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DAMPING CORRECTION FACTORS FOR APPLICATION WITH EUROCODE 8

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Abstract

One method to design structures equipped with Passive Energy Dissipation systems (PEDs) is the response spectrum procedure used in ASCE/SEI 7-16. With this procedure, the different sources of energy dissipation (PEDs, inherent viscous damping and post-yielding hysteretic behavior of main structure) are characterized by effective viscous damping ratios $\xi_{eff,i}$ (one for each mode) typically above the 5% value generally used in codes to define seismic action through elastic pseudo-acceleration spectra. A convenient way to account for higher damping ratios is the simple scaling of 5% damping spectral ordinates by means of a damping correction factor (DCF).

Discussion of DCFs proposed in different studies show that they must be individually derived for spectral acceleration (η_a), velocity (η_v) and displacement (η_d); and that they are dependent on period T (especially in the short-period range), site-class, and ground-motion duration $D_{5\text{-}95\%}$ (the duration between 5% and 95% of the total Arias Intensity input). The influence of duration can also be expressed considering its dependence on magnitude and source-to-site distance.

The current version of Eurocode 8 (EN1998) contemplates a simple expression of DCF to be applied to spectral pseudo-acceleration (or spectral displacement), that neglects the period effect in the range typical of flexible structures (approximately 0.5s to 4s), and renders constant values for viscous damping over 28%. This conservative feature makes it inadequate for response prediction in the case of high damping (over 30%); moreover, the code lacks expressions for velocity and acceleration. Eurocode 8 features two shapes for the 5% elastic spectrum, Type 1 for high seismicity regions (associated with strong-motion significant duration over 16s approximately), and Type 2 for low-to-moderate seismicity regions (with duration below 16s).

In this study, expressions for DCFs to be applied to spectral displacement, velocity and acceleration, are derived from analysis of Single-Degree-Of-Freedom systems subjected to 880 far-field accelerograms recorded in Europe. The resulting expressions, which are based on the existing Eurocode 8 equation, are dependent on parameters adjusted to consider the influence of site-class and significant duration. The influence of the former is proved to be moderate; the influence of the latter is, however, quite relevant. Thus, two sets of parameters, for high- and moderate-seismicity (to be used, respectively, with Type 1 and Type 2 spectra) are proposed. The expressions are compared with those proposed by other authors, and the improvements are shown qualitatively. The same dataset is then used to derive Correction Factors for Velocity (CF_V), which relate true spectral velocity to pseudo-velocity.

Keywords: damping correction factors, elastic spectrum, high damping, significant duration.

1. Introduction

High levels of damping in structures subjected to earthquake action are associated with energy dissipation. This happens in systems equipped with velocity-dependent damping devices, aimed at protecting the main structure from damage. Large levels of damping involve significant lengthening of the fundamental undamped structural period. For convenience, some seismic design methods replace the energy dissipated by structural elements through macroscopic plastic deformations by an equivalent viscous damping, although there is no physical principle that justifies the existence of a stable relationship between the energy dissipated in the non-linear force-deformation loop of the maximum displacement excursion and equivalent viscous damping, particularly for highly inelastic systems. This is the case of the substitute structure method [1] and the capacity spectrum method [2], where the behavior of a yielding structure is predicted using a series of single-degree of freedom (SDOF) systems with effective properties (stiffness and viscous damping ratio). The effective properties account for all energy dissipation sources (inherent damping, post-yielding structural hysteresis, energy dissipated by devices added to the structure), and lengthening of structural period. Stiffness is defined as secant stiffness at peak displacement, which generally requires definition of the non-linear force-displacement curve for the structure (pushover curve). The SDOF systems are used to predict the modal response of the original system, using elastic response spectrum analysis (RSA). The procedure described is implemented in the ASCE/SEI 7 standard [3] and is being considered for inclusion in the next generation of Eurocode 8 for structures with velocity-dependent dampers, providing a robust and simple alternative or benchmark to time history analysis (THA) for regular structures.

Application of the method, though, requires construction of elastic spectra for high values of damping. A convenient way to obtain them is by scaling conventional 5% elastic spectra using damping correction factors (DCF). The factors are different for spectral displacement S_d, spectral velocity S_v and spectral acceleration S_a, and are defined, respectively, as:

$$\eta_d(T,\xi) = S_d(T,\xi) / S_d(T,5\%) \tag{1}$$

$$\eta_v(T,\xi) = S_v(T,\xi) / S_v(T,5\%) \tag{2}$$

$$\eta_a(T,\xi) = S_a(T,\xi) / S_a(T,5\%) \tag{3}$$

where T is the period; ξ is the viscous damping ratio; and η_d, η_v, η_a, are the DCFs for displacement, velocity and acceleration. Often the true velocity and true acceleration spectra are not available, and instead the pseudo-velocity or pseudo-acceleration spectra are used in Eqns. (2) and (3); this approximation renders poor results, which are inadequate for the analysis of velocity-dependent devices, such as viscous dampers; several authors [4], [5], [6], have proposed to approximate the true spectral velocity through a correction factor for velocity, CF_v, defined as:

$$CF_v(T,\xi) = S_v(T,\xi) / PS_v(T,\xi), \tag{4}$$

where PS_v is the spectral pseudo-velocity. Of special interest is $CF_v\,(T,\ 5\%)$, that converts 5% spectral pseudo-velocity to 5% spectral velocity. Using CF_v, the spectral velocity can be expressed as:

$$S_v(T,\xi) = \eta_v(T,\xi) CF_v(T,5\%) PS_v(T,5\%), \tag{5}$$

in which the spectral pseudo-velocity is generally found as $\omega \cdot S_d\,(T,5\%)$.

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DCFs were introduced first by Newmark & Hall [7] for elastic systems with viscous damping ratios up to 20%; their work was expanded to inelastic systems and higher damping ratios (50%) by Wu & Hanson [8]; these authors acknowledged the influence of period in damping effectiveness, which is larger in the velocity-sensitive region of the spectrum. Ramirez *et al.* [6] used 20 scaled accelerograms to derive DCFs for acceleration, proposing a tri-linear relationship between the inverse of η_a and period; these values were adopted by FEMA, and remain in its Recommended Seismic Provisions up to the last version [9].

Several studies developed DCFs based on an empirical method (i.e., the response of single-degree-of freedom subjected to motion databases), sometimes with contradictory results. Naeim & Kircher [10] validated the FEMA DCFs using 1046 records with magnitude $M_w > 5$, and Peak Ground Acceleration (PGA) > 0.05g. Lin & Chang, however, [11], [12] used a 1053 U.S. ground motion database to question the FEMA values (which they found conservative for periods below 2s and unsafe for higher periods); these authors proposed a set of DCFs for displacement, velocity and acceleration, and found the influence of site class to be mild. Cameron & Green [13] used two databases; one for stable continental regions with 592 records and one for active seismic regions with 676 records, showing the influence of tectonic characteristics and magnitude, and proposed tabulated values of DCFs that take into account these parameters. Hatzigeorgiou [14] considered far-fault and near-fault records, and artificial accelerograms compatible with Type 1 Eurocode 8 spectrum, to propose a functional form of DCFs, proving that site class influence need only be considered by making a difference between rock and soil, and that near- and far-fault records lead to similar DCFs. Finally, Rezaeian *et al.* [15] used 2250 records for horizontal component and 2229 records for vertical component, extracted from the NGA-West2 database [16], to propose a functional form of the DCF for displacement, which is dependent on period, damping ratio, magnitude and rupture distance. All these studies, however, acknowledged that DCFs converge to unity for very short and very long periods.

An interesting explanation of the loss of effectiveness of damping with increasing period has been given by Naeim & Kircher [10]: during earthquake action, structures tend to vibrate with their own fundamental period; thus, the number of cycles sustained by structures with long periods is smaller; because damping is more effective for a larger number of cycles, its influence decreases with longer periods; these ideas were developed further by Bommer & Mendis [18], who used four sets of attenuation equations and basic dynamic considerations to show the dependency of DCFs on earthquake duration; this relationship was quantified by Stafford *et al.* [19], and acknowledged by Cameron & Green [13], and Rezaeian *et al.* [15]; these last authors found that the trend of dependency on duration is opposite for damping ratios below and above 5%, and because duration is not generally part of seismic design scenarios, proposed to capture instead its influence through magnitude and distance.

Codes generally define earthquake action through uniform hazard spectra (UHS) for 5% damping and include DCFs to correct spectral ordinates for higher damping. The DCFs in ASCE/SEI 7 [3], based on those proposed by Ramirez *et al.* [6], are only dependent on viscous damping ratio from 0% to 100%, and do not take into account any of the variables discussed in the studies mentioned above. The DCF in the current version of Eurocode 8 [20], based on a proposal by Bommer *et al.* [21], consists on a simple expression for pseudo-acceleration and displacement, dependent only on viscous damping ratio:

$$\eta = \sqrt{0.10/(0.05+\xi)} \geq 0.55. \quad (6)$$

The expression limit of 0.55 applies for viscous damping ratios over 28%, a very conservative limit which is often surpassed, particularly in higher modes of flexible structures equipped with viscous dampers. Although the value obtained is constant for all spectral regions, at very short and very long periods the spectrum definition is modified so that the overall effect is similar to the one obtained by DCFs converging to unity. In the current code version, two types of spectrum are defined (Type 1 and 2), associated with regions of high and moderate seismicity according to M_s magnitude of predominant events. Mendis & Bommer [22] suggested a correlation between significant duration $D_{5\text{-}95\%}$ (motion duration between 5 and 95% of the Arias

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Intensity) and M_s, and estimated that $D_{5\text{-}95\%} \leq 16$s corresponds to events representative of Type 2 spectrum, whereas $D_{5\text{-}95\%} > 16$s corresponds well to events representative of Type 1 spectrum.

This study aims at extending the application range of the Eurocode 8 displacement DCF for high damping ratios, proposing also specific DCFs for velocity and acceleration. Because the DCFs are intended to be used in combination with the Eurocode 5% elastic spectrum, only records with coherent tectonic characteristics (i.e. European records) are used. The influence of magnitude and source distance is not taken into account, as these variables are not part of the definition of earthquake action in the current code version. Significant duration, however, is included, as the studies cited above allow its correlation with seismicity region. Site class is considered in the code spectral definition and therefore its influence is considered in the study. Eurocode 8 defines spectra for displacement, from which pseudo-velocity can be derived. Because pseudo-velocity is a poor approximation to velocity, particularly for short and long periods, the study is extended to derive CF_vs. Special attention has been given to the short period range, in which the modal response of higher modes with increased damping ratio generally falls.

2. Description of study

For this study, 890 records were binned in eight groups according to significant duration $D_{5\text{-}95\%}$ and site class. The records were selected from the European Strong Motion Database [23], [24]. Only far-field records with epicentral distance ≥ 10km and moment magnitude $M_w \geq 5$ were selected. The main features of the records are described in Reference [25]. Records with duration $D_{5\text{-}95\%} \leq 16$s are associated with regions of low-to-moderate seismicity (Eurocode 8 Type 2 spectrum) whereas records with $D_{5\text{-}95\%} > 16$s correspond to regions of high seismicity (Eurocode 8 Type 1 spectrum).

Elastic SDOF with periods ranging from 0s to 4s in 0.01s increments and viscous damping ratios ranging from 10% to 90% in 10% increments were subjected to the previous records, using the exact piecewise method [26]. The response for 5% damping ratio was then found and for each record, period and damping value, DCFs were calculated using expressions (1) (displacement), (2) (velocity) and (3) (acceleration). Mean and median values throughout records were obtained for each of the eight groups and found to be very close, with mean values (slightly more conservative) finally chosen as representative of the group. The same process, using expression (4), was followed to obtain CF_vs.

3. Study results

The values of η_v for site class B are shown in Fig. 1; additional results for η_d, η_a, and other site classes can be found in reference [25]. Fig. 2 displays the values of CF_v obtained for all groups. Based on these results, approximate parametric expressions were proposed and adjusted numerically to the available data. The small number of records available for site class D, renders its results unreliable, and in fact the expressions derived do not approximate well the actual data for this site class.

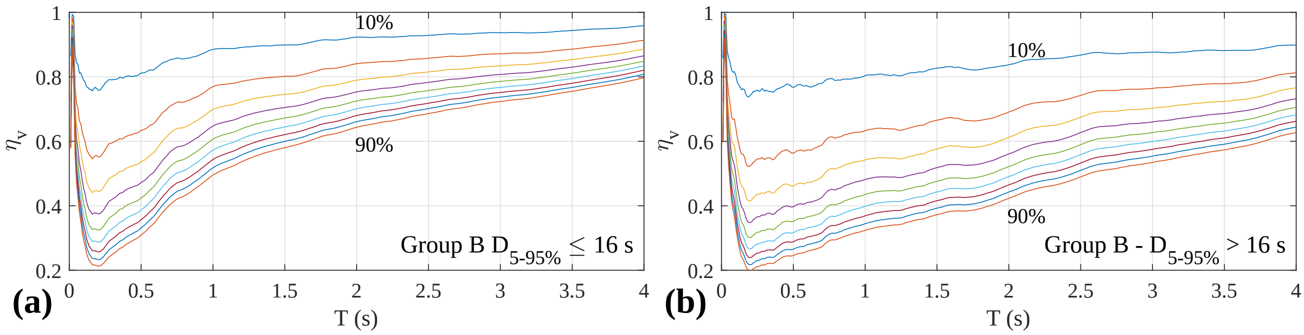

Fig. 1 – η_v for site class B binned by significant duration; (a) $D_{5\text{-}95\%} \leq 16$s ; (b) $D_{5\text{-}95\%} > 16$s.

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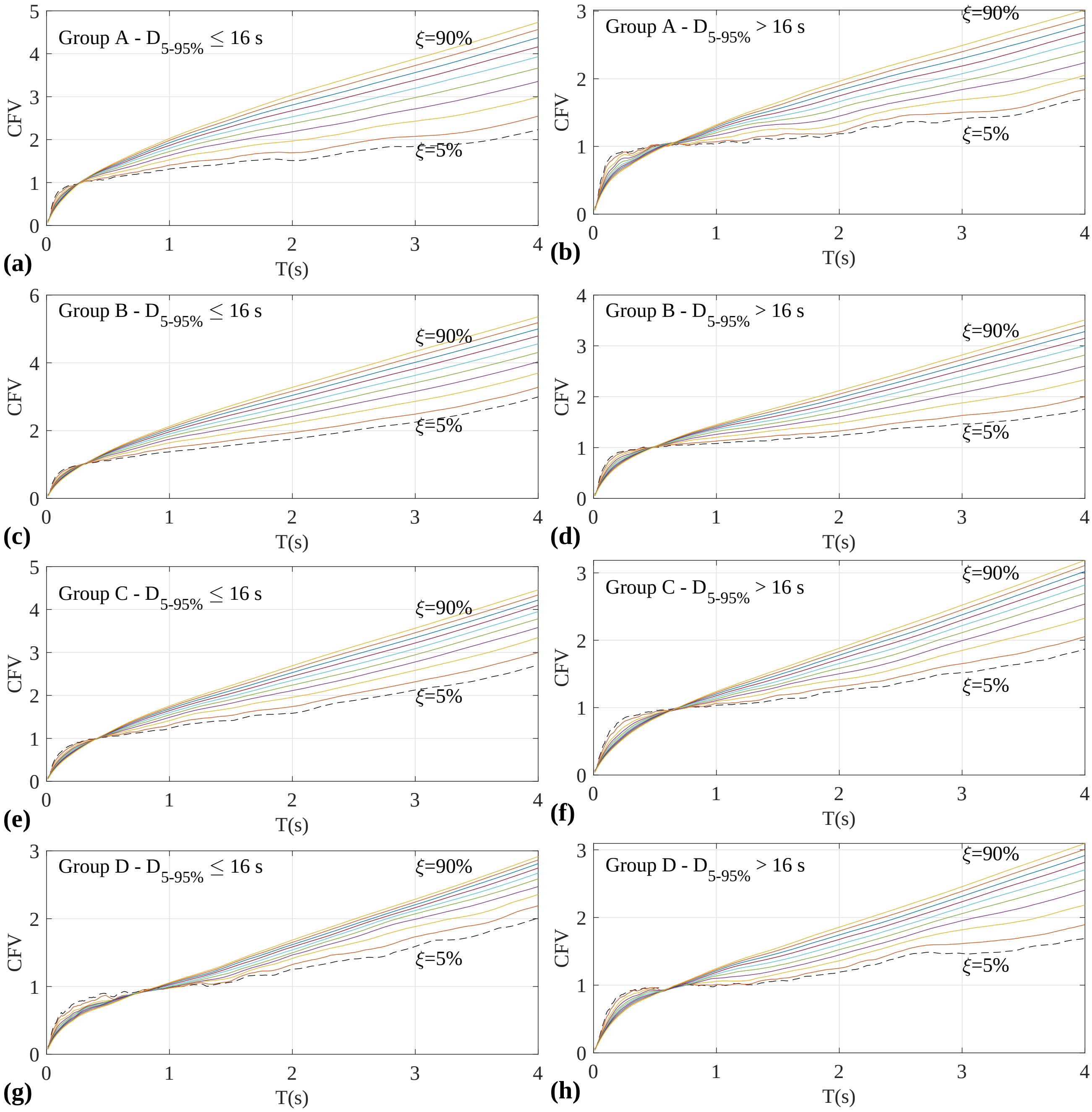

Fig. 2 – CF_v for all site classes binned by significant duration $D_{5\text{-}95\%}$.

3.1 Approximate expressions for DCFs

Expressions to approximate the DCFs obtained in analysis were proposed. In every case, the current Eurocode 8 DCF η, without the 0.55 limit established in the code, Eqn. (7), was used as kernel:

$$\eta = \sqrt{0.10/(0.05+\xi)}, \quad (7)$$

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$$\eta_d(T,\xi) = \left[1 + \left(\frac{1}{\eta} - 1\right)\left(\frac{T_R}{T}\right)^{\alpha \frac{T-T_R}{T}}\right]^{-1} \quad (8)$$

$$\eta_v(T,\xi) = \left[1 + \beta\left(\frac{1}{\eta} - 1\right)\left(\frac{T_R}{T}\right)^{\alpha \frac{T-T_R}{T}}\right]^{-1} \quad (9)$$

$$\eta_a(T,\xi) = \eta_d(T,\xi) + \varepsilon\, \xi^{\lambda} T \quad (10)$$

The previous expressions contemplate the change of tendency of the DCFs between the short and long period ranges, with the minimum possible number of parameters; for this reason the mathematical functions are cumbersome, but nonetheless it is advantageous to handle a single expression for the whole period range. The parameters were adjusted by least-square fit, and the resulting coefficient of determination R^2 and Root Mean Square Error *RMSE* were obtained and are listed in Table 2 as 'Best-Fit'. In addition, a single set of parameters, less accurate when considered individually, but suitable for all groups, was derived and is listed in the same table as 'Simple Fit'. A comparison between DCFs obtained from analysis and resulting expressions is shown for site class B, both significant durations and a selection of ξ values in Fig. 3.

3.2 Approximate expressions for CF_v

An approximate expression for CF_v was proposed and adjusted. The expression is based on the following observations: i) the different curves tend to 0 as T approaches 0; ii) at every group, for a certain period T_1 all curves are coincident for an approximate value of $CF_v = 1$. Adjustment was performed in two steps: first, the following expression was proposed for the 5% case:

$$CF_v(T,5\%) = \frac{\exp(bT) - \exp(cT)}{\exp(bT_1) - \exp(cT_1)}, \quad (11)$$

with parameters b, c and T_1; the expression equals 1 for period T_1, and 0 for $T = 0$. Least-squares fit of Expression (11) to the available data resulted in the parameter values in Table 3, featuring a good adjustment to data in the whole period range. Then, a modified expression was proposed for other values of ξ:

$$CF_v(T,\xi) = CF_v(T,5\%) + a(T - T_1)(1 - 1/\eta) \geq 0, \quad (12)$$

with parameter a. The resulting values for all groups are listed in Table 3, and shown graphically for some cases in Fig. 4.

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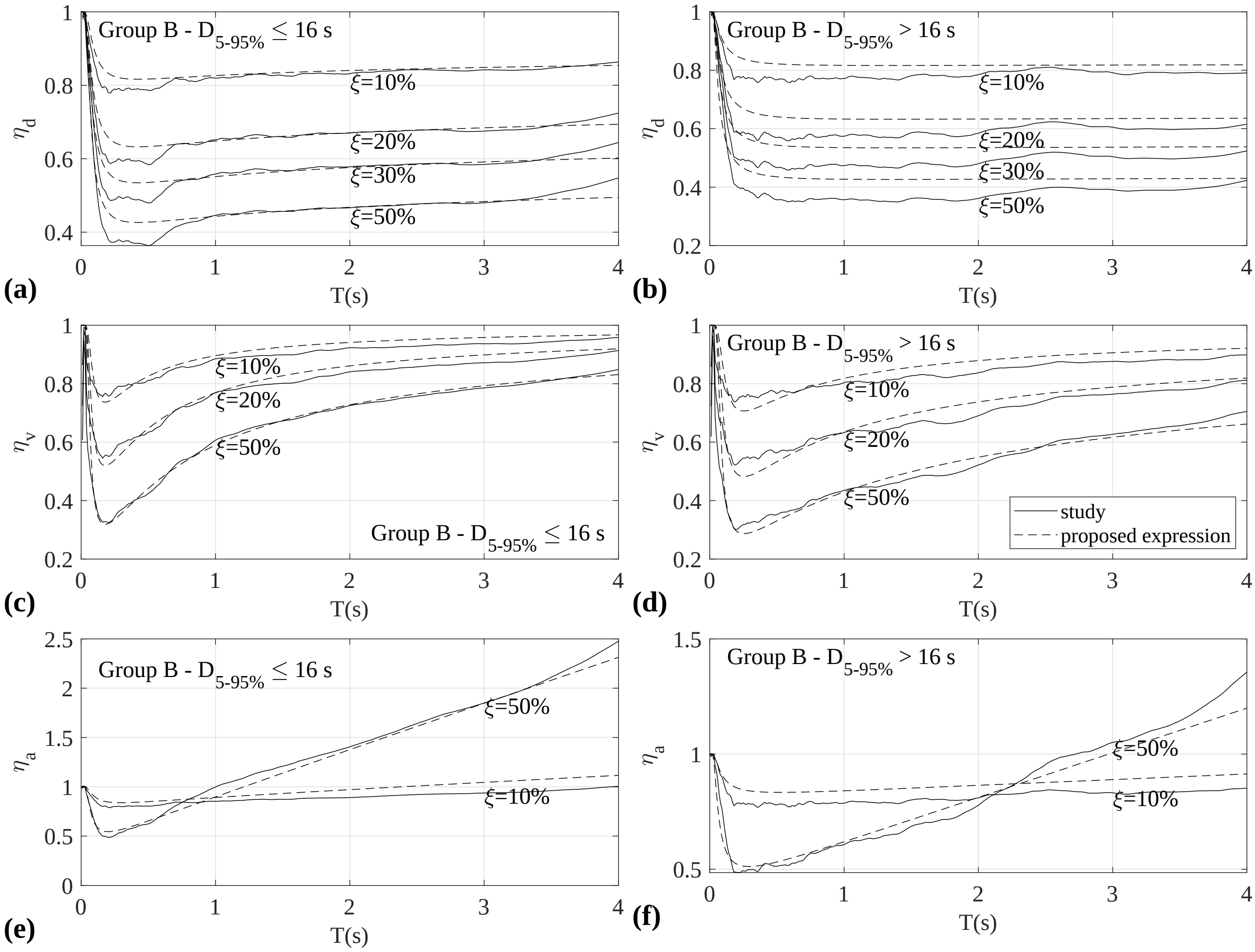

Fig. 3 – Comparison of DCFs and approximate expressions, site class B, binned by duration $D_{5\text{-}95\%}$.

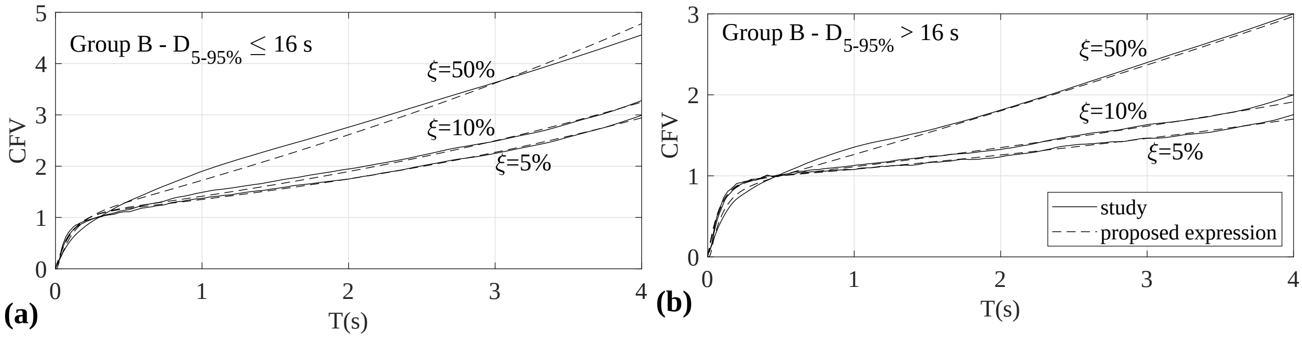

Fig. 4 – Comparison of CF_v and approximate expressions, site class B, binned by duration $D_{5\text{-}95\%}$.

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Table 2 – Parameters and fit results in Expressions (8), (9) and (10).

		SIGNIFICANT DURATION D5-95%							
		≤ 16 s				**> 16 s**			
Site class		**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
η_d **Best Fit**	T_R (s)	0,792	0,423	0,461	0,789	1,180	1,365	1,158	1,054
	α	0,036	0,137	0,198	0,145	0,024	0,021	0,053	0,056
	R^2	0,982	0,996	0,979	0,898	0,900	0,877	0,896	0,840
	RMSE	0,022	0,011	0,024	0,056	0,056	0,060	0,057	0,073
η_d **Simple Fit**	T_R (s)	0,44				1,30			
	α	0,13				0,03			
	R^2	0,931	0,977	0,955	0,855	0,908	0,900	0,900	0,832
	RMSE	0,045	0,025	0,035	0,063	0,053	0,056	0,055	0,071
η_v **Best Fit**	T_R (s)	0,149	0,178	0,257	0,718	0,227	0,254	0,547	0,668
	α	0,650	0,791	0,845	1,167	0,535	0,613	0,928	1,201
	β	1,591	1,589	1,572	1,564	1,898	1,847	1,695	1,748
	R^2	0,976	0,991	0,989	0,980	0,975	0,973	0,988	0,955
	RMSE	0,024	0,016	0,018	0,026	0,026	0,027	0,020	0,039
η_v **Simple Fit**	T_R (s)	0,20				0,33			
	α	0,80				0,70			
	β	1,56				1,80			
	R^2	0,919	0,949	0,923	-	0,879	0,899	0,921	0,872
	RMSE	0,051	0,040	0,048	-	0,066	0,060	0,053	0,068
η_a **Best Fit with** η_d **from 'Best-Fit'**	ε	0,826	1,047	0,901	0,474	0,387	0,474	0,474	0,457
	λ	1,240	1,204	1,185	1,110	1,235	1,301	1,237	1,315
	R^2	0,963	0,993	0,991	0,870	0,964	0,975	0,912	0,868
	RMSE	0,105	0,066	0,066	0,146	0,050	0,051	0,107	0,126
η_a **Simple Fit**	ε	1,00				0,47			
	λ	1,20				1,27			
	R^2	0,868	0,987	0,974	-	0,891	0,973	0,870	0,803
	RMSE	0,272	0,084	0,119	-	0,101	0,049	0,107	0,134

4. Comparison with existing expressions

A comparison with existing expressions is shown in Tables 4 and 5, for site class B and both significant durations; similar values are reached for other site classes. Only comparable expressions (those that can be expressed as a function of ξ and T) are considered. The tabulated value is:

$$D(\xi) = \frac{1}{P}\sum_{i=1}^{P}\left|\frac{y(T_i,\xi)-x(T_i,\xi)}{x(T_i,\xi)}\right|, \tag{13}$$

Where P is the number of period points, y is the approximate expression considered, and x the value obtained from this study. D takes a value of 0 for a perfect match. The expressions proposed in this study result in the best fit for η_v, η_a and CF_v, and also for η_d for duration $D_{5\text{-}95\%} \leq$ 16s. For duration $D_{5\text{-}95\%} >$ 16s, other

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expressions provide a better fit; however, the proposed expression still produces a remarkable improvement over the current Eurocode 8 provision.

Table 3 – Parameters and fit results in Expressions (11) and (12).

$D_{5\text{-}95\%}$		≤ 16s				> 16s			
Site Class		**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
$CF_v(T,5\%)$ Best Fit	T_1	0.219	0.233	0.334	1.101	0.698	0.494	0.858	0.872
	b	0.175	0.259	0.258	0.239	0.150	0.151	0.193	0.172
	c	-9.793	-9.731	-8.686	-11.441	-14.406	-12.308	-9.750	-10.378
	R^2	0.984	0.998	0.997	0.997	0.985	0.996	0.997	0.974
	$RMSE$	0.048	0.028	0.031	0.020	0.030	0.018	0.018	0.048
$CF_v(T,5\%)$ Simple Fit	T_1		0.248		-		0.656		
	b		0.245		-		0.165		
	c		-9.566		-		-11.614		
	R^2	0.515	0.972	0.984	-	0.946	0.989	0.977	0.959
	$RMSE$	0.086	0.033	0.023	-	0.019	0.009	0.017	0.020
$CF_v(T,\xi)$ Best Fit	a	-0.363	-0.362	-0.273	-0.184	-0.222	-0.269	-0.233	-0.235
	R^2	0.990	0.987	0.990	0.986	0.985	0.996	0.991	0.988
	$RMSE$	0.100	0.131	0.096	0.077	0.071	0.044	0.063	0.071
$CF_v(T,\xi)$ Simple Fit	a		-0.343		-		-0.254		
	R^2	0.943	0.970	0.912	-	0.933	0.975	0.982	0.961
	$RMSE$	0.233	0.201	0.289	-	0.152	0.112	0.090	0.125

Table 4 – Comparison with existing expressions for $D_{5\text{-}95\%} \leq$ 16s, site class B.

	SIGNIFICANT DURATION $D_{5\text{-}95\%} \leq$ 16s									
	Damping ratio ξ	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**
η_d	Best Fit	1.2%	**1.7%**	**2.3%**	**2.8%**	**3.3%**	**3.9%**	**4.8%**	5.8%	6.7%
	Simple Fit	**1.1%**	1.8%	2.6%	3.2%	3.7%	4.1%	4.8%	**5.6%**	**6.5%**
	Hatzigeorgiou (2010)	1.5%	4.1%	6.0%	7.5%	9.3%	*12.9%*	*21.1%*	*32.7%*	*46.8%*
	Lin & Chang (2004)	1.9%	4.7%	7.5%	10.3%	13.1%	*16.1%*	*19.4%*	*23.0%*	*26.7%*
	Ramirez (2000)	1.9%	3.8%	5.5%	6.8%	8.0%	12.7%	15.2%	19.1%	22.3%
	EC8 (2004)	2.7%	6.5%	7.1%	10.1%	20.2%	30.5%	40.3%	49.8%	59.0%
	FEMA (2015)	1.9%	3.8%	6.4%	9.4%	12.3%	14.8%	17.1%	19.1%	20.8%
η_v	Best Fit	2.3%	2.9%	2.5%	**2.1%**	**1.8%**	**1.7%**	**2.1%**	**2.7%**	**3.3%**
	Simple Fit	**2.0%**	**2.4%**	**2.3%**	2.2%	2.7%	3.4%	4.1%	4.7%	5.3%
	Hatzigeorgiou (2010)	2.6%	6.0%	8.0%	8.7%	8.6%	*8.0%*	*7.3%*	*6.4%*	*6.1%*
η_a	Best Fit	1.6%	3.2%	4.2%	**4.9%**	**5.5%**	**6.1%**	**6.7%**	**7.3%**	**7.9%**
	Simple Fit	2.5%	**4.8%**	**6.7%**	8.4%	9.9%	11.2%	12.4%	13.7%	14.9%
	Hatzigeorgiou (2010)	3.2%	7.2%	10.7%	14.1%	18.3%	*24.3%*	*34.4%*	*47.8%*	*64.0%*
	Lin & Chang (2004)	**2.0%**	4.5%	6.2%	7.6%	9.1%	*10.8%*	*12.8%*	*15.2%*	*18.5%*
CF_v	Best Fit	**2.5%**	**3.6%**	**4.2%**	**4.9%**	**5.4%**	**5.8%**	**6.1%**	**6.4%**	**6.6%**
	Simple Fit	5.7%	6.7%	7.2%	7.6%	8.0%	8.2%	8.4%	8.4%	8.5%
	Sadek *et al* (2000)	29.7%	32.6%	33.8%	34.5%	35.1%	*35.6%*	*35.9%*	*36.0%*	*35.9%*
	Ramirez *et al* (2000)	50.6%	54.3%	55.9%	57.3%	58.2%	58.7%	59.2%	59.3%	59.5%

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Table 5 – Comparison with existing expressions for $D_{5\text{-}95\%}$ >16s, site class B.

SIGNIFICANT DURATION $D_{5\text{-}95\%}$ > 16s										
	Damping ratio ξ	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**
η_d	Best Fit	4.3%	7.5%	9.7%	11.9%	14.0%	16.1%	18.2%	20.2%	22.3%
	Simple Best Fit	4.4%	7.7%	10.0%	12.2%	14.3%	16.4%	18.5%	20.6%	22.6%
	Hatzigeorgiou (2010)	6.5%	11.9%	15.7%	20.7%	28.0%	*38.0%*	*51.2%*	*67.8%*	*87.8%*
	Lin & Chang (2004)	4.9%	9.0%	10.2%	9.9%	8.5%	*7.1%*	*6.6%*	*7.1%*	*9.1%*
	Ramirez (2000)	6.1%	12.6%	19.8%	23.8%	20.8%	13.9%	12.4%	8.9%	8.5%
	Wu & Hanson (1989)	**4.0%**	**6.9%**	**7.3%**	**6.8%**	**5.8%**	***6.2%***	*9.9%*	*14.1%*	*18.7%*
	Newmark (1982)	9.6%	22.3%	*46.4%*	*68.4%*	*89.0%*	*108.7%*	*127.7%*	*146.4%*	*164.7%*
	EC8 (2004)	4.2%	7.5%	12.8%	29.5%	45.2%	60.2%	74.7%	88.9%	102.8%
	FEMA (2015)	6.1%	12.6%	13.6%	12.9%	11.5%	10.3%	9.4%	8.9%	9.0%
η_v	Best Fit	**3.6%**	**4.5%**	**4.1%**	**4.0%**	**4.4%**	**4.6%**	**4.9%**	**5.2%**	**5.4%**
	Simple Best Fit	3.8%	5.4%	5.3%	5.2%	5.7%	6.2%	6.6%	7.0%	7.3%
	Hatzigeorgiou (2010)	5.5%	10.1%	13.1%	16.2%	19.7%	*24.0%*	*28.9%*	*34.6%*	*41.0%*
η_a	Best Fit	**6.5%**	**7.0%**	**4.6%**	4.5%	4.3%	4.0%	3.8%	3.8%	5.1%
	Simple Best Fit	7.1%	7.9%	5.2%	**4.4%**	**4.2%**	**3.9%**	**3.7%**	**3.7%**	**4.8%**
	Hatzigeorgiou (2010)	16.5%	27.4%	23.7%	17.9%	17.5%	*18.5%*	*20.1%*	*22.3%*	*25.4%*
	Lin & Chang (2004)	8.6%	10.8%	7.6%	4.2%	5.2%	*7.3%*	*10.7%*	*13.7%*	*16.4%*
CF_v	Best Fit	**1.5%**	**2.0%**	**2.5%**	**2.8%**	**2.9%**	**2.9%**	**3.2%**	**3.6%**	**4.0%**
	Simple Fit	2.7%	4.6%	6.0%	7.1%	7.8%	8.2%	8.5%	8.7%	8.8%
	Sadek *et al* (2000)	3.4%	5.4%	6.2%	6.7%	6.8%	*6.5%*	*6.3%*	*6.2%*	*6.2%*
	Ramirez *et al* (2000)	30.4%	34.6%	36.5%	38.0%	38.8%	39.1%	39.4%	39.3%	39.2%

5. Conclusion

Spectral analysis methods for yielding structures equipped with dampers require definition of response spectra for high values of viscous damping ratio. These can be obtained scaling 5%-damped elastic response spectra with Damping Correction Factors (DCFs); independent values of correction factors are necessary for displacement (η_d), velocity (η_v) and acceleration (η_a).

DCFs are dependent on the properties of the earthquake input. Past studies show that the most relevant parameters are site-class and ground motion duration, which captures the dependence on magnitude and source-to-site distance. DCFs are also dependent on period; for very short and very long periods the factors converge to unity.

The current version of Eurocode 8 presents only an expression for displacement DCF, which renders constant values for viscous damping over 28%; no DCFs for velocity or acceleration are given. Within this framework, application of spectral methods for structures with dampers, neglect the important effect of high viscous damping ratio in flexible structures. For this reason, development of a set of DCFs to be used with the Eurocode 5% elastic spectrum is desirable.

In this study, DCFs are derived from a database of 880 far-field European earthquakes, binned according to site class (as defined in Eurocode 8) and significant ground motion duration $D_{5\text{-}95\%}$ (duration between instants of 5% and 95% of total Arias Intensity). A total of 8 groups are created, corresponding to 4 site classes (A, B, C and D) and 2 durations ($D_{5\text{-}95\%} \leq 16$s and $D_{5\text{-}95\%} > 16$s), which can be roughly identified with spectrum types 2 (moderate seismicity) and 1 (high seismicity) of Eurocode 8, respectively. Expressions to approximate the values obtained as a function of period, damping ratio, site class and spectrum type are suggested, using the current expression in Eurocode 8 as kernel. The results are compared to other

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expressions proposed in the literature. The study does not contemplate impulsive or near-source earthquakes. The results obtained for soft soils are not conclusive.

The behavior of viscous and visco-elastic devices is velocity-dependent. Analysis of these devices requires an accurate estimate of maximum velocity, which at 5% damping differs considerable from the 5% pseudo-spectral velocity. The previous motion database is used to derive Correction Factors for Velocity (CF_v) based on European motions. These factors relate true spectral velocity with spectral pseudo-velocity at a certain period and damping ratio. Approximate expressions are suggested and the values are compared to other expressions proposed in the literature.

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