Strength Reduction Factors for Performance Based Seismic Design

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ABSTRACT: According to Performance Based Seismic Engineering (PBSE) philosophy a design approach based on strength reduction factors is presented here. More specifically, by taking into account structural damage, reduction factor spectra are evaluated for spectra sub-soil classes A, B and C (EC8) and a wide set of ductility parameters and damping factors. Reduction factors spectra are numerically carried out by analysing the dynamic seismic response of non-linear SDOF systems to a set of synthetic excitations by considering the Park and Ang damage index.

1 INTRODUCTION

As we know, the Performance Based Seismic Engineering (PBSE) philosophy implies design, evaluation, and construction of engineered facilities whose performances, under normal and extreme loads, respond to the different needs and objectives of owner-users and society. The application of PBSE philosophy requires, amongst other things, synthetic and reliable damage evaluation for overall systems which are subject to defined seismic excitations. Damage evaluation for a building is a complex task, involving the evaluation of several response parameters. Structural performance is generally evaluated by considering Interstorey Drift Index and/or maximum beam plastic rotation by carrying out a push-over non-linear analysis.

At the present time, 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) format. 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 result in a large scatter in the results. Push-Over Analysis is not lacking in uncertainties and approximations and, moreover, can lead to results which may be sensitive to the way of pushing and the adopted load profile (Albanesi T., Nuti C. & Vanzi I., 2000).

In this context, a classical approach based on the use of reduction factors could be an attractive methodology in the design process since it avoids non-linear analysis.

Numerous results regarding the reduction factors can be found in scientific literature, amongst which, of note are (Newmark & Hall, 1973), (Riddell & Newmark, 1979), (Berrill et. al., 1980), (Miranda, 1993). In these works, the seismic performances of structures are essentially measured through their "ductility". Other studies, such as (Uang & Bertero, 1988), have shown how seismic damage is a function not only of ductility demands but also of other response parameters, and above all, dissipated hysteretic energy.

The present work presents an analytical study aimed at assessing strength reduction factors for different spectra sub-soil classes and for constant structural damage conditions defined by the Park & Ang index (Park YJ & Ang AH-S, 1985). In particular, reduction factor spectra of the elastic response are carried out through a numerical analysis of the elastic-plastic behaviour of SDOF systems subjected to synthetic accelerograms which are compatible with spectra sub-soil classes A, B and C defined by EuroCode 8. From a parametric analysis, carried out over wide intervals spanning the fundamental period of vibration, the available monotonic ductility and the level of viscous dissipation, formulas are explicitly assessed to define the reduction factors to be adopted for structural design within the philosophy of PBSE. The reduction factor spectra thus defined are compared to those of EC8.

2 SEISMIC ACCELEROGRAMS CHARACTERIZATION

In order to assess strength reduction factors of pseudo-acceleration elastic spectra to design structures with elastic-plastic behaviour and equipped with viscous-elastic dissipation devices, simulated seismograms were generated that were compatible with the spectrum defined in EC8. More specifically, through the use of the SIMQKE programme [Vanmarcke E.H., Cornell C.A., Gasparini D.A., & Hou S.N., 1976], 60 seismic excitations, compatible with elastic spectrum defined by the maximum expected event with a return period of T=475 years, for sub-soils Type A, B and C (Fig. 1-4), were generated.

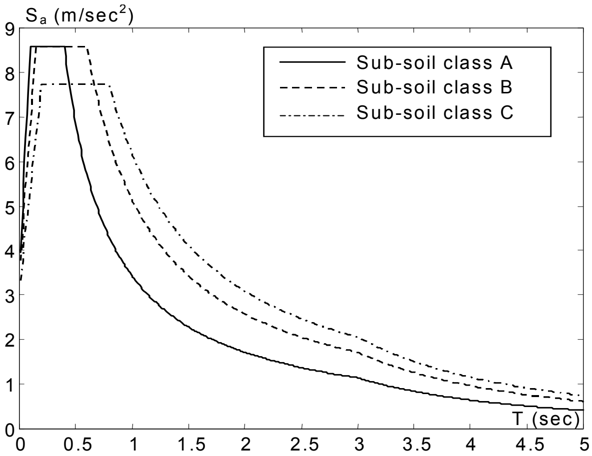

Figure 1: Elastic response spectrum for the maximum expected seismic event, return period 475 years (EC 8).

The generated seismic events lasted for 60 secs. and the maximum accelerations were attained in a time window with a width of 10 secs. The elastic spectra associated with each seismogram presents, within the interval of the considered period (0.1-5 sec.), a deviation of 10% in comparison with the reference spectra, figures 2-4.

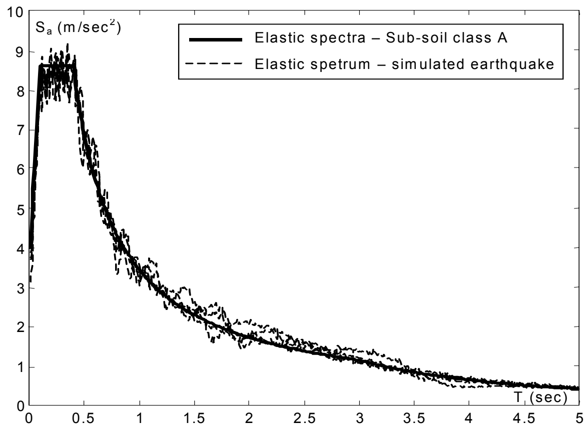

Figure 2: Comparison between the sub-soil class A (EC-8) and simulated earthquakes elastic spectrum

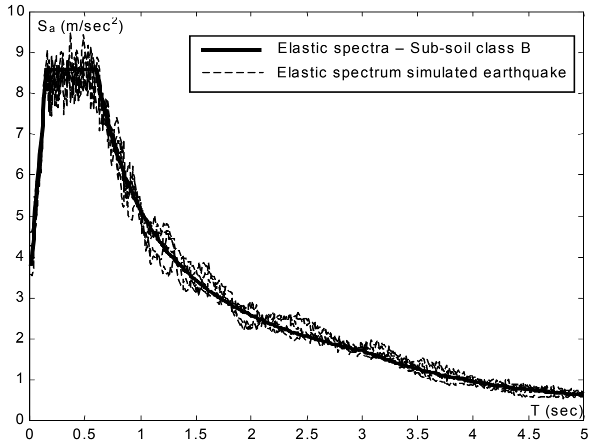

Figure 3: Comparison between the sub-soil class B (EC-8) and simulated earthquakes elastic spectrum

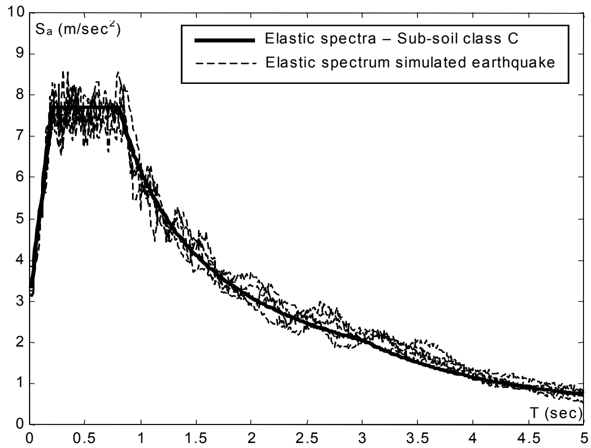

Figure 4: Comparison between the sub-soil class C (EC-8) and simulated earthquakes elastic spectrum

Table 1 shows the comparison between the simulated excitations and real seismic events by means of several hazard 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 be thus rendered by :

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

- ***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 the average number of the 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):

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

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 – 286°	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
Mean simulated event	**Type A sub-soil**	**343.35**	**641.27**	**5.90**	**44.47**
Mean simulated event	**Type B sub-soil**	**343.35**	**734.48**	**5.33**	**28.81**
Mean simulated event	**Type C sub-soil**	**343.35**	**805.61**	**7.49**	**30.06**

It may be seen that, as far as the Cosenza-Manfredi index is concerned, the simulated accelerograms show values which are similar to those typical of destructive events (Chile 1985, Mexico City 1985, Campano-Lucano 1980). The Arias index reaches the maximum values relative to real excitations. However, the values obtained through Saragoni's factor seem closer to the average of those evaluated for actual seismic events. Therefore, since this study aims to estimate reduction factors by comparing the inelastic and the elastic response to simple oscillators subjected to the same excitations, the simulated accelerograms seem to be significant for the numerical experimentation to be undertaken.

3 STRENGTH REDUCTION FACTORS FOR ELASTIC DAMPED SPECTRA

By using these simulated accelerograms the response of single degree of freedom (SDOF) with linear behaviour is investigated for a wide value span for period of vibration T of the elastic system and viscous damping ξ:

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

To achieve this, a procedure was defined and executed with SIMULINK-MATLAB code, which is able to assess, for each case, the maximum displacement, the ductility demand, the absolute maximum acceleration, the input energy and the rate of dissipated hysteretic and viscous energy.

For any assigned system, the strength reduction factors are defined by the ratio between the elastic strength and the minimum one for ductility cases to overcome the considered seismic event.

The results have pointed toward the possibility of modelling the values of such factors through the following bilinear function:

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

where T_0, T_1 represent respectively the transition period between constant velocity and acceleration zones, for the considered spectra, and maximum period considered (T_1=5 sec.). Reduction factor spectra (4) are defined by *RF* values corresponding to the periods T_0 e T_1 on varying the viscous damping. Therefore, by minimizing the mean square error between the experimental data and appropriate quadratic functions in the variable ξ, the experimental formulas 5-7 were found. Figure 5, for example, represents the reduction factor spectra in the case of Type A spectra on varying the damping.

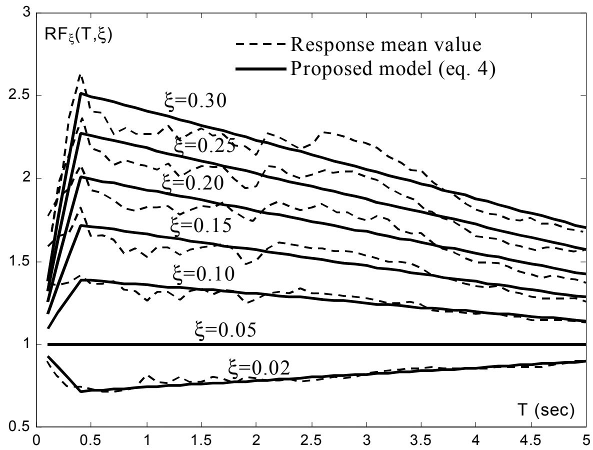

Figure 5: Reduction factor spectra for different viscous damping levels – sub-soil class A (EC 8)

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

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

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

Figure 6 shows, in the specific case of Type A spectra, the comparison between the reduction factors obtained by the equations 5-7 and those assessed through the following formula proposed by EuroCode 8:

$$FR_\xi = 1/\eta \ \text{con} \ \eta = \sqrt{\frac{10}{5+\xi}} > 0.55 \quad (8)$$

From the figure 6 it can be observed how the reduction values assessed in this study are quite noticeably different from those defined by (8), in particular for low and high periods.

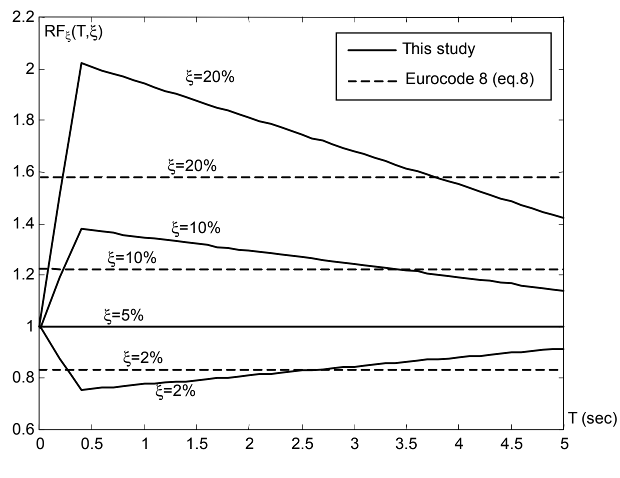

Figure 6: Reduction factors for different viscous damping levels: this study vs Eurocode 8 – Sub-soil class A

4 STRENGTH REDUCTION FACTORS FOR INELASTIC DAMPED SPECTRA

In the case of perfect elastic-plastic behaviour, the same set of structures is analysed for different strength R and monotonic ductility $\mu_{u,mon}$:

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

Figure 7 shows the strength reduction factors assessed for simulated excitations for Type A spectra, in the case of viscous damping ξ=10% and monotonic ductility μ_{mon}=4.

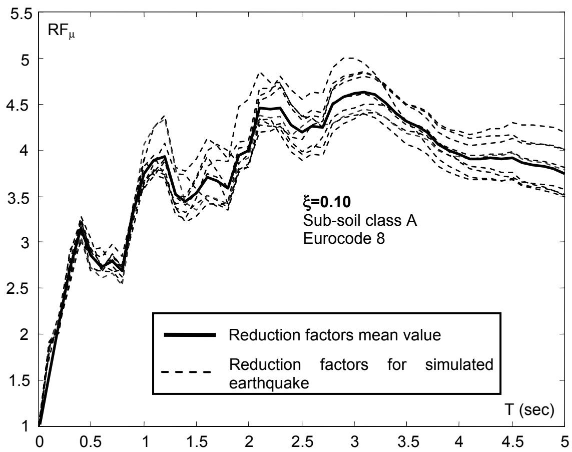

Figure 7: Reduction factor spectra for monotonic ductility, μ_{mon}=4

Figures 8-10 show the average value of the inelastic reduction factors RF (dotted line) on varying the ductility demand and with 10% damping. The same figure shows functions $RF(T,\xi)$ which interpolate the calculated values (continuous line). The aforementioned functions are defined by :

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

where T_0, T_1 represent respectively the transition period between the constant velocity and acceleration zones and between the constant velocity and displacement zones for the considered elastic spectra. $T_2 = 5\,\text{sec}$ represents the maximum value of the considered periods.

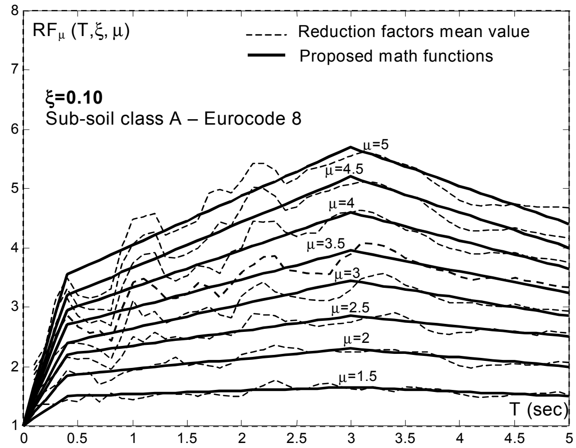

Figure 8: Inelastic reduction factor spectra – sub-soil class A – viscous damping 10%

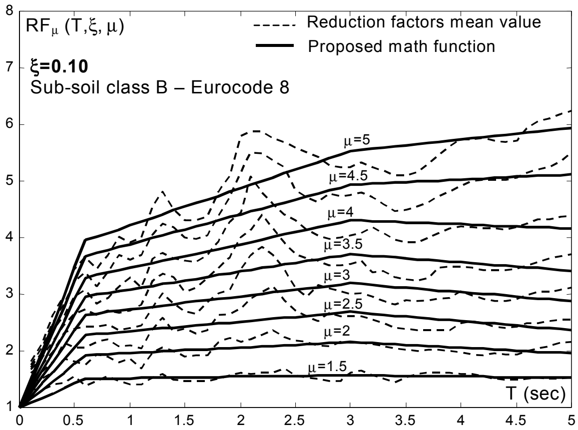

Figure 9: Inelastic reduction factor spectra – sub-soil class B – viscous damping 10%

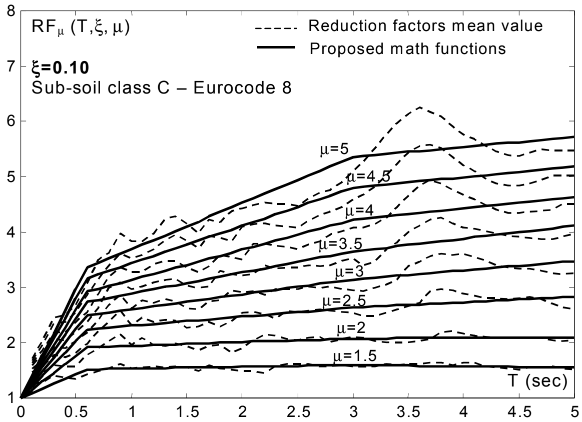

Figure 10: Inelastic reduction factor spectra – sub-soil class C – viscous damping 10%

Formulas (9) are defined by knowledge of the reduction factors corresponding to periods T_0, T_1 and T_2. Therefore, by taking into account quadratic functions for the ductility demand variable and linear-hyperbolic damping one, by the minimisation of mean square error between the experimental data and the proposed functions, the relationships 10-18 are obtained.

Spectrum Type A:

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

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

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

Spectrum Type B:

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

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

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

Spectrum Type C:

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

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

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

Figure 11 shows the percentage error between the proposed formulas (10-18) and the average of the experimental data for ξ=10% in the case of Type A spectra. It can be seen that the maximum error is in the order of 10%. The maximum error for the other examined cases is identical.

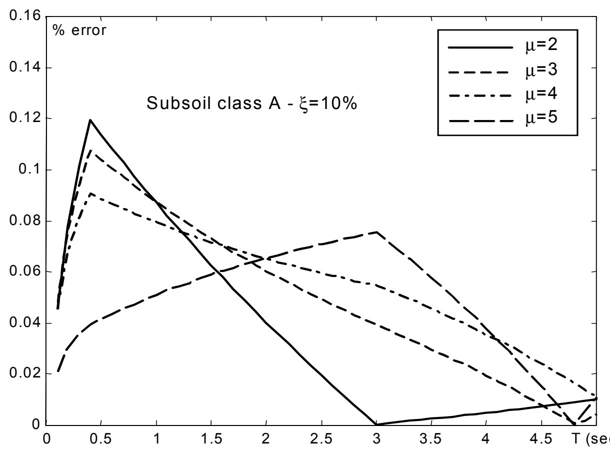

Figure 11: Percentage of error committed through the proposed mathematical model – sub-soil class A

Figures 12–14 show the comparison between the reduction factor spectra assessed in this way and those proposed by other authors (Miranda 1993, Y.H. Chai et al. 1998, W.D. Zhuo 2000, EuroCode 8 1996, X. Zhu 2001) for a damping level of 5% and for ductility demand levels equal to 2, 4 and 6.

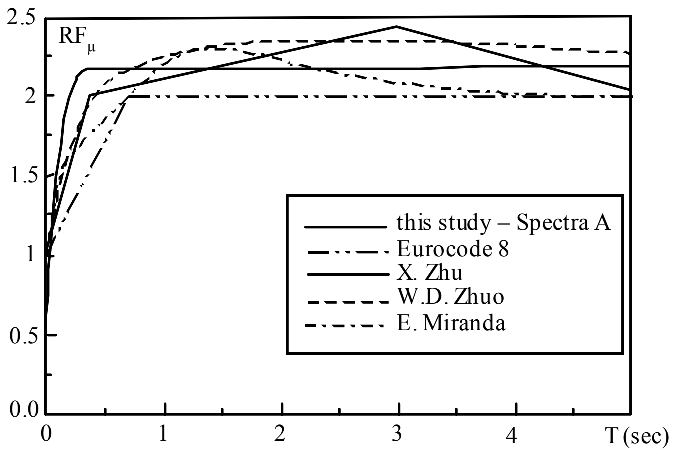

Figure 12: Comparison between the proposed reduction factor spectra and the ones evaluated by other authors - $\mu = 2$ - $\xi = 0.05$.

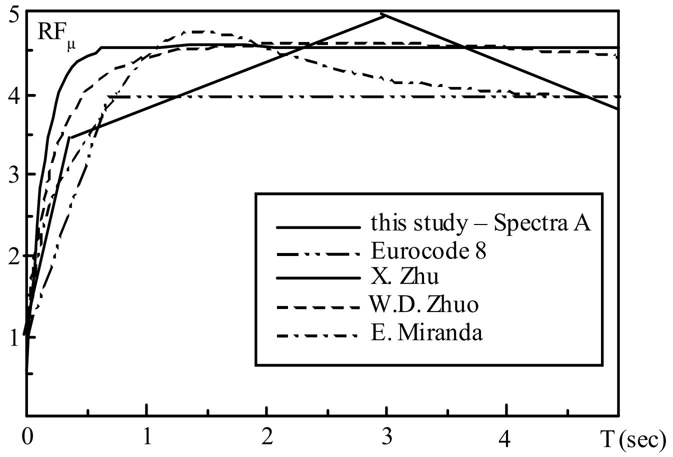

Figure 13: Comparison between the proposed reduction factor spectra and the ones evaluated by other authors - $\mu = 4$ - $\xi = 0.05$.

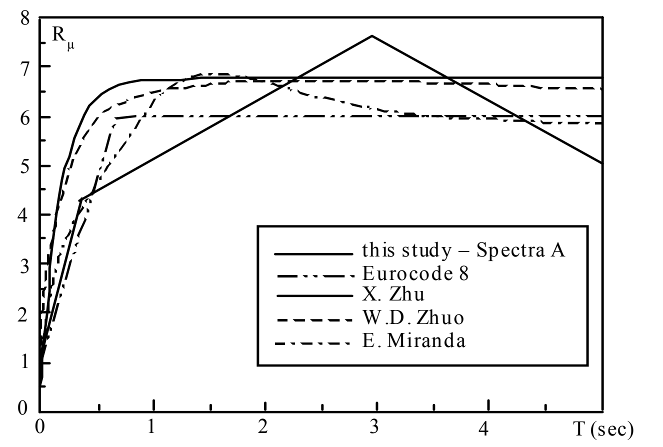

Figure 14: Comparison between the proposed reduction factor spectra and the ones evaluated by other authors - $\mu = 6$ - $\xi = 0.05$.

From an analysis of the figures it evolves quite clearly how, particularly for high levels of ductility demand, the proposed reduction factors are more cautious for low and high periods whilst in the interval of 2-3 second periods, they are less cautious. It can be seen that the reduction factor values obtained in high periods agree with results from other studies [Miranda E., 1993].
Finally it can be observed that in the case of structures with elastic-plastic behaviour and viscous damping doesn't equal 5%, the reduction factor spectrum is given by the product:

$$RF(T,\xi,\mu) = RF_{\xi}(T,\xi) \cdot RF_{\mu}(T,\xi,\mu) \qquad (19)$$

5 STRENGTH REDUCTION FACTORS FOR DAMAGE SPECTRA

As noted, seismic damage to built structures is, amongst other things, a function of ductility demand and hysteretic energy. To these parameters the following damage indexes may be respectively associated:

$$D_{\mu} = \frac{\mu - 1}{\mu_{u,mon} - 1} \qquad (20)$$

$$D_{E} = \frac{\mu_e - 1}{\mu_{e,u,mon} - 1} \qquad (21)$$

where $\mu_{u,mon}$ and $\mu_{e,u,mon}$ are used for effective and hysteretic ductility in correspondence to the ultimate limit state for monotonic load. A damage index which considers both criteria is from Park and Ang (Park YJ & Ang AH-S, 1985), defined by :

$$D_{P.A.} = \frac{x_{\max}}{x_{u,mon}} + \beta \frac{E_H}{F_y x_{u,mon}} = \frac{\mu_S + \beta(\mu_e - 1)}{\mu_{u,mon}} \qquad (22)$$

Formula (22) defines a sort of equivalent ductility which takes into account both the ductility demand $\mu_S = x_{\max} / x_y$, and the hysteretic ductility $\mu_e = 1 + [E_H / (F_y x_y)]$. On the basis of such an approach, the unitary value of the damage function is not attained when the ductility demand reaches the value of the monotonic ductility, but for lower values in consideration of damage associated with hysteretic energy by means of μ_e. The value of index $D_{P.A.}$ is always greater than D_{μ}, and generally lower than D_E.
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.

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 values for different structural performance levels

PERFORMANCE LEVEL	$D_{P.A.}$
OPERATIONAL	0.2
IMMEDIATE OCCUPANCY	0.3
LIFE SAFETY	0.5
STRUCTURAL STABILITY	0.8

In the present study the damage reduction spectra are assessed on equivalent ductility defined through equation (23).

$$\mu_{P.A.} = D_{P.A.} \cdot \mu_{u,mon} = \mu_S + \beta(\mu_e - 1) \qquad (23)$$

Ductility $\mu_{P.A.}$ is bound to index $D_{P.A.}$ of Park and Ang (Park, Ang & Weng, 1987) through the monotonic ductility of the structure and is shown to be both a function of ductility demand in terms of displacement μ_s and in terms of hysteretic energy μ_e. Also established is $\beta = 0.15$ (Cosenza et al., 1993). Noting ductility $\mu_{P.A.}$ there is immediate assessment by index $D_{P.A.}$ of Park & Ang, once the monotonic ductility $\mu_{u,mon}$ of the considered structure is fixed.

In order to define the inelastic spectrum for the same set of examined structures under consideration, reduction factors have been assessed for assigned levels of damage expressed in terms of $\mu_{P.A.}$ (eq. 23), figs. 15-17 (marked dotted line). The reduction factors thus obtained are interpolated by the trilinear functions $RF(T,\xi)$ (continuous thin line) :

$$RF_{\mu_{PA}}(T,\xi,\mu_{PA}) = \begin{cases} \dfrac{RF_{\mu_{PA}}(T_0,\xi,\mu_{PA})-1}{T_0}T+1 & T<T_0 \\ \dfrac{RF_{\mu_{PA}}(T_1,\xi,\mu_{PA})-RF_{\mu_{PA}}(T_0,\xi,\mu_{PA})}{T_1-T_0}T+RF_{\mu_{PA}}(T_0,\xi,\mu_{PA}) & T_0<T<T_1 \\ \dfrac{RF_{\mu_{PA}}(T_2,\xi,\mu_{PA})-RF_{\mu_{PA}}(T_1,\xi,\mu_{PA})}{T_2-T_1}T+RF_{\mu_{PA}}(T_1,\xi,\mu_{PA}) & T_1<T<T_2 \end{cases} \qquad (24)$$

where T_0, T_1 and T_2 are analogous to those described in equation (9).

For these functions, the values assumed by the reduction factors in correspondence to periods T_0, T_1 and T_2 are represented by functions 25-33. These values are obtained by minimising the mean square error between the experimental data and the proposed functions.

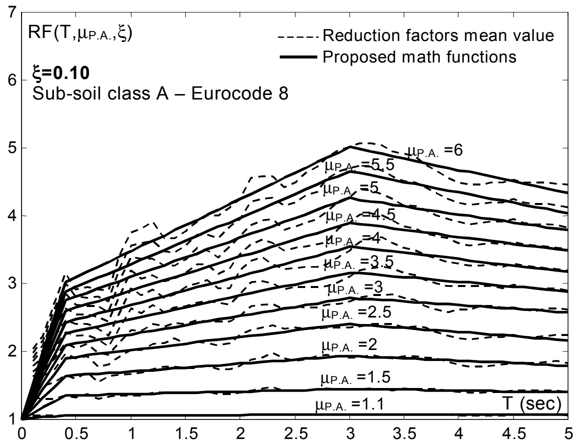

Figure 15: Constant damage reduction factor spectra – sub-soil class A – viscous damping 10%

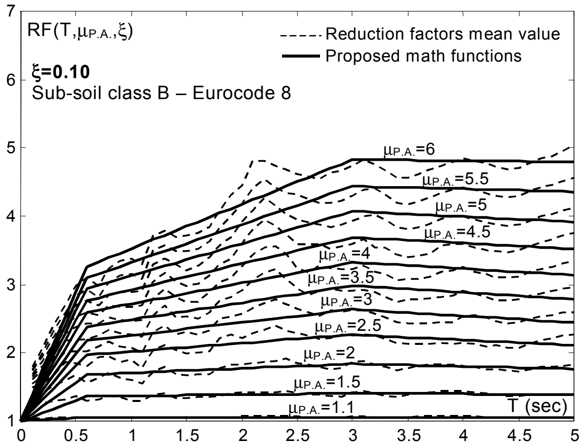

Figure 16: Constant damage reduction factor spectra – sub-soil class B – viscous damping 10%

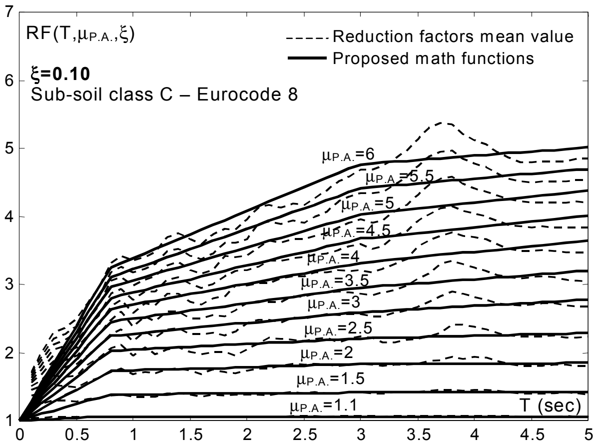

Figure 17: Constant damage reduction factor spectra – sub-soil class C – viscous damping 10%

Spectrum Type A:

$$RF_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0007}{\xi} + 0.036\xi - 0.052)\mu_{PA}^{\ 2} + (\frac{0.011}{\xi} - 0.38\xi + 0.703)\mu_{PA} + (-\frac{0.0103}{\xi} + 0.344\xi + 0.349) \qquad (25)$$

$$RF_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-\frac{0.0002}{\xi} + 0.034\xi - 0.031)\mu_{PA}^{\ 2} + (\frac{0.007}{\xi} - 0.97\xi + 1.051)\mu_{PA} + (-\frac{0.0068}{\xi} + 0.936\xi - 0.02) \qquad (26)$$

$$RF_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (0.053\,\xi - 0.0383)\,\mu_{PA}^{\,2} + (-0.519\,\xi + 0.9321)\,\mu_{PA} + (0.466\,\xi + 0.106) \quad (27)$$

Spectrum Type B:

$$RF_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0008}{\xi} + 0.031\xi - 0.049)\mu_{PA}^{\,2} + (-\frac{0.013}{\xi} - 0.505\xi + 0.732)\mu_{PA} + (\frac{0.0138}{\xi} + 0.474\xi + 0.317) \quad (28)$$

$$RF_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-\frac{0.0003}{\xi} + 0.023\xi - 0.013)\mu_{PA}^{\,2} + (\frac{0.006}{\xi} - 0.57\xi + 0.853)\mu_{PA} + (-\frac{0.0057}{\xi} + 0.547\xi + 0.16) \quad (29)$$

$$RF_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (-0.126\xi + 0.0152)\mu_{PA}^{\,2} + (\frac{0.003}{\xi} + 0.529\xi + 0.659)\mu_{PA} + (-\frac{0.003}{\xi} - 0.403\xi + 0.326) \quad (30)$$

Spectrum Type C:

$$RF_{\mu_{PA}}(T_0,\xi,\mu_{PA}) = (-\frac{0.0008}{\xi} + 0.085\xi - 0.066)\mu_{PA}^{\,2} + (\frac{0.013}{\xi} - 0.737\xi + 0.846)\mu_{PA} + (-\frac{0.0122}{\xi} + 0.652\xi + 0.22) \quad (31)$$

$$RF_{\mu_{PA}}(T_1,\xi,\mu_{PA}) = (-0.023\,\xi - 0.017)\,\mu_{PA}^{\,2} + (\frac{0.007}{\xi} - 0.687\,\xi + 0.878)\,\mu_{PA} + (-\frac{0.007}{\xi} + 0.71\xi + 0.139) \quad (32)$$

$$RF_{\mu_{PA}}(T_2,\xi,\mu_{PA}) = (-0.052\,\xi - 0.019)\,\mu_{PA}^{\,2} + (-0.672\,\xi + 1.04)\,\mu_{PA} + (0.724\,\xi - 0.021) \quad (33)$$

In this case too, the reduction factors for structures with elastic-plastic behaviour and viscous damping different than 5% are assessed through expression (19).

6 USE OF REDUCTION FACTORS IN THE WITHIN OF "*PBE*"

The introduction of an explicit measurement of damage within the definition of strength reduction factors allows for a defining of design spectra for assigned structural performance levels. It would be particularly useful to define a simplified integrated design methodology within "Performance Based Seismic Design PBSE".

If a steel-framed structure is considered, in which the objective of "Life Safety" performance is required for events defined by a return period of T=475 years, from Table 3, maximum damage expressed in terms of index $D_{P.A.}$ equal to 0.5 would be admissible. For the same structure, with strategic territorial functions, the performance objective would be "Operational", which corresponds to damage index $D_{P.A.}$ equal to 0.2.

Figures 18 – 19 show the comparison between the reduction factor spectra for considered performance levels, taking into account the monotonic ductility (eq. 9) and those proposed by EuroCode 8 for a regular frame system with "enhanced ductility", in the hypothesis of spectra of Type A, available monotonic ductility $\mu_{u,mon}$= 6 and considering two levels of viscous damping equal to 5% and 20%.

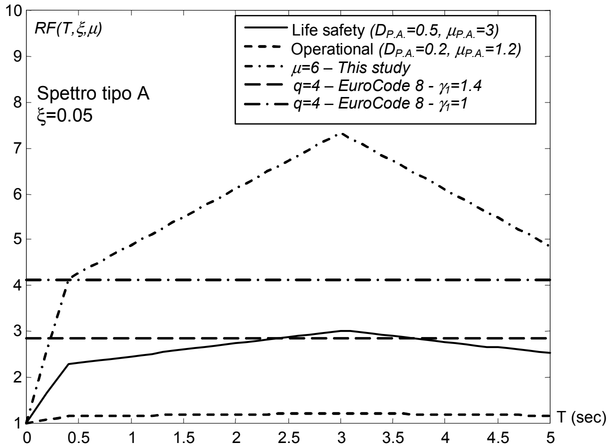

Figure 18: Comparison between proposed reduction factor spectra for different performance level and the ones suggested by EuroCode 8, $\mu_{u,mon}$= 6 and **ξ= 0.05**

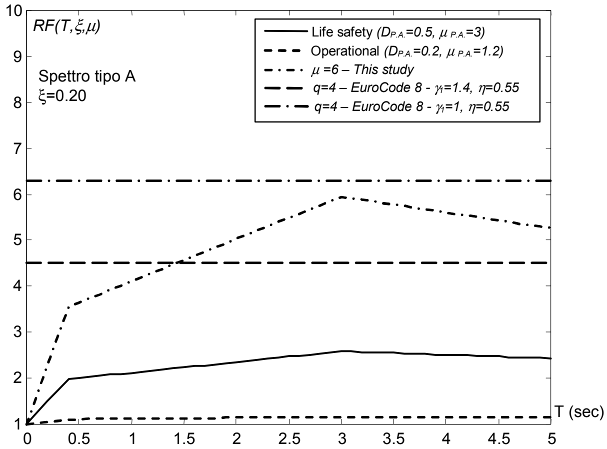

Figure 19: Comparison between proposed reduction factor spectra for different performance levels and the ones suggested by Eurocode 8, $\mu_{u,mon}$= 6 and **ξ= 0.20**

From these figures it emerges that strength reduction factors proposed by EuroCode 8 may be inadequate in attaining suitable performance levels in the case of seismic events with high return periods. In particular, comparing the strength reduction spectra related to the "Life safety" and "Operational" performance levels respectively with the EuroCode 8 ones for importance factor equal to 1.0 and 1.4, a remarkable difference can be observed: for 5% and 20% damping the divergence is respectively about 1.5 and 3 in terms of ratio. Moreover, it can be observed that the possibility of increasing viscous dissipation by means of extra-structural devices, leading to higher values of reduction factors, enables more efficient control to be attained for pre-assigned seismic performance.

7 CONCLUSION

The present study has put forward the preliminary results of broad numerical experimentation aimed at

assessing strength reduction factor spectra for seismic design code to take into account pre-assigned performance within the philosophy of PBSE.
The proposed reduction factors, for which an analytical formulation has been given, are based on explicit assessment of damage levels expressed by the Park & Ang index and allow for the design of structures even in the presence of high viscous damping for the case of structures equipped with extra-structural damping devices.
The proposed formulas show how the reduction factors to be adopted, when there is a need to ensure definite and explicit performance levels, may be noticeably lower than those defined by EC8.

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