DESIGN SPECTRA REDUCTION COEFFICIENTS FOR SYSTEMS WITH SEISMIC ENERGY DISSIPATING DEVICES LOCATED ON FIRM GROUND

S. E. Ruiz[1], J. P. H. Toxqui[2] and J. L. Rivera[3]

[1] *Professor, Instituto de Ingeniería , Universidad Nacional Autónoma de México, México City*
[2] *Graduate Student, Instituto de Ingeniería, Universidad Nacional Autónoma de México, México City*
[3] *Ph.D., formerly at Instituto de Ingeniería , Universidad Nacional Autónoma de México, México City*
Email: sruizg@iingen.unam.mx, jhidalgot@iingen.unam.mx

ABSTRACT:

A probabilistic demand seismic analysis is performed to calculate damping coefficients that take into account the effect of energy dissipation on the design spectral ordinates. Two types of EDDs are studied: a) linear viscous devices, and b) yielding damping systems. The systems analyzed are located on firm ground.

KEYWORDS: Damping factors, reduction coefficients, spectral ordinates, energy dissipating devices

1. INTRODUCTION

Several simplified design approaches have been proposed for the seismic design of structures with energy dissipating devices (Collins *et al* 1995, Ramirez et al 2000, Hanson and Soong 2001, FEMA-450, Whittaker et al 2003). Those approaches are commonly based on the reduction of the acceleration design spectrum by means of damping coefficients that take into account the effect produced by the energy dissipating devices (EDDs). The reduction factors have been obtained, in general, from deterministic non-linear response-history analysis of single-degree-of-freedom (SDOF) systems with EDDs, subjected to recorded or simulated ground motions.

The difference between the present study and those found in the literature is that here we take into account the effect of all the possible ground motion intensities expected at the site, by means of the corresponding seismic hazard curves (Cornell 1968, Esteva 1968).

2. OBJECTIVE

The objective of this study is to present a procedure for calculating damping factors needed to reduce the design pseudo-acceleration spectral ordinates, due to the presence of energy dissipating devices (EDDs) on the structural system. In order to reach this objective a probabilistic demand seismic analysis (PDSA) is performed to single-degree-of-freedom (SDOF) systems with EDDS, located on firm ground. Two types of EDDs are considered: a) linear viscous systems and b) yielding damping devices.

3. METHODOLOGY

First, the uniform annual failure rate (UAFR) spectra of the system without EDDs (conventional system) and, alternatively, with EDDs (combined system) are calculated using the algorithm presented in the next section. Based on this information, the ratio between the spectrum for the conventional system and that corresponding to a system with linear viscous EDDs is obtained. Those ratios (Q^d) are the reduction coefficients of the spectrum associated with the conventional structure. The viscous EDDs considered in this study are supposed to have damping coefficients equal to 5, 10, 15, 20 and 25% of the critical.

Next, we obtained the UAFR spectra for different values of SDOF systems with hysteretic dampers. The mechanical characteristics of the EDDs are given by means of the parameters α and γ, defined as follows: $\alpha = K_d / K_c$ and $\gamma = F_{yd} / F_{yc}$, where K_d is the stiffness of the, K_c is the stiffness of the main SDOF system, F_{yd} is the yield force of the EDDs, and F_{yc} is the yield force of the main SDOF system. These parameters are illustrated in Figure 1.

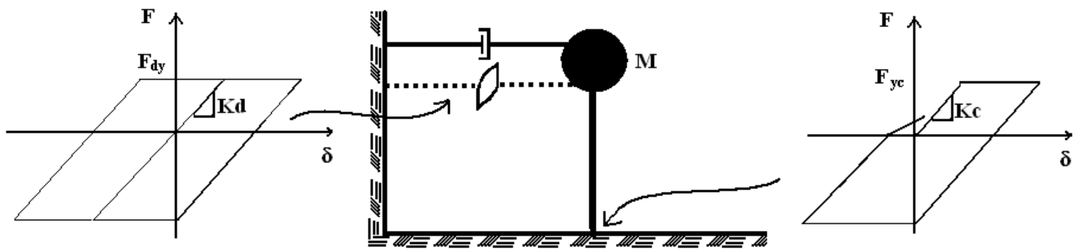

Figure 1. Main structural system with hysteretic EDDs

Next, we plotted on the same graph the UAFR spectra corresponding to systems with hysteretic dampers and the UAFR spectra associated with systems with viscous dampers. In this manner we found the intersection points between both spectra and, based on the coincidences, we established equivalences between the two types of combined systems. Particularly, we found the viscous damping value of a conventional system with an annual probability of failure equal to that corresponding to a system having hysteretic EDDs with α and γ parameters.

4. UNIFORM ANNUAL FAILURE RATE SPECTRA

In order to obtain the damping factors it is first necessary to construct the uniform annual failure rate (UAFR) spectra corresponding to the SDOF systems with EDDs. In the following we reproduce the algorithm proposed by the authors (Rivera and Ruiz 2007) for systems with hysteretic devices.

1. As a first step, values of the following parameters corresponding to the combined system are proposed: seismic coefficient (C_y), nominal structural vibration period T and mass M, as well as values of the ratios $\alpha = K_d / K_c$ and $\gamma = F_{yd} / F_{yc}$).
2. Next, the nominal value of the lateral stiffness of the combined system is calculated $(K_T = 4\pi^2 M / T^2)$. The nominal stiffness values (K_c, K_d) associated respectively with the conventional and with the dissipating systems are obtained ($K_c = K_T / (1+\alpha)$ and $K_d = \alpha K_c$).
3. The yield displacement value of the combined system (d_{yT}) is calculated: $d_{yT} = C_y W / (K_c + K_d)$.

4. Using the relations mentioned above, the yield displacement values of the conventional and of the dissipating systems are calculated ($d_{yc} = C_y W / (K_c + \gamma K_d)$ and $d_{yd} = \gamma d_{yc}$).
5. The values of the stiffness and of the yield displacements of the conventional system (K_c and d_{yc}, respectively) are used to calculate the parameters Γ_{4c} and Γ_{5c} (that correspond to Baber and Wen 1981 model). In the case of a conventional reinforced concrete structure, these parameters are given by $\Gamma_{5c} = -2\Gamma_{4c} = -\dfrac{1}{\upsilon_c}\left(\dfrac{K_c}{F_{yc}}\right)^{\Gamma_{6c}}$, where $F_{yc} = K_c d_{yc}$.
6. In a similar way, the values of the stiffness and of the yield displacements corresponding to the dissipating system (K_d and d_{yd}, respectively) are used to calculate the values of the parameters Γ_{4d} and Γ_{5d}. For steel made dissipating elements: $\Gamma_{5d} = \Gamma_{4d} = \dfrac{1}{2\upsilon_d}\left(\dfrac{K_d}{F_{yd}}\right)^{\Gamma_{6c}}$.
7. Each combined SDOF system is subjected to a different accelerogram. Here we generate artificial ground motions. Each of these is scaled so that the spectral acceleration associated with the fundamental period of the system under study has the same return interval (T_R) (Shome and Cornell 1999). The ratio between the spectral acceleration value and the inverse of the return interval is given by the site seismic hazard curve, which is assumed to be known.
8. The peak system displacement is obtained step by step in time. Then, the peak structural ductility demand (μ_i) corresponding to the *i*-th simulated record is calculated.
9. A nominal value of the ductility capacity of the combined system is proposed (μ_a).
10. The structural failure of the SDOF system occurs when the ductility demand is greater than the available ductility (capacity); that is, when $\mu_i / \mu_a = Q_i \geq 1$. The annual structural failure rate is evaluated by means of (Esteva and Ruiz 1989):

$$\nu_F = \int \left| \frac{d\nu}{dS_a} \right| P\left(Q \geq 1 \middle| S_a\right) dS_a \tag{1}$$

    where $|d\nu / dy|$ it is the absolute value of the derivative of the site seismic hazard curve (which is assumed to be known), and $P(Q \geq 1 | y)$ is the conditional probability that the structural failure occurs, given a seismic intensity S_a.
11. The integral is evaluated numerically for different values of C_y, α, γ and μ_a. With the results, the demand hazard curves associated with SDOF combined systems with different vibration periods are constructed. In this study the structural demand is taken as the elastic force coefficient (S_a / g), so the demand hazard curve is a S_a / g - versus - ν_F graph, where g = gravity.
12. The UAFR spectra are drawn on the basis of the demand hazard curves associated with different structural vibration periods.

The same algorithm was applied to systems with linear viscous devices, except that in this case the algorithm becomes simpler than that described above.

5. GROUND MOTION AND SEISMIC HAZARD CURVES

The SDOF combined systems analyzed are located on firm soil. One hundred simulated ground motions were used as excitations (see step 7 of the above algorithm). The simulations were based on the record obtained in “Filo de Caballo” station during the September 19, 1985 earthquake. The record is shown in Figure 2a, and its fitted spectral density, $S(\omega)$, is presented in Figure 2b. The effective duration was taken equal to 25s.

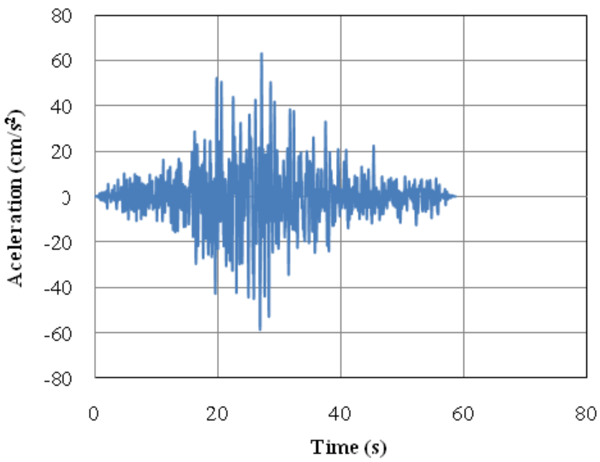

Figure 2a Base record

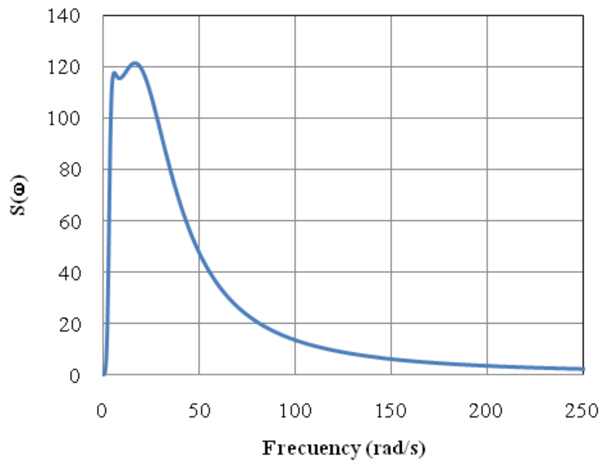

Figure 2b Adjusted spectral density of the base record

The corresponding site seismic hazard curves, for different structural periods, are shown in Figure 3.

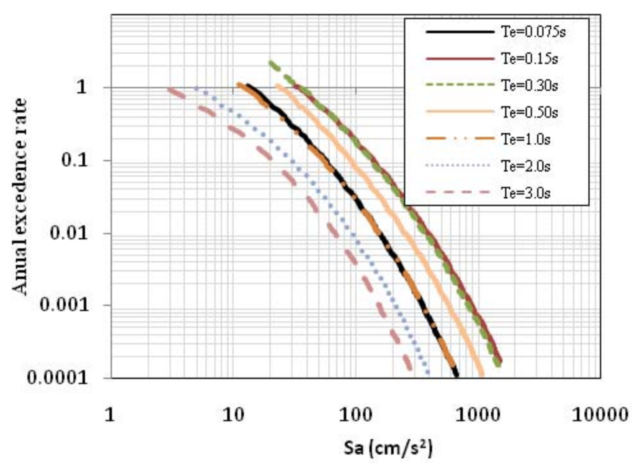

Figure 3. Seismic hazard curves corresponding to the SCT site

6. UAFR SPECTRA FOR STRUCTURES WITH LINEAR VISCOUS DEVICES

The UAFR spectrum was calculated (with the algorithm mentioned above) for different values of linear viscous damping added to the main system. In this study, a mean failure structural rate equal to 0.008 was used. The UAFR spectra corresponding to six different ratios of critical damping ($\varsigma_e^{'}$ = 5, 10, 15, 20, 25 and 30%) are shown in Figure 4a. From these spectra, the ratio between each of them and that corresponding to ς = 5% was obtained. That ratio (Q^d), presented in figure 4b, is the reduction coefficient of the strength spectrum that takes into account the presence of the viscous dampers. Figure 4b correspond to values of Q^d for different structural periods and for relations of critical damping ratios equal to $\varsigma_e / \varsigma_e^{'}$ = 5/30, 5/25, 5/20, 5/15 and 5%/10%.

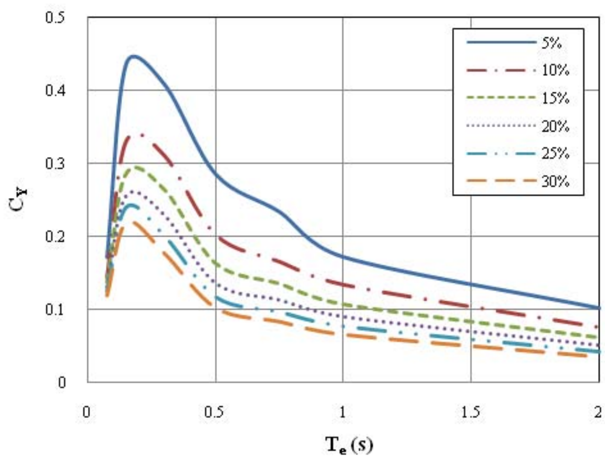

Figure 4a. UAFR spectra for different percentages of viscous damping

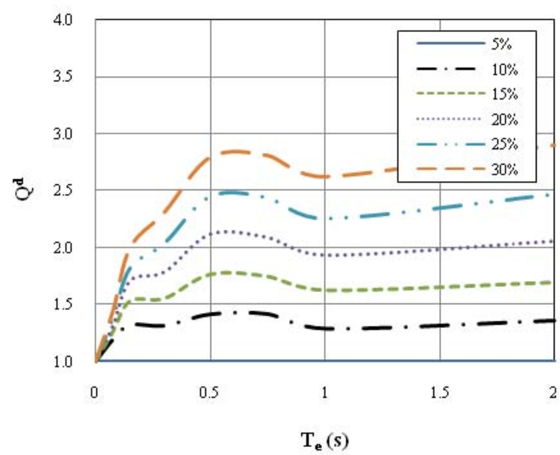

Figure 4b. Reduction factors. Viscous damping

Based on Figure 4b it is possible to establish rules for the construction of design spectra that consider the effect of extra damping added to the main structural system. For example, the authors have proposed to the technical committee in charge of formulating the Seismic Design Comision Fededral de Electricidad (CFE) Manual (now under revision) to incorporate the following damping factor expression:

$$\beta(T_e) = \frac{1}{Q^d} = \left(\frac{0.05}{\varsigma_e^{'}}\right)^{\lambda}$$

Where β is the damping factor that multiplies the design acceleration spectrum for 0.05 damping, in order to take into account the presence of the extra damping of the structure

T_e is the structural period of interest

$\varsigma_e^{'}$ is the fraction of critical damping of the structure plus EDDs

$$\lambda = \begin{cases} 0.45 & ; \quad \text{if} \quad T_e < T_c \qquad (2a) \\ 0.45\left(\dfrac{T_c}{T_e}\right)^{0.6} & ; \quad \text{if} \quad T_e \geq T_c \qquad (2b) \end{cases}$$

T_c is the period where the form of the spectrum changes

7. UAFR SPECTRA FOR STRUCTURES WITH HYSTERETIC DEVICES

Following the algorithm listed in section 4, we constructed a number of UAFR spectra for SDOF systems with hysteretic devices. Those spectra correspond to SDOF systems having EDDs with different values of the parameters α and γ (those were defined in section 3, figure 1).

Each of the UAFR spectra of SDOF with hysteretic dissipating devices was plotted on the same Figure 4a (which correspond to spectra for systems with viscous dampers) in order to find coincidence points between their ordinates and, in this way, to find the "equivalent" viscous damping for each case. In the following we will try to explain this procedure by means of an example.

Figure 5 shows (with discontinuous lines) the spectra that appear in Figure 4a (they correspond to SDOF with viscous dampers) as well as the spectrum (with black full line) that corresponds to SDOF with hysteretic dampers. For this example we have selected the following parameters: $\alpha = 1$ and $\gamma = 0.30$. In Figure 5 we also indicate several full red circles that correspond to six points where the discontinuous curves (viscous damping case) intersect the black continuous curve (hysteretic damping case).

The corresponding "equivalent" viscous damping for the structural periods (T_e) indicated in Figure 5 are presented in the third column of Table 1, where the first column represents the structural period and the second is the seismic coefficient (vertical axis of Figure 5).

The pairs of values of the first and the third column in Table 1 are presented graphically in Figure 6. This shows that the "equivalent" effective critical damping ratio ς_e depends on the structural period, and presents its maximum value close to the dominant period of the spectrum (in this case, equal to 0.15s).

The form of the fitted curve in Figure 6 (for periods longer than the dominant period) could be, for example, the following expression:

$$\varsigma_e = (T_e + A)^{-6} + B \qquad (3)$$

where A and B are constants that depend on the α and γ values.

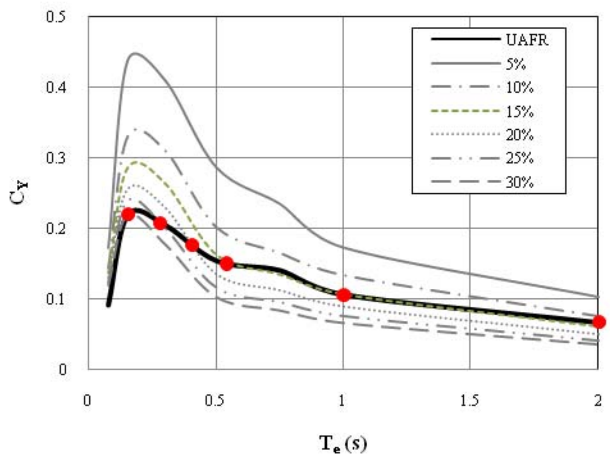

Figure 5. Intersection of the spectrum corresponding to the systems with hysteretic EDDs (black continuous line) with the spectra corresponding to the systems with viscous dampers (discontinuous lines)

Table 1 Equivalent viscous damping for different periods

Period T_e (s)	C_y	ς_e
0.155	0.22	0.30
0.28	0.208	0.25
0.405	0.177	0.20
0.54	0.15	0.15
1.0	0.105	0.15
2.0	0.067	0.125

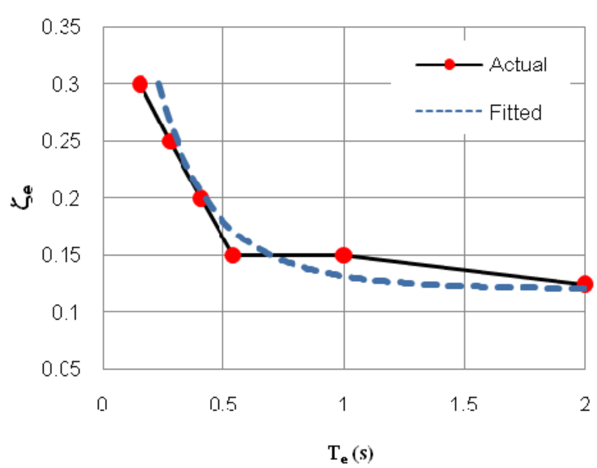

Figure 6. Effective critical damping ratios corresponding to a system with $\alpha = 1$, $\gamma = 0.3$ and critical damping ratio equal to 5%.

6. CONCLUSIONS

We have shown a general procedure for the calculation of reduction factors based on the ratio between the UAFR spectrum corresponding to the conventional frame and that of the systems with EDDs, both associated with the same annual failure rate. This approach is being followed at the National University of Mexico for the calculation of damping factors. Those will be submitted for their possible inclusion in the CFE Seismic Design Manual.

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