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DAMPING COEFFICIENTS FOR THE SINGLE-DEGREE-OF-FREEDOM (SDOF) SYSTEM SUBJECTED TO NEAR-FAULT SEISMIC EXCITATIONS

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ABSTRACT

Damping coefficients for the single-degree-of-freedom (SDOF) system subjected to near-fault ground motions are calculated for a wide range of periods and damping levels. The results indicate that damping coefficients proposed in design codes and previous studies based on far-field ground motion records are not conservative for near-fault seismic excitations. A new approach is recommended for the derivation of damping coefficients appropriate for engineering analysis and design in the immediate vicinity of the earthquake fault. This includes the normalization of the period axis with respect to the duration of the ground velocity pulses recorded in the near-fault region. The pulse duration is controlled by the rise time on the fault plane and scales directly with earthquake magnitude.

Introduction

Earthquake-resistant buildings are often designed through the use of building codes that provide design spectral values only for 5% of critical damping. However, base-isolated buildings are typically designed with higher values of damping to allow for greater energy dissipation caused by seismic excitation. In order to provide safe design parameters for these buildings, spectral values for these alternative values of damping are required. Damping coefficients are being utilized as a simple way to adjust the spectral values of 5% critical damping to the higher values of damping needed for design. Damping coefficients (B) are defined as:

$$B\,(T,\beta) = S_a(T,0.05)\,/\,S_a(T,\beta) \tag{1}$$

where T is the elastic period, β is the damping ratio, and S_a is the pseudo-spectral acceleration for particular values of T and β.

Several investigators have recommended damping coefficients for various levels of damping (e.g., Newmark and Hall, 1982; Ashour, 1987; Wu and Hanson, 1989; Tolis and Faccioli, 1999; Bommer et al., 2000; Ramirez et al., 2002; Lin and Chang, 2003; Priestley, 2003; among others). In addition, other studies have focused on the investigation of certain parameters

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such as the earthquake magnitude, source-to-site distance, site classification, tectonic setting, duration, and number of cycles on damping coefficients (e.g., Lin and Chang, 2004; Pavlou and Constantinou, 2004; Bommer and Mendis, 2005; Cameron and Green, 2007; Stafford et al., 2008; among others).

Ground motions recorded at a distance closer to the seismic source exhibit amplitude, frequency and duration characteristics that differ from those of far-field records that are typically used to develop design codes. In this study, damping coefficients for the single-degree-of-freedom (SDOF) system subjected to near-fault ground motions are calculated for a wide range of periods and damping levels. The results are directly compared to recommendations of building codes and previous studies on damping coefficients in order to assess their adequacy for aseismic design in the near-fault region. The normalization of the period axis with respect to the duration of the ground velocity pulses, a characteristic parameter that is typical of near-fault ground motions, is also investigated as a more effective means of modeling damping coefficients.

Strong Ground Motion Database

Not all ground motion time histories recorded by stations in the vicinity of a fault exhibit intense velocity pulses. A comprehensive review of the factors that influence the near-fault ground motions is presented by Mavroeidis and Papageorgiou (2002, 2003). Forward directivity and permanent translation (fling) are the two main causes for the velocity pulses observed the near-fault region. Forward directivity occurs when the fault rupture propagates toward a site with a rupture velocity approximately equal to the shear-wave velocity. In this case, most of the elastic energy arrives coherently in a single, intense, relatively long-period pulse at the beginning of the record, representing the cumulative effect of almost all the seismic radiation from the fault. On the other hand, permanent translation at a site is a consequence of permanent fault displacement due to an earthquake; it appears in the form of step displacement and one-sided velocity pulse in the strike-parallel direction for strike-slip faults or in the strike-normal direction for dip-slips faults.

Table 1 lists the actual near-fault ground motion records with “distinct” velocity pulses used in the present study. Information regarding the earthquake magnitude, closest distance to the fault, and peak ground velocity values is also provided in the table. These records are part of the near-fault strong ground motion database compiled by Mavroeidis and Papageorgiou (2003). Fig. 1 illustrates the ground motion velocity pulses of all records listed in Table 1 in a visually informative manner. Fig. 2a shows the 5% damped pseudo-acceleration response spectra of the elastic SDOD system subjected to the near-fault records of Table 1. The median (solid) and median-plus-one-standard-deviation (dashed) pseudo-acceleration response spectra are displayed in Fig. 2b assuming a lognormal distribution of the response spectral values. The gray region represents the range of variation of the spectral amplitudes.

Table 1. Near-fault ground motion records with distinct velocity pulses used in the present study (from Mavroeidis and Papageorgiou, 2003).

Location	Date	M_w	Station	Fault Distance (km)	Component	Recorded PGV (cm/sec)
Parkfield, CA	27-Jun-66	6.20	C02	0.1	SN	75.1
San Fernando, CA	9-Feb-71	6.55	PCD	3.0	SN	120.0
Gazli, USSR	17-May-76	6.80	KAR	3.0	Rad	60.0
Tabas, Iran	16-Sep-78	7.11	TAB	1.2	SP	122.0
Coyote Lake, CA	8-Jun-79	5.63	GA6	1.2	SN	47.5
Imperial Valley, CA	15-Oct-79	6.50	E04	6.0	SN	78.3
			E05	2.7	SN	91.8
			E06	0.3	SN	112.0
			E07	1.8	SN	109.0
			EMO	1.2	SN	115.0
Mexicali Valley, Mexico	9-Jun-80	6.37	VCT	3.0	SN	76.7
Morgan Hill, CA	24-Apr-84	6.15	HAL	2.0	SN	39.8
Palm Springs, CA	8-Jul-86	6.09	NPS	4.0	SN	73.6
			DSP	6.4	SN	29.2
Whittier Narrows, CA	10-Oct-87	5.93	DOW	16.4	SN	30.7
			NWK	15.7	SN	20.0
Superstition Hills, CA	24-Nov-87	6.40	PTS	0.7	SN	109.0
			ELC	13.6	SN	52.0
Loma Prieta, CA	17-Oct-89	6.90	LGP	3.0	SN	102.0
			STG	8.3	SN	56.4
Sierra Madre, CA	28-Jun-91	5.56	COG	9.4	Rad	15.3
Erzincan, Turkey	13-Mar-92	6.63	ERZ	2.0	SN	95.2
Landers, CA	28-Jun-92	7.20	LUC	1.1	SN	114.0
Northridge, CA	17-Jan-94	6.70	JFA	5.2	SN	105.0
			RRS	6.0	SN	173.0
			SCG	5.1	SN	134.0
			SCH	5.0	SN	122.0
			NWS	5.3	SN	117.0
Aigion, Greece	15-Jun-95	6.33	AEG	6.0	Long	40.9
			AEG	6.0	Tran	52.0
Izmit, Turkey	17-Aug-99	7.40	ARC	14.0	SN	44.3
			SKR	3.1	SP	80.3
			GBZ	11.0	SN	41.4
			GBZ	11.0	SP	28.7
Chi-Chi, Taiwan	20-Sep-99	7.60	TCU052	0.8	SN	270.0
			TCU068	0.2	SN	380.0
			TCU075	0.6	SN	115.0
			TCU076	2.3	SN	88.0

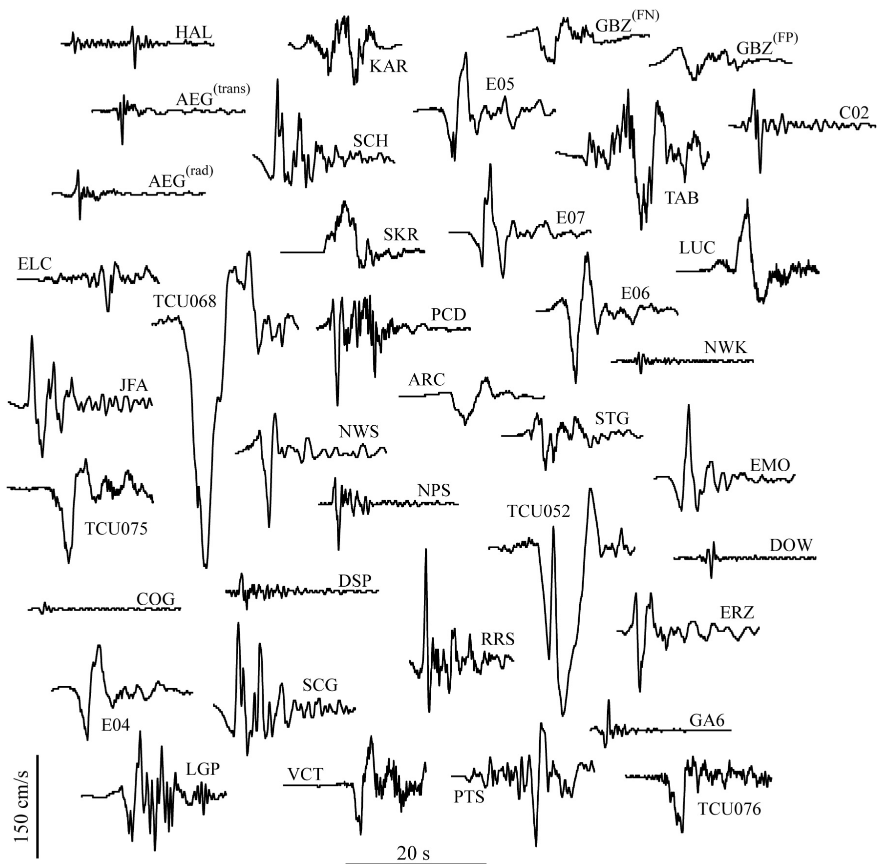

Figure 1. Near-fault strong ground motion records with "distinct" velocity pulses used in the present study (from Mavroeidis and Papageorgiou, 2003).

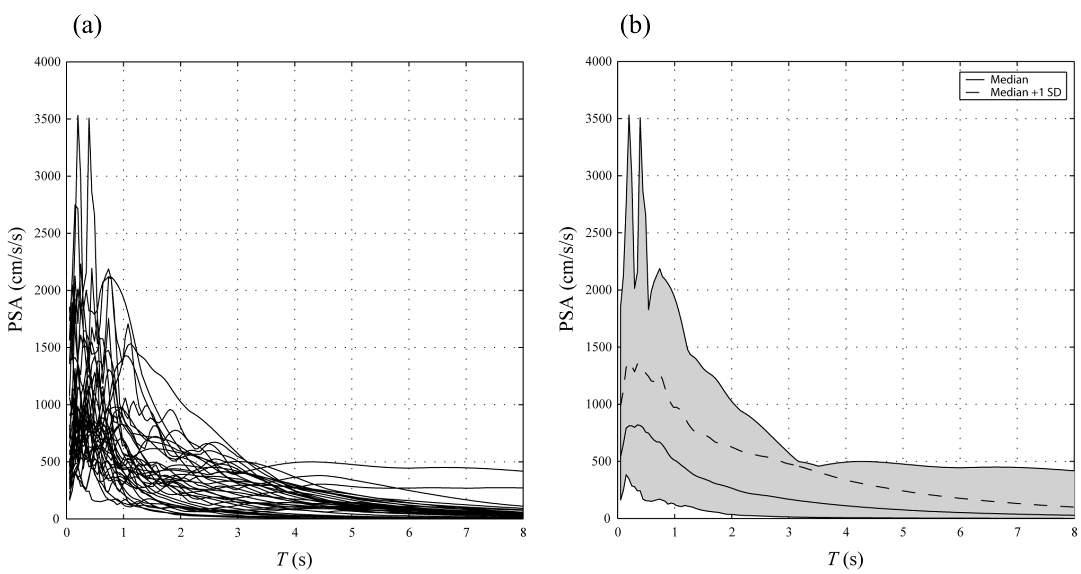

Figure 2. Pseudo-acceleration response spectra of the elastic SDOD system (5% damping) subjected to the near-fault strong motion records of Table 1: (a) all spectra, and (b) median (solid) and median-plus-one-standard-deviation (dashed) spectra.

Damping Coefficients

Linear response-history analysis was used to obtain the pseudo-spectral accelerations, $S_a(T,\beta)$, for a wide range of periods (*T*) and damping ratios (β). Fig. 3 illustrates the average relationships between the damping coefficient (*B*) and the period (*T*) that were established for damping ratios in the range of 5% to 100% using the ground motion records of Table 1.

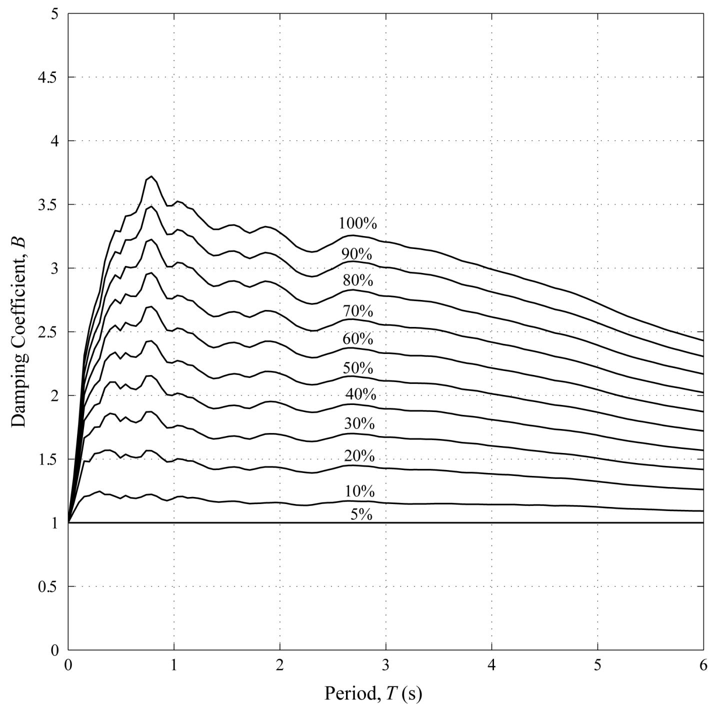

Figure 3. Calculated damping coefficients for the near-fault ground motion records of Table 1.

Comparison with Codes and Previous Studies

The calculated damping coefficients of Fig. 3 are compared to recommendations of building codes and previous studies on damping modification factors. While most of these recommendations have not been developed based on near-fault ground motion records specifically, they are being considered to determine their adequacy for aseismic design in the vicinity of the fault. Due to space limitations, only indicative results are presented in this article.

Fig. 4 shows the comparison of the calculated damping coefficients against the recommendations of NEHRP (2003) and EC8 (CEN, 2004). In order for the building codes to be considered conservative, their recommended damping coefficient values need to be below those derived in the present study from near-fault data exclusively. Fig. 4a indicates that the *B* values recommended by NEHRP (2003) are consistently higher than the *B* values generated from the near-fault ground motions for any period greater than about 1 second and damping ratios up to 40% of critical damping. For higher damping ratios, the *B* values recommended by NEHRP (2003) are not conservative for all period values. Likewise, Fig. 4b indicates that EC8 (CEN, 2004) is consistently not conservative for all values of damping.

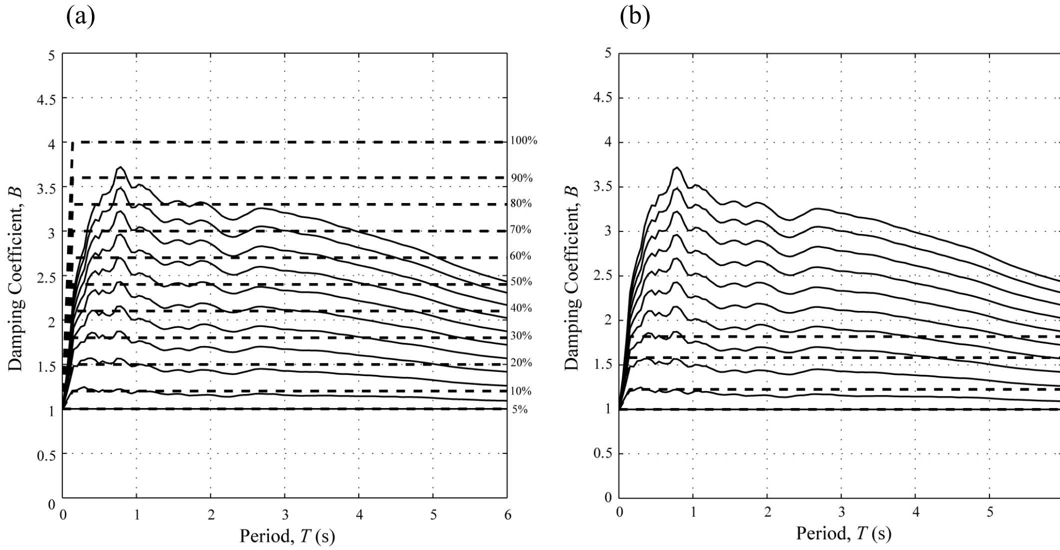

Figure 4. Comparison of the calculated damping coefficients against (a) NEHRP (2003) and (b) EC8 (CEN, 2004) recommendations.

Fig. 5a shows the comparison of the calculated damping coefficients against the recommendations of Lin and Chang (2003) derived from far-field ground motion records. The *B* values proposed by Lin and Chang depend upon both the period and the damping ratio. As illustrated in Fig. 5a, these recommendations are also not conservative for near-fault seismic excitations. Priestley (2003) proposed damping coefficients specifically for use with near-fault earthquakes. The recommended *B* values seem to be conservative for all periods. While this is the first study considered here to yield conservative results, it might be deemed that these results are overly conservative. Namely, for higher values of damping, some of the results appear to be just over half of the value needed to be conservative.

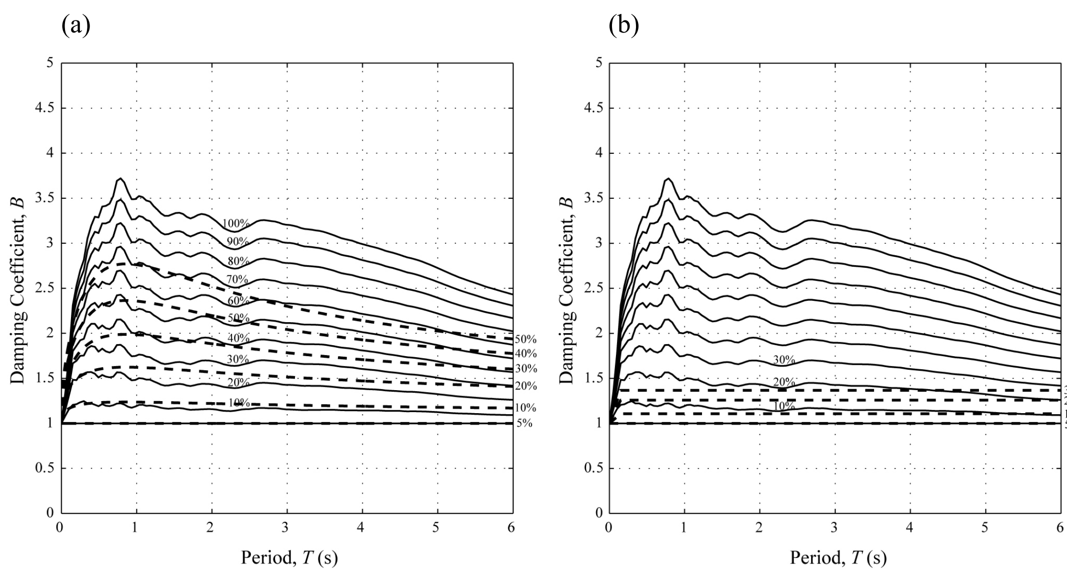

Figure 5. Comparison of the calculated damping coefficients against (a) Lin and Chang (2003) and (b) Priestley (2003) recommendations.

Effect of Earthquake Magnitude on Damping Coefficients

In order to investigate the effect of earthquake magnitude on damping coefficients, the seismic events of Table 1 are grouped into three categories: moderate (M_w = 5.6-6.3), moderate-to-large (M_w = 6.4-6.7), and large (M_w = 6.8–7.6) earthquakes. The variations of the damping coefficients with period for these three categories are displayed in Figs. 6b-d. For completeness, the damping coefficients obtained using the entire ground motion dataset are also illustrated in Fig. 6a.

While the damping coefficients for all three earthquake magnitude categories attain approximately the same peak values for a given damping ratio, the period range over which these peak values occur clearly depends on earthquake magnitude. In addition, the damping coefficient curves derived from the entire ground motion ensemble (Fig. 6a) smooth out the effect of earthquake magnitude and therefore do not capture the particular features of the damping coefficient plots illustrated in Figs. 6b-d. In general, for periods greater than approximately 1.5 seconds, the *B* values of Fig. 6a appear to be conservative compared to the *B* values of Figs. 6c-d and not conservative compared to the *B* values of Fig. 6b. For periods less than approximately 1.5 seconds, this trend is reversed especially for higher values of damping.

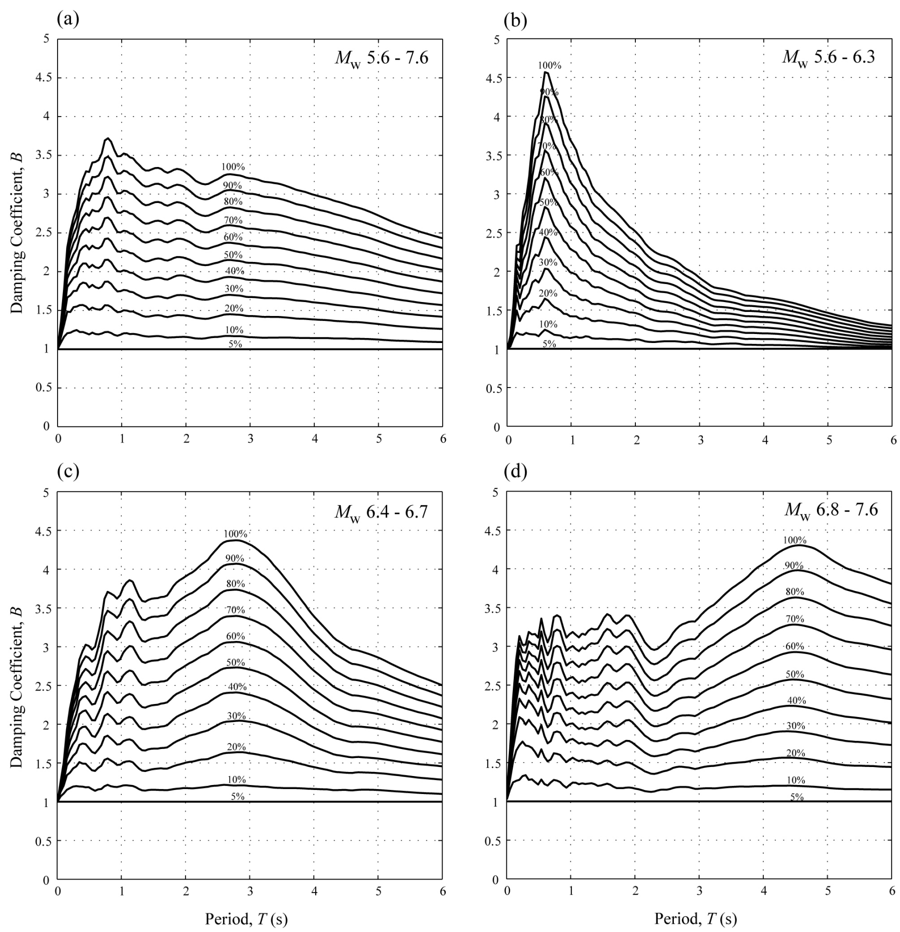

Figure 6. Calculated damping coefficients for the near-fault ground motion records of Table 1: (a) all earthquakes (M_w = 5.6-7.6); (b) moderate earthquakes (M_w = 5.6-6.3); (c) moderate-to-large earthquakes (M_w = 6.4-6.7); and large earthquakes (M_w = 6.8–7.6).

Near-fault ground motions are characterized by intense long-period velocity pulses, the duration (T_p) of which is related to the rise time (τ) on the fault plane and scales directly with earthquake magnitude (M_w) (Mavroeidis and Papageorgiou, 2003; Mavroeidis et al., 2004):

$$\log T_p = -2.9 + 0.5\, M_w \tag{2}$$

Therefore, the normalization of the period axis with respect to T_p may be an effective way to account for the effect of earthquake magnitude on damping coefficients. Parameter T_p has previously been used to normalize the elastic and inelastic response spectra of the SDOF system subjected to near-fault ground motion records, as well as for the specification of normalized design spectra and strength reduction factors for near-fault seismic excitations (Mavroeidis et al., 2004).

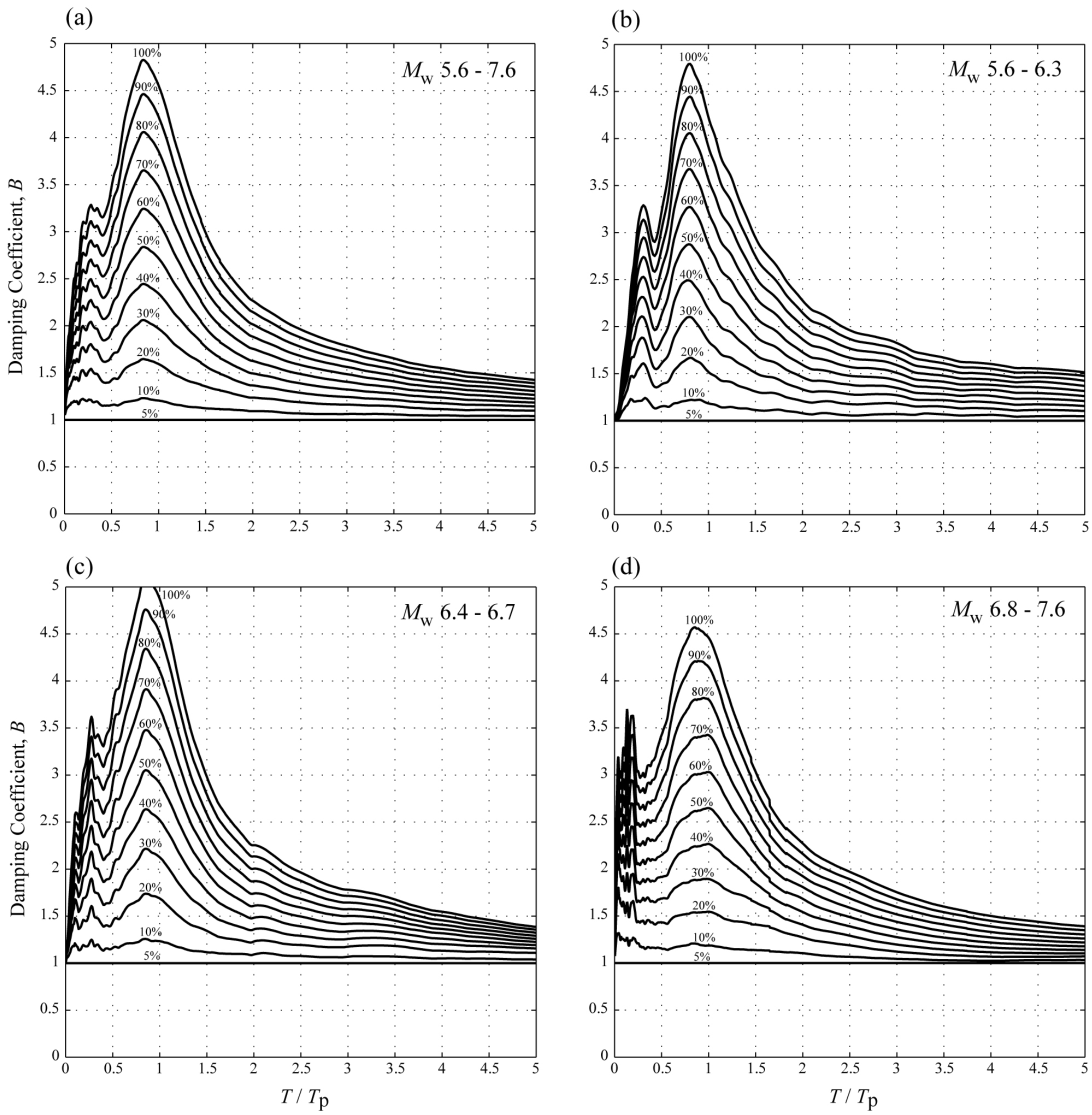

Figure 7. Normalized damping coefficients for the near-fault ground motion records of Table 1: (a) all earthquakes (M_w = 5.6-7.6); (b) moderate earthquakes (M_w = 5.6-6.3); (c) moderate-to-large earthquakes (M_w = 6.4-6.7); and large earthquakes (M_w = 6.8–7.6).

Fig. 7 illustrates the variation of the damping coefficients with normalized period for the entire ground motion dataset (Fig. 7a) and the three earthquake magnitude categories (Figs. 7b-d) discussed previously. The results indicate that the normalization of the period axis with respect to the duration of the near-fault velocity pulses yields damping coefficient curves characterized by almost identical shapes. More specifically, the damping coefficients for all groups of records attain comparable peak values for a given damping ratio and the normalized periods over which these peak values occur coincide. Therefore, the damping coefficients of Fig. 7 along with Eq. 2 provide a more effective approach for adjusting the spectral values of 5% critical damping to the higher values of damping needed for design in the near-fault region. Finally, Fig. 7 also indicates that damping becomes more effective when $T \approx T_p$.

Conclusions

Damping coefficients for the single-degree-of-freedom (SDOF) system subjected to near-fault ground motions were calculated for a wide range of periods and damping levels. The results indicated that damping coefficients proposed in building codes (NEHRP, 2003 and EC8, 2004) and previous studies (e.g., Lin and Chang, 2004) based on far-field ground motion records are not conservative for near-fault seismic excitations. On the other hand, the recommendation by Priestley (2003), the only study with special consideration for near-fault motions, appears to be over-conservative when compared to the calculated damping coefficients. Finally, a new approach was recommended for the derivation of damping coefficients in the immediate vicinity of the earthquake fault by normalizing the period axis with respect to the duration of the ground motion pulses. The pulse duration is controlled by the rise time on the fault plane and scales directly with earthquake magnitude.

Acknowledgments

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