η factors, the frequency content and significant duration of the selected records are determined. The significant duration was defined as the time interval corresponding to 5% and 95% of Arias intensity [25]. The mean period T_m was adopted as the measure of frequency content [26, 27]. The results showed that, in general, inslab events have higher frequency content, i.e. lower T_m values, attributed to high stress drop source parameters. Considering a high-frequency record, a rigid structure undergoes more cycles in comparison to a more flexible structure; thus the effect of damping is more significant for the former [28]. This explains the lower/higher damping reduction factors at shorter periods for inslab events at low/high damping levels, which have richer high-frequency content. As expected, records for the selected interface events have considerably longer durations than those for the crustal and inslab events because of the inclusion of very large events, i.e. the M9 2011 Tohoku event. A decrease in the η factors as a result of increase in ground motion duration has been reported in the literature [29, 30]. Based on a study of harmonic excitation of single-degree-of-freedom systems, Zhou et al. [29] also reported that the maximum displacement reaches a plateau and does not increase further when the system is subjected to a higher number of cycles, resulting in almost constant damping reduction factors at each damping level. The relatively smaller, and near-constant η factors obtained for interface events in this work are in agreement with previous studies. Figure 4 illustrates an example of the obtained results for both soil classes considered. The effect of T^* on duration and T_m is found to be negligible, mainly because minor differences in **M**-R_{rup} combinations resulted in the majority of the records selected for each scenario being similar.

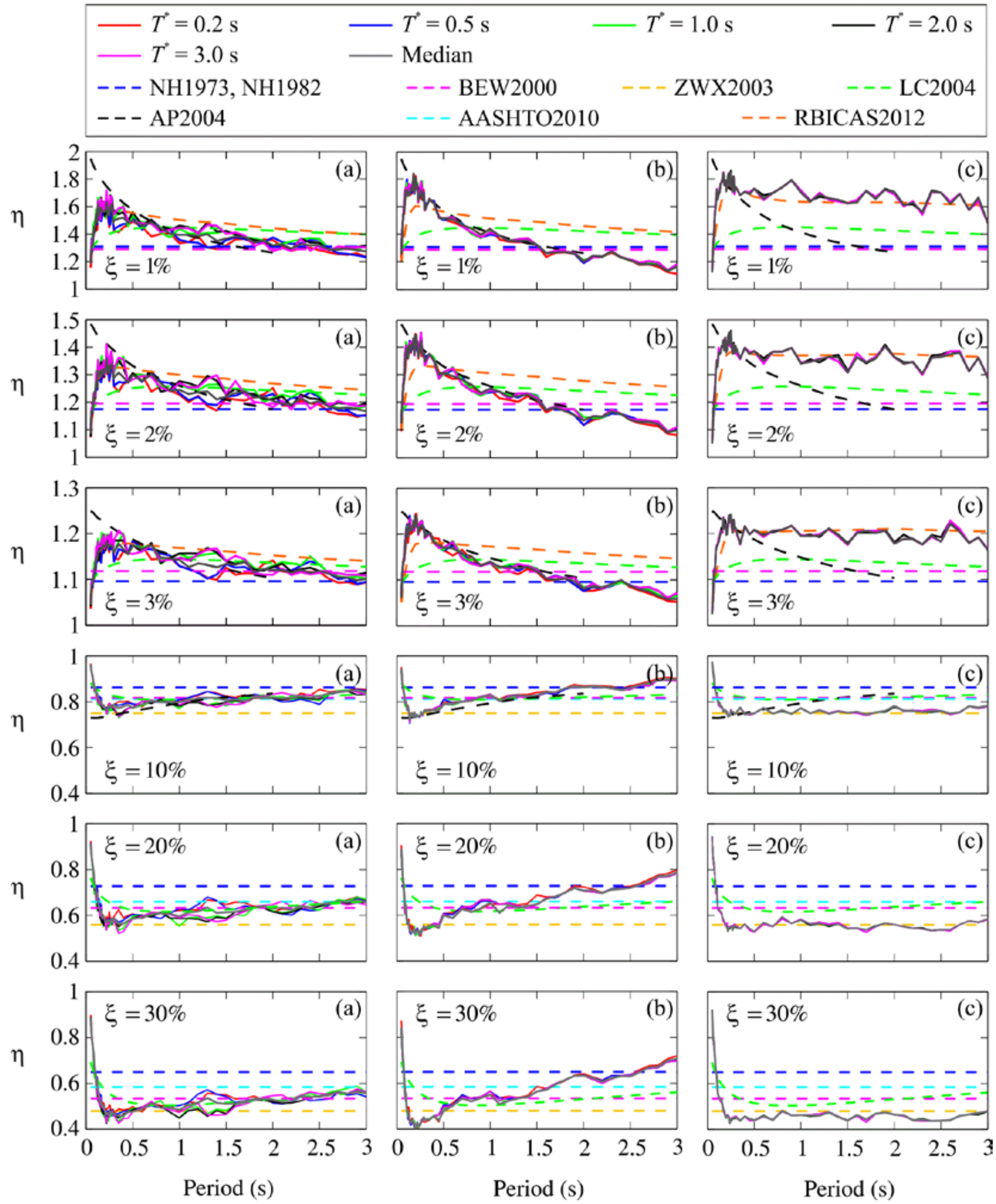

Fig. 2 – Computed damping modification factors for: (a) crustal, (b) inslab, and (c) interface records for soil class C and predictions of some available equations (NH1978 [5, 6]; BEW2000 [7]; ZWX2003 [9]; LC2004 [10]; AP2004 [11]; RBICAS [15])

Figures 2 and 3 also show that, in general, T^* does not have a significant effect on the η factors, particularly for inslab and interface events. This is also due to the minor differences between the deaggregation results at different T^*, as presented in Table 1. Nevertheless, negligible changes in η factors were observed at intermediate periods for crustal records. Figures 2 and 3 also illustrate the minor effect of soil class on the η factors. This was also reported in some of the previous studies, [e.g. 10, 17]. A comparison between the deaggregation results for soil classes C and D also explains the negligible differences. As the trends in η factors are not significantly affected by the T^* considered, we combined all already selected records for different T^* and computed the corresponding median η factors at each period T. These median η factors are shown in Figures 2 and 3 alongside those previously discussed. It can be seen that the median η factors could satisfactorily represent the results for each event.

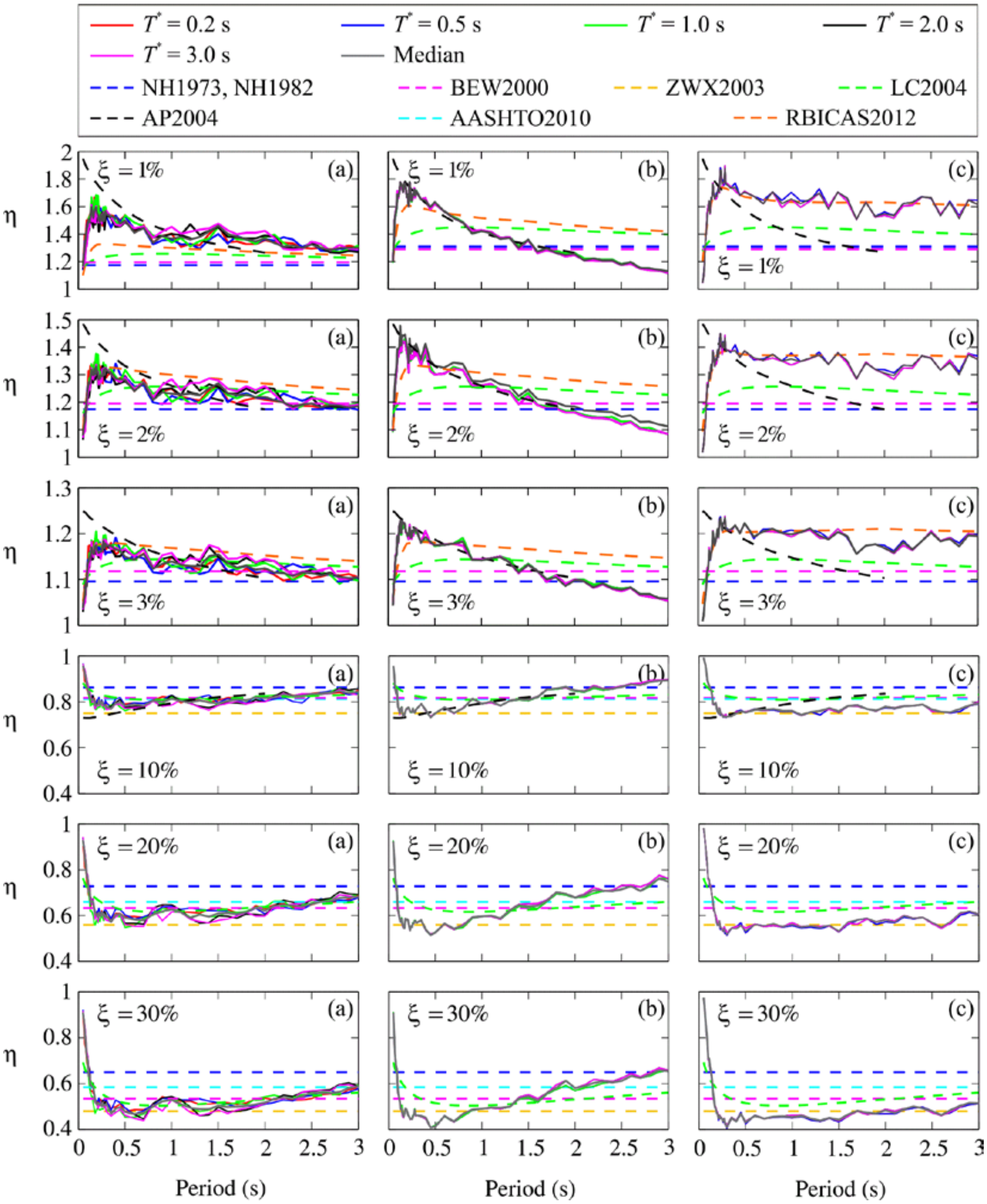

Fig. 3 – Computed damping modification factors for (a) crustal, (b) inslab, and (c) interface records for soil class D and predictions of some available equations (NH1978 [5, 6]; BEW2000 [7]; ZWX2003 [9]; LC2004 [10]; AP2004 [11]; RBICAS [15])

4. Proposed Model Equation for Damping Reduction Factors

Figures 2 and 3 compare the predictions of a number of equations proposed in the literature [5-7, 9-11, 15] to η factors obtained in this study. The observed disagreement between currently available equations and computed η factors is not surprising as these equations were proposed based on records which do not necessarily share the same characteristics as those selected for this study. This is particularly evident for highly period-dependent η factors from inslab records. The η factors provided by Atkinson and Pierre [11], despite not covering the entire period range of study, show an acceptable agreement with the computed η factors for crustal and inslab events. Predictions by Rezaeian et al. [15] also agree well with η factors computed for interface events at low damping levels. Predictions by Zhou et al. [9] show acceptable agreement with results from interface events at high damping levels, however, this agreement diminishes as damping level increases.

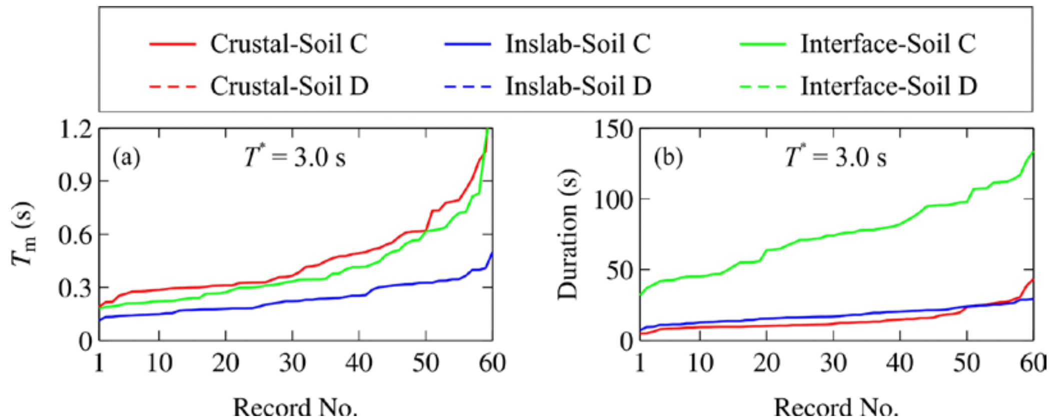

Fig. 4 - (a) Mean period T_m and (b) duration for the 5%-95% Arias intensity interval of the selected records from the three event types at T^* = 3.0 s

In what follows, we present a model equation capable of predicting η factors corresponding to deep inslab and interface subduction earthquakes, as well as shallow crustal events. After several trials, the following expression could be adapted to match displacement spectra, corresponding to the three event types, with the least misfit

$$\eta = 1-(1+a_1[-\ln\xi]^{a_2})(a_3+T)^{a_4}\exp(a_5 T^{a_6}) \tag{2}$$

The coefficients a_1 to a_2 in Eq. (2) can be determined through nonlinear regression analyses using least-squares. Based on the observed trends in Figs. 2 and 3 and the obtained results from several trials to determine the coefficients, it is concluded that, at least two sets of regression coefficients corresponding to $0 \leq T < 1$ s and $1 \text{ s} < T \leq 3$ s, are required to obtain acceptable predictions. Using more sets of coefficients corresponding to intervals below 1 s would enhance the predictions at the very short period range, but at the same time, complicate the use of the equation. The coefficients for both period intervals are presented in Tables 2 to 5 for soil classes C and D. To provide a smoother transition between the two intervals, the η factor at 1 s was calculated as the average of the outcomes of predicting expressions at periods immediately before and after 1 s. For brevity, Fig. 5 only compares the predicted η factors obtained using Eq. (2) to median η factors computed for some low and high damping levels from records corresponding to T^* = 3 s and the median for the three considered event types and two soil classes C and D.

The obtained results show a generally good agreement between the proposed predictions and computed η factors for all three event types. Standard deviations corresponding to the median η factors for soil classes C and D show that the dispersion increases with damping level, however, without exceeding 0.3 units for both soil classes. For crustal records, the observed dispersion of η factors about the mean are due to the larger variations of the selected records at each T^*. The selected inslab and interface records are quite similar for each T^* and thus the corresponding dispersion about the mean does not vary significantly with T^*.

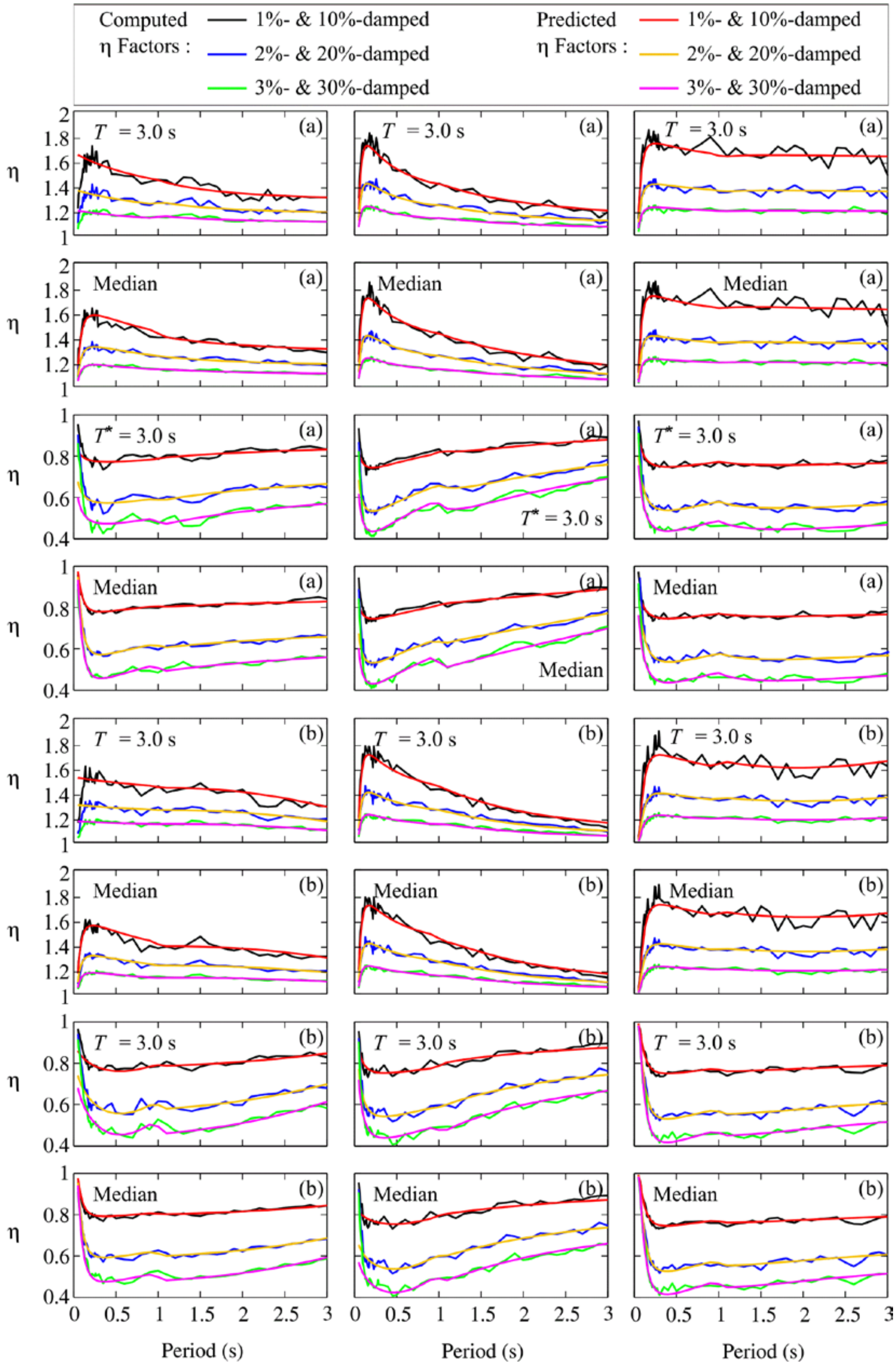

Fig. 5 - Comparison of the computed and predicted damping reduction factors for crustal (left), inslab (middle), and interface (right) events and soil types (a) C and (b) D

Table 2 – Coefficients for 1%-, 2%-, 3%-, and 4%-damping for both period ranges (PR) and soil classes C and D

Event	T^*	PR	Soil Class C						Soil Class D					
			a_1	a_2	a_3	a_4	a_5	a_6	a_1	a_2	a_3	a_4	a_5	a_6
Crustal	0.2	PR1	-0.2583	1.2334	1.00	-0.7950	-0.0039	-2.00	-0.2061	1.4387	1.00	-1.0927	-0.015	-1.50
		PR2	-0.6388	0.4088	1.00	0.9905	-0.1312	2.00	-0.3967	0.8448	0.50	-0.777	0.2226	1.00
	0.5	PR1	-0.2769	1.1686	1.00	-0.5271	-0.0031	-2.00	-0.4121	0.8059	0.00	-0.2289	-0.005	-2.00
		PR2	-0.3728	0.9039	-0.75	-0.4064	-0.8798	-2.00	-0.4713	0.6879	0.00	0.7088	-0.1085	2.00
	1.0	PR1	-0.1684	1.6287	1.00	-0.7698	-0.2616	-0.25	-0.3089	1.0722	0.00	0.0506	-0.5564	3.00
		PR2	-0.5900	0.4819	0.00	-0.0277	0.6659	-0.50	-0.3370	0.9969	0.00	0.6679	-0.4291	1.00
	2.0	PR1	-0.2513	1.2565	1.00	-0.5138	-0.0862	0.00	-0.2701	1.1934	1.00	-0.7144	-0.0049	-2.00
		PR2	-0.7576	0.2532	0.00	0.1845	1.3891	-0.50	-0.6637	0.3743	3.00	0.6008	-0.0242	3.00
	3.0	PR1	-0.2516	1.2562	1.00	-0.5895	-0.0685	0.00	-0.4181	0.7934	1.00	-0.2186	0.2624	0.00
		PR2	-0.7972	0.2067	0.00	0.2549	1.5650	-0.50	-0.5291	0.5809	3.00	0.3264	-0.0215	3.00
	Median	PR1	-0.2527	1.2533	1.00	-0.6770	-0.0040	-2.00	-0.2655	1.2083	1.00	-0.715	-0.0035	-2.00
		PR2	-0.6050	0.4589	0.00	-0.0381	0.6293	-0.50	-0.5260	0.5864	3.00	0.2148	-0.0139	3.00
In-slab	0.2	PR1	-0.3907	0.8538	0.00	-0.6892	-0.1270	-1.00	-0.3039	1.0814	0.50	-0.5842	-0.0002	-3.00
		PR2	-0.4253	0.7824	1.00	0.0400	-0.1138	2.00	-0.3156	1.0700	0.00	-1.1927	-0.36	-3.00
	0.5	PR1	-0.4117	0.8078	0.00	-0.3903	-0.0047	-2.00	-0.3006	1.0925	0.50	-0.724	-0.0039	-2.00
		PR2	-0.4140	0.8103	0.00	-0.4134	-0.0484	2.00	-0.3156	1.0700	0.00	-1.1927	-0.36	-3.00
	1.0	PR1	-0.3078	1.0719	0.50	-0.8405	-0.0034	-2.00	-0.3006	1.0925	0.50	-0.724	-0.0039	-2.00
		PR2	-0.3683	0.9201	0.00	-0.9036	-0.1818	-3.00	-0.3156	1.0709	0.00	-1.1497	-0.3415	-2.00
	2.0	PR1	-0.4126	0.8044	0.00	-0.4100	-0.0048	-2.00	-0.3762	0.8866	0.00	-0.3371	-0.0047	-2.00
		PR2	-0.3752	0.9030	0.50	-0.7230	0.1470	-2.00	-0.3199	1.0581	0.00	-1.1989	-0.3073	-2.00
	3.0	PR1	-0.4126	0.8044	0.00	-0.4100	-0.0048	-2.00	-0.3762	0.8866	0.00	-0.3371	-0.0047	-2.00
		PR2	-0.4080	0.8247	0.00	-0.7198	-0.0429	-2.00	-0.3199	1.0581	0.00	-1.1989	-0.3073	-2.00
	Median	PR1	-0.4002	0.8321	0.00	-0.3828	-0.0048	-2.00	-0.3686	0.9046	0.00	-0.3316	-0.0048	-2.00
		PR2	-0.3971	0.8469	0.00	-0.5321	-0.0407	-2.00	-0.3239	1.0453	0.00	-1.1815	-0.3329	-3.00
Interface	0.2	PR1	-0.2715	1.1833	0.00	-0.1360	-0.0042	-2.00	-0.2816	1.1512	0.00	-0.1957	-0.0089	-2.00
		PR2	-0.2610	1.2232	0.00	-0.0680	-0.0938	-2.00	-0.2361	1.3146	0.50	-0.4265	0.044	2.00
	0.5	PR1	-0.2715	1.1833	0.00	-0.1360	-0.0042	-2.00	-0.2816	1.1512	0.00	-0.1957	-0.0089	-2.00
		PR2	-0.2610	1.2232	0.00	-0.0680	-0.0938	-2.00	-0.2361	1.3146	0.50	-0.4265	0.044	2.00
	1.0	PR1	-0.2787	1.1600	0.00	-0.1576	-0.0045	-2.00	-0.2930	1.1161	0.00	-0.2044	-0.0093	-2.00
		PR2	-0.2165	1.3982	0.00	-0.3011	-0.2676	-2.00	-0.2360	1.3144	0.50	-0.4568	0.0478	2.00
	2.0	PR1	-0.2787	1.1600	0.00	-0.1576	-0.0045	-2.00	-0.2930	1.1161	0.00	-0.2044	-0.0093	-2.00
		PR2	-0.2729	1.1839	0.00	0.1973	-0.0459	-2.00	-0.2360	1.3144	0.50	-0.4568	0.0478	2.00
	3.0	PR1	-0.2715	1.1833	0.00	-0.1360	-0.0042	-2.00	-0.2930	1.1161	0.00	-0.2044	-0.0093	-2.00
		PR2	-0.2610	1.2232	0.00	-0.0680	-0.0938	-2.00	-0.2360	1.3144	0.50	-0.4568	0.0478	2.00
	Median	PR1	-0.2802	1.1551	0.00	-0.1264	-0.0012	-2.50	-0.2812	1.1525	0.00	-0.1867	-0.0091	-2.00
		PR2	-0.2613	1.2229	0.00	-0.0889	-0.0898	-2.00	-0.2409	1.2944	0.50	-0.3395	0.0328	2.00

Table 3 - Coefficients for 10%-, 15%-, 20%-, 25%-, and 30%-damping for both period ranges (PR) and soil classes C and D

Event	T*	PR	Soil Class C						Soil Class D					
			a_1	a_2	a_3	a_4	a_5	a_6	a_1	a_2	a_3	a_4	a_5	a_6
Crustal	0.2	PR1	-0.3130	1.0543	1.00	-0.3679	-0.0051	-2.00	-0.286	1.1355	1.00	-0.4608	-0.0184	-1.50
		PR2	-0.4274	0.7743	1.00	-0.0282	-0.0112	2.00	-0.3978	0.8381	0.50	0.585	-0.3221	1.00
	0.5	PR1	-0.3005	1.0924	1.00	-0.3848	-0.0051	-2.00	-0.4368	0.7441	0.00	-0.0717	-0.0056	-2.00
		PR2	-0.3451	0.9703	1.00	-0.1756	-0.1151	-2.00	-0.4324	0.7597	0.00	0.3082	-0.0572	2.00
	1.0	PR1	-0.3005	1.0924	1.00	-0.3843	-0.0051	-0.25	-0.2885	1.1276	0.00	0.1492	-0.3686	3.00
		PR2	-0.2860	1.1422	0.00	-0.3001	-0.1555	-0.50	-0.2851	1.1477	0.00	0.3055	-0.2697	1.00
	2.0	PR1	-0.2259	1.3561	1.00	-0.0542	-0.286	0.00	-0.2305	1.3377	0.00	0.2708	-0.5437	3.00
		PR2	-0.2983	1.1034	0.00	-0.2611	-0.1432	-0.50	-0.3185	1.0434	3.00	-0.0732	-0.0136	3.00
	3.0	PR1	-0.2001	1.4696	1.00	-0.3712	-0.1329	-0.50	-0.1935	1.4988	0.00	0.283	-0.4626	2.00
		PR2	-0.3173	1.0473	0.00	-0.2530	-0.1338	-0.50	-0.3087	1.0715	3.00	-0.0931	-0.0115	3.00
	Median	PR1	-0.2830	1.1469	1.00	-0.4443	-0.0057	-2.00	-0.3283	1.0076	1.00	-0.3143	-0.0058	-2.00
		PR2	-0.3254	1.0243	0.00	-0.2016	-0.1691	-0.50	-0.3482	0.9619	3.00	-0.0775	-0.0082	3.00
In-slab	0.2	PR1	-0.1668	1.6345	1.00	-0.7997	-0.0334	-1.00	-0.2206	1.3747	0.00	0.1755	-0.3741	2.00
		PR2	-0.4102	0.8122	1.00	-0.0692	-0.0551	2.00	-0.3328	1.0053	0.00	-0.5173	-0.1317	-3.00
	0.5	PR1	-0.1713	1.6101	1.00	-0.8125	-0.044	-0.75	-0.2206	1.3747	0.00	0.1755	-0.3741	2.00
		PR2	-0.4261	0.7759	0.00	-0.0436	-0.0524	2.00	-0.3328	1.0053	0.00	-0.5173	-0.1317	-3.00
	1.0	PR1	-0.1913	1.4987	1.00	-0.8814	-0.0033	-2.00	-0.171	1.6111	1.00	-0.5301	-0.056	-1.00
		PR2	-0.2965	1.1118	0.00	-0.6207	-0.3099	-2.00	-0.3325	1.0063	0.00	-0.5041	-0.1159	-2.00
	2.0	PR1	-0.1582	1.6838	1.00	-0.8783	-0.0337	-1.00	-0.1882	1.5223	1.00	-0.5087	-0.0481	-1.00
		PR2	-0.3170	1.0496	0.00	-0.6126	-0.3211	-3.00	-0.3714	0.9045	0.00	-0.4691	-0.0332	-2.00
	3.0	PR1	-0.1582	1.6838	1.00	-0.8783	-0.0337	-1.00	-0.1882	1.5223	1.00	-0.5087	-0.0481	-1.00
		PR2	-0.3170	1.0496	0.00	-0.6126	-0.3211	-3.00	-0.3714	0.9045	0.00	-0.4691	-0.0332	-2.00
	Median	PR1	-0.1711	1.6111	1.00	-0.7974	-0.0311	-1.00	-0.2243	1.3594	0.00	0.168	-0.3747	2.00
		PR2	-0.4119	0.8080	0.00	-0.1661	-0.0404	2.00	-0.3597	0.9339	0.00	-0.4691	-0.0763	-3.00
Interface	0.2	PR1	-0.1740	1.5927	1.00	-0.4994	-0.0558	-1.0	-0.2089	1.424	1.00	-0.4591	-0.0095	-2.00
		PR2	-0.1837	1.5443	0.00	-0.2009	-0.3620	-1.0	-0.1988	1.4716	1.00	-0.2868	-0.0886	-2.00
	0.5	PR1	-0.1740	1.5927	1.00	-0.4994	-0.0558	-1.0	-0.2089	1.424	1.00	-0.4591	-0.0095	-2.00
		PR2	-0.1894	1.5162	1.00	-0.2296	-0.2111	-2.0	-0.1988	1.4716	1.00	-0.2868	-0.0886	-2.00
	1.0	PR1	-0.1612	1.6640	1.00	-0.5255	-0.0592	-1.0	-0.2204	1.3749	1.00	-0.4369	-0.0093	-2.00
		PR2	-0.1880	1.5225	1.00	-0.2340	-0.2015	-2.0	-0.2014	1.46	1.00	-0.295	-0.0893	-2.00
	2.0	PR1	-0.1612	1.6640	1.00	-0.5255	-0.0592	-1.0	-0.2204	1.3749	1.00	-0.4369	-0.0093	-2.00
		PR2	-0.1880	1.5225	1.00	-0.2340	-0.2015	-2.0	-0.2014	1.46	1.00	-0.295	-0.0893	-2.00
	3.0	PR1	-0.1740	1.5927	1.00	-0.4994	-0.0558	-1.0	-0.2204	1.3749	1.00	-0.4369	-0.0093	-2.00
		PR2	-0.1894	1.5162	1.00	-0.2296	-0.2111	-2.0	-0.2014	1.46	1.00	-0.295	-0.0893	-2.00
	Median	PR1	-0.1695	1.6172	1.00	-0.5019	-0.0578	-1.0	-0.2066	1.4343	1.00	-0.4756	-0.0097	-2.00
		PR2	-0.1882	1.5221	1.00	-0.2347	-0.2033	-2.0	-0.2048	1.4446	1.00	-0.2906	-0.0824	-2.00

5. Conclusions

Spectral displacements at damping levels other than the conventional 5% and the corresponding damping modification factors are important in seismic design and analysis of both lightly- and highly-damped structures, such as transmission lines and structures equipped with energy dissipating systems, respectively. In this paper, we investigated and characterized damping modification factors corresponding to inslab and interface earthquakes, a subject that has been rarely addressed in the literature. Damping modification factors for crustal events were also investigated for comparison purposes. A large data set of 2,302 records from the PEER-NGA, K-NET, KiK-net, and SKnet databases was first compiled. For each event type and soil type, i.e. NBCC soil classes C and D, 60 horizontal components were selected from the preliminary data set based on seismic deaggregation results for Vancouver, the largest urban center in southwestern British Columbia. The median damping modification factors for this final selection of records were then determined. We observed that while damping modification factors for inslab events were highly period-dependent, this dependency was less pronounced for their crustal and interface counterparts. It was also seen that the period at which PSHA was performed did not have a significant effect on damping modification factors. Similarly, minor differences were observed between the damping modification factors from soil classes C and D. A study of frequency content and duration of the records used in the study showed that the rich high frequency content of inslab records contributes to the observed significant period dependency of the corresponding damping modification factors. Furthermore, the considerably longer duration of interface records for very large events resulted in nearly constant damping modification factors. This is an important consideration in seismic design for the great Cascadia subduction event. We also found that the median of the damping modification factors computed from all the selected records, regardless of the period at which PSHA is performed, can be a good representative for the median damping modification factors for each event type. A new model equation capable of more accurately predicting, in comparison to available equations, the damping modification factors for all the three considered earthquake types was developed. We showed that the proposed predictions provide a satisfactory evaluation of damping reduction factors corresponding to crustal, inslab, and interface earthquakes.

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