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REDUCTION FACTORS FOR PERFORMANCE BASED SEISMIC DESIGN OF STRUCTURES WITH SUPPLEMENTAL DAMPERS

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SUMMARY

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.

INTRODUCTION

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 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. Admissible structural damage is closely related to the functions for which the construction is designed. 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).

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

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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, and this does not allow to apply this design philosophy for buildings equipped with supplemental dampers. Therefore, there's an urgent need for simple and reliable design tool for structures equipped with extra-structural dissipation devices.
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. In particular, the following design problem can be defined:

1. *Direct Problem - DP*

   Given the spectral seismic demand, the dissipation device characteristics and the performance level to be achieved, the q-factor can be directly evaluated from equation (3) in the case of design of new buildings;

2. *Inverse Problem - IP*

   In the case of existing buildings, by assessing the ductility and strength capacities, the proposed representation for q-factors leads to the minimum damping factor ξ which allows for the performance level to be achieved;

3. *Mixed Problem – MP*

   For new or existing buildings, a given performance level may be attained by increasing both strength and damping. In this case, equation (3) could be recursively applied to evaluate optimal design parameters according to technological and economical constraints.

Since the third problem is a recursive application of the first two, in the following only the *DI* and the *IP* problems will be discussed by means of practical examples.

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

- $\boldsymbol{I_A}$ (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:

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

- $\boldsymbol{P_D}$ (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:

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

- $\boldsymbol{I_D}$ (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):

$$I_D = \frac{2g}{\pi}\frac{I_A}{PGA \cdot PGV} \qquad (3)$$

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.

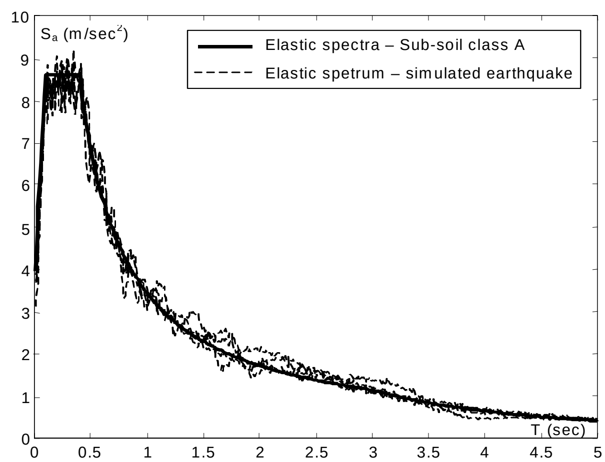

Figure 1. Comparison between sub-soil class A (EC-8) and synthetic earthquake elastic spectra

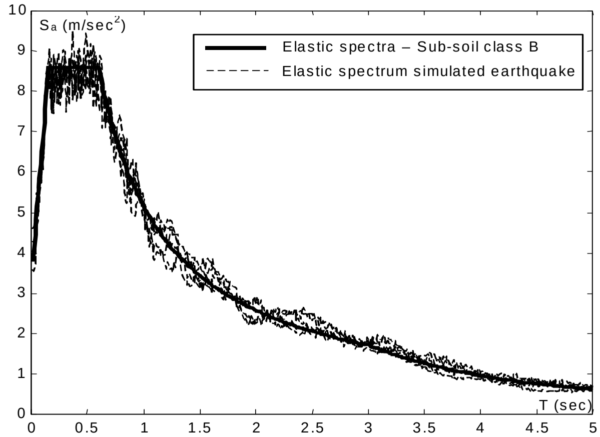

Figure 2. Comparison between sub-soil class B (EC-8) and synthetic earthquake elastic spectra

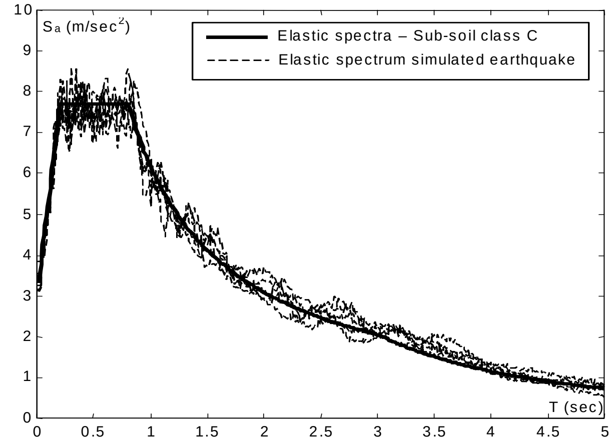

Figure 3. Comparison between sub-soil class B (EC-8) and synthetic earthquake elastic spectra

Table 1. 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**

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_2 represent respectively the transition period between constant velocity and constant acceleration regions for the considered spectra, and the maximum considered period $T_2=5$ *sec.*. q-factor formulae (4) are defined by the values of q corresponding to the periods T_0 and T_2. 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.
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.

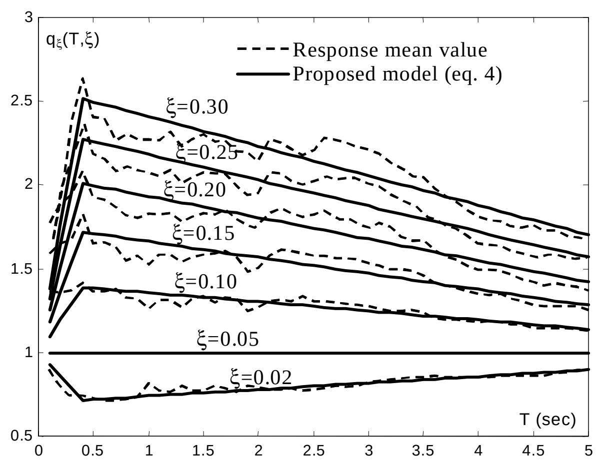

Figure 4. q-factors for no damage performance – sub-soil class A (EC 8)

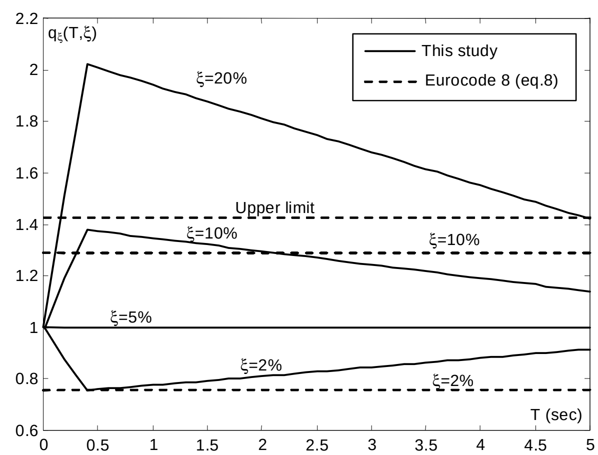

Figure 5. q-factors comparison: this study vs Eurocode 8 – Sub-soil class A

$$\begin{aligned} q_\xi(T_0,\xi) &= -7.6\xi^2+8.7\xi+0.584 \\ q_\xi(T_2,\xi) &= 2.8\xi+0.86 \end{aligned} \quad \text{spectrum sub-soil class A} \quad (5)$$

$$\begin{aligned} q_\xi(T_0,\xi) &= -8.5\xi^2+8.7\xi+0.585 \\ q_\xi(T_2,\xi) &= 2.9\xi+0.85 \end{aligned} \quad \text{spectrum sub-soil class B} \quad (6)$$

$$\begin{aligned} q_\xi(T_0,\xi) &= -7.96\xi^2+8.9\xi+0.574 \\ q_\xi(T_2,\xi) &= 3.82\xi+0.809 \end{aligned} \quad \text{spectrum sub-soil class C} \quad (7)$$

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):

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

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.

STRENGTH q-FACTORS FOR DAMAGE CONTROL

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

$$D_{P.A.} = \frac{x_{\max}}{x_{u,mon}} + \beta \frac{E_H}{F_y x_{u,mon}} = \frac{\mu_S + \beta(\mu_e - 1)}{\mu_{u,mon}} \qquad (9)$$

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 $\beta=0.025$ for steel frames and $\beta=0.05$ for reinforced concrete frames. The experimental values for such parameters vary from -0.3 to 1.2 with a mean value, here considered as $\beta=0.15$ (Cosenza et al., 1993). q-factors are evaluated by taking damage into account by means of the following equivalent ductility:

$$\mu_{P.A.} = D_{P.A.} \cdot \mu_{u,mon} = \mu_S + \beta(\mu_e - 1) \qquad (10)$$

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. 6-8 (marked dotted line).
The q-factors thus obtained could be interpolated by tri-linear functions $q_{\mu PA}(T,\xi,\mu_{P.A.})$ (continuous thin line in figures 6-8), reported in equation 11.

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

$$q_{\mu_{PA}}(T,\xi,\mu_{PA})=\begin{cases}\dfrac{q_{\mu_{PA}}(T_0,\xi,\mu_{PA})-1}{T_0}T+1 & T<T_0\\ \dfrac{q_{\mu_{PA}}(T_1,\xi,\mu_{PA})-q_{\mu_{PA}}(T_0,\xi,\mu_{PA})}{T_1-T_0}(T-T_0)+q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) & T_0<T<T_1\\ \dfrac{q_{\mu_{PA}}(T_2,\xi,\mu_{PA})-q_{\mu_{PA}}(T_1,\xi,\mu_{PA})}{T_2-T_1}(T-T_1)+q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) & T_1<T<T_2\end{cases} \quad (11)$$

where T_1 represent the transition period between the constant velocity and displacement regions for the considered elastic spectra. Formulae (11) 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 12-20 are obtained by minimizing the mean square error.

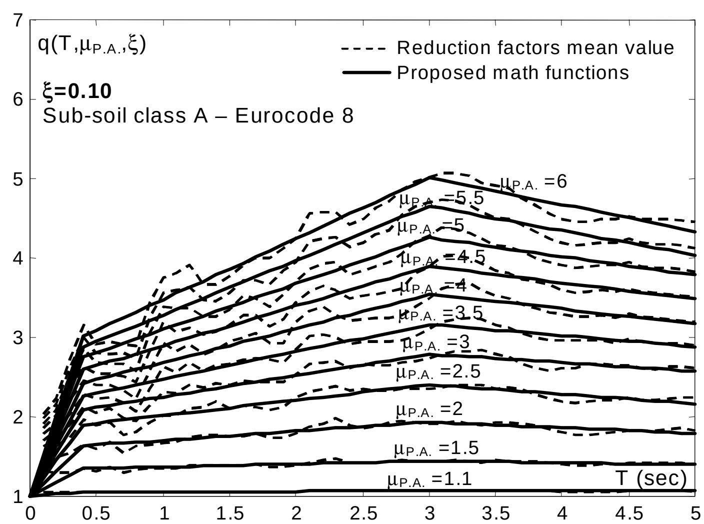

Figure 6. Constant damage q-factors– sub-soil class A – viscous damping 10%

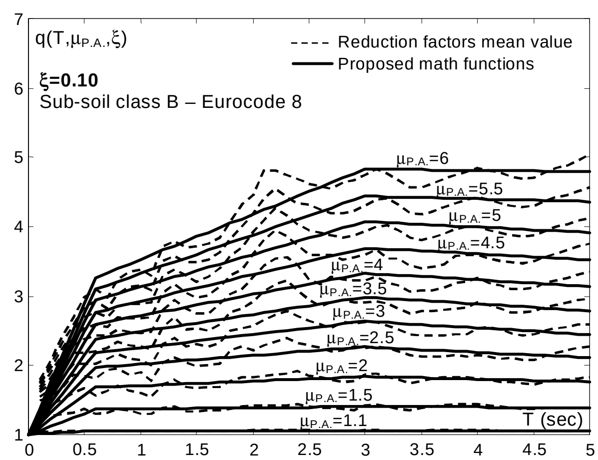

Figure 7. Constant damage q-factors, sub-soil class B – viscous damping 10%

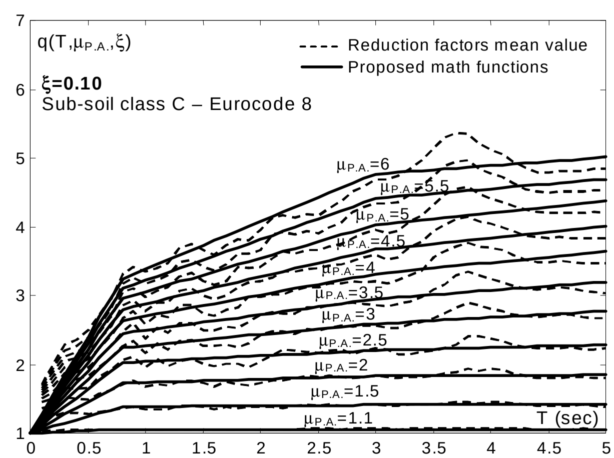

Figure 8. Constant damage q-factors, sub-soil class C – viscous damping 10%

Damage q-factors Sub-soil class A:

$$q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0007}{\xi} + 0.036\xi - 0.052)\mu_{PA}^2 + (\frac{0.011}{\xi} - 0.38\xi + 0.703)\mu_{PA} + (-\frac{0.0103}{\xi} + 0.344\xi + 0.349) \tag{12}$$

$$q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-\frac{0.0002}{\xi} + 0.034\xi - 0.031)\mu_{PA}^2 + (\frac{0.007}{\xi} - 0.97\xi + 1.051)\mu_{PA} + (-\frac{0.0068}{\xi} + 0.936\xi - 0.02) \tag{13}$$

$$q_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (0.053\,\xi - 0.0383)\,\mu_{PA}^2 + (-0.519\,\xi + 0.9321)\,\mu_{PA} + (0.466\,\xi + 0.106) \tag{14}$$

Damage q-factors Sub-soil class B:

$$q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0008}{\xi} + 0.031\xi - 0.049)\mu_{PA}^2 + (-\frac{0.013}{\xi} - 0.505\xi + 0.732)\mu_{PA} + (\frac{0.0138}{\xi} + 0.474\xi + 0.317) \tag{15}$$

$$q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-\frac{0.0003}{\xi} + 0.023\xi - 0.013)\mu_{PA}^2 + (\frac{0.006}{\xi} - 0.57\xi + 0.853)\mu_{PA} + (-\frac{0.0057}{\xi} + 0.547\xi + 0.16) \tag{16}$$

$$q_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (-0.126\xi + 0.0152)\mu_{PA}^2 + (\frac{0.003}{\xi} + 0.529\xi + 0.659)\mu_{PA} + (-\frac{0.003}{\xi} - 0.403\xi + 0.326) \tag{17}$$

Damage q-factors Sub-soil class C:

$$q_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0008}{\xi} + 0.085\xi - 0.066)\mu_{PA}^2 + (\frac{0.013}{\xi} - 0.737\xi + 0.846)\mu_{PA} + (-\frac{0.0122}{\xi} + 0.652\xi + 0.22) \tag{18}$$

$$q_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-0.023\xi - 0.017)\,\mu_{PA}^2 + (\frac{0.007}{\xi} - 0.687\,\xi + 0.878)\,\mu_{PA} + (-\frac{0.007}{\xi} + 0.71\xi + 0.139) \tag{19}$$

$$q_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (-0.052\,\xi - 0.019)\,\mu_{PA}^2 + (-0.672\,\xi + 1.04)\,\mu_{PA} + (0.724\,\xi - 0.021) \tag{20}$$

By considering both the viscous dissipation and the no-linear behavior effects, the overall q-factor can be evaluated as:

$$q(T,\xi,\mu) = q_{\xi}(T,\xi)\cdot q_{\mu_{PA}}(T,\xi,\mu) \tag{21}$$

EXAMPLE OF DIRECT PROBLEM SOLVING

Let us consider a framed structure having monotonic ductility $\mu_{u,mon} = 6$ (enhanced ductility in terms of EC8) and viscous dissipation level $\xi = 5\%$.

In the case of "*Life Safety*" performance requirements for rare events, the admissible damage level in terms of the Park & Ang index should be less than 0.6 from Table 2. Instead, for the "*Operational*" performance level, a maximum damage level of 0.25 is allowed. Therefore, the partial q-factors to be considered should be respectively represented by the curves corresponding to $\mu_{P.A.} = \mu_{u,mon}\cdot 0.5 = 3$ (*Life Safety*) and $\mu_{P.A.} = \mu_{u,mon}\cdot 0.2 = 1.2$ (*Operational*) in figs. 6-8.

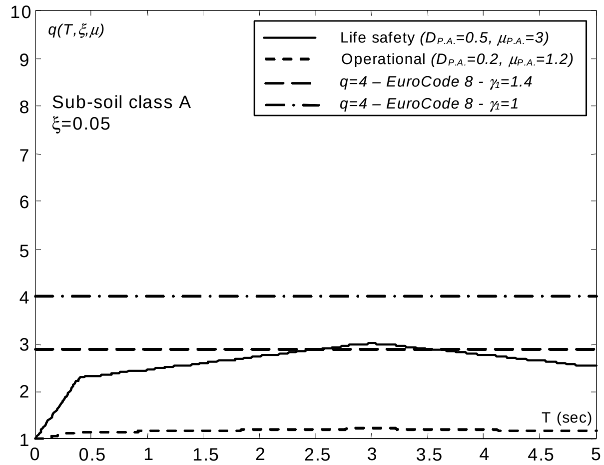

Figure 9. Comparison between proposed q-factors for different performance levels: this study vs EC 8, $\mu_{u,mon}$= 6, ξ= 0.05 Sub-soil class A

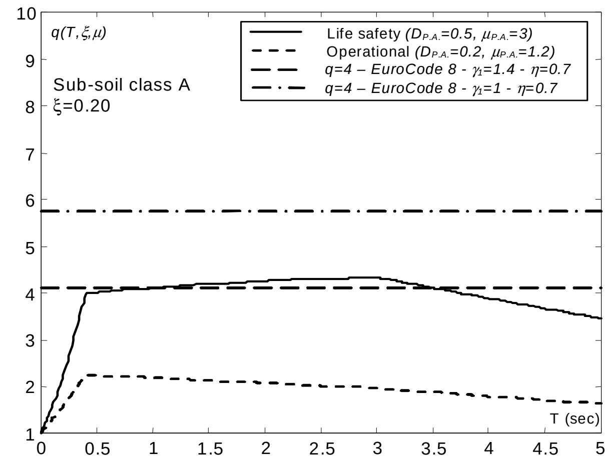

Figure 10. Comparison between proposed q-factors for different performance levels: this study vs EC 8, $\mu_{u,mon}$= 6, ξ= 0.20 Sub-soil class A

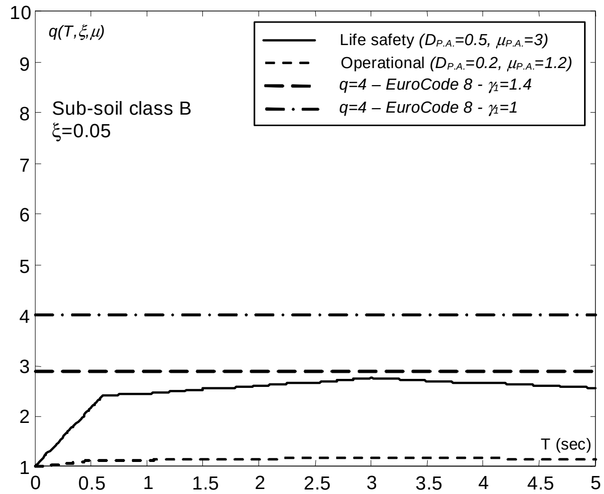

Figure 11. Comparison between proposed q-factors for different performance levels: this study vs EC 8, $\mu_{u,mon}$= 6, ξ= 0.05 Sub-soil class B

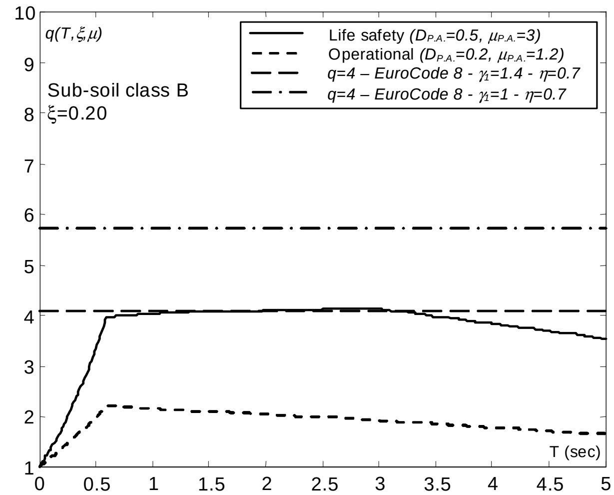

Figure 12. Comparison between proposed q-factors for different performance levels: this study vs EC 8, $\mu_{u,mon}$= 6, ξ= 0.20 Sub-soil class B

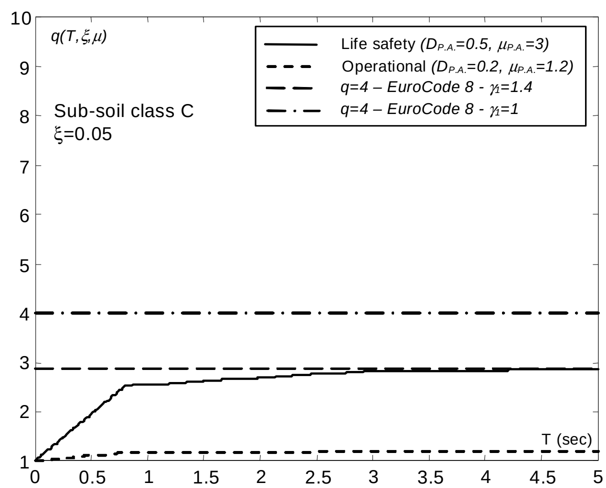

Figure 13. Comparison between proposed q-factors for different performance levels: this study vs EC 8, $\mu_{u,mon}$= 6, ξ= 0.05 Sub-soil class C

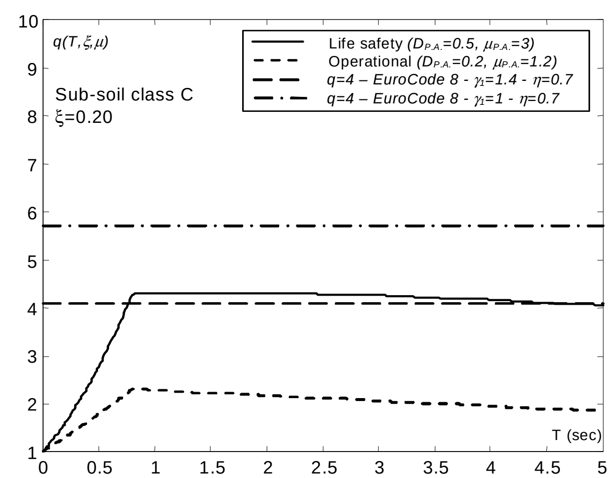

Figure 14. Comparison between proposed q-factors for different performance levels: this study vs EC 8, $\mu_{u,mon}$= 6, ξ= 0.05 Sub-soil class C

Figures 9-10 show the comparison between the proposed q-factors (equation 3) and those proposed by EuroCode 8 (ENV 1998-1-1), for importance factor γ=1 (standard buildings) and γ=1.4 (strategic buildings), respectively in the case without and with extra-structural damping devices capable of an overall damping of 20%. Figures 11-14 show the same comparison for seismic demand expressed by Soil class B and C Spectra.
By comparing the cases with and without extra-structural damping devices, the effectiveness of passive control strategy is established. Moreover, results show that the q-factors proposed by EC8 do not allow for the *Life Safety* and *Operational* performances as requested by PBSE.

EXAMPLE OF INVERSE PROBLEM SOLVING

Let us consider the benchmark structure proposed by (B.F. Spencer, Jr., R.E. Christenson, Y. Ohtori and S.J. Dyke, 2000) (figure 15). The nine-storey building's lateral load-resistant system is a steel perimeter moment-resisting frame. The plane is 45.73 m by 45.73 m wide and the total height is 37.19 m. The bays are 9.15 m at the center in both directions.

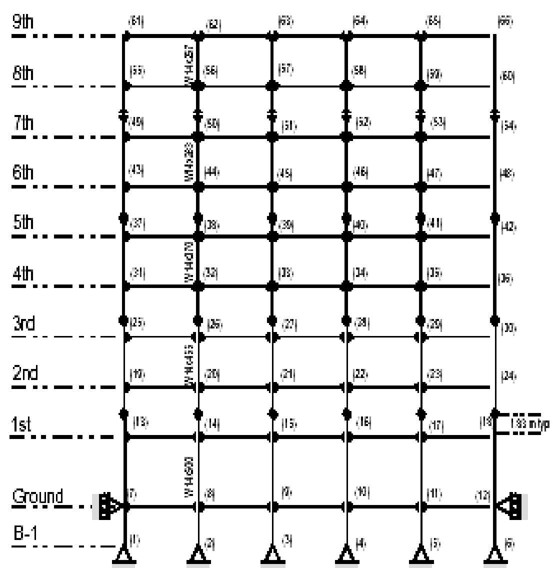

Figure 15. Considered benchmark structure, 9 levels – NS Frame

The seismic mass of the ground level is $9{,}65 \cdot 10^5\,Kg$, for the first level $1{,}01 \cdot 10^6\,Kg$, for the second through eighth levels $9{,}89 \cdot 10^5\,Kg$ and for the roof $1{,}07 \cdot 10^6\,Kg$. The first five natural frequencies are 0.443, 1.18, 2.05, 3.09 e 4.27 Hz.
A monotonic ductility capacity $\mu_{u,mon} = 6$ and damping of 5% are assumed. The ratios between the elastic strength for Soil class A, B and C spectra with $a_{g,\max} = 0{,}35 \cdot g$ and the design strength of the structure are respectively equal to 1.08, 1.62 and 2.00. By comparing these strength ratios with the proposed q-factors for "*Life Safety*" and "*Operational*" performance requirements (table 4), it follows that for Soil class A spectrum "*Operational*" performance is achieved, while for Soil class B and C spectra only "*Life Safety*" performance level is achieved. These conclusions can also be proved by means of non-linear dynamic analyses. Table 5 represents the mean and the standard deviation of the seismic response in terms of Park & Ang damage to the benchmark structure under consideration which was subjected to 60 synthetic

excitations compatible with sub soil classes A, B and C (Palazzo, Petti, De Iuliis, 2003). The results show the effectiveness of the proposed q-factor to foresee seismic performance within the context of PBSE.

Table 4. Comparison between benchmark strength ratio and q-factors required for *Operational* and *Life Safety* performance

	Soil class A	*Soil class B*	*Soil class C*
Benchmark strength ratios	**1.08**	**1.62**	**2.00**
"Operational"	1.19	1.16	1.18
"Life safety"	2.81	2.61	2.72

Table 5. Park & Ang index mean value and standard deviation for 5% viscous damping

Damping ξ=5%	**Sub-soil class A**	**Sub-soil class B**	**Sub-soil class C**
Mean value	**0.2418** *Operational*	**0.3841** *Occupancy*	**0.5018** *Life Safety*
Standard deviation	**0.0211**	**0.0344**	**0.0616**

In the case of retrofit design with extra-structural dissipation devices, the overall damping need to achieve the Operational performance level can be evaluated by looking for the q-factors equal to strength ratios 1.62 and 2.00 which lead to the allowed damage $D_{P.A.}=0.2$ from table 2. In particular, from equation 10, the damage is represented by the following equivalent ductility $\mu_{P.A.} = \mu_{u,mon} \cdot 0.2 = 1.2$. From figures 16-17, the required overall damping for Soil classes B and C is respectively 12.4% and 17.5%.

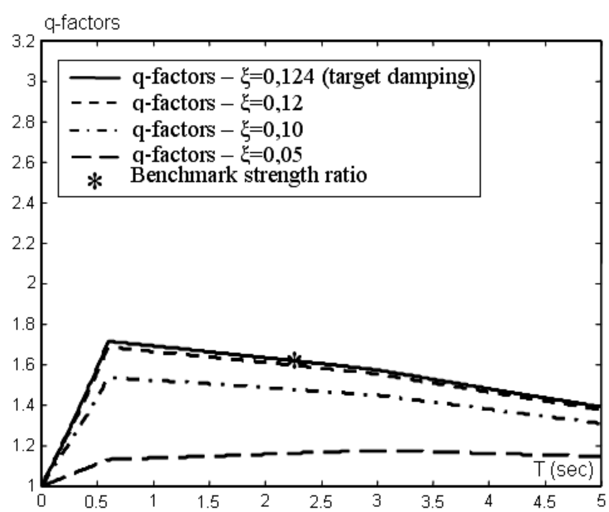

Figure 16. q-factors for different damping amount, soil class B spectrum and "Operational" performance level $\mu_{P.A.} = 1.2$

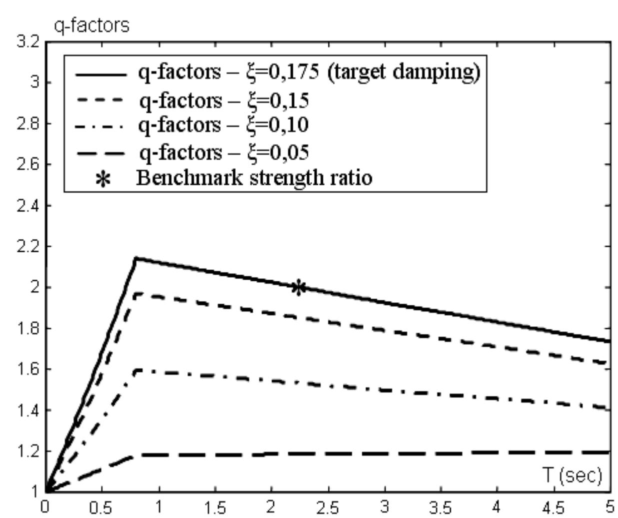

Figure 17. q-factors for different damping amount, soil class C spectrum and "Operational" performance level $\mu_{P.A.} = 1.2$

To achieve the required damping level, the dissipation devices are then placed using an iterative procedure which aims to maximize a performance index representing "overall dissipated power" proposed by (Petti, De Iuliis, 2003), whose results are shown in figures 18-19.

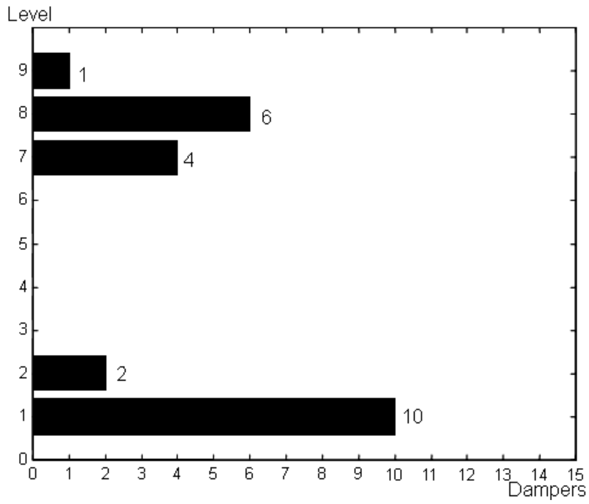

Figure 18. Dampers arrangement - soil class B spectrum (unitary damping characteristics: *c=200000 Kgsec/m*)

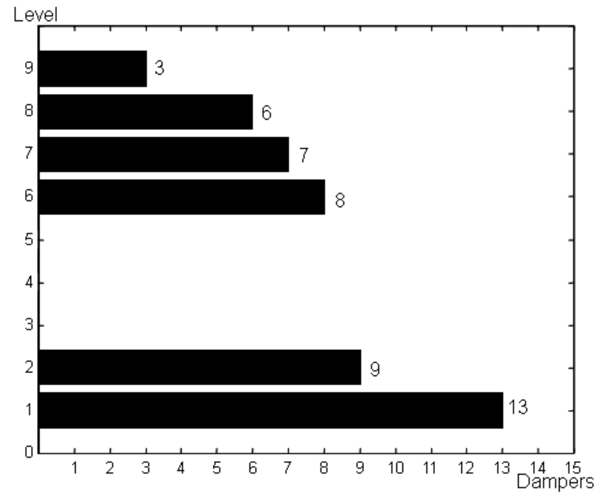

Figure 19. Dampers arrangement - soil class C spectrum (unitary damping characteristics: *c=200000 Kgsec/m*)

In order to evaluate the effectiveness of the proposed design methodology, the non-linear seismic response of the benchmark structure equipped with extra-structural dissipation devices and subjected to the same set of 60 synthetic accelerograms is evaluated. Table 6 represents the mean and the standard deviation of the seismic response in terms of Park&Ang damage. Results show that the designed extra-structural dissipation devices allow for the "Operational" performance level. The low values of the standard deviation show the effectiveness of the design procedure.

Table 6. Park & Ang index mean value and standard deviation for an extra-structural damped structure

Extra-structural damped structure	**Sub-soil class B** ξ **= 0,124**	**Sub-soil class C** ξ **= 0,175**
Mean value	**0.2247** *Operational*	**0.2341** *Operational*
Standard deviation	**0.0198**	**0.0198**

CONCLUSIONS

A new design methodology for structures equipped with extra-structural dissipation devices in accord with Performance Based Seismic Engineering (PBSE) criteria is presented. The proposed design methodology is based on the use of new q-factors which are able to take into account damage levels by means of the Park & Ang index within the sphere of PBSE.

The following three design problems are defined and discussed:

1. *Direct Problem (DP)* to evaluate q-factors to design new structures equipped with extra-structural dissipation devices;
2. *Inverse Problem (IP)* to design extra-structural dissipation devices for existing buildings;
3. *Mixed Problem (MP)* to design extra-structural dissipation devices and strength for both new or existing buildings according to technological and economical constraints.

Results showed the effectiveness of the proposed design procedure and that the q-factors proposed in EC8 do not generally allow for seismic performance as envisaged by PBSE.

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