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Soil structure interaction effects on strength reduction factors

Müberra Eser*, Cem Aydemir and İbrahim Ekiz

Department of Civil Engineering, Yıldız Technical University, Istanbul, Turkey

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Abstract. In this study, strength reduction factors are investigated for SDOF systems with period range of 0.1-3.0 s with elastoplastic behavior considering soil structure interaction for 64 different earthquake motions recorded on different site conditions such as rock, stiff soil, soft soil and very soft soil. Soil structure interacting systems are modeled and analyzed with effective period, effective damping and effective ductility values differing from fixed-base case. For inelastic time history analyses, Newmark method for step by step time integration was adapted in an in-house computer program. Results are compared with those calculated for fixed-base case. A new equation is proposed for strength reduction factor of interacting system as a function of structural period of system (T), ductility ratio (μ) and period lengthening ratio ($\tilde{T}/T$). It is concluded that soil structure interaction reduces the strength reduction factors for soft soils, therefore, using the fixed-base strength reduction factors for interacting systems lead to non-conservative design forces.

Keywords: soil-structure interaction; strength reduction factors; ductility demand; structural analysis

1. Introduction

Current seismic provisions allow nonlinear response of building structures in the event of strong ground motions due to economic factors. As a matter of such a design approach, the strength reduction factor (R_μ) which is the ratio of elastic base shear to the one required for a target ductility level are used in seismic design codes.

Strength reduction factors have been the topic of several investigations so far. The first well-known studies on the strength reduction factors were conducted by Veletsos and Newmark (1960), Newmark and Hall (1973). They proposed formulas for strength reduction factors as functions of structural period and displacement ductility to be used in the short-, medium- and long period regions. Alternative formulas were proposed by Lai and Biggs (1980), Riddell *et al.* (1989). Riddell and Newmark proposed new formulas for strength reduction factors considering the effect of stiffness degrading on strength reduction factors. Similarly to the previous study by Newmark, these formulas depend on structural period and displacement ductility but also on the damping ratio, β, (Riddell and Newmark 1979). The effect of stiffness degrading was also studied by Vidic *et al.* (1992). The effect of different hysteretic models on strength reduction factors was studied by Lee *et al.* (1999). The first study that considered the effects of soil conditions on the strength reduction

*Corresponding author, Ph.D., E-mail: meser@yildiz.edu.tr

factors was conducted by Elghadamsi and Mohraz (1987). Strength reduction factors were computed using the ground motions recorded on rock and alluvium. Another study which considered the site effects on the strength reduction factors was conducted by Nassar and Krawinkler, also considering the effects of yield level, strain hardening ratio and the type of inelastic material behavior (Nassar and Krawinkler 1991). More recently, Miranda (1993) studied the influence of local site conditions on strength reduction factors, using a group of 124 ground motions classified into three groups as; ground motions recorded on rock, alluvium and very soft soil. Afterwards, mean strength reduction factors were computed for each soil group. As a consequence of site effects, the formulas for strength reduction factors on soft soil depend on the ratio of structural period to predominant period of ground motion whereas strength reduction factors on rock and alluvium depend on the structural period. During last decade, soil-structure interaction effects on strength reduction factors have been the topic of some investigations. Aviles and Perez-Rocha studied on strength reduction factors using the great 1985 Michoacan earthquake recorded at one site representative of the lakebed zone in Mexico City (2005). Also Ghannad *et al.* (2007) studied on strength reduction factors for two different aspect ratios (h/r = 1, 3) two values of non-dimensional frequency ($a_0 = 1, 3$) and three levels of nonlinearity ($\mu = 2, 4, 6$). The effect of soil-structure interaction on inelastic displacement ratio of structures has been studied by Eser and Aydemir (2011). They proposed a new equation for inelastic displacement ratio of interacting system, as a function of structural period of interacting system, strength reduction factor and period lengthening ratio. Besides, the effects of topographical and geotechnical irregularities on the dynamic response of the 2-D soil-structure systems under ground motion have been investigated by Duzgun and Budak (2011). Also there are the effects of topographical and geotechnical irregularities on the dynamic response of the 2-D soil-structure systems under ground motion by coupling finite and infinite elements.Also some other researches on earthquake induced behavior of structures considering soil structure interaction phenomenon (Sarkani *et al*. 1999, Doo and Yun 2003).

In the present study, strength reduction factors are investigated for SDOF systems with period range of 0.1-3.0 s with elastoplastic behavior for five different aspect ratios ($h/r = 1, 2, 3, 4, 5$) and five levels of ductility ($\mu = 2, 3, 4, 5, 6$) considering soil structure interaction. Aspect ratio is defined as the ratio of height to foundation radius of system whereas the strength reduction factor used in seismic design codes is the ratio of elastic base shear to the one required for a target ductility level. 64 ground motions recorded on different site conditions such as rock, stiff soil, soft soil and very soft soil are used for the analyses. Results are compared with those calculated for fixed-base case.

2. Description of soil-structure model

An elastoplastic SDOF system represented with mass, m, height, h is used to model the structure as shown in Fig. 1. The SDOF system may be viewed as representative of more complex multistory buildings that respond as a single oscillator in their fixed-base condition. In this case, the parameters m and h denote the effective mass and effective height, respectively.

Natural period and damping ratio for a system in elastic case are given by

$$T = 2\pi(m/k)^{0.5} \tag{1}$$

$$\beta = c/2(km)^{0.5} \tag{2}$$

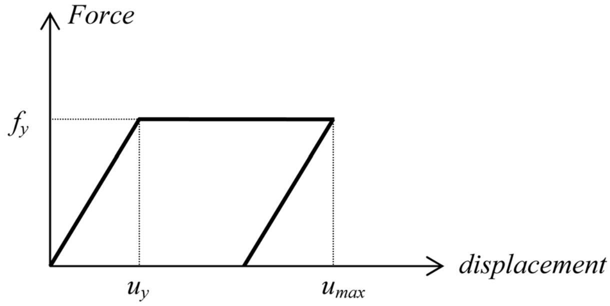

Fig. 1 Elastoplastic model of an SDOF system

where k and c are the initial stiffness and viscous damping, respectively.

For fixed-base case, there is no need to define the foundation beneath the structure. For interacting case, the foundation is modeled as a circular rigid disk of radius r. The soil under the foundation is considered as a homogenous half-space and characterized by shear wave velocity V_s, dilatational wave velocity V_p, mass density ρ and Poisson's ratio υ. The supporting soil is replaced with springs and dampers for the horizontal and rocking modes. The foundation is represented for all motions using a spring-dashpot-mass model with frequency-independent coefficients. The modeling of the foundation on deformable soil is performed in the same way as that of the structure and is coupled to perform a dynamic SSI analysis (Wolf 1997). Based on the Truncated Cone Model of Meek and Wolf (1992), spring stiffnesses (K_x and K_θ) and damping coefficients (C_x and C_θ) are used for sway and rocking motions, respectively.

$$K_x = \frac{8 \cdot \rho \cdot V_s^2 \cdot r}{2 - \upsilon} \tag{3}$$

$$K_\theta = \frac{8 \cdot \rho \cdot V_s^2 \cdot r^3}{3 \cdot (1 - \upsilon)} \tag{4}$$

$$C_x = \rho \cdot V_s \cdot \pi \cdot r^2 \tag{5}$$

$$C_\theta = \rho \cdot V_p \cdot \pi \cdot \frac{r^4}{4} \tag{6}$$

3. Analysis method

The soil structure analysis may be conducted either in the frequency domain using harmonic impedance functions or in the time domain using impulsive impedance functions. However, the frequency-domain analysis is not practical for structures that behave nonlinearly. On the other hand, the time-domain analysis can be conducted by using constant springs and dampers regardless of frequency to represent the soil. With this simplification, the convolution integral describing the soil interaction forces is avoided, and thus the integration procedure of the equilibrium equations is carried out as for the fixed-base case. In the present study, the described soil-structure model is analyzed in time domain. The dynamic equation of motion of an SDOF system is given by

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g \tag{7}$$

Table 1 Earthquake ground motions used in analyses

Earthquake	M	Station	Station no	Dist. (km)	Comp. 1	PGA (g)	PGV (cm/s)	Comp. 2	PGA (g)	PGV (cm/s)	Site class
Loma Prieta 18/10/89	7.1	Coyote Lake Dam	57217	21.8	CYC195	0.151	16.2	CYC285	0.484	39.7	A
Loma Prieta 18/10/89	7.1	Monterey City Hall	47377	44.8	MCH000	0.073	3.5	MCH090	0.063	5.8	A
Loma Prieta 18/10/89	7.1	SC Pacific Heights	58131	80.5	PHT270	0.061	12.8	PHT360	0.047	9.2	A
Northridge 17/01/94	6.7	Lake Hughes 9	127	28.9	L09000	0.165	8.4	L09090	0.217	10.1	A
Northridge 17/01/94	6.7	Wrıghtwood - Jackson Flat	23590	68.4	WWJ090	0.056	10	WWJ180	0.037	7	A
Northridge 17/01/94	6.7	Sandberg Bald Mtn	24644	43.4	SAN090	0.091	12.2	SAN180	0.098	8.9	A
Kocaeli 17/08/99	7.8	Gebze	-	17	GBZ000	0.244	50.3	GBZ270	0.137	29.7	A
Northridge 17/01/94	6.7	MT Wılson-Cıt Sta.	24399	36.1	MTW000	0.234	7.4	MTW090	0.134	5.8	A
Loma Prieta 18/10/89	7.1	Anderson Dam Downstream	1652	20	AND270	0.244	20.3	AND360	0.24	18.4	B
Northridge 17/01/94	6.7	Castaic Old Ridge	24278	25.4	ORR090	0.568	52.1	ORR360	0.514	52.2	B
Northridge 17/01/94	6.7	LA Century City North	24389	18.3	CCN090	0.256	21.1	CCN360	0.222	25.2	B
Kocaeli 17/08/99	7.8	Arçelik	-	17	ARC000	0.218	17.7	ARC090	0.149	39.5	B
Loma Prieta 18/10/89	7.1	Golden Gate Bridge	1678	85.1	GGB270	0.233	38.1	GGB360	0.123	17.8	B
Northridge 17/01/94	6.7	Ucla Grounds	24688	16.8	UCL090	0.278	22	UCL360	0.474	22.2	B
Northridge 17/01/94	6.7	LA Univ. Hospital	24605	34.6	UNI005	0.493	31.1	UNI095	0.214	10.8	B
Düzce 12/11/99	7.3	Lamont 1061	1061	15.6	1061-E	0.107	11.5	1061-N	0.134	13.7	B
Landers 28/06/92	7.4	Yermo Fire Station	22074	26.3	YER270	0.245	51.5	YER360	0.152	29.7	C
Loma Prieta 18/10/89	7.1	Hollister - South & Pine	47524	28.8	HSP000	0.371	62.4	HSP090	0.177	29.1	C
Northridge 17/01/94	6.7	Downey-Birchdale	90079	40.7	BIR090	0.165	12.1	BIR180	0.171	8.1	C
Northridge 17/01/94	6.7	LA-Centinela	90054	30.9	CEN155	0.465	19.3	CEN245	0.322	22.9	C
Imperial Valley 15/10/79	6.9	Chihuahua	6621	28.7	CHI012	0.27	24.9	CHI282	0.254	30.1	C
Imperial Valley 15/10/79	6.9	Delta	6605	32.7	DLT262	0.238	26	DLT352	0.351	33	C
Loma Prieta 18/10/89	7.1	Gilroy Array #4	57382	16.1	G04000	0.417	38.8	G04090	0.212	37.9	C
Düzce 12/11/99	7.3	Bolu	Bolu	17.6	BOL000	0.728	56.4	BOL090	0.822	62.1	C
Loma Prieta 18/10/89	7.1	Appel 2 Redwood City	1002	47.9	A02043	0.274	53.6	A02133	0.22	34.3	D
Northridge 17/01/94	6.7	Montebello	90011	86.8	BLF206	0.179	9.4	BLF296	0.128	5.9	D
Superstition Hills 24/11/87	6.6	Salton Sea Wildlife Refuge	5062	27.1	WLF225	0.119	7.9	WLF315	0.167	18.3	D
Loma Prieta 18/10/89	7.1	Treasure Island	58117	82.9	TRI000	0.1	15.6	TRI090	0.159	32.8	D
Kocaeli 17/08/99	7.8	Ambarli	-	78.9	ATS000	0.249	40	ATS090	0.184	33.2	D
Morgan Hill 24/04/84	6.1	Appel 1 Redwood City	58375	54.1	A01040	0.046	3.4	A01310	0.068	3.9	D
Düzce 12/11/99	7.3	Ambarlý	-	193.3	ATS030	0.038	7.4	ATS300	0.025	7.1	D
Kobe 16/01/95	6.9	Kakogawa		26.4	KAK000	0.251	18.7	KAK090	0.345	27.6	D

where u is the relative displacement and $\ddot{u}_g$ is the acceleration of ground motion. Newmark method for step by step time integration was adapted in an in-house computer program for inelastic time history analyses. A total of 64 earthquake acceleration time-histories recorded on different soil types are used in this study. Ground motions are selected to represent far-field earthquakes based on far field definition in ATC documents (1996, 2008). Near-field records are deliberately excluded in the present study, because especially fault-normal near-field records with forward directivity are known to yield extremely high amplifications in the strength-based spectra compared to relatively small amplifications observed in the ductility-based spectra (Aydinoglu and Kacmaz 2002). Details of selected ground motions are listed in Table 1. Site classes given in Table 1 are in accordance with United States Geological Survey site classification system (Boore 1993) which correspond to shear wave velocity value higher than 750 m/s for site class A, between 360-750 m/s for site class B, 180-360 m/s for site class C and lower than 180 m/s for site class D. In analyses, soil - structure interacting systems are assumed to be located on soil profiles with shear velocities of 750 m/s for site class A, 400 m/s for site class B, 250 m/s for site class C and 150 m/s for site class D.

3.1 Equivalent fixed-base model

The most common approach to consider soil structure interaction effects is to use a single degree of freedom replacement oscillator with effective period and damping of the system. The first well-known studies on the use of replacement oscillator were conducted by Veletsos and his co-workers (Veletsos *et al.* 1974, 1975, 1977). Effective period and damping of the system are denoted by $\tilde{T}$ and $\tilde{\beta}$, respectively, as they are used in current U.S. codes (ATC 3-06/1984, FEMA 450/2003).

Effective period of the interacting system is given by the equation below

$$\tilde{T} = T\sqrt{1+\frac{k}{K_x}\left(1+\frac{K_x h^2}{K_\theta}\right)} \tag{8}$$

Rearranging this equation gives the equivalent stiffness of the interacting system as follows

$$\frac{1}{k_{eq}} = \frac{1}{k}+\frac{1}{K_x}+\frac{h^2}{K_\theta} \tag{9}$$

Effective damping of the interacting system as the overall damping factor of the elastically supported structure $\tilde{\beta}$ was determined from analyses of the harmonic response at resonance of simple systems and given by the equation below

$$\tilde{\beta} = \beta_0 + \frac{0.05}{\left(\frac{\tilde{T}}{T}\right)^3} \tag{10}$$

where β_0 represents the contribution of the foundation damping, and the second term represents the contribution of the structural damping. The latter damping is assumed to be of the viscous type. Eq. (10) corresponds to the value of $\beta = 0.05$ used in the development of the response spectra for rigidly supported systems. The foundation damping factor, β_0, incorporates the effects of energy dissipation in the soil due to the following sources: the radiation of waves away from the foundation, known as radiation or geometric damping, and the hysteretic or inelastic action in the soil, also known as soil material damping. This factor depends on the geometry of the foundation-soil contact area and on

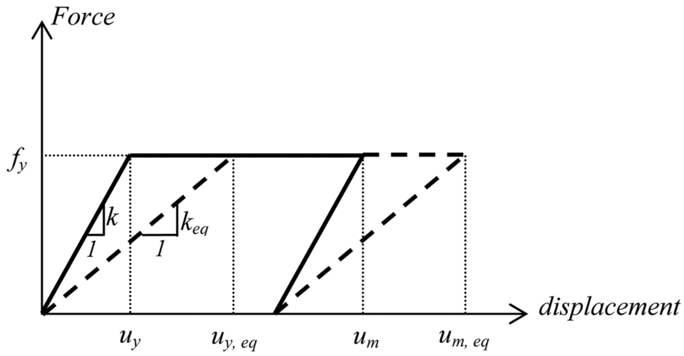

Fig. 2 Force-displacement relationships for the actual structure (solid line) and equivalent fixed-base model (dashed line) (Aviles and Perez-Rocha 2003)

the properties of the structure and the underlying soil deposits. The variation of β_0 with $\tilde{T}/T$ and h/r for two levels of excitation is given in current U.S. codes (ATC 3-06/1984, FEMA 450/2003).

For elastic range, it is adequate to modify the structural period and damping ratio of interacting system to consider elastic interaction effects whereas the ductility capacity of the structure has to be modified to consider inelastic interaction effects in the inelastic range. Based on this approach, an effective ductility for the interacting system has to be defined. Effective ductility of interacting system is defined as providing the same yielding force of the fixed-base structure. The yielding forces are selected in a way to produce presumed ductility demand for the fixed-base structure. Also it is possible to obtain the effective ductility of the interacting system with the equation given below as proposed by some researches in the past (Muller and Keintzel 1982, Ghannad and Ahmadnia 2002, Aviles and Perez-Rocha 2003)

$$\tilde{\mu} = \left(\frac{T}{\tilde{T}}\right)^2(\mu - 1) + 1 \tag{11}$$

The force-displacement relationship for the actual structure and equivalent fixed-base model is shown in Fig. 2.

4. Statistical study for strength reduction factors considering soil structure interaction

Using the procedure described above, a total of 65280 analyses have been conducted for elastoplastic SDOF systems with period range of 0.1-3.0s, five aspect ratios (h/r = 1, 2, 3, 4, 5), five levels of ductility (μ = 2, 3, 4, 5, 6) and 64 ground motions recorded on different soil conditions.

4.1 Mean strength reduction factors

Fig. 3 shows the mean strength reduction factors for all ground motions (regardless of site class) and all aspect ratios. It can be seen from the figure that, mean strength reduction factors of interacting system can be characterized as approximately equal to ductility value in the long-period range. In the short and medium period range, the reduction factors exhibit significant variations due to changes in period and ductility.

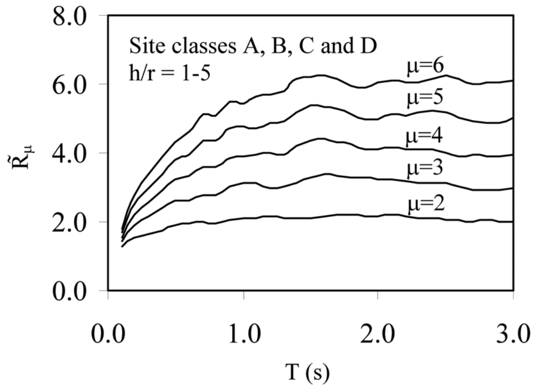

Fig. 3 Mean strength-reduction factors for interacting systems

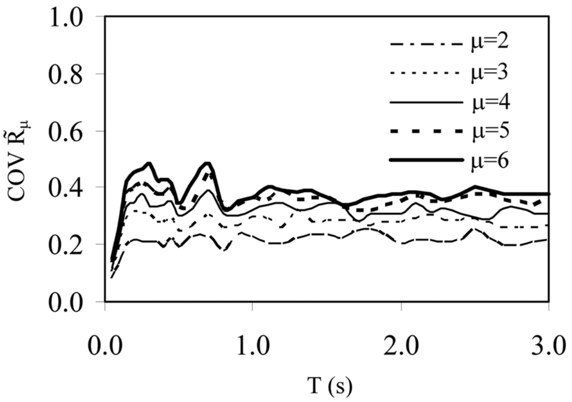

Fig. 4 COV values of strength-reduction factors for interacting systems

4.2 Dispersion

A common and effective way to quantify the dispersion is through the coefficient of variation (COV), which is defined as the ratio of the standard deviation to the mean. Fig. 4 shows COV values of strength reduction factors corresponding to ground motions from all site classes and all aspect ratios considered herein. It can be seen that, the dispersion in strength-reduction factors for interacting case, increases with increasing displacement ductility ratio. Except the short period range, coefficients of variation of strength-reduction factors exhibit only small variations due to changes in the period. This is the same conclusion as for the fixed base models (Miranda 1993).

4.3 Effect of soil conditions

Variations of mean strength-reduction factors against period on different soil types with (solid line) and without (dashed line) interaction for an interacting system with ductility demands of 2 and 4 and aspect ratio of 3 are shown in Fig. 5. It can be seen from the figure that, interaction effects are negligible for site classes A and B, whereas these effects should be considered for site classes C and especially D.

The ratios of mean strength-reduction factors of interacting and fixed base systems are shown in Fig. 6 for different soil types. It can be seen that, as expected, aforementioned ratios decrease for lower values of shear wave velocity. Although the ratio of strength-reduction factors are very close to unity for $T > 0.5\ s$ for site classes A and B, this ratio is smaller than unity for site classes C and D. But for $T < 0.5\ s$, SSI exhibits an important variation for different site classes. The effect of interaction is clearer for site classes C and D. Therefore, it is an acceptable and reasonable approach not to consider soil structure interaction for shear wave velocities higher than approximately 250 m/s.

The influence of soil conditions on strength-reductions factors can be seen in Fig. 7 where mean $\tilde{R}_\mu$ spectra are plotted for interacting systems on different site classes with displacement ductility demands of 2, 4 and 6 and aspect ratio of 1 and 5 when subjected to ground motions recorded on rock, on alluvium, and on soft-soil sites. As shown in this figure, the shape of $\tilde{R}_\mu$ is very sensitive to the variations in the structure period and site classes especially for higher ductility demands. Strength reduction factors of interacting systems corresponding to site classes A, B and C are

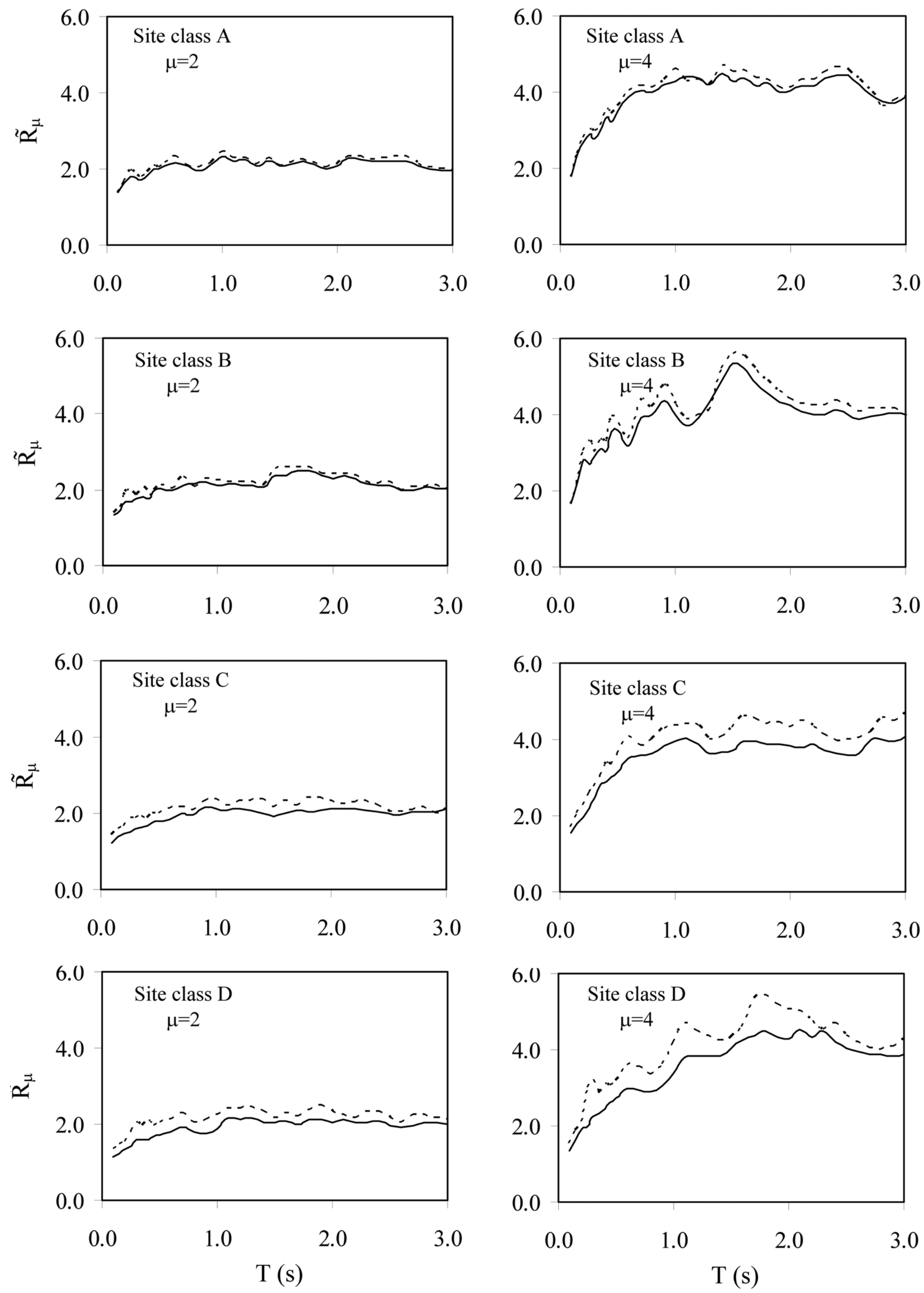

Fig. 5 Variations against period and mean strength-reduction factors on different soil types with (solid line) and without (dashed line) interaction for $\mu = 2$ and 4. Results correspond to an interacting system with $h/r = 3$

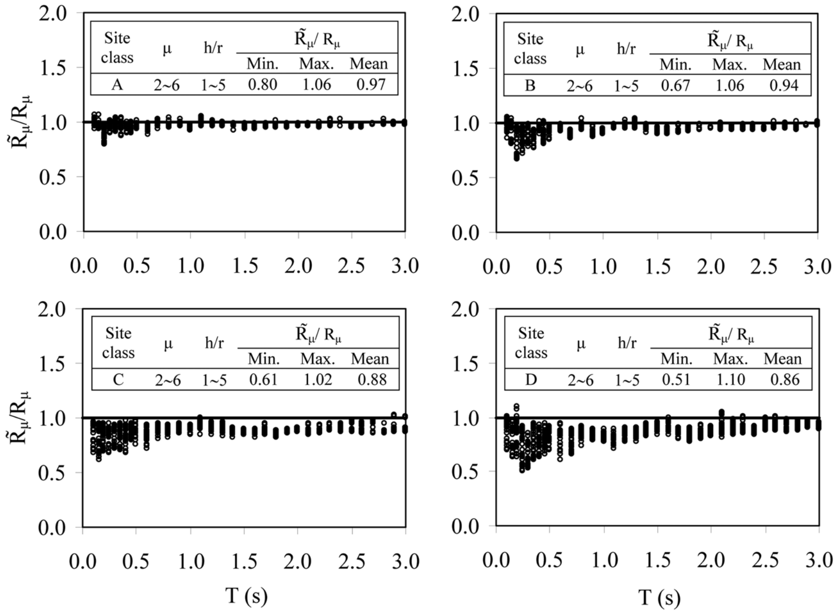

Fig. 6 Variations against period and the ratio for mean strength-reduction factors with and without interaction on different soil types

slightly affected by variation of ductility demand and aspect ratio. But for site class D, strength reduction factors are affected by ductility demand primarily and aspect ratio secondly. Strength reduction factors of site class D are smaller than strength reduction factors of site classes A, B and C for periods smaller than 1.2 s for increasing ductility and aspect ratio levels. From this period, strength reduction factors of site class D are larger than the corresponding ones of site classes A, B and C.

4.4 Nonlinear regression analysis

A complete nonlinear regression analysis is carried out on the basis of the data obtained by the aforementioned response analyses. The relation of the strength reduction factors versus the structural period and ductility demand is regressed for the series of 65280 analyses so that the effect of the soil type and the period lengthening ratio to be taken into account in the resulting expression. Thus, the proposed equation for mean strength reduction factors of interacting system is a function of structural period (T), ductility ratio (μ) and period lengthening ratio ($\tilde{T}/T$). Correlations of structural variables on strength reduction factors are given in Table 2.

In order to obtain an appropriate formula to represent the mean strength reduction factors for all records, ductility ratios, aspect ratios and structural periods combined, a nonlinear regression analysis is carried out. Using the Levenberg-Marquardt method (Bates and Watts 1988) in the regression module of STATISTICA (Statsoft Inc. 1995) nonlinear regression analyses were conducted to derive a simplified expression for estimating mean strength reduction factors. The resulting regression formula is appropriately simplified and expressed as

$$\tilde{R}_\mu = 1 + a(\mu - 1)(\mu^b + T^c)^{\frac{1}{T}} \tag{12}$$

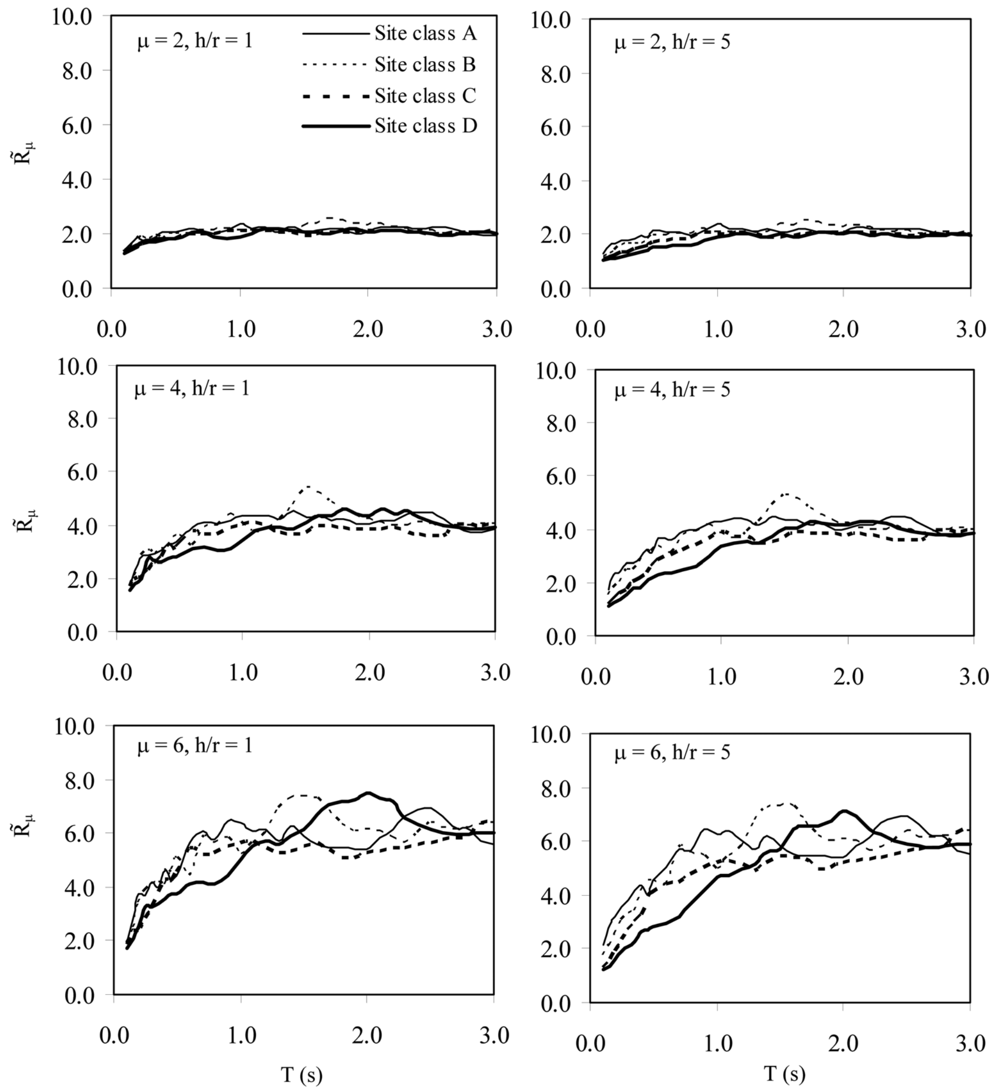

Fig. 7 Variations against period of mean strength-reduction factors on different soil types for μ = 2, 4 and 6. Results correspond to an interacting system with *h/r* = 1 and 5

Table 2 Correlation matrix of structural variables on mean strength reduction factors

	μ	T	h/r	$\tilde{T}$	$\tilde{R}_\mu$	$\tilde{T}/T$
μ	1.00					
T	0.00	1.00			Sym.	
h/r	0.00	0.00	1.00			
$\tilde{T}$	0.00	1.00	0.03	1.00		
$\tilde{R}_\mu$	0.77	0.40	-0.05	0.39	1.00	
$\tilde{T}/T$	0.00	-0.34	0.23	-0.29	-0.33	1.00

Table 3 Parameter summary for Eq. (12)

Site class	a	b	c	Correlation coefficient
A	0.54	$-0.11+0.04\frac{\tilde{T}}{T}$	$0.65+0.89\frac{\tilde{T}}{T}$	0.98
B	0.54	$-0.06-0.01\frac{\tilde{T}}{T}$	$-0.375+2.03\frac{\tilde{T}}{T}$	0.97
C	0.48	$-0.07-0.02\frac{\tilde{T}}{T}$	$-0.14+1.70\frac{\tilde{T}}{T}$	0.98
D	0.42	$0.05-0.07\frac{\tilde{T}}{T}$	$0.01+2.47\frac{\tilde{T}}{T}$	0.98
All sample	0.49	$0.02-0.06\frac{\tilde{T}}{T}$	$-2.88+4.65\frac{\tilde{T}}{T}$	0.97

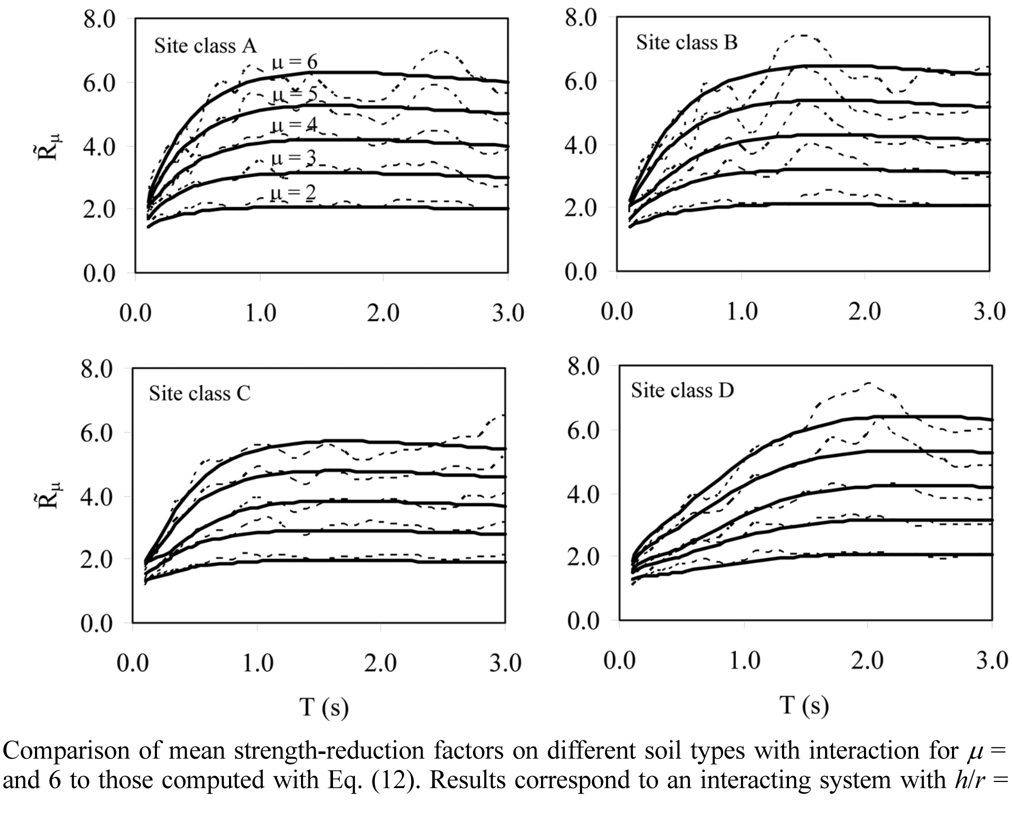

Fig. 8 Comparison of mean strength-reduction factors on different soil types with interaction for μ = 2, 3, 4, 5 and 6 to those computed with Eq. (12). Results correspond to an interacting system with h/r = 3

In Eq. (12), a, b and c are coefficients which take into account the influence of period lengthening ratio. The coefficients a, b and c are summarized in Table 3 for different site classes individually and considering all sample.

Fig. 8 shows the fitness of the regressed function of the mean $\tilde{R}_\mu$ factor for different soil classes. In this figure, the solid line represents the values obtained from the regressed function Eq. (12) and the dashed line represents the actual mean values of $\tilde{R}_{\mu}$ factors obtained from non-linear dynamic analyses of interacting systems with ductility of 2, 3, 4, 5 and 6 and aspect ratio of 3.

5. Conclusions

In this study, strength reduction factors are investigated for SDOF systems of period range of 0.1-3.0s with elastoplastic behavior considering soil structure interaction for 64 different earthquake motions recorded on different site conditions such as rock, stiff soil, soft soil and very soft soil. Soil structure interacting systems are modeled with effective period, effective damping and effective ductility values differing from fixed-base case. A new equation is proposed for strength reduction factor of interacting system as a function of structural period of system (T), ductility ratio (μ) and period lengthening ratio ($\tilde{T}/T$). The fitness of the regressed function of the strength reduction factor is shown in figures. The following conclusions can be drawn from the results of this study.

Mean strength reduction factor of interacting system can be characterized as approximately equal to ductility value in the long-period range whereas in short and medium period range, the reduction factor exhibit important variations due to changes in period and ductility.

The dispersion in strength-reduction factors increases with increasing displacement ductility ratio. Except short period range, COV of mean strength-reduction factors vary slightly against period.

The minimum ratio of mean strength reduction factors with interaction to the fixed base case is 0.8 for site class A, 0.67 for site class B, 0.61 for site class C and 0.51 for site class D in short period region. Although the ratio of strength-reduction factors are very close to unity for medium and long period region for site classes A and B, this ratio is smaller than unity for site classes C and D. Soil structure interaction effect is negligible for site class A and $T > 0.5$s region for site class B, whereas this effect should be considered for $T < 0.5$s range of site class B and for site classes C and especially D regardless of period.

Strength-reduction factors corresponding to site classes A, B and C are slightly affected by variation of ductility demand and aspect ratio. But for site class D, strength reduction factors are affected by ductility demand primarily and aspect ratio secondly. Strength reduction factors of site class D are smaller than strength reduction factors of site classes A, B and C for periods smaller than 1.2 s for increasing ductility and aspect ratio levels. From this period, strength reduction factors of site class D are larger than the corresponding ones of site classes A, B and C.

A new equation is proposed to represent the mean strength reduction factors for all records, ductility ratios, aspect ratios and structural periods as a function of structural period (T), ductility ratio (μ) and period lengthening ratio ($\tilde{T}/T$). The proposed simplified expression provides a good approximation of mean strength reduction factors of SDOF systems having elastoplastic behavior.

References

Applied Technology Council - ATC (1984), Tentative provisions for the development of seismic regulations for buildings, Rep. ATC-3-06, Applied Technology Council, California.

Applied Technology Council - ATC (1996), Seismic evaluation and retrofit of concrete buildings, ATC-40, Applied Technology Council, California.

Applied Technology Council - ATC (2008), Quantification of building seismic performance factors. ATC-63,

Applied Technology Council, California.
Aviles, J. and Perez-Rocha, L.E. (2003), "Soil structure interaction in yielding systems", *Earthq. Eng. Struct. Dyn.*, **32**, 1749-1771.
Aviles, J. and Perez-Rocha, L.E. (2005), "Influence of foundation flexibility on R_μ and C_μ factors", *J. Struct. Engi. - ASCE,* **131**(2).
Aydýnoğlu, M.N. and Kaçmaz, Ü (2002), "Strength-based displacement amplification spectra for inelastic seismic performance evaluation", *KOERI Depart. Earthq. Eng. Report,* No. 2002/2.
Bates, D.M. and Watts, D.G. (1988), *Nonlinear regression analysis and its applications*, Wiley, New York.
Boore, D.M. (1993), "Some notes concerning the determination of shear-wave velocity and attenuation", *Proceedings of geophysical techniques for site and material characterization*, 129-34.
Doo, K.K. and Yun, C.B. (2003), "Time domain earthquake response analysis method for 2-D soil-structure interaction systems". *Struct. Eng. Mech.,* **15**(6), 717-733.
Duzgun, O.A. and Budak, A. (2011), "A study on the topographical and geotechnical effects in 2-D Soil-Structure Interaction analysis under ground motion", *Struct. Eng. Mech.,* **40**(6), 829-845.
Elghadamsi, F.E. and Mohraz, B. (1987), "Inelastic earthquake spectra", *Earthq. Eng. Struct. Dyn.*, **15**, 91-104.
Eser Aydemir, M. and Aydemir, C. (2011), "The effect of soil-structure interaction on inelastic displacement ratio of structures", *Struct. Eng. Mech*., **39**(5), 683-701.
Federal Emergency Management Agency - FEMA (2003), Recommended provisions for seismic regulations for new buildings and other structures, Rep. FEMA-450, Federal Emergency Management Agency, Washington (DC).
Ghannad, M.A. and Ahmadnia, A. (2002), "The effect of soil structure interaction on ductility demand of structure", *12th European Conference on Earthquake Engineering*, London.
Ghannad, M.A. and Jahankhah, H. (2007), "Site-dependent strength reduction factors for soil-structure systems", *Soil Dyn, Earthq. Eng.*, **27**, 99-110.
Lai, S.P. and Biggs, J.M. (1980), "Inelastic response spectra for a seismic building design", *J. Struct. Eng. - ASCE*, **106**, 1295-310.
Lee, L.H., Han, S.W. and Oh, Y.H. (1999), "Determination of ductility factor considering different hysteretic models", *Earthq. Eng. Struct. Dyn.*, **28**(9), 957-77.
Miranda, E. (1993), "Site dependent strength reduction factors", *J. Struct. Eng. - ASCE*, **119**(12), 3503-3519.
Muller, F.P. and Keintzel, E. (1982), "Ductility requirements for flexibly supported antiseismic structures", *Proceedings of the Seventh European Conference on Earthq. Eng.*, **3**, 27-34.
Nassar, A.A. and Krawinkler, H. (1991), Seismic demands for SDOF and MDOF systems, Report No.95, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, California.
Newmark, N.M. and Hall, W.J. (1973), Seismic design criteria for nuclear reactor facilities, Report No. 46, Building Practices for Disaster Mitigation, National Bureau of Standards, U.S. Department of Commerce, 209-236.
Riddell, R. and Newmark, N.M. (1979), Statistical analysis of the response of nonlinear systems subjected to earthquakes, Structural Research Series No. 468, Department of Civil Engineering, University of Illinois, Urbana.
Riddell, R., Hidalgo, P. and Cruz, E. (1989), "Response modication factors for earthquake resistant design of short period structures", *Earthq. Spectra*, **5**(3), 571-90.
Sarkani, S., Lutes, L.D., Jin, S. and Chan, C. (1999), "Stochastic analysis of seismic structural response with soil-structure interaction", *Struct. Eng. Mech.,* **8**(1), 53-72.
Stat Soft Inc. (1995), STATISTICA V.6.0 for Windows. Tulsa, OK, USA.
Veletsos, A.S. and Newmark, N.M. (1960), "Effect of inelastic behavior on the response of simple systems to earthquake motions", *Proceedings of The Second World Conference on Earthquake Engineering*, Tokyo, 895-912.
Veletsos, A.S. and Meek, J.W. (1974), "Dynamic behavior of building-foundation systems", *Earthq. Eng. Struct. Dyn.*, **3**, 121-138.
Veletsos, A.S. and Nair, V.V.D. (1975), "Seismic interaction of structures on hysteretic foundations", *J. Struct. Eng. - ASCE,* **101**(1).
Veletsos, A.S. (1977), *Dynamics of structure-foundation systems, Structural Geotechnical Mechanics*., Ed. W. J.

Hall, Prentice-Hall, Englewood Cliffs, N.J.

Vidic, T., Fajfar, P. and Fischinger, M. (1992), "A procedure for determining consistent inelastic design spectra", *Proceeding of Workshop on nonlinear seismic analysis of RC structures*, Slovenia.

Wolf, J.P. (1994), *Foundation vibration analysis using simple physical models*, Englewood Cliffs, Prentice-Hall NJ.