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REDUCTION FACTORS FOR PERFORMANCE BASED SEISMIC DESIGN

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ABSTRACT

In this paper new reduction factors (*q-factors*) of elastic spectra demand for linear seismic design within the Performance Based Seismic Engineering (PBSE) philosophy are proposed. Such new q-factors take directly into account structural damage levels, viscous damping and ductility in the case of A, B and C linear seismic spectra defined in EC8 – ENV 1998-1-1 for rare events. Structural damage is considered through the use of the Park and Ang damage index.

1. INTRODUCTION

As is already known, PBSE implies the design, evaluation, and construction of engineered facilities whose performance, under normal and extreme loads, responds to the different needs and objectives of owner-users and society. It has been shown that by varying the intensity levels of the seismic excitations, admissible structural damage is closely related to the functions for which the construction is designed (Bertero R.D., Bertero V.V., 2002). Damage evaluation depends from different parameters that influence seismic demand, among them the main parameters are: the spectral characteristics of the seismic excitation, the fundamental vibration period, the viscous damping level, the ductility capacity and the amount of hysteretic energy dissipated by the structure.

Several methodologies have been developed to assess seismic performance by comparing the so-called “capacity” and “demand” curves on the Acceleration Displacement Response Spectra (ADRS) representation. The demand is described by the spectral response for the specific seismic event while the capacity is described by the structural non-linear behavior for properly equivalent static forces. The main non-linear static procedures (Push-Over Analysis) are: Capacity Spectrum Method (CSM - Freeman, 1978), Displacement Coefficient Method (DCM - FEMA 273, 1997) and N2 method (N2 - Fajfar P. & Fischinger M., 1988). These procedures often lead to a large scatter in the results and are sensitive to the “push mode” and to the adopted load profile (Albanesi T., Nuti C. & Vanzi I., 2000) (Wilkinson S., 2002).

The present work proposes an elastic design approach based on the definition of new q-factors by directly taking into account the damage level according to PBSE performance criteria.

As is known, based on the elastic and inelastic response spectra of the NS component of El

Centro 1940, Newmark and Hall (N.M. Newmark, W.J. Hall, 1973) first presented a piece-wise curve of strength q-factors, while mathematical formulation for strength reduction factors, related to collapse spectra, was originally proposed by Fraternali and Palazzo (Fraternali F., Palazzo B., 1987). An initial approach to define strength reduction factors based on structural damage performance was recently examined by Zhu and Ni (X. Zhu, Y. Ni, 2002). Based on a parametric study of a composite hysteretic model, Zhu and Ni calculated reduction factors through the regression formulae suggested by L.H. Lee et al. (L.H. Lee et al., 1999). However, no studies are available concerning both high viscous damping and ductility effects on seismic demand.

According to A, B and C elastic spectra, as defined in Eurocode 8 (EC8 ENV 1998-1-1) for the maximum expected seismic event (475-year return period), q-factors are herein evaluated for pre-assigned seismic performance within the PBSE criteria. In particular, through parametric analysis, carried out over wide intervals spanning the fundamental period of vibration, the available monotonic ductility and the level of viscous dissipation, this study proposes new q-factor formulae to elastically design earthquake resistant structures. The high values of viscous dissipation considered here also allow for the design of structures with extra-structural damping devices.

2. SEISMIC ACCELEROGRAM CHARACTERIZATION

In order to evaluate strength q-factors of pseudo-acceleration elastic spectra to design structures with elastic-plastic behavior and equipped with extra-structural viscous-elastic dissipation devices, synthetic seismograms have been generated. More specifically, through the use of the SIMQKE code (Vanmarcke E.H., Cornell C.A., Gasparini D.A., & Hou S.N., 1976), 60 seismic excitations, compatible with an elastic spectrum defined by the maximum expected event with a return period of T=475 yrs (10% probability of occurrence in 50 years) for sub-soil classes A, B and C, have been carried out. The synthetic accelerograms lasted for 60 sec. and the maximum accelerations were achieved in a time window of 10 sec.. The elastic spectrum associated with each event, within the interval of the considered period (0.1-5 sec.), presents a maximum deviation of 10% in comparison with the reference spectra, figures 1-3.

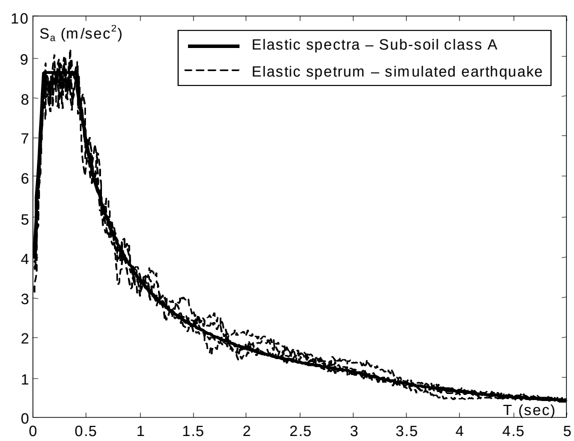

Figure 1. Comparison between sub-soil class A (EC-8) and synthetic earthquake elastic spectra

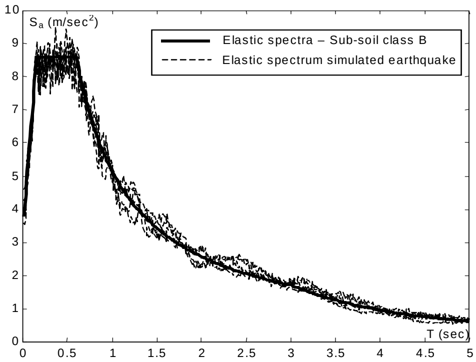

Figure 2. Comparison between sub-soil class B (EC-8) and synthetic earthquake elastic spectra

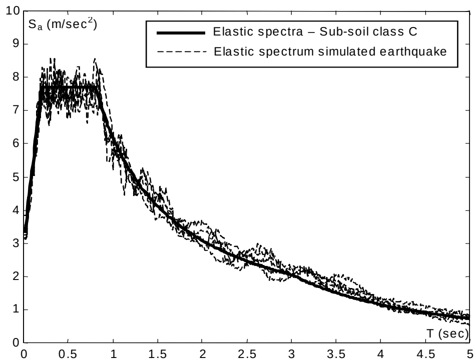

Figure 3. Comparison between sub-soil class B (EC-8) and synthetic earthquake elastic spectra

Table 1 shows the comparison between the synthetic excitations and real seismic events by means of the following indexes:

- ***I_A*** (*Arias index*): represents a measure of seismic intensity in terms of the energy dissipated by the structure during the seismic event (Arias, 1970). An assessment of this can thus be rendered by:

$$I_A = \frac{\pi}{2g} \int_0^t a^2(\tau) d\tau \qquad (1)$$

- ***P_D*** (*Saragoni's factor*): is a measure of the effects on a built structure by a seismic event. It has been shown (Saragoni, 1990) that the destructiveness of a seismic event, measured in terms of ductility demand, is directly related to the input energy and to the average number of accelerogram sign inversions (ν_0) in the time unit:

$$P_D = (\pi \int_0^{t_W} a^2(t)dt)/(2g\nu_0^2) = I_A / \nu_0^2 \qquad (2)$$

- ***I_D*** (*Cosenza and Manfredi's factor*) : is an assessment of the number of plastic cycles and of the average value of their relative distribution during a particular seismic event (Cosenza, Manfredi 1997):

$$I_D = \frac{2g}{\pi} \frac{I_A}{PGA \cdot PGV} \tag{3}$$

Table 1. Main accelerometric parameters for considered seismic events

Earthquake	Registration station	PGA [cm/sec^2]	I_A [cm/sec]	P_D [cm·s]	I_D
San Fernando - 1971	Pacoima DAM	1148.1	797.2	16.28	3.80
Nahanni	S1-L	1080.5	462.5	1.61	5.50
Northridge - 1994	Santa Monica – 90°	865.9	269.4	7.78	4.84
Kobe 1995	JMA - NS	817.8	838.4	36.45	6.91
Chile 1985	Llolleo - N	639.5	1520.8	16.85	35.8
Ancona 1972	Rocca NS	538.1	67.8	0.01	6.94
Montenegro 1979	Petrovac - NS	429.3	446.2	19.75	15.3
Imperial Valley - 1940	El Centro 270°	341.7	174.8	6.11	8.59
Friuli 1976	Tolmezzo WE	315.2	119.9	4.66	7.25
Loma Prieta - 1989	Oakland Outer – 270°	270.4	83.71	8.26	5.21
Bucharest	Incerc - NS	192.3	71.4	3.75	3.66
Mexico 1985	SCT - EW	167.9	243.8	189.81	14.5
Campano-Lucano 1980	Calitri - WE	156.0	134.1	7.77	17.8
Kern County 1959	Taft – 69°	152.7	53.05	1.85	12.9
Synthetic event – mean	**sub-soil class A**	**343.35**	**641.27**	**5.90**	**44.47**
Synthetic event – mean	**sub-soil class B**	**343.35**	**734.48**	**5.33**	**28.81**
Synthetic event – mean	**sub-soil class C**	**343.35**	**805.61**	**7.49**	**30.06**

It may be seen that, as far as the Cosenza-Manfredi index is concerned, the synthetic accelerograms show values which are similar to those of the destructive event (Chile 1985, Mexico City 1985, Campano-Lucano 1980). The Arias index for synthetic events reaches the maximum values obtained for the real excitations. Finally, the values obtained through Saragoni's factor seem closer to the average of those evaluated for real seismic events. Therefore, since this study aims to evaluate q-factors by comparing the inelastic and the elastic response of SDOF systems subjected to the same set of excitations, these synthetic accelerograms can be considered significant in terms of numerical experimentation. Moreover, by considering the high ductility and hysteretic demand from Cosenza and Manfredi's index, the q-factors examined here can also be representative of near-fault events, for which the ductility demand, more than the hysteretic energy, represents a significant index of destructiveness.

3. q-FACTORS FOR "NO DAMAGE" PERFORMANCE REQUIREMENT

By using the synthetic accelerograms, the response of a single degree of freedom (SDOF) system with linear behavior (no damage) was first investigated for a wide range of values concerning both the period of vibration T of the elastic system and viscous damping ξ:

$$T \in [0,5] \text{ - } \Delta T = 0.1$$
$$\xi \in [0.02, 0.30] \text{ - } \Delta\xi = 0.03 \div 0.05$$

System behavior has been investigated by the SIMULINK-MATLAB procedure, which is able to evaluate the maximum displacement, the ductility demand, the absolute maximum acceleration, the input energy and the rate of dissipated hysteretic and viscous energy. For the combinations of the parameters under consideration, the q-factors are defined by the ratio between elastic strength and the minimum necessary to stand up to a seismic events with no damage by considering an elastic system having ξ=0.05.

The results (Fig. 4) have pointed toward the possibility of modeling the values of such q-factors through the following bilinear function:

$$q_\xi(T,\xi)=\begin{cases}\dfrac{q_\xi(T_0,\xi)-1}{T_0}T+1 & T<T_0\\ \dfrac{q_\xi(T_1,\xi)-q_\xi(T_0,\xi)}{T_1-T_0}\left(T-T_0\right)+q_\xi(T_0,\xi) & T_0<T<T_1\end{cases} \quad (4)$$

where T_0, T_1 represent respectively the transition period between constant velocity and constant acceleration regions for the considered spectra, and the maximum considered period T_1=5 sec. q-factor formulae (4) are defined by the values of *q* corresponding to the periods T_0 and T_1. Such values can be evaluated by minimizing the mean square error between the experimental data and a quadratic function representation (equations 5-7). Figure 4 represents the q-factors in the case of sub-soil class A on varying the damping.

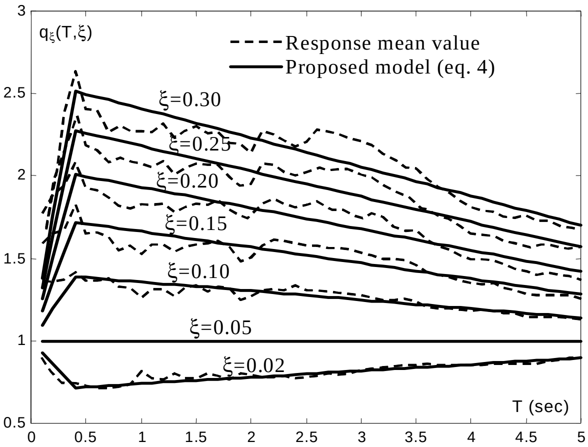

Figure 4. q-factors for no damage performance – sub-soil class A (EC 8)

$$\begin{cases}q_\xi(T_0,\xi)=-7.6\xi^2+8.7\xi+0.584\\ q_\xi(T_1,\xi)=2.8\xi+0.86\end{cases}\quad \text{spectrum sub-soil class A} \quad (5)$$

$$\begin{cases} q_\xi(T_0,\xi) = -8.5\xi^2 + 8.7\xi + 0.585 \\ q_\xi(T_1,\xi) = 2.9\xi + 0.85 \end{cases} \text{ spectrum sub-soil class B} \quad (6)$$

$$\begin{cases} q_\xi(T_0,\xi) = -7.96\xi^2 + 8.9\xi + 0.574 \\ q_\xi(T_1,\xi) = 3.82\xi + 0.809 \end{cases} \text{ spectrum sub-soil class C} \quad (7)$$

Figure 5 shows the comparison between the q-factors obtained for sub-soil class A and those proposed by EuroCode 8 (ENV 1998-1-1):

$$q_\xi = 1/\eta \text{ with } \eta = \sqrt{\frac{7}{2+\xi}} > 0.7 \quad (8)$$

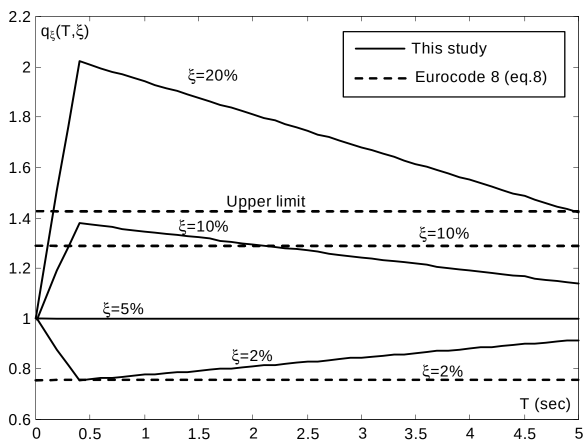

Figure 5. q-factors comparison: this study vs Eurocode 8 – Sub-soil class A

Results show that EuroCode 8 (eq. 8) allows for higher reduction factor values in low and high period ranges for a low value of damping, while for high damping levels EuroCode 8 shows significantly lower values.

4. q-FACTORS FOR NO COLLAPSE REQUIREMENT

In the case of elastic-perfectly plastic behavior and a no-damage control requirement, the system response has been analyzed for different strengths *R* and monotonic ductility $\mu_{u,mon}$:

$$\mu_{u,mon} \in [1,6] \text{ - } \Delta\mu_{u,mon} = 0.2$$

Figure 6 shows the q-factors for sub-soil class A spectra, in the case of viscous damping ξ=10% and monotonic ductility $\mu_{u,mon}$ =4.

Figures 7-9 show the average value of the inelastic q-factors (dotted line) on varying the ductility demand for 10% damping and the modelled q-factors by the proposed formula $q_\mu(T,\xi)$ (continuous line):

$$q_\mu(T,\xi,\mu)=\begin{cases}\dfrac{q_\mu(T_0,\xi,\mu)-1}{T_0}T+1 & T<T_0\\ \dfrac{q_\mu(T_1,\xi,\mu)-q_\mu(T_0,\xi,\mu)}{T_1-T_0}\left(T-T_0\right)+q_\mu(T_0,\xi,\mu) & T_0<T<T_1\\ \dfrac{q_\mu(T_2,\xi,\mu)-q_\mu(T_1,\xi,\mu)}{T_2-T_1}\left(T-T_1\right)+q_\mu(T_1,\xi,\mu) & T_1<T<T_2\end{cases} \qquad (9)$$

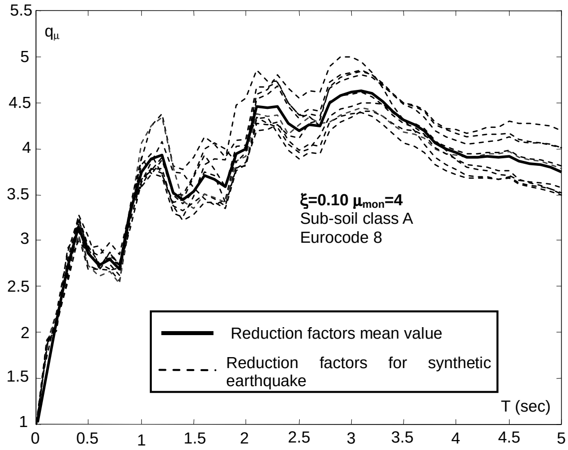

Figure 6. q-factors evaluated for monotonic ductility, μ_{mon}=4

where T_0, T_1 represent respectively the transition period between the constant velocity and acceleration regions and the constant velocity and displacement regions for the considered elastic spectra. $T_2 = 5\sec$ is the maximum value of the considered periods. Formulae (9) are defined by knowledge of the q-factors for periods T_0, T_1 and T_2. Therefore, by taking into account quadratic functions for the ductility demand variable and linear-hyperbolic functions for damping, formulae 10-18 are obtained by minimizing the mean square error.

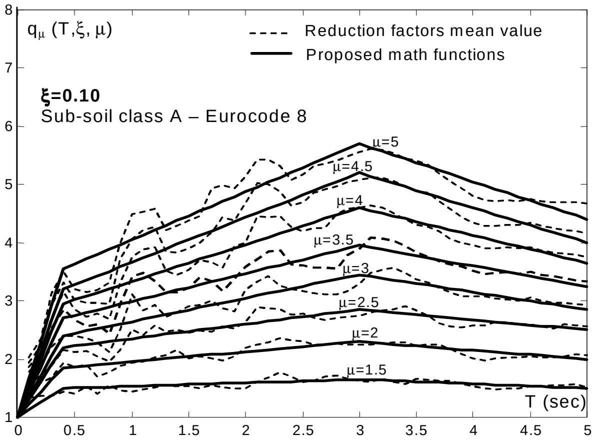

Figure 7. Inelastic q-factors, sub-soil class A – viscous damping 10%

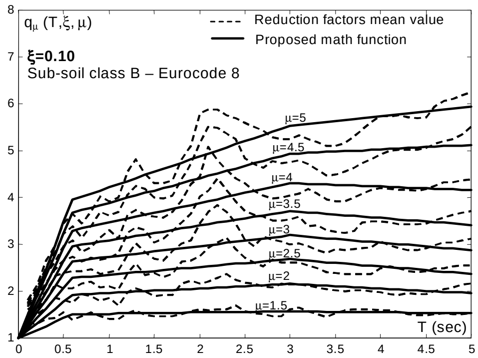

Figure 8. Inelastic q-factors, sub-soil class B – viscous damping 10%

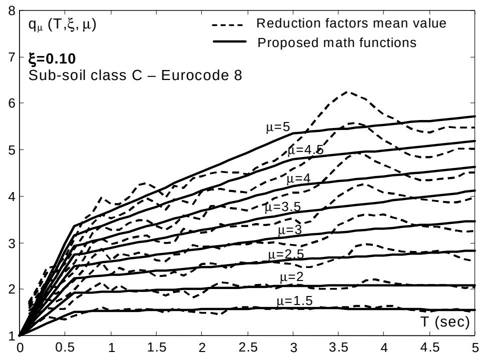

Figure 9. Inelastic q-factors, sub-soil class C – viscous damping 10%

Inelastic Spectrum Sub-soil class A:

$$q_{\mu}(T_0,\xi,\mu) = (-\frac{0.0018}{\xi} + 0.071\xi - 0.048)\mu^2 + (\frac{0.02}{\xi} - 0.544\xi + 0.82)\mu + (-\frac{0.0182}{\xi} + 0.473\xi + 0.228) \quad (10)$$

$$q_{\mu}(T_1,\xi,\mu) = (-\frac{0.0014}{\xi} - 0.086\xi - 0.0006)\mu^2 + (\frac{0.0138}{\xi} - 0.851\xi + 1.264)\mu + (-\frac{0.0124}{\xi} + 0.937\xi - 0.263) \quad (11)$$

$$q_{\mu}(T_2,\xi,\mu) = (\frac{0.0001}{\xi} + 0.287\xi - 0.0778)\mu^2 + (\frac{0.0009}{\xi} - 1.31\xi + 1.251)\mu + (-\frac{0.001}{\xi} + 1.023\xi - 0.173) \quad (12)$$

Inelastic Spectrum Sub-soil class B:

$$q_{\mu}(T_0,\xi,\mu) = (-\frac{0.0018}{\xi} + 0.071\xi - 0.048)\mu^2 + (\frac{0.02}{\xi} - 0.544\xi + 0.82)\mu + (-\frac{0.0182}{\xi} + 0.473\xi + 0.228) \quad (13)$$

$$q_{\mu}(T_1,\xi,\mu) = (-\frac{0.0004}{\xi} + 0.114\xi + 0.0007)\mu^2 + (\frac{0.0077}{\xi} - 0.51\xi + 1.051)\mu + (-\frac{0.0073}{\xi} + 0.396\xi - 0.052) \quad (14)$$

$$q_{\mu}(T_2,\xi,\mu) = (-\frac{0.0016}{\xi} - 0.427\xi + 0.1825)\mu^2 + (\frac{0.0102}{\xi} + 2.065\xi + 0.165)\mu + (-\frac{0.0086}{\xi} + 1.638\xi + 0.6525) \quad (15)$$

Inelastic Spectrum Sub-soil class C:

$$q_{\mu}(T_0,\xi,\mu) = (-\frac{0.0024}{\xi} + 0.173\xi - 0.091)\mu^2 + (\frac{0.025}{\xi} - 1.24\xi + 1.124)\mu + (-\frac{0.0266}{\xi} + 0.652\xi + 0.22) \quad (16)$$

$$q_{\mu}(T_1,\xi,\mu) = (-\frac{0.0003}{\xi} - 0.0026\xi + 0.005)\mu^2 + (\frac{0.011}{\xi} - 1.073\xi + 1.062)\mu + (\frac{0.0107}{\xi} + 1.076\xi - 1.067) \quad (17)$$

$$q_{\mu}(T_2,\xi,\mu) = (\frac{0.0017}{\xi} + 0.131\xi - 0.045)\mu^2 + (-\frac{0.0074}{\xi} - 1.538\xi + 1.509)\mu + (\frac{0.0057}{\xi} + 1.407\xi - 0.464) \quad (18)$$

Errors between the proposed formulae (10-18) and the average of the experimental data for ξ=10% in the case of subsoil class A spectrum are shown in fig. 10. The same results have been achieved for subsoil classes B and C.

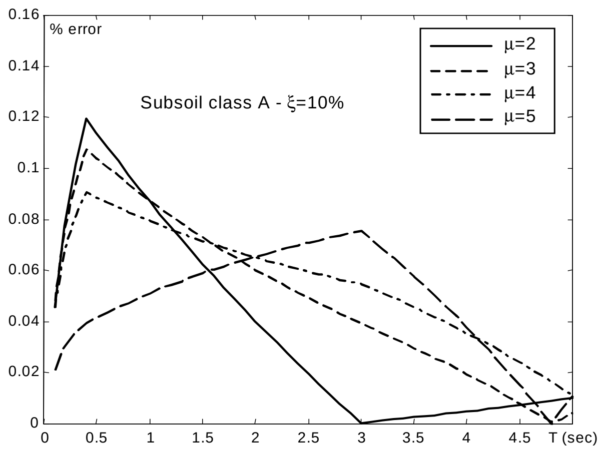

Figure 10. Percentage of error committed through the proposed mathematical model – sub-soil class A

Figures 11–13 show the comparison between the proposed q-factors and those of other authors (Miranda 1993, Y.H. Chai et al. 1998, W.D. Zhuo 2000, EuroCode 8 1996, X. Zhu 2000) for a damping level of 5% and for ductility capacity equal to 2, 4 and 6. Figures show that for high ductility levels the proposed q-factors are more conservative for low and high periods. Moreover, the proposed q-factor values in high periods agree with results from other studies (Miranda E., 1993) which lead to an increase in the seismic demand.

By combining the viscous damping and ductility effects, the q-factor can be evaluated as:

$$q(T,\xi,\mu) = q_{\xi}(T,\xi) \cdot q_{\mu}(T,\xi,\mu) \quad (19)$$

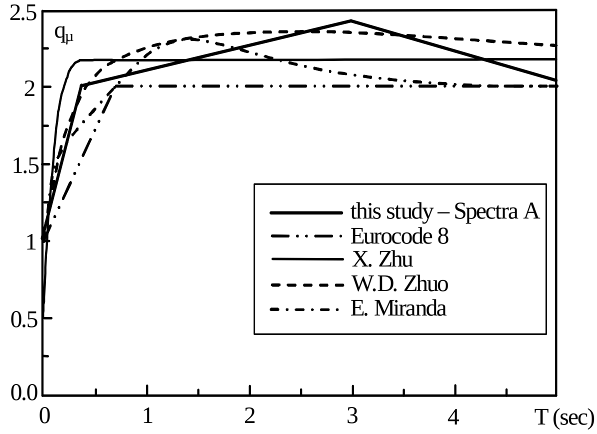

Figure 11. Comparison between the proposed q-factors and those evaluated by other authors - $\mu = 2$ - $\xi = 0.05$.

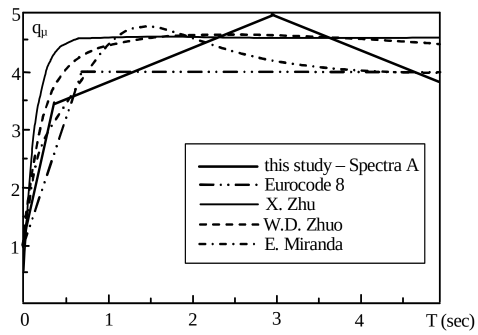

Figure 12. Comparison between the proposed q-factors and those evaluated by other authors - $\mu = 4$ - $\xi = 0.05$.

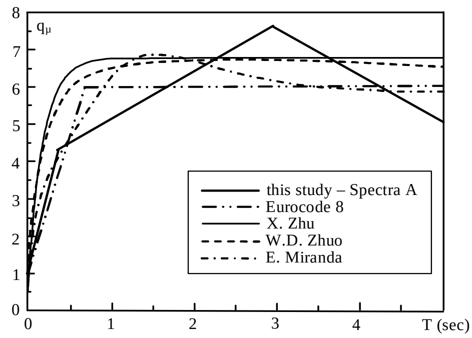

Figure 13. Comparison between the proposed q-factors and those evaluated by other authors - $\mu = 6$ - $\xi = 0.05$.

5. STRENGTH q-FACTORS FOR DAMAGE CONTROL

The damage is here considered by the Park and Ang index (Park YJ & Ang AH-S, 1985):

$$D_{P.A.} = \frac{x_{\max}}{x_{u,mon}} + \beta \frac{E_H}{F_y x_{u,mon}} = \frac{\mu_S + \beta(\mu_e - 1)}{\mu_{u,mon}} \tag{20}$$

this expression defines an equivalent ductility which takes into account both the cinematic ductility $\mu_S = x_{\max} / x_y$, and the hysteretic ductility $\mu_e = 1 + [E_H /(F_y x_y)]$. The coefficient β can be regarded as a “model degrade parameter” due to the dissipated plastic energy (Kunnath et al., 1990). Park proposed a formula based on 260 experimental tests, in which β depends on cross-sectional normal and shear stress, longitudinal and transversal reinforcement (Park, 1984). Park and Ang suggest using *β=0.025* for steel frames and *β=0.05* for reinforced concrete frames. The experimental values for such parameters vary from -0.3 to 1.2 with a mean value, here considered as *β=0.15* (Cosenza et al., 1993). q-factors are evaluated by taking damage into account by means of the following equivalent ductility:

$$\mu_{P.A.} = D_{P.A.} \cdot \mu_{u,mon} = \mu_S + \beta(\mu_e - 1) \tag{21}$$

where the ductility $\mu_{P.A.}$ depends both on the cinematic μ_s and hysteretic μ_e ductilities. Therefore, $D_{P.A.}$ can be evaluated from $\mu_{P.A.}$ once the monotonic ductility $\mu_{u,mon}$ is established.

From experimenting with different typologies it is possible to relate the damage level to the damage index $D_{P.A.}$ (Table 2) and to the Performance levels (Table 3), as defined in ATC-40. q-factors are here evaluated for defined damage levels expressed in terms of $\mu_{P.A.}$, figs. 14-16 (marked dotted line).

The q-factors thus obtained could be interpolated by the following tri-linear functions $q_{\mu PA}(T, \xi, \mu_{P.A.})$ with the same meaning of equation 9 (continuous thin line in figures 14-16).

Table 2. Structural damage for different Park & Ang index values

DAMAGE LEVEL	$D_{P.A.}$
COLLAPSE	> 1
SEVERE	0.5 – 1.0
MODERATE	0.3 – 0.5
SMALLER	0.1 – 0.3
NO DAMAGE	0 – 0.1

Table 3. Park & Ang index ranges for different structural performance levels

PERFORMANCE LEVEL	$D_{P.A.}$
OPERATIONAL	0 – 0.25
IMMEDIATE OCCUPANCY	0.25 – 0.4
LIFE SAFETY	0.4 – 0.7
STRUCTURAL STABILITY	0.7 - 1

$$q_{\mu_{PA}}(T,\xi,\mu_{PA}) = \begin{cases} \dfrac{q_{\mu_{PA}}(T_0,\xi,\mu_{PA})-1}{T_0}T+1 & T<T_0 \\ \dfrac{q_{\mu_{PA}}(T_1,\xi,\mu_{PA})-q_{\mu_{PA}}(T_0,\xi,\mu_{PA})}{T_1-T_0}(T-T_0)+q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) & T_0<T<T_1 \\ \dfrac{q_{\mu_{PA}}(T_2,\xi,\mu_{PA})-q_{\mu_{PA}}(T_1,\xi,\mu_{PA})}{T_2-T_1}(T-T_1)+q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) & T_1<T<T_2 \end{cases} \tag{22}$$

The values of q-factors for T_0, T_1 and T_2, obtained by minimizing the mean square error between the experimental data and the proposed functions, are represented by equations 23-31.

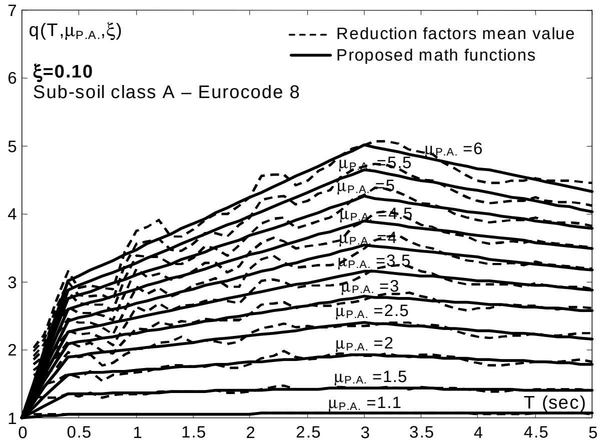

Figure 14. Constant damage q-factors– sub-soil class A – viscous damping 10%

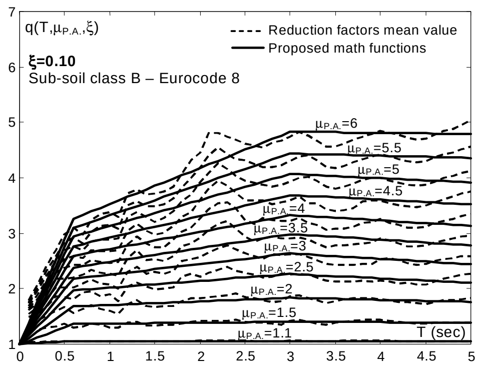

Figure 15. Constant damage q-factors, sub-soil class B – viscous damping 10%

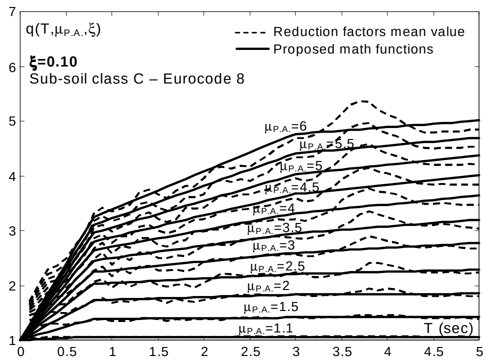

Figure 16. Constant damage q-factors, sub-soil class C – viscous damping 10%

Damage q-factors Sub-soil class A:

$$q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = \left(-\frac{0.0007}{\xi} + 0.036\xi - 0.052\right)\mu_{PA}^{\ 2} + \left(\frac{0.011}{\xi} - 0.38\xi + 0.703\right)\mu_{PA} + \left(-\frac{0.0103}{\xi} + 0.344\xi + 0.349\right) \quad (23)$$

$$q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = \left(-\frac{0.0002}{\xi} + 0.034\xi - 0.031\right)\mu_{PA}^{\ 2} + \left(\frac{0.007}{\xi} - 0.97\xi + 1.051\right)\mu_{PA} + \left(-\frac{0.0068}{\xi} + 0.936\xi - 0.02\right) \quad (24)$$

$$q_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (0.053\,\xi - 0.0383)\ \mu_{PA}^{\ 2} + (-0.519\,\xi + 0.9321)\ \mu_{PA} + (0.466\,\xi + 0.106) \quad (25)$$

Damage q-factors Sub-soil class B:

$$q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0008}{\xi} + 0.031\xi - 0.049)\mu_{PA}^{2} + (-\frac{0.013}{\xi} - 0.505\xi + 0.732)\mu_{PA} + (\frac{0.0138}{\xi} + 0.474\xi + 0.317) \quad (26)$$

$$q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-\frac{0.0003}{\xi} + 0.023\xi - 0.013)\mu_{PA}^{2} + (\frac{0.006}{\xi} - 0.57\xi + 0.853)\mu_{PA} + (-\frac{0.0057}{\xi} + 0.547\xi + 0.16) \quad (27)$$

$$q_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (-0.126\xi + 0.0152)\mu_{PA}^{2} + (\frac{0.003}{\xi} + 0.529\xi + 0.659)\mu_{PA} + (-\frac{0.003}{\xi} - 0.403\xi + 0.326) \quad (28)$$

Damage q-factors Sub-soil class C:

$$q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0008}{\xi} + 0.085\xi - 0.066)\mu_{PA}^{2} + (\frac{0.013}{\xi} - 0.737\xi + 0.846)\mu_{PA} + (-\frac{0.0122}{\xi} + 0.652\xi + 0.22) \quad (29)$$

$$q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-0.023\xi - 0.017)\mu_{PA}^{2} + (\frac{0.007}{\xi} - 0.687\xi + 0.878)\mu_{PA} + (-\frac{0.007}{\xi} + 0.71\xi + 0.139) \quad (30)$$

$$q_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (-0.052\xi - 0.019)\mu_{PA}^{2} + (-0.672\xi + 1.04)\mu_{PA} + (0.724\xi - 0.021) \quad (31)$$

7. CONCLUSIONS

New strength reduction factors directly considering damage, expressed in terms of the Park and Ang index, and a wide range of damping factors have been proposed. The proposed q-factors have been examined by means of non-linear analysis according to the seismic demands described by sub-soil classes A, B and C spectra in EuroCode 8 (ENV 1998-1-1) for rare seismic excitations.

As is known, many q-factors formulations are available in literature according to classical design criteria, the introduction of a “performance” concept and new seismic protection strategies has led to the need for a modern approach to the problem. Therefore, the scope of the present work is to pursue a mathematical formulation of strength reduction factors which are coherent both with the new “design performance philosophy” and the possibility of using extra-structural dissipation devices to assess high structural damping levels.

For a damping level of 5%, the proposed q-factors have a good accord with other author’s proposals and they agree with results from other studies (Miranda E., 1993) which lead to an increase of the seismic demand in high period region.

The direct damage consideration allows for a definition of design spectra according to a required structural performance level within the “Performance Based Seismic Design PBSE” philosophy.

Results can be applied to linearly designed structures which are also equipped with extra-structural damping devices.

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