Stochastic-based damping reduction factors

Stochastic-Based Damping Reduction Factors

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KEY WORDS: Damping reduction factor; soil predominant frequency; Kanai-Tajimi power spectral density

ABSTRACT

Most of the actual formulas available in both scientific literature and seismic codes for the damping reduction factors to be used for the seismic design of highly damped structures are derived through statistical analyses of the time-history response of SDOF systems subjected to earthquake accelerograms. In this study, analytical formulations of the damping reduction factor based on power spectral density functions are derived and compared with the main formulas available in the scientific literature. The surface ground motion is modelled with the Kanai-Tajimi power spectral density, i.e. as an "ideal white noise" at the bedrock filtered through the soil deposit. It is found that the ratio between the ground predominant period and the structure fundamental period significantly influences the reduction due to high damping and that, in some cases (e.g. stiff low-rise buildings), the actual code formulations may become unconservative. Finally, simple code-like formulas for the estimation of the damping reduction factor accounting for the ratio between the ground predominant period and the structure fundamental period are proposed.

1. INTRODUCTION

The design spectra specified in most of the actual seismic design codes can be generally reduced by: (a) ductility factors, (b) over-strength factors, and (c) damping reduction factors (Castillo and Ruiz, 2014). Damping reduction factors, generally indicated as η, are mainly used to reduce the spectral ordinates of the 5% elastic design spectrum to account for the dissipation provided by the additional dampers or, alternatively, to account for structural

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inelastic response (e.g. equivalent damping concept within the framework of Displacement Based Design approaches, Priestley et al. 2007).

The first extensive studies directly focused on the damping reduction factor are dated back to the 1980s. A comprehensive literature review on the topic can be found in the work by Castillo and Ruiz (2014). Hereafter the main contributions are briefly reported.

Newmark and Hall (1982) proposed a widely known procedure to estimate the elastic response spectrum corresponding to systems with high damping ratios. The procedure is based on the tripartite response spectrum and makes use of the acceleration, velocity and displacement amplification factors, each one defined within a specific period range. The effect of the inherent and supplemental damping on the spectral displacements was studied by Ashour in 1987, for SDOF systems with natural periods from 0.5 s to 3.0 s and viscous damping ratios from 2% to 150% The mathematical expression of the damping reduction factors obtained from that study was adopted by NEHRP provisions for the design of buildings with passive energy dissipation systems. In 1989, Wu and Hanson studied the elasto-plastic response of SDOF systems. They selected structures with fundamental periods in the constant acceleration region (between 0.1 s and 0.5 s), in the constant velocity region (between 0.5 s and 3.0 s) and in the constant displacement region (between 3.0 s and 10.0 s). Ductility ratios from 1 to 6 were considered. Bommer and Elnashai (1999) derived attenuation laws for horizontal displacement response spectral ordinates based on a large dataset of European strong motion records. In their work, they also suggested a simple formula for the spectral displacement damping reduction factor, which was adopted by Eurocode 8 (2004). A variant of the previous expressions was proposed by Tolis and Faccioli (1999), on the basis of displacement response spectra derived from the records of the 1995 Kobe earthquake. Ramirez et al. (2000) computed values of the damping reduction factor by analyzing the earthquake response of linear elastic SDOF systems with damping ratios ranging from 2% to 100% subjected to twenty horizontal components of ten recorded ground motions, selected with magnitude larger than 6.5, epicentral distance between 10 and 20 km, and site conditions characterized by soil classes C–D in accordance with the 2000 NEHRP Provisions. Based on a statistical analysis of the results of the numerical simulations, they proposed a trilinear model for the damping reduction factor. A simplified two-parameter model was adopted by the NEHRP 2000 for the design of buildings equipped with added dampers. Naeim and Kircher (2001) studied the dependence of the viscous damping

reduction factors on the vibration period of the ground for a large number of seismic response spectra and introduced damping adjustment factors. Lin and Chang (2003) proposed a period-dependent formula derived from the displacement response of linear elastic SDOF systems with damping ratios between 2 and 50% and with vibration periods from 0.01 to 10 s. In their study, a total of 1053 acceleration time histories from 102 earthquakes recorded in the U.S.A. were selected as input ground motions. A Comprehensive review and comparison of different formulations for damping reduction factors from previous researches were given in the work by Bommer and Mendis (2005). In their work, the authors discussed the observed trends in the previously proposed formulations and their dependence on magnitude, site-to-source distance and site condition. Cameron and Green (2007) found that the damping reduction factor for SDOF systems depends on the frequency content, the distance between the site and the source, the earthquake magnitude and the tectonic characteristics of the site. Cardone et al. (2009) examined the accuracy of the main damping reduction factor formulations included in the actual design codes, highlighting that, for single earthquakes, the current formulations may be considered reasonably accurate only for damping ratios smaller than 10%. For response spectra representing groups of earthquakes, the accuracy of the estimate strongly depends on the selected damping reduction factor formulation and on the considered period range.

The effect of damping on inelastic response spectra was investigated by Al-Sulaimani and Roesset in 1987 and reduction factors were proposed for acceleration, velocity and displacement spectra. Behavior factors accounting for the single modes to be used in the framework of response spectrum analysis have been proposed by Papagiannopoulos and Beskos (2010, 2011). In recent works (Silvestri et al. 2010, Palermo et al. 2013), also the authors developed statistical studies aimed at evaluating damping reduction factors and behavior factors for SDOF systems subjected to earthquake excitation.

Almost all the above-mentioned researches are based on statistical analyses of the time-history response of SDOF damped systems subjected to earthquake accelerograms. Nonetheless, despite the large amount of research effort devoted to the problem, a clear understanding of the observed trends is still missing. Figure 1 collects and displays some available formulations for the damping reduction factor from both scientific literature and building codes. It can be noted that the curves are characterized by a significant scatter. As illustrative example, for a damping ratio equal to 0.3, the use of the Japanese Code (BCJ

1997) formula leads to a damping reduction factor which is approximately one half of that obtained according to the formulation by Priestley (2003).

In this study, a stochastic-based approach is used to provide insights into the observed trends and to identify the key-parameters which govern the damping reduction factor. The main objective is to develop a physically grounded formulation for the damping reduction factor based upon basic principles of structural dynamics. Finally, a simple formulation is proposed and compared with those available in literature and obtained using real ground motion records.
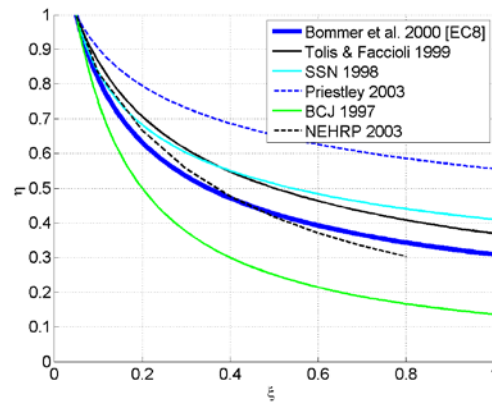

Figure 1. η curves from literature and codes.

2. TIME-HISTORY-BASED DAMPING REDUCTION FACTORS

The trends of the damping reduction factors based on the time-history linear response of SDOF systems to recorded ground motions are here discussed. A set of 50 acceleration records selected from the PEER strong motion database (with peak ground acceleration PGA > 0.1 g and shear wave velocity $360 < v_s < 800$ m/s, i.e. soil type B according to EC8) is used. The main aim of this section is to describe how the damping reduction factor varies with ξ and T (on average) and also how the damping reduction factor may vary from record to record. First, the trends of the average η (as obtained from the whole ensemble) are described, then, as illustrative example, the typical record-to-record variability of η is showed by considering two specific records.

For each seismic record, the damping reduction factor η is evaluated as the ratio between $S_{a,\xi}$ and $S_{a,\xi=5\%}$:

$$\eta = \frac{S_{a,\xi}}{S_{a,\xi=5\%}} \tag{1}$$

where $S_{a,\xi}$ and $S_{a,\xi=5\%}$ are the values of the pseudo-accelerations for a generic damping ratio ξ and for the specific damping ratio $\xi = 0.05$, respectively.

Figure 2a displays the reduction factors as obtained for each seismic record, together with their mean (over the 50 records), for eight values of damping ratio ξ (e.g. 0.1, 0.2, ... , 0.8). It can be noted that the damping reduction factors rapidly decrease for periods $0 < T < 0.5s$. Then, for periods $T > 0.5s$, mean values of η are quite smooth and approximately constant. The results reflect the smooth shape of the average response spectra as represented in Figure 2b (note that all records are scaled to the same PGA = 1 g). For a better understanding, Figure 3 provides the mean values and the dispersions of η for the eight selected ξ values. As expected, η decreases as ξ increases. The dispersion is quite low for $\xi = 0.1$ (COV around 0.13), while it increases as ξ increases (COV around 0.5 for $\xi = 0.8$). Table 1 and Figure 4 provide the along-the-period mean values of η (calculated for $T > 1.0s$). It can be noted that the along-the-period mean values of η, referred to as η_{T-H} (T-H stands for time-history), can be well fitted assuming a functional form of type $\eta = \left(\frac{10}{5+\xi}\right)^{\chi}$ with coefficient $\chi = 0.55$ (best fit in the least squares sense). It should be noted that this specific result has been obtained with reference to type B soil records and thus valid only for this soil. Note that the functional form of above is similar to the one proposed by Bommer et al. (2000) and adopted by the Eurocode 8 (2004).
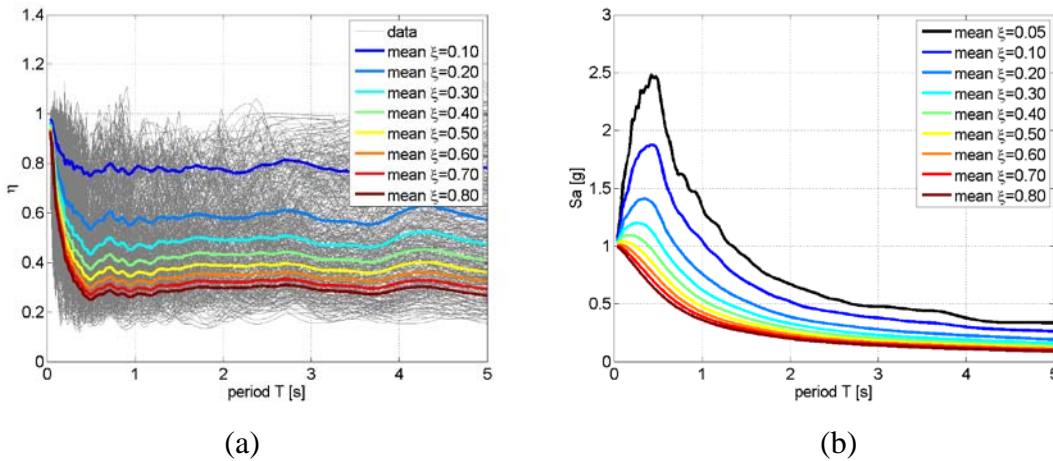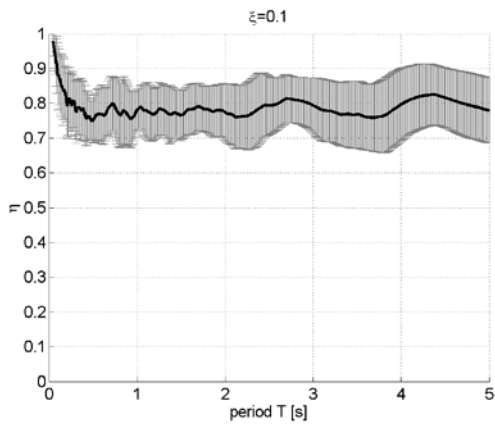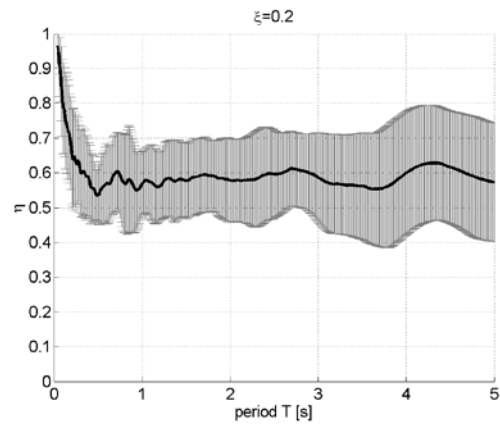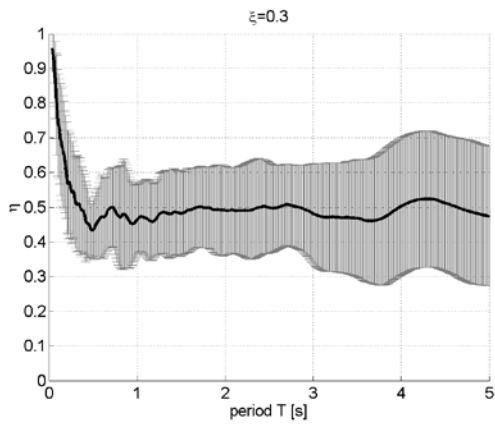

(a)   (b)

Figure 2. (a) η vs. T curves for damping ratios between 0.1 and 0.8; (b) Average response spectra for damping ratios between 0.1 and 0.8.

(a)

(b)

(c)

(d)

(e)

(f)

(g)   (h)
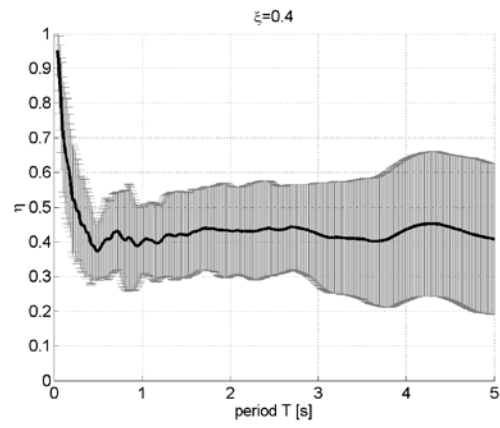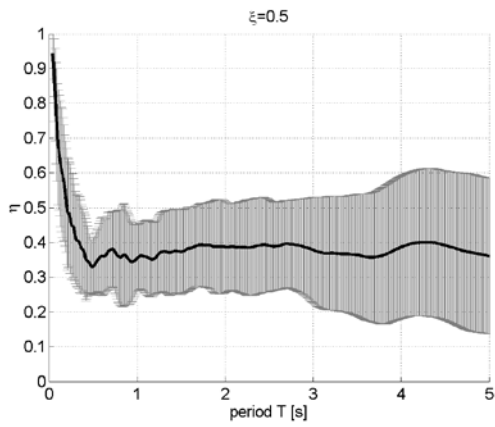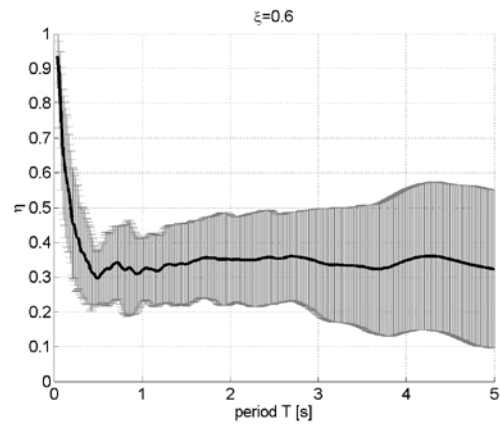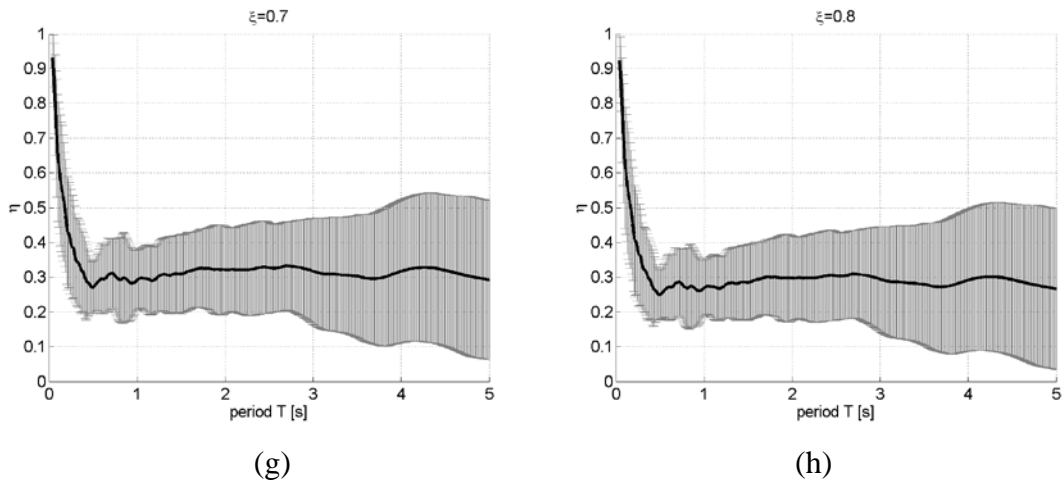
Figure 3. Average damping reduction factor η and dispersion for ξ between 0.1 and 0.8.

Table 1. Mean values of η for selected ξ.

ξ	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
η	0.79	0.59	0.49	0.43	0.38	0.34	0.31	0.29
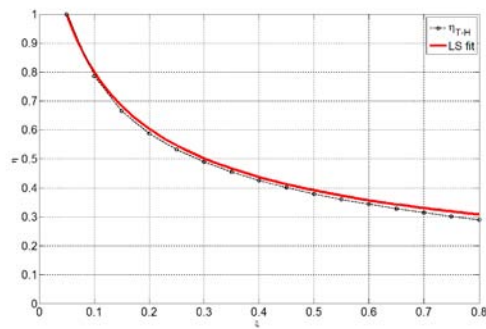
Figure 4. Along-the-period mean values of η_{T-H} and its fit in the least squares sense (LS fit).

Figure 5 provides the damping reduction factor η for damping ratios ξ between 0.1 and 0.8 for two specific ground motions (Northridge 1994 and Friuli 1976). It can be noted that the values and the trends of η are quite variable from earthquake to earthquake and are strongly dependent on the shape of the response spectra and therefore on the frequency content of the specific ground motion.
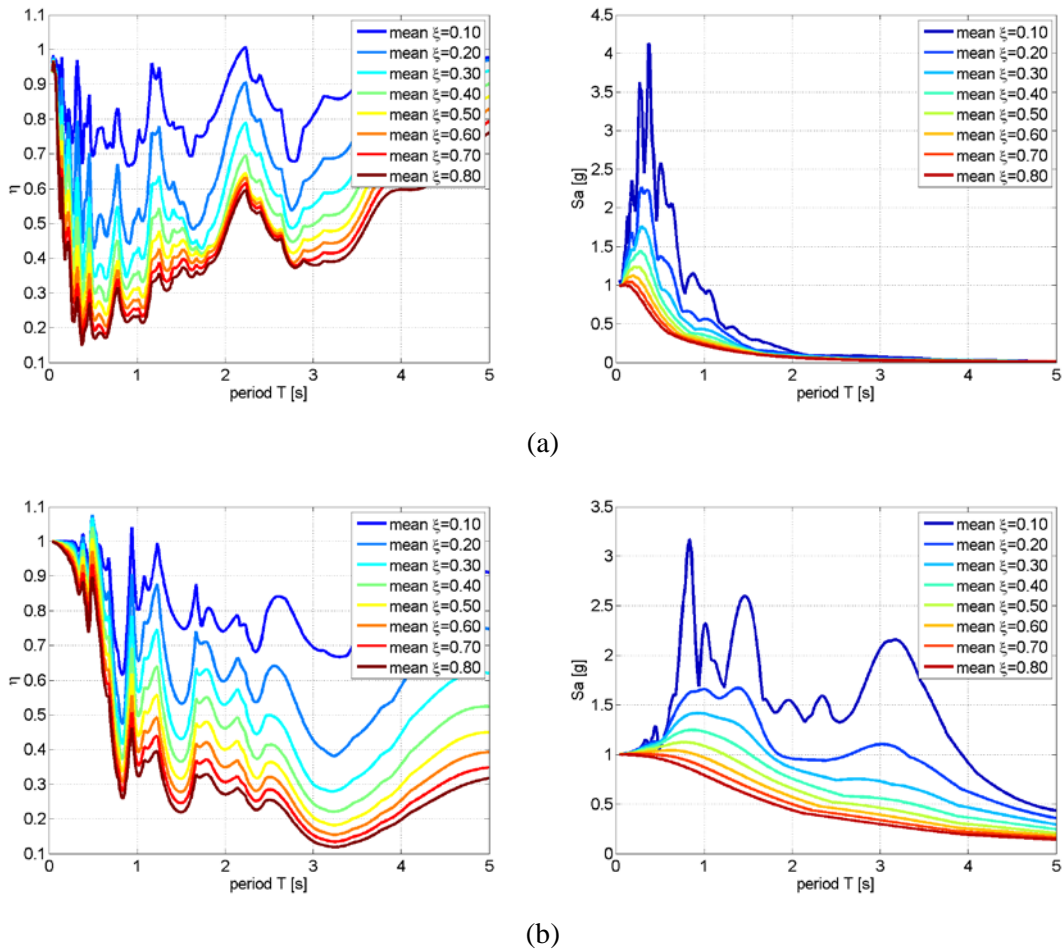
Figure 5. Damping reduction factor η and response spectra for damping ratios between 0.1 and 0.8 for two specific ground motions: (a) Northridge 1/17/94, Featherly Park - Park Maint.; (b) Friuli 09/11/76, Forgaria Cornino.

Higher reductions (i.e. smaller values of η) are observed within the period ranges of the highest dynamic amplifications (the peaks of the spectrum), while lower reductions (i.e. larger values of η) are observed within the period ranges of lower dynamic amplifications.

In the next section, a new formulation for the damping reduction factor based on a stochastic approach is introduced and discussed. This formulation allows to provide an explanation, in a simplified way, for the observed variability of η due to the characteristics of the specific ground motion.

3. STOCHASTIC-BASED DAMPING REDUCTION FACTORS

Let us consider a SDOF system subjected to an harmonic input. From structural dynamics (Chopra 1995), it is well know that the magnitude of the system complex frequency response, $H(\omega)$, is given by the following expression:

$$\left|H(\omega)\right| = \frac{1}{\sqrt{\left[1-(\omega/\omega_n)^2\right]^2 + \left[2\xi(\omega/\omega_n)^2\right]^2}} \tag{2}$$

where ω_n is the natural frequency of the SDOF system.

Based on the Kanai's study (1975) on the frequency content of real strong ground motions, Tajimi (1960) proposed the following well known Power Spectral Density (PSD) function, hereafter referred to as the K-T PSD:

$$G(\omega) = G_0 \cdot \frac{1+\left[2\xi(\omega/\omega_g)^2\right]^2}{\left[1-(\omega/\omega_g)^2\right]^2 + \left[2\xi_g(\omega/\omega_g)^2\right]^2} \tag{3}$$

Physically, the K-T PSD may be interpreted as an "ideal white noise" excitation at bedrock level filtered through the overlaying soil deposits (Lai 1982). In this context: ξ_g and ω_g are the soil damping ratio and the soil predominant frequency, respectively; G_0 is the intensity of the ideal with noise excitation at the bedrock. On the basis of 140 recorded ground motions (22 on rock sites and 118 on soil sites), Lai (1982) suggested the following mean values:

- for rock sites: ξ_g = 0.35 and ω_g = 26.7 rad/s (corresponding to a predominant period T_g = 0.23 s);

- for soil sites: ξ_g = 0.32 and ω_g = 19.1 rad/s (corresponding to a predominant period T_g = 0.33 s).

It is worth noticing that the values of the soil equivalent damping ratio ξ_g for the two site conditions are quite close to each other.

From soil dynamics (Kramer 1996), it is known that a soft soil on a rigid rock may be idealised with the Kelvin-Voigt model. The predominant period (referred to as "characteristic site period") depends on the geometrical configuration of the site (basically its depth H_s) and on the shear wave velocity of the soil (v_s), which are related to the density and elastic soil properties (Young modulus E and Poisson's ratio v).

Using Eqs. 2 and 3, the spectral density of the displacement response of an SDOF subjected to the K-T PSD can be evaluated according to:

$$O(\omega)=\left|H(\omega)\right|^2 G(\omega)=G_0 \frac{1+\left[2\xi(\omega/\omega_g)^2\right]^2}{\left(\left[1-(\omega/\omega_n)^2\right]^2+\left[2\xi(\omega/\omega_n)^2\right]^2\right)\left(\left[1-(\omega/\omega_g)^2\right]^2+\left[2\xi_g(\omega/\omega_g)^2\right]^2\right)}$$

(4)

The mean square of the displacement response is given by (Crandall and Mark, 1963):

$$\sigma^2=\int_{\Delta\omega}\left|H(\omega)\right|^2 G(\omega)d\omega$$

(5)

which is coincident with the variance for the case of zero-mean processes; $\Delta\omega=\left(0,\overline{\omega}\right)$ is the integration interval. The standard deviation of the displacement response, that is a measure of the amplitude of the displacement response of the system subjected to the K-T stochastic input, is given by:

$$\sigma=\sqrt{\int_{\Delta\omega}\left|H(\omega)\right|^2 G(\omega)d\omega}$$

(6)

As per its definition, the following analytical expression of the damping reduction factor may be obtained:

$$\eta_{K-T}=\frac{\sigma(\xi)}{\sigma(\xi=5\%)}=\frac{\sqrt{\int_{\Delta\omega}\left|H(\omega,\xi)\right|^2 G(\omega)d\omega}}{\sqrt{\int_{\Delta\omega}\left|H(\omega,\xi=5\%)\right|^2 G(\omega)d\omega}}$$

(7)

Eq. 7 provides an analytical expression of the damping reduction factor for a specific soil characterized by ξ_g and ω_g.

If a "white noise" PSD $(G(\omega)=G_0)$ is considered instead of the K-T PSD, Eq. 7 simplifies into:

$$\eta_{W-N}=\frac{\sigma(\xi)}{\sigma(\xi=5\%)}=\frac{\sqrt{\int_{\Delta\omega}\left|H(\omega,\xi)\right|^2 d\omega}}{\sqrt{\int_{\Delta\omega}\left|H(\omega,\xi=5\%)\right|^2 d\omega}}$$

(8)

Eq. 8 provides a useful reference, since it can be interpreted as an "average" damping reduction factor. The reference white noise input can be reasonably adopted in the case of unknown soil properties.

For given $\xi_g = \overline{\xi_g}$ and $\omega_g = \overline{\omega_g}$ and introducing parameters $\beta = \omega / \omega_n$ and $k = \omega_n / \overline{\omega_g} = \overline{T_g} / T_n$, Eq. 7 and 8 may be rewritten as follows:

$$\eta_{K-T}\left(\Delta\beta, k, \xi, \overline{\xi_g}\right) = \frac{\sqrt{\int_{\Delta\beta} G\left(\beta, k, \overline{\xi_g}\right) \cdot \left|H\left(\beta,\xi\right)\right|^2 d\beta}}{\sqrt{\int_{\Delta\beta} G\left(\beta, k, \overline{\xi_g}\right) \cdot \left|H\left(\beta,\xi=5\%\right)\right|^2 d\beta}} \tag{9}$$

$$\eta_{W-N}\left(\Delta\beta, \xi\right) = \frac{\sqrt{\int_{\Delta\beta} \left|H\left(\beta,\xi\right)\right|^2 \cdot d\beta}}{\sqrt{\int_{\Delta\beta} \left|H\left(\beta,\xi=5\%\right)\right|^2 \cdot d\beta}} \tag{10}$$

where $\Delta\beta$ is the integration interval: $\Delta\beta = \left(0,\overline{\beta}\right)$.

An analytical solution of the integral forms of Eqs. 9 and 10 has not been found yet by the authors. Thus simple and useful closed-form expressions of Eqs. 9 and 10 are not available. Nonetheless they can be calculated numerically.

However, from Eqs. 9 and 10 it clearly appears that, in the general case, η_{K-T} depends on $\Delta\beta$, k, ξ, $\overline{\xi_g}$, whilst η_{W-N} depends on $\Delta\beta$ and k. Parameter $\overline{\xi_g}$ (representative of the soil damping properties) can be reasonably assumed as constant (in the range of 0.30-0.35). In the next subsections, the influence of $\Delta\beta$ and k on the η_{K-T} values are briefly investigated.

3.1. ON THE $\Delta\beta$ INTERVAL

It is clear that, in general, η_{K-T} is affected by the choice of the integration interval $\Delta\beta$. Nonetheless, due to the specific shape of the functional form of the indefinite integral of the functions $\left|H\left(\beta,\xi\right)\right|^2$ and $G\left(\beta,k\right)$, the numerical values of η_{K-T} are not significantly affected by the choice of the integration interval $\Delta\beta$, once the superior extreme of the interval $(\overline{\beta})$ is set to be enough big. As illustrative example, Figure 6 displays the indefinite integral of $\left|H\left(\beta,\xi\right)\right|^2$, whose trend can be assimilated to that of an arctangent function. From a computational point of view, $\overline{\beta}$ may be set in order to satisfy the following condition:
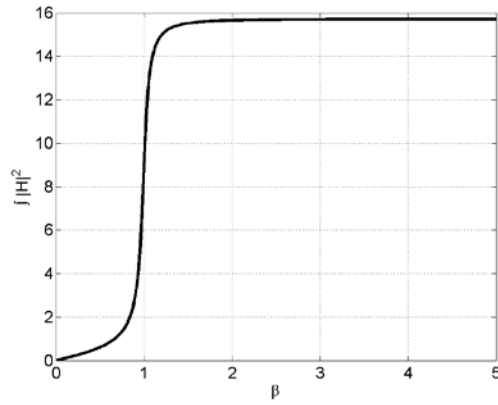
$$\overline{\beta} \geq \min(3.3 \cdot k) \tag{11}$$

Figure 6. The indefinite integral of $\left|H\left(\xi,\beta\right)\right|^2$ for $\xi = 0.05$.

3.2. ON THE *K* PARAMETER

It has been shown that, once parameter $\overline{\xi_g}$ and $\Delta\beta$ are appropriately set, η_{K-T} depends only on k and ξ. The influence of k on η_{K-T} is now discussed. Figures 7 displays the η_{K-T} curves (Eq. 9) for selected k values between 0.25 and 3.0 and for $\overline{\xi_g} = 0.33$. It clearly appears that parameter k significantly affects the damping reduction factor. The scatter is similar to that showed by the different curves available from the scientific literature (see Figure 1).

Figure 7. η_{W-N} and η_{K-T} curves for selected k between 0.25 and 3.0.
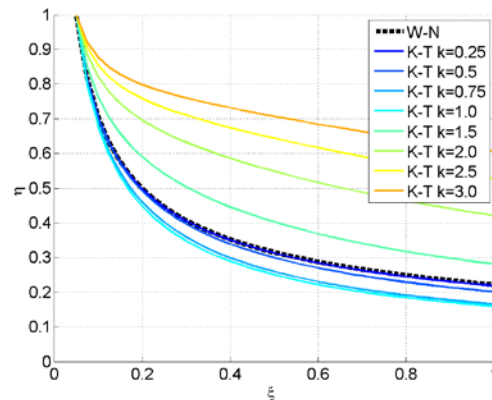
In more detail, inspection of Figure 7 leads to the following observations:

- As expected, the case of $k=1.0$ (i.e. ground predominant period coincident with structure fundamental period) leads to the highest reductions due to high damping ratios (i.e. lowest values of η_{K-T}). As illustrative example, for $\xi = 0.3$, $\eta_{K-T} = 0.35$ is

obtained. Rigorously speaking, the condition of the maximum reduction is not obtained for the case of $k = 1.0$, but it is obtained for a specific value k^* depending on the ratio $\overline{\xi_g} / \xi$:

$$k^* = \frac{\sqrt{1 - \xi^2}}{\sqrt{1 - \overline{\xi_g}^2}} \qquad (12)$$

It can be easily shown that k^* is around $0.85 - 1.15$, for ξ varying between 0.05 and 0.50 and for $\overline{\xi_g} = 0.35$.

- For k larger than 1.0, as k increases, the reductions due to high damping ratios significantly decrease (i.e. values of η_{K-T} become larger). As illustrative example, for $\xi = 0.3$, going from $k = 1.5$ to $k=3.0$ leads to an increase of η_{K-T} from 0.5 to 0.75 (i.e. - 50% in the reduction due to high damping).

- For k smaller than 1.0, η_{K-T} curves are closer to each other and the variations in the damping reduction factors are not significant. As illustrative example, for $\xi = 0.3$, going from $k = 0.25$ to $k=1.0$ leads to a decrease of η_{K-T} from 0.4 to 0.35 (i.e. +12% in the reduction due to high damping).

- The η_{W-N} curve is almost coincident with the η_{K-T} curve for $k=0.25$.

4. DISCUSSION

The results presented in the previous section through the η_{K-T} curves (Figure 7) may explain the large scatter resulting from the available formulations of η from both scientific literature and building codes (Figure 1). Assuming the idealized SDOF model subjected to a K-T PSD, it has been found that the damping reduction factor η is significantly dependent on the k ratio between the ground predominant period and the structure fundamental period. Therefore, the large variability of the actual formulations for η may be attributed to the different average predominant frequency content of the ground motion ensemble used for their calibration. For instance, in Figure 8 compare the η curves from the scientific literature are compared with the η_{K-T} curves for three selected values of k=1.0; 1.5; 2.5 and with the

η_{W-N} curve. It can be noted that the overall variability of the available formulations of η can be reproduced by the η_{K-T} curves considering different values of the k ratio.

In more detail, inspection of Figure 8 allows the following observations:

- The highest (i.e. leading to the lowest reductions due to high damping) η curve (Priesteley 2003) corresponds to the η_{K-T} curve with $k = 2.5$.

- The lowest (i.e. leading to the highest reductions due to high damping) η curve (BCJ 1997) corresponds to the η_{K-T} curve with $k = 1.0$.

- The EC8 formula (Bommer et al. 2000) corresponds to the η_{K-T} curve with $k = 1.5$.

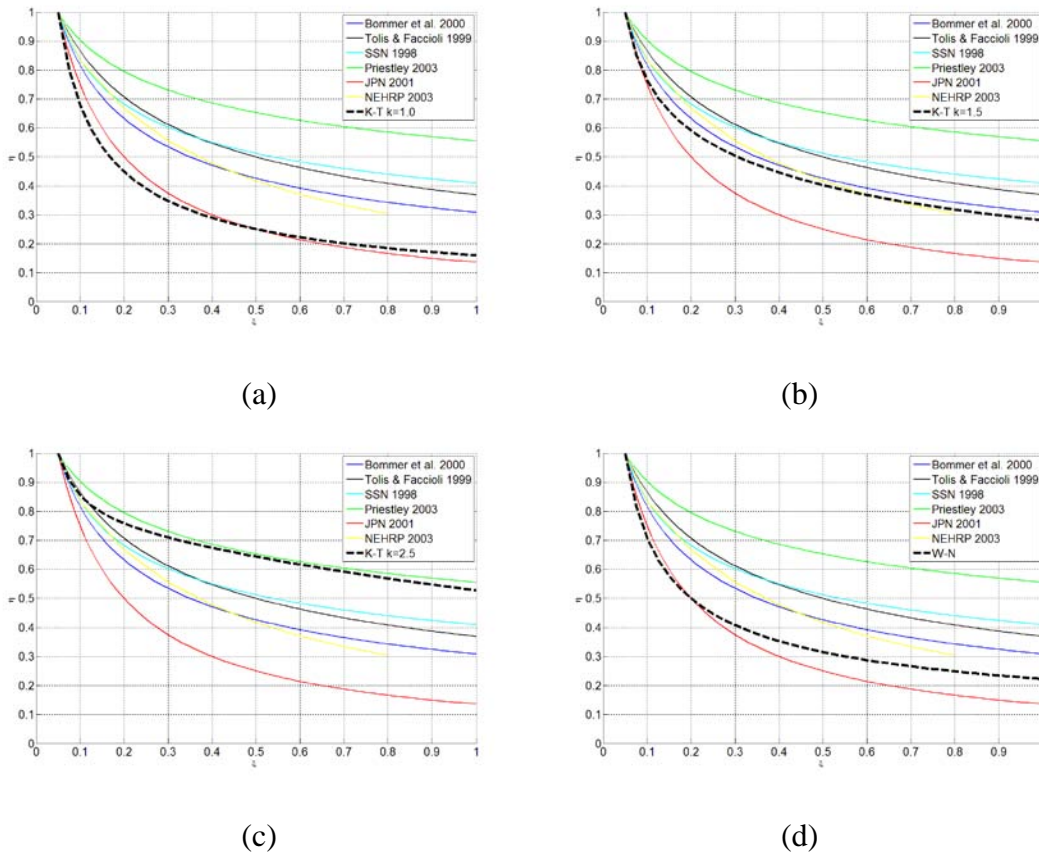- The η_{W-N} curve is between the BCJ 1997 curve and the EC8 formula.

(a)   (b)

(c)   (d)

Figure 8. (a) η curves from the scientific literature together with: (a) η_{K-T} for k=1.0; (b) η_{K-T} for k=1.5; (c) η_{K-T} for k=3.0; (d) η_{W-N} .

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5. PROPOSED DAMPING REDUCTION FACTOR

In this section, the results of the stochastic-based analysis are used to obtain a simple formulation for the damping reduction factor, which accounts for the *k* ratio between the ground predominant period and the structure fundamental period. In the light of the obtained results, the following simple code-like formula (which can be seen as a generalization of the EC8 formulation by Bommer et al. (2000) and Priesteley (2003)) is proposed:

$$\eta_{proposed} = \left(\frac{10}{5+\xi}\right)^{\chi} \tag{13}$$

where χ is a constant depending on the *k* ratio. For instance, the $\eta_{proposed}$ curves for 13 values of χ from 0.2 to 0.8 are displayed in Figure 9, together with the η_{K-T} curves for $k = 0.5$, 1.0, 1.5, 2.0, 2.5, 3.0. Table 2 gives the values of χ leading to a specific η_{K-T} curve. In Figure 10, η_{W-N} is displayed together with the corresponding $\eta_{proposed}$ (the one leading to the best fit in the least squares sense) and the along-the-period mean η_{T-H} curve obtained with reference to ground motions recorded on type B soil.
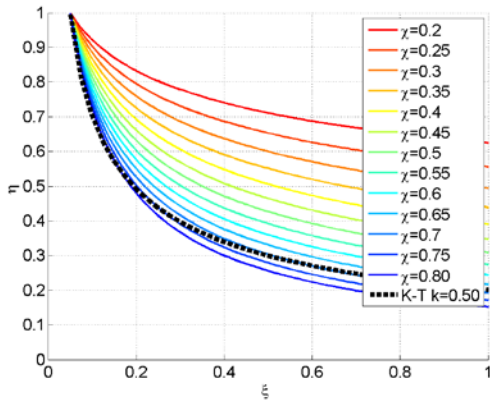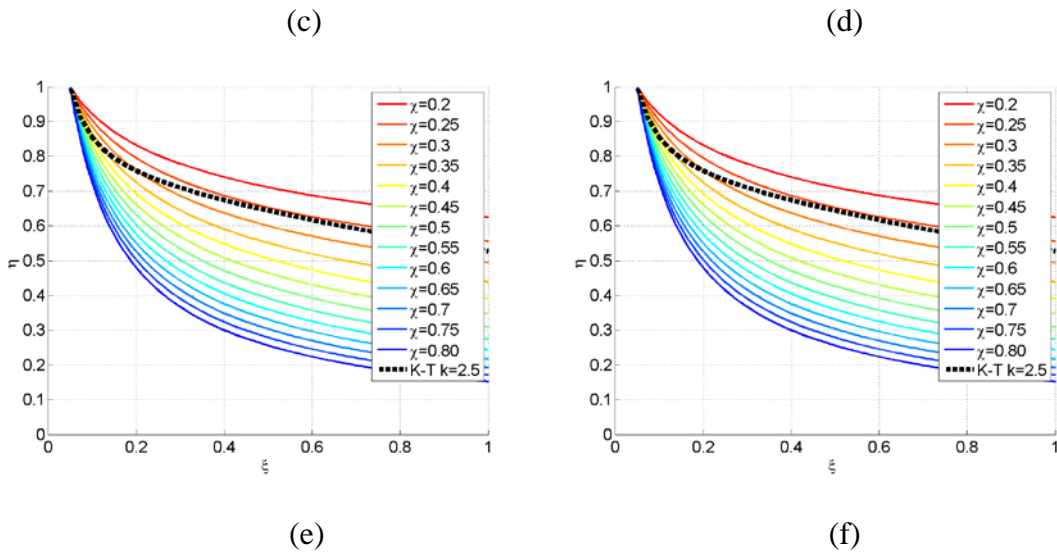

(a)
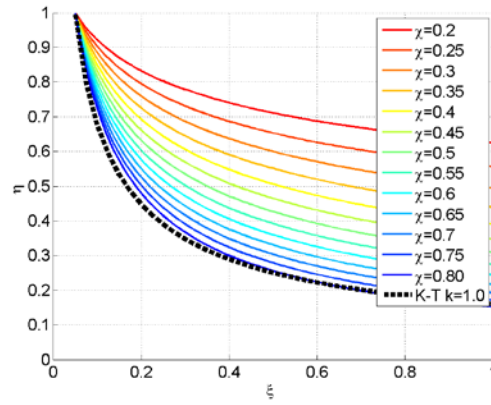
(b)
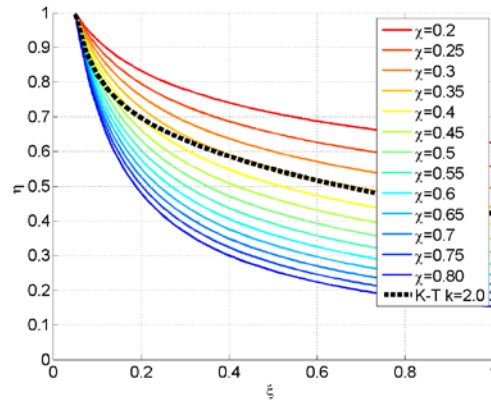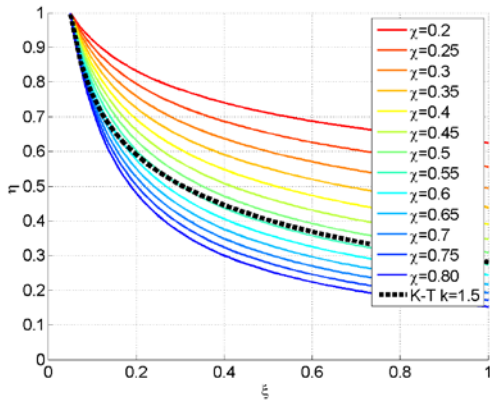
Figure 9. (a) $\eta_{proposed}$ curves for selected values of χ from 0.2 to 0.8 together with: (a) η_{K-T} for k=0.5; (b) η_{K-T} for k=1.0; (c) η_{K-T} for k=1.5; (d) η_{K-T} for k=2.0; (e) η_{K-T} for k=2.5; (f) η_{K-T} for k=3.0.

Table 2. Values of the χ exponent corresponding to a certain k ratio.

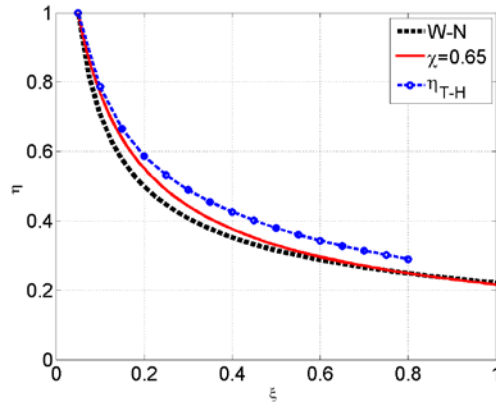| χ	0.7	0.8	0.55	0.35	0.25	0.2
k	0.5	1.0	1.5	2.0	2.5	3.0

Figure 10. $\eta_{proposed}$ curve for χ=0.65 together with η_{W-N} and η_{T-H}.

The comparison of the graphs provided in Figures 9 ($\eta_{proposed}$ vs. η_{K-T}) and 10 ($\eta_{proposed}$ vs. η_{W-N} and η_{T-H}), together with the information reported in Table 2 (χ vs. k), leads to the following observations:

- In the case of $k = 1$, the value of $\chi = 0.8$ is suggested.

- In the case of $k < 1$, values of χ between 0.6 and 0.7 are suggested.

- For high values of k ($k > 2$), values of χ between 0.2 and 0.35 are recommended.

- For $\chi = 0.25$, Eq. 13 is coincident with the formulation by Priestley (2003), which was suggested in the case of near-field regions, where the velocity pulse may reduce the effectiveness of the damping. This case is representative of a situation with k ratio around 2.5.

- For $\chi = 0.5$, Eq. 13 is coincident with the formulation by Bommer et al. (2000). This case is representative of a situation with k ratio around 1.2.

- The η_{W-H} curve is fitted by Eq. 13 using $\chi = 0.65$. Note that η_{W-H} is slightly below the along-the-period mean η_{T-H}, which can be considered as representative of the average damping reduction factor for type B soils.

6. CONCLUSIONS

The present study gives an insight into the damping reduction factor (η) to be used for the seismic design of structures equipped with added dampers. By modelling the response spectrum as a random process, an analytical expression of η based on the use of the Kanai-Tajimi Power Spectral Density has been derived. The obtained formulation allows to account, in a simplified way, for the influence of the soil predominant period on the amount of reduction due to high damping ratios. It is showed that the ratio between the soil predominant period and the structure fundamental period significantly affects the amount of reduction and may explain the large scatter between the actually available design formulations for the damping reduction factor.

On this regard, a simple code-like formula is proposed. The formula generalizes the actual formulation adopted by Eurocode 8 (2004), also encompassing the formulation by Priestely (2003), through the introduction of an exponent χ which has to be calibrated using the stochastic formulation of η.

The fundamental conclusions of the study may be summarised as follows:

- The exponent χ can be directly correlated to the k ratio between the soil predominant period and the structure fundamental period. For soil type B, on average, the value $\chi = 0.65$ can be suggested.

- Structures characterized by fundamental periods close to the ground predominant period show the highest reductions due to damping ratios (i.e. smallest values of η). In this case, the actual EC8 formulation appears slightly conservative.

- Flexible structures with large fundamental periods (typically tall buildings) are characterized by damping reduction factors close to the smallest values. In this case, the actual EC8 formulation leads to reasonable predictions.

- Stiff structures with small fundamental periods (typically low-rise buildings) exhibit damping reduction factors which can be reasonably predicted using the Priestley (2003) formulation.

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