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Soil structure interaction effects on structural parameters for stiffness degrading systems built on soft soil sites

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Abstract. In this study, strength reduction factors and inelastic displacement ratios are investigated for SDOF systems with period range of 0.1-3.0 s considering soil structure interaction for earthquake motions recorded on soft soil. The effect of stiffness degradation on strength reduction factors and inelastic displacement ratios is investigated. The modified-Clough model is used to represent structures that exhibit significant stiffness degradation when subjected to reverse cyclic loading and the elastoplastic model is used to represent non-degrading structures. The effect of negative strain – hardening on the inelastic displacement and strength of structures is also investigated. 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. New equations are proposed for strength reduction factor and inelastic displacement ratio of interacting system as a function of structural period ($\tilde{T}$, T), ductility (μ) and period lengthening ratio ($\tilde{T}/T$).

Keywords: soil-structure interaction; stiffness degradation; strength reduction factor; inelastic displacement ratio; ductility demand; structural analysis

1. Introduction

Current earthquake – resistant design provisions allow the nonlinear response of building structures in the event of severe earthquake ground motions because of economic factors. Such a design approach requires the usage of strength reduction factor ($R\mu$) in seismic design codes. For a single-degree-of freedom system, strength reduction factor can be defined as the ratio of elastic base shear to the one required for a target ductility level, μ. Besides, current performance-based seismic design procedures aim at controlling earthquake damage to structural elements and many types of nonstructural elements by limiting lateral deformations on structures. Generally accepted standpoints of seismic design methodologies establish that structures should be capable of resisting relatively frequent, minor intensity earthquakes without structural damage or damage to nonstructural elements, moderate earthquakes without structural damage, or with some nonstructural damage, and severe, infrequent earthquakes with damage to both the resisting systems and to nonstructural components. Therefore, it is important to estimate lateral structural displacement demands for the design, evaluation and rehabilitation of structures. With this purpose,

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inelastic displacement ratios ($C\mu$) are used to estimate peak inelastic displacement demands from peak elastic displacement demands. Inelastic displacement ratios can be described as the ratio of peak inelastic displacement to peak elastic displacement for a system with same damping ratio and period of vibration.

Strength reduction factors and inelastic displacement ratios have been the topic of several investigations so far. The first well-known studies on strength reduction factors were conducted by Veletsos and Newmark (1960) and 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. 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, (1979). Alternative formulas were proposed by Lai and Biggs (1980) and Riddell *et al*. (1989). 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 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 (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 (2005) investigated strength reduction factors and displacement modification factors for a single elastoplastic structure with flexible foundation excited by vertically propagating shear waves and a site-dependent reduction rule proposed elsewhere for fixed-base systems were adjusted for interacting systems. In another study of the same authors, an equivalent ductility factor for the combined structure and foundation is derived to determine the design strength (Aviles and Perez-Rocha, 2011). 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 foundation nonlinearity on the structural response of low-rise steel moment-resisting frame buildings in terms of base moment, base shear, story drift, and ductility demand was investigated (Raychowdhury 2011). The effect of soil-structure interaction on strength reduction factors has been studied by Eser *et al.* (2012). They proposed a new equation for strength reduction factor of interacting system with elastoplastic behavior, and 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 nonconservative design forces.

The first well-known studies on inelastic displacement ratios were conducted by Veletsos and Newmark (1960, 1965) using the response of SDOF systems having elastoplastic hysteretic behavior and predefined levels of displacement ductility, μ, when subjected to a limited range of earthquake ground motions and periods of vibration. Since then, several researchers have performed statistical studies to evaluate constant-ductility inelastic displacement ratios using larger sets of ground motions and for wider range of periods than those pioneer studies. Ruiz-Garcia and Miranda have studied the effects of post-yield stiffness and stiffness and strength degradation on inelastic displacement ratios of SDOF systems on soft soils. They have concluded that, structures with stiffness degradation, having periods shorter than the predominant period of the ground motion, can experience lateral strength demands larger than those of non-degrading structures whereas the opposite is valid for structures with periods equal or longer than the predominant period of the ground motion (Miranda and Ruiz-Garcia 2002, Ruiz-Garcia and Miranda 2004, 2006). Also, Decanini *et al*. (2003) and Chopra and Chintanapakdee (2004) studied on inelastic displacement ratios and presented a series of new functions based on statistical studies to obtain the ratio of the maximum inelastic to the maximum elastic displacement for SDOF systems. Roy and Dutta studied the inelastic seismic response of low-rise buildings through adequate idealization of structure and sub-soil medium. They concluded that, buildings depicts that inelastic response of the asymmetric structure relative to its symmetric counterpart is not appreciably influenced due to soil–structure interaction (Roy and Dutta 2010). The effect of soil-structure interaction on inelastic displacement ratio of structures has been studied by Eser and co-workers (2011, 2012). They proposed new equations for inelastic displacement ratio of interacting system with elastoplastic behavior, as a function of structural period, strength reduction factor or ductility and period lengthening ratio.

The objective of this study is to present the results of an investigation conducted to provide more information on the soil structure interaction effects on strength reduction factors and inelastic displacement ratios for stiffness degrading structures built on soft soils when subjected to earthquake ground motions. In particular this study tried to: (1) study on SDOF systems with period range of 0.1-3.0 s and five levels of ductility (μ = 2, 3, 4, 5, 6); (2) focus on stiffness degrading structures with strain hardening ratios of α = -10%, -5%, -2%, 0, 2%, 5% and 10%; (3) analyze interacting SDOF systems for five aspect ratios (h/r = 1, 2, 3, 4, 5); (3) use a set of ground motions recorded on soft soil; and (4) propose new equations for strength reduction factor and inelastic displacement ratio of interacting system as a function of structural period ($\tilde{T}$, T), ductility ratio (μ) and period lengthening ratio ($\tilde{T}$/T).

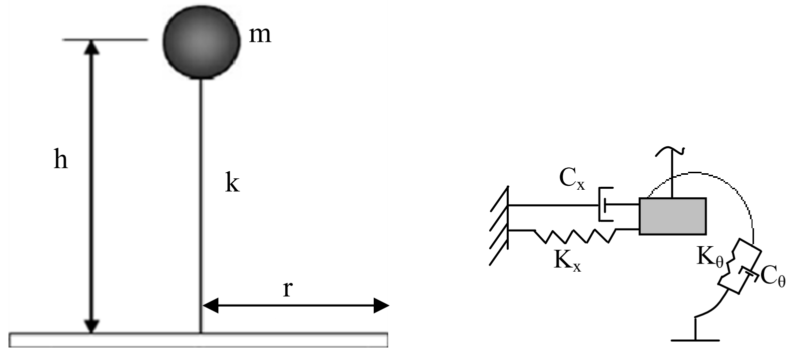
2. SSI system and simplified reference model

A SDOF system represented with mass, m, height, h used to model the structure and schematical view considering soil structure interaction modeling of supports are shown in Fig. 1(a) and Fig. 1(b). The SDOF system may be viewed as representative of more complex multistory buildings that respond as a single oscillator in their fixed-base condition.

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 foundation is represented for all motions using a spring-dashpot-mass model with frequency-independent coefficients. More details on the method of modelling can be found in Eser and Aydemir (2011).

The stiffness and damping coefficients for the horizontal (K_x, C_x) and rocking modes (K_θ, C_θ) of soil medium are defined as follows (Wolf 1994)

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



(a) (b)

Fig. 1(a) SDOF system; (b) mathematical model of supports with soil structure interaction

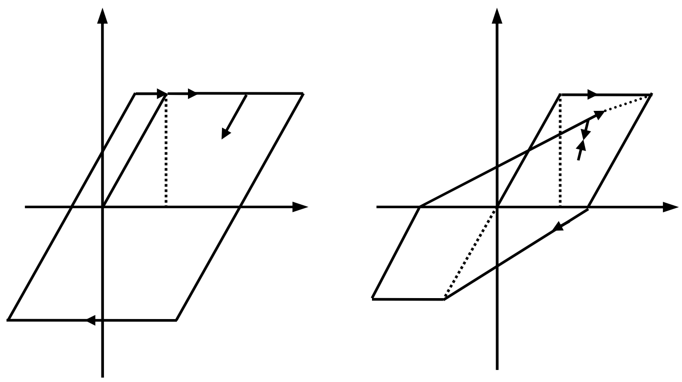
$$K_{\theta} = \frac{8 \cdot \rho \cdot V_s^2 \cdot r^3}{3 \cdot (1 - \upsilon)} \tag{4}$$

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

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

3. Load-deformation hysteretic models

Many hysteretic models have been proposed to represent the load-deformation characteristics of reinforced concrete structures when subjected to reverse cyclic loading. One of the first models to include the effect of stiffness degradation was the one proposed by Clough and Johnston (1966). This model has an elasto-plastic-perfectly-plastic envelope, however it differs from the EPP model in that, after the initial yielding, further loading branches are directed towards the furthest unloading point in the direction of loading, thus with a lateral stiffness smaller than the initial stiffness. In order to represent structures with stiffness degradation the modified-Clough model is used in this study. This model is based on the Clough model, and several studies have concluded that the modified-Clough model is capable of reproducing the behavior of properly designed reinforced concrete structures where shear failure is avoided and the behavior is primarily flexural (Miranda and Ruiz-Garcia 2002). The influence of stiffness degradation on the seismic demands of structures has been the topic of several studies (Clough and Johnston 1966, Rahnama and Krawinkler 1993, Gupta and Krawinkler 1998, Gupta and Kunnath 1998, Borzi *et al*. 2001). Also Miranda and his co-workers have studied on the effects of stiffness degradation on structures subjected to ground motions recorded on very soft soils (Miranda and Ruiz-Garcia 2002, Ruiz-Garcia and Miranda 2004, 2006). In 2009, to advance the understanding of degradation and dynamic instability by developing practical suggestions, where possible, to account for nonlinear degrading response in the context of current seismic analysis procedure FEMA P440A guideline was prepared (FEMA P440A 2009). Another research conducted by Ayoub and Chenouda (2009) has focused on the development of response spectra plots for inelastic degrading structural systems subjected to seismic excitations and conclusions regarding the behavior and collapse potential of different structural systems are drawn. However, none of these studies has considered the influence of soil structure interaction phenomenon. Therefore, the present study focuses on the effect of stiffness degradation on strength reduction factors and inelastic displacement ratios for soil structure interacting case. For this purpose, elastoplastic and modified-Clough hysteretic models shown in Figure 2 are considered in this study. Besides, different strain hardening ratios (α = -10%, -5%, -2%, 0, 2%, 5% and 10%) for both elastoplastic and modified-Clough hysteretic models are considered in analyses.



(a) (b)

Fig. 2 Load-deformation hysteretic models used in this study: (a) elastoplastic; (b) modified-clough

4. Negative strain hardening

P-delta effect caused by gravity loads acting on the deformed configuration of the structure will always lead to a decrease in stiffness and effective strength and an increase in lateral displacements. If the P-delta effect causes a negative post-yield stiffness in any one story, it may affect significantly the interstory drift and may lead to incremental collapse if the structure has not sufficient strength. Therefore, if certain target ductility is required, more strength must be provided for the structural system. In the present study, strain hardening ratios of α = -10%, -5%, -2%, 0, 2%, 5% and 10% are considered, respectively, to study the strain hardening / softening effect on structural behavior parameters.

5. Method of analysis

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. As the frequency-domain analysis is not practical for structures that behave nonlinearly, the time-domain analysis can be conducted by using constant springs and dampers regardless of frequency to represent the soil (Wolf and Somaini 1986). 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 soil-structure model is analyzed in time domain with Newmark method adapted in an in-house computer program for inelastic time history analyses. A set of earthquake acceleration time-histories recorded on soft soil (site classes C and D) are used in this study. Details of selected ground motions are listed in Table 1. More details on the selection of earthquake records and site classes can be found in (Eser and Aydemir 2011).

A total of 403200 analyses have been conducted for SDOF structures with period range of 0.1-3.0 s for five aspect ratios (h/r = 1, 2, 3, 4, 5) and fixed-base case, five levels of ductility (μ = 2, 3, 4, 5, 6), 32 ground motions, seven strain hardening ratios (α = -10%, -5%, -2%, 0, 2%, 5%, 10%) and two types of hysteretic behavior (EP and MC).

5.1 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 and Meek 1974, 1975, Veletsos 1977). Effective period and damping of the system denoted by $\tilde{T}$ and $\tilde{\beta}$, respectively, are given by the equations below, as they are used in current U.S. codes (ATC-3-06 1984, FEMA 450 2003).

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

$$\tilde{\beta} = \beta_0 + \frac{0.05}{\left(\frac{\tilde{T}}{T}\right)^3} \tag{9}$$

where β_0 denotes the foundation damping factor and values for this factor should be read from the figure given in aforementioned codes. More details regarding equivalent fixed-base model can be found in (Eser and Aydemir 2011).

6. Statistical study for mean inelastic displacement ratios and strength reduction factors

6.1 Effective structural parameters for inelastic displacement ratios and strength reduction factors

A complete nonlinear regression analysis is carried out on the basis of the data obtained by the procedure described above. The relation of the inelastic displacement ratio and strength reduction factor versus the structural period of interacting system and ductility demand is regressed for the series of the aforementioned analyses. Correlations of structural variables on inelastic displacement ratios and strength reduction factors are given in Table 2.

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
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	Ambarlı	-	193.3	ATS030	0.038	7.4	ATS300	0.025	7.1	D
Kobe 16/01/95	6.9	Kakogawa	0	26.4	KAK000	0.251	18.7	KAK090	0.345	27.6	D

Table 2 Correlation matrix of structural variables on mean strength reduction factors and inelastic displacement ratios

	μ	T	α	h/r	$\tilde{T}$	$\tilde{R}_\mu$	$\tilde{C}_\mu$	$\tilde{T}/T$
μ	1.00							
T	0.00	1.00						
α	0.00	0.00	1.00			Sym.		
h/r	0.00	0.00	0.00	1.00				
$\tilde{T}$	0.00	1.00	0.00	0.05	1.00			
$\tilde{R}_\mu$	0.85	0.40	0.04	0.04	0.40	1.00		
$\tilde{C}_\mu$	0.09	-0.72	-0.09	-0.13	-0.72	-0.42	1.00	
$\tilde{T}/T$	0.00	-0.41	0.00	0.24	-0.35	-0.18	0.34	1.00

6.2 Mean inelastic displacement ratios

In Fig. 3, variations of mean inelastic displacement ratios against period are shown for cases with (dashed line) and without (solid line) interaction. The top graphs show the results for site class C whereas the bottom graphs show the results for site class D. Results are presented for systems with ductility demands of 2, 4 and 6 and aspect ratio of 3. It is seen from the both top and bottom figures that, inelastic displacement ratios of fixed-base and interacting cases are very close to each other and approximately equal to unity for periods longer than 0.5 s. This behavior is in accordance with well-known “equal displacement rule” for long period range. But especially for short period region, inelastic displacement ratios of fixed-base and interacting system are considerably different for increasing ductility levels.

Variations of mean inelastic displacement ratios against period for increasing values of h/r are shown in Fig. 4. Results are presented for systems with ductility demand of 4 and strain hardening ratio of 10% and -10%. The top graphs show the results for site class C whereas the bottom graphs show the results for site class D. It can be seen from the figure that, aspect ratio is an effective parameter for inelastic displacement ratios in high frequency region for all strain hardening ratios. There is a decrease tendency up to a certain period, say 0.8 s, for increasing values of aspect ratio, but from this period point the effect of aspect ratio on inelastic displacement ratios is negligible.

6.3 Mean strength reduction factors

Variations of mean strength reduction factors against period with (dashed line) and without (solid line) interaction is shown in Fig. 5. The top graphs show the results for site class C whereas the bottom graphs show the results for site class D. Results are presented for systems with ductility demands of 2, 4 and 6 and aspect ratio of 3. It can be seen from the figure that, interaction effects can’t be neglected for soft soil. Also it should be noted that, strength reduction factors of interacting systems are almost always smaller than the fixed-base strength reduction factors.

Variations of mean strength reduction factors against period for increasing values of h/r are shown in Fig. 6. The top graphs show the results for site class C whereas the bottom graphs show the results for site class D. Results are presented for systems with ductility demand of 4 and strain hardening ratio of 10% and -10%. It can be seen from the figure that, – as inelastic displacement ratios – aspect ratio is an effective parameter for strength reduction factors in short period region for all strain hardening ratios. There is an increase tendency for increasing values of aspect ratio up to nearly 0.8 s, but from this period point the effect of aspect ratio on strength reduction factors is negligible.

6.4 Effect of hysteretic behavior

In this section, the effect of hysteretic behavior on mean strength reduction factors and inelastic displacement ratios is studied by considering the well-known elastoplastic model and Modifed-Clough model to represent non-degrading and degrading structural systems. For this purpose, variations of mean strength reduction factors with ductility for elastoplastic (dashed line) and Modified Clough (solid line) behavior for an interacting system with α = 5% and h/r = 3 are

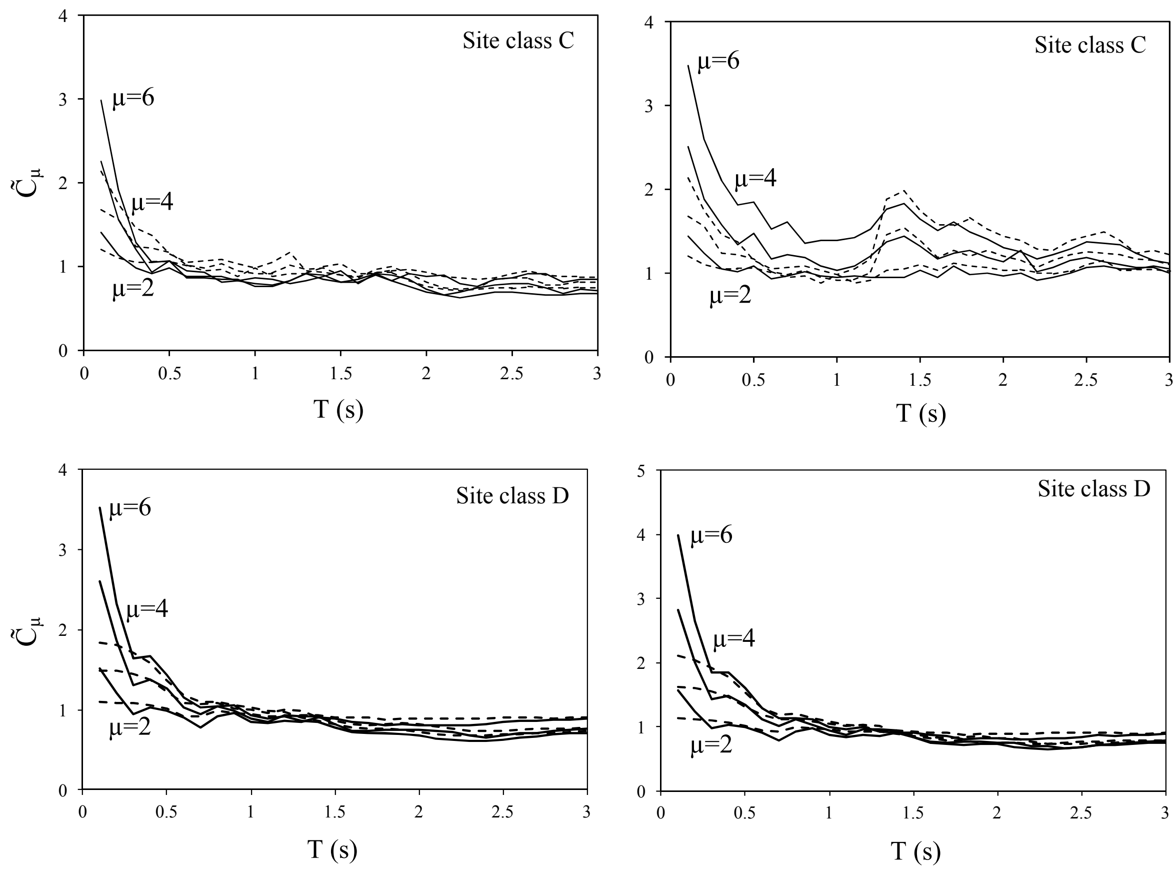


Fig. 3 Variations of mean inelastic displacement ratios against period with (dashed line) and without (solid line) interaction for α= 5% and -5%. Results correspond to an interacting system with *h*/*r* = 3

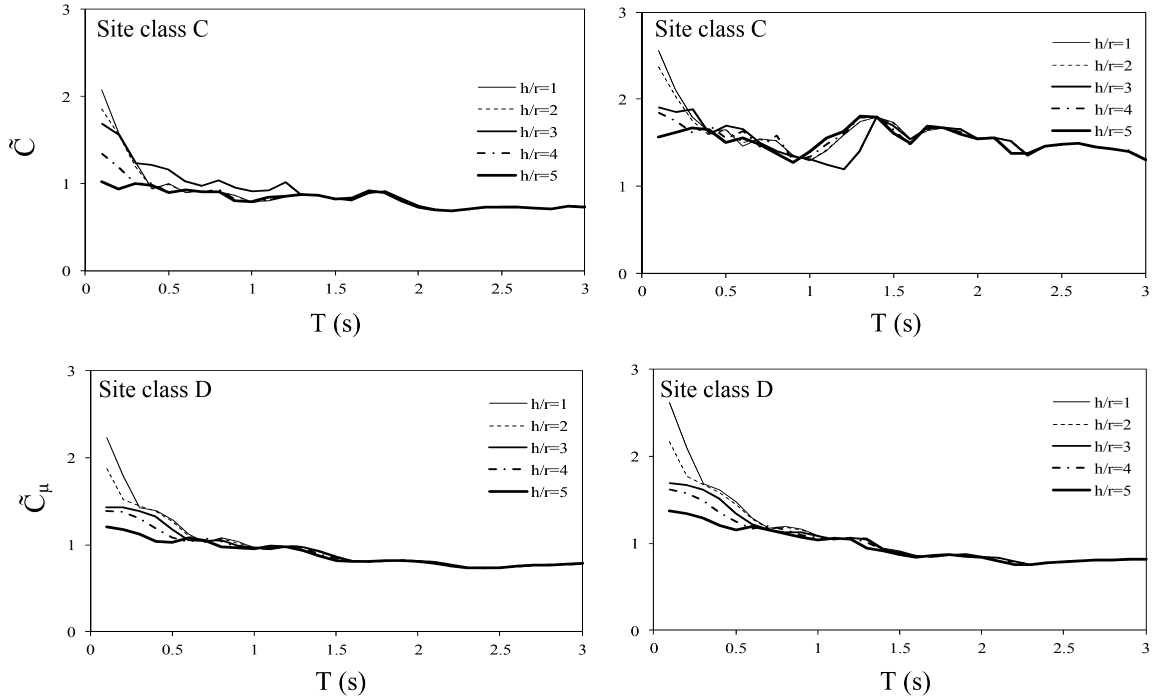


Fig. 4 Variations of mean inelastic displacement ratios against period and increasing values of aspect ratio for α= 10% and -10%. Results correspond to an interacting system with μ= 4

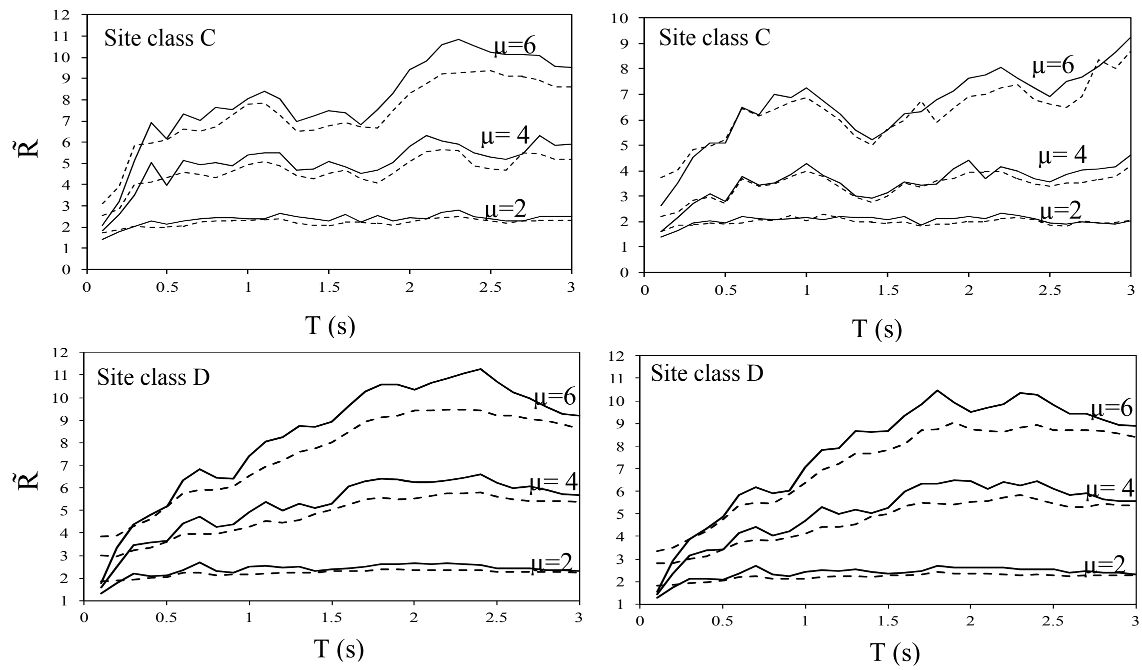


Fig. 5 Variations of mean strength-reduction factors against period with (dashed line) and without (solid line) interaction for α= 5% and -5%. Results correspond to an interacting system with h/r = 3

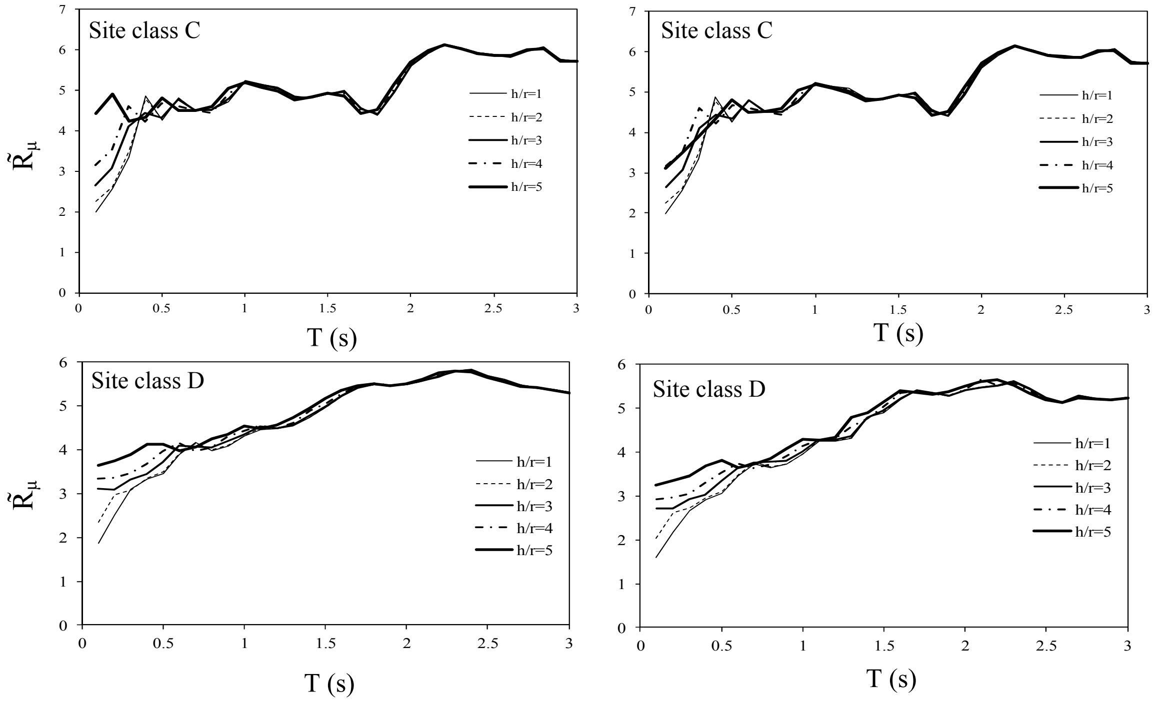


Fig. 6 Variations of mean strength reduction factors against period and increasing values of aspect ratio for α = 10% and -10%. Results correspond to an interacting system with μ = 4

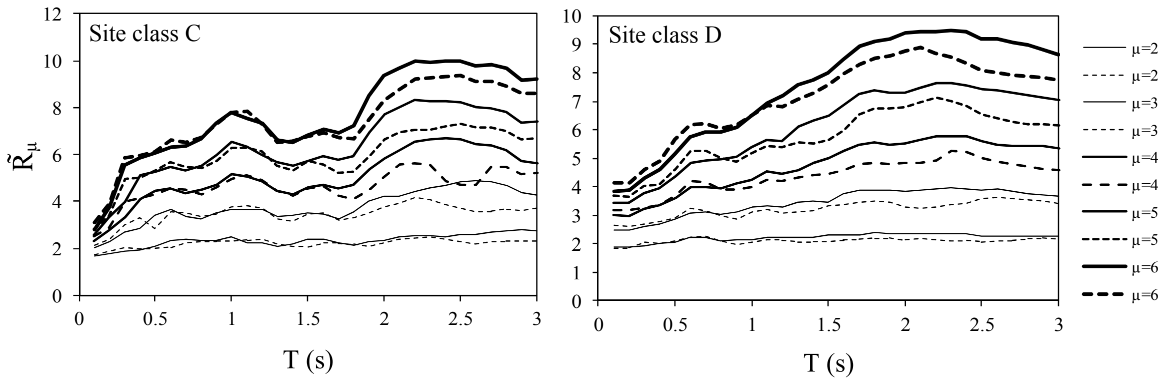


Fig. 7 Variations of mean strength reduction factors for elastoplastic behavior (dashed line) and Modified Clough (solid line) behavior against period for α= 5%. Results correspond to an interacting system with *h/r* = 3

presented in Fig. 7. The left graph shows the results for site class C whereas the right graph shows the results for site class D. It can be seen from Fig. 7 that, in general, mean strength reduction factors are smaller than the target ductility up to a certain period, but from this period, mean strength reduction factors are significantly greater than the target displacement ductility ratio. Also it should be noted that, the strength reduction factors for degrading systems are smaller than the corresponding ones of non-degrading systems up to period of nearly 0.8 s and from this period point vice versa.

Variations of mean inelastic displacement ratios with ductility for elastoplastic (dashed line) and Modified Clough (solid line) behavior are also shown in Fig. 8. Results are presented for an interacting system with α = 5% and h/r = 3 and the left graph shows the results for site class C whereas the right graph shows the results for site class D. It is seen from Figure 8 that, mean inelastic displacement ratios for degrading systems are greater than the corresponding ones of non-degrading systems up to period of nearly 1.0 s and from this period point vice versa. It can also be seen that, although the upper curve in the graph corresponds to a ductility value of 6 for period range before the mentioned certain period, this curve has the smallest inelastic displacement ratio values from this period point.

Variations of mean strength reduction factors with aspect ratio for elastoplastic (dashed line) and Modified Clough (solid line) behavior for an interacting system with α = 5% and ductility demand of 3 are presented in Fig. 9. It can be seen from the figure that, strength reduction factors for degrading systems are much greater than the corresponding ones of non-degrading systems from the period of nearly 0.8 s for all aspect ratios but before this period point, strength reduction factors for degrading and non-degrading systems are very close to each other.

In Fig. 10, variations of mean inelastic displacement ratios with aspect ratio for elastoplastic (dashed line) and Modified Clough (solid line) behavior for an interacting system with α = 5% and ductility demand of 3 are given. It is seen from Fig. 10 that, mean inelastic displacement ratios for degrading systems are smaller than the corresponding ones of non-degrading systems from the period of nearly 1.0 s. But before this period point, aspect ratio is an effective parameter on inelastic displacement ratios that, as the aspect ratio increases, inelastic displacement ratio decreases.

In order to study further the effect of stiffness degradation on the structural demands, and particularly to quantify the effect of stiffness degradation on lateral strength and displacement demands, non-degrading to degrading inelastic demand ratios were computed. Variation of these ratios is shown in Fig. 11. The left graph shows the ratio of the strength reduction factors in non-degrading system, $\tilde{R}_{\mu(EP)}$, to the strength reduction factors in stiffness degrading system, $\tilde{R}_{\mu(MC)}$, and the right graph shows the ratio of inelastic displacement ratios in non-degrading system, $\tilde{C}_{\mu(EP)}$, to inelastic displacement ratios in stiffness degrading system, $\tilde{C}_{\mu\,(MC)}$.

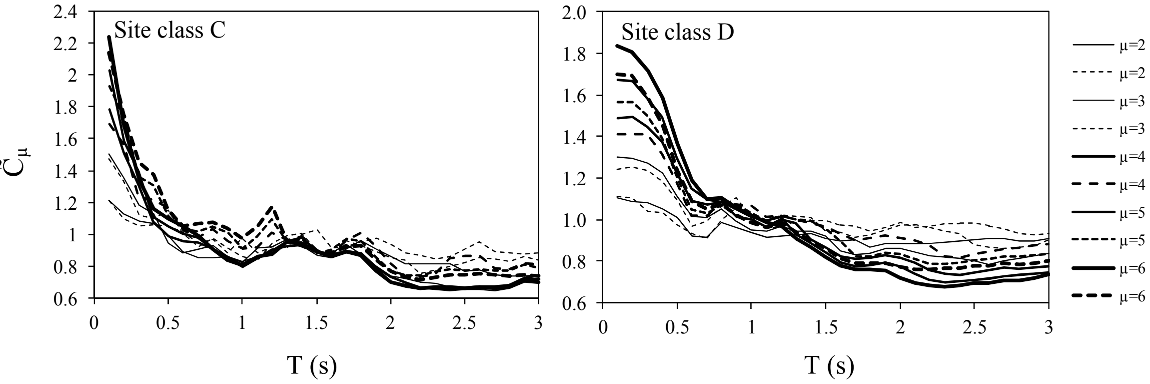


Fig. 8 Variations of mean inelastic displacement ratios for elastoplastic behavior (dashed line) and Modified Clough (solid line) behavior against period for α = 5%. Results correspond to an interacting system with *h/r* = 3

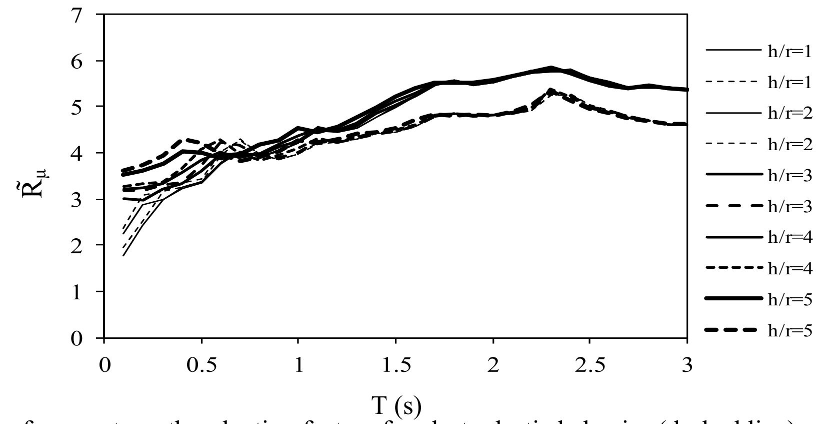


Fig. 9 Variations of mean strength reduction factors for elastoplastic behavior (dashed line) and Modified Clough (solid line) behavior against period for α = 5%. Results correspond to an interacting system with μ = 3

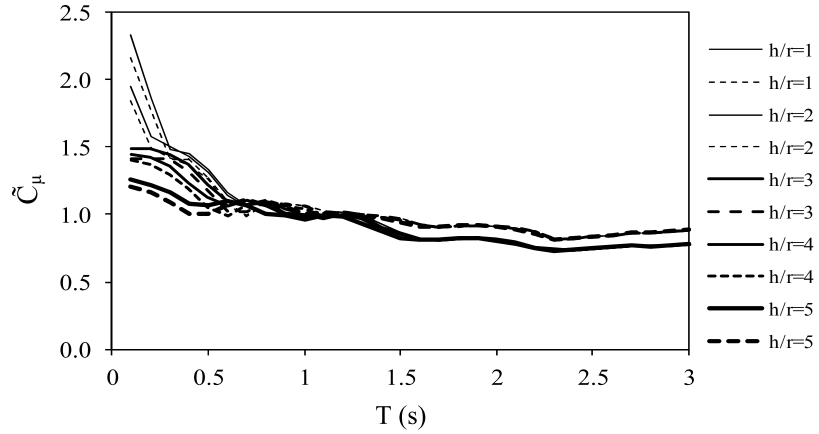


Fig. 10 Variations of mean inelastic displacement ratios for elastoplastic behavior (dashed line) and Modified Clough (solid line) behavior against period for α= 5%. Results correspond to an interacting system with μ = 3

It can be seen from Fig. 11 that, spectral regions and ductility ratios, where this ratio is larger than one, correspond to situations in which strength reduction factors of non-degrading systems are larger than those of degrading systems. Similarly, values in which this mean ratio is smaller than one correspond to situations in which the strength reduction factors of degrading systems are larger than those of non-degrading systems. It can be seen that, up to a certain period value this ratio is larger than one, from that period is smaller than one. These limiting values divide the region where it is unconservative to neglect the effects of stiffness degradation from spectral regions where it is conservative to neglect the effects of stiffness degradation. These limiting period values are not constant and increase as the level of inelastic behavior increases. Besides, it can be seen that there are spectral regions in which inelastic displacements of stiffness degrading systems are larger than those of elastoplastic systems (typically for small period values), while in

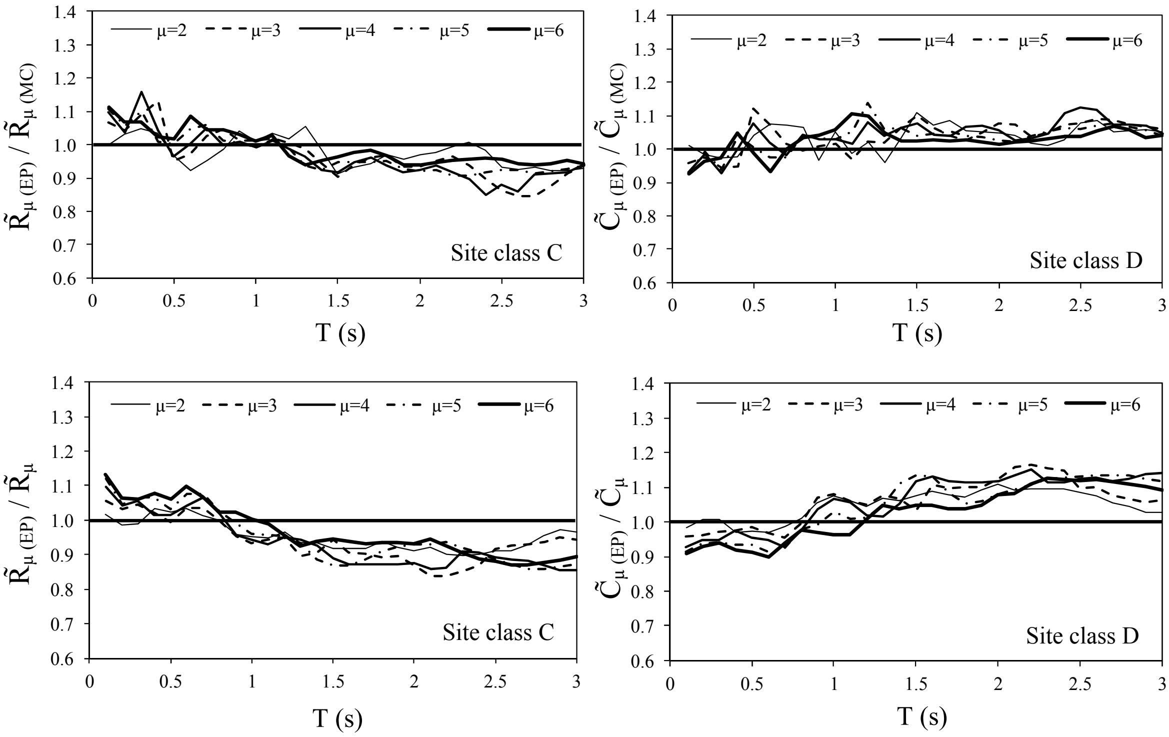


Fig. 11 Variations of the ratio between elastoplastic behavior and Modified Clough behavior against period for α= 5%. Results correspond to an interacting system with *h/r* = 3

other spectral regions the opposite is true (primarily for $T > 1.0$ s). It can be seen that limiting period values that separate spectral regions where inelastic displacements are larger for stiffness-degrading system from spectral regions where inelastic displacements are larger for elastoplastic systems are not constant and increase as the level of inelastic behavior increases.

6.5 Effect of strain hardening ratio

In Fig. 12, variations of mean strength reduction factors with strain hardening ratio for fixed-base (left) and interacting cases (right) are shown for site class D. Results are presented for a system with μ = 6 and h/r = 5. As mentioned above, the considered strain hardening ratio values in analyses are α = -10%, -5%, -2%, 0, 2%, 5%, 10%, respectively. It can be seen from Fig. 12 that, mean strength reduction factors of fixed-base case are almost always smaller than the corresponding ones of interacting case for all strain hardening ratios. Also it is seen that, strain hardening / softening has a significant effect on seismic response. Mean strength reduction factors decrease as the strain hardening ratio values decrease (i.e., for systems with negative hardening). Therefore, the strength of systems with a negative hardening stiffness needs to be increased considerably compared to hardening systems in order to limit the inelastic deformations to the same ductility ratio.

Variations of mean inelastic displacement ratios with strain hardening ratio for fixed-base (left) and interacting cases (right) are shown in Fig. 13 for a system with μ = 6 and h/r = 5 and for site

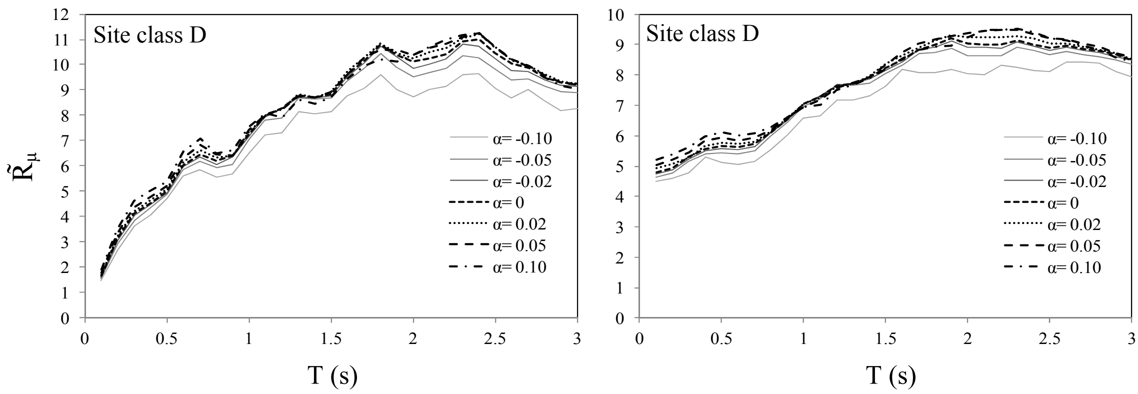


Fig. 12 Variations of mean strength reduction factors with strain hardening ratio for fixed-base (left) and interacting cases (right). Results correspond to a system with μ = 6 and h/r = 5

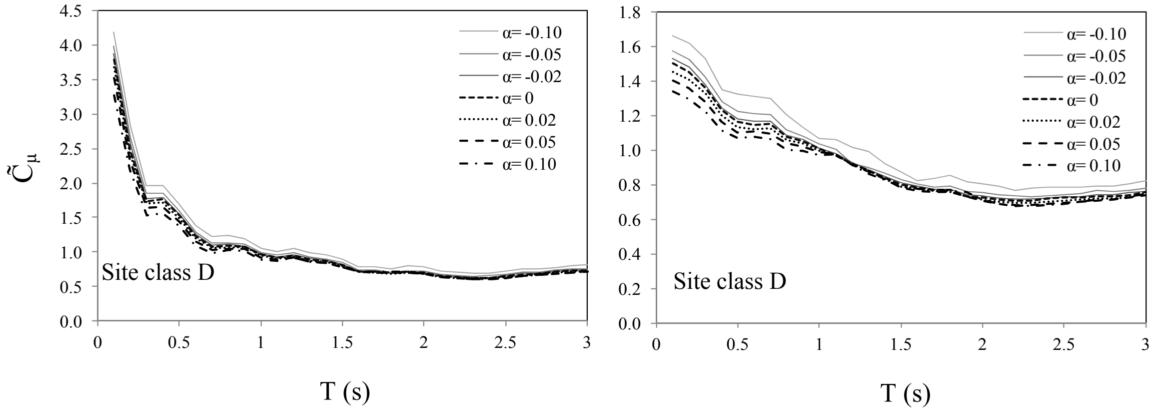


Fig. 13 Variations of mean inelastic displacement ratios with strain hardening ratio for fixed-base (left) and interacting cases (right). Results correspond to a system with μ = 6 and h/r = 5

class D. It is clearly seen from Fig. 13 that, mean inelastic displacement ratios of fixed base case are almost always greater than the corresponding ones of interacting case for all strain hardening ratios. Also, there is a significant strain hardening / softening effect on inelastic displacement demands. The figure illustrates that, for a given ductility, maximum inelastic deformation demands decrease as the level of post-yield stiffness ratio increases, and that the reduction in displacement demands depends on the spectral region. Fig. 14 shows the variation of mean strength reduction factors and mean inelastic displacement ratios with strain hardening ratio for site class C for a system with $\mu = 6$ and $h/r = 5$. It can be seen from the figure that, the same tendency of the results of site class D is also valid for the results of site class C.

7. Nonlinear regression analysis

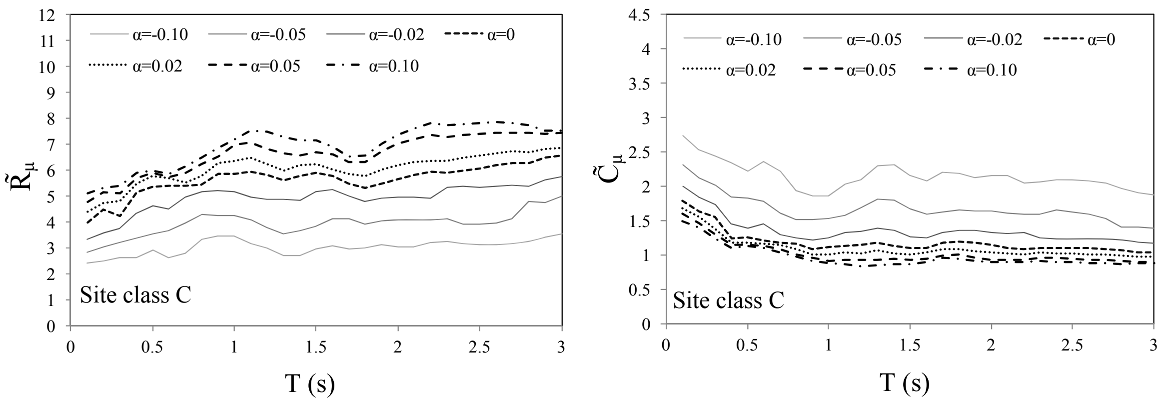


Fig. 14 Variations of mean strength reduction factors and inelastic displacement ratios with strain hardening ratio interacting cases. Results correspond to a system with $\mu = 6$ and h/r=5

In order to obtain appropriate formulas to represent the mean strength reduction factors and inelastic displacement ratios for all records, ductility values, aspect ratios, structural periods and strain hardening ratios 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 simplified expressions for estimating mean strength reduction factors and inelastic displacement ratios. The resulting regression formulas are appropriately simplified and expressed as

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

$$\tilde{C}_{\mu} = 1 + a(\mu - 1)(\tilde{T}^{b} + c) \tag{13}$$

The coefficients a ~ c are summarized in Table 3 for all data.

Fig. 15 shows the fitness of the regressed function of the mean $\tilde{R}_{\mu}$ and $\tilde{C}_{\mu}$ factors for all records, ductility values, aspect ratios and strain hardening ratios. The horizontal axis shows the calculated $\tilde{R}_{\mu}$ and $\tilde{C}_{\mu}$ values whereas the vertical axis shows the corresponding values obtained with proposed equations (Eqs. (12) and (13)).

Fig. 16 shows the fitness of the regressed function of the mean $\tilde{R}_{\mu}$ factor for different strain hardening ratios. In this figure, the dashed line represents the values obtained from the regressed function (Eq. 12) and the solid line represents the actual mean values of $\tilde{R}_{\mu}$ factors obtained from non-linear dynamic analyses. Results are presented for an interacting system with $\mu = 4$ and $h/r = 3$.

Table 3 Parameter Summary for Eq. (12) and Eq. (13)

Parameter	a	b	c	Correlation coefficient
$\tilde{R}_{\mu}$	0.542	$2.886 - 0.102\dfrac{\tilde{T}}{T}$	--	0.99
$\tilde{C}_{\mu}$	0.181	-0.591	-0.944	0.98

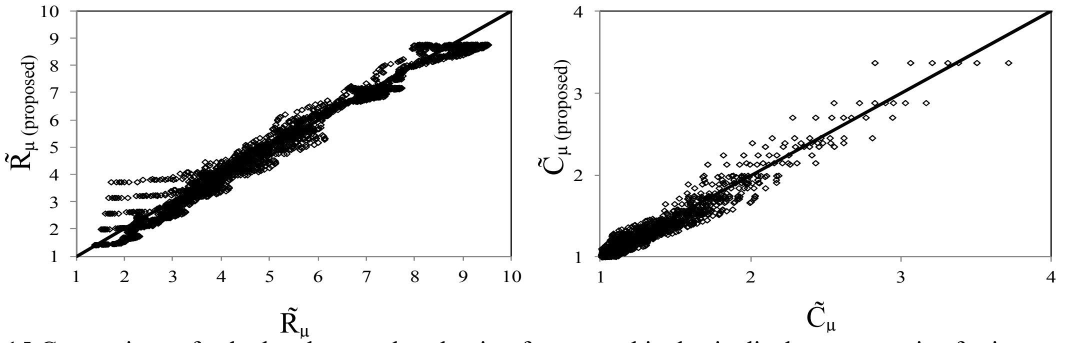


Fig. 15 Comparison of calculated strength reduction factors and inelastic displacement ratios for interacting systems with corresponding values obtained with proposed equation (Eq. (12) and Eq. (13))

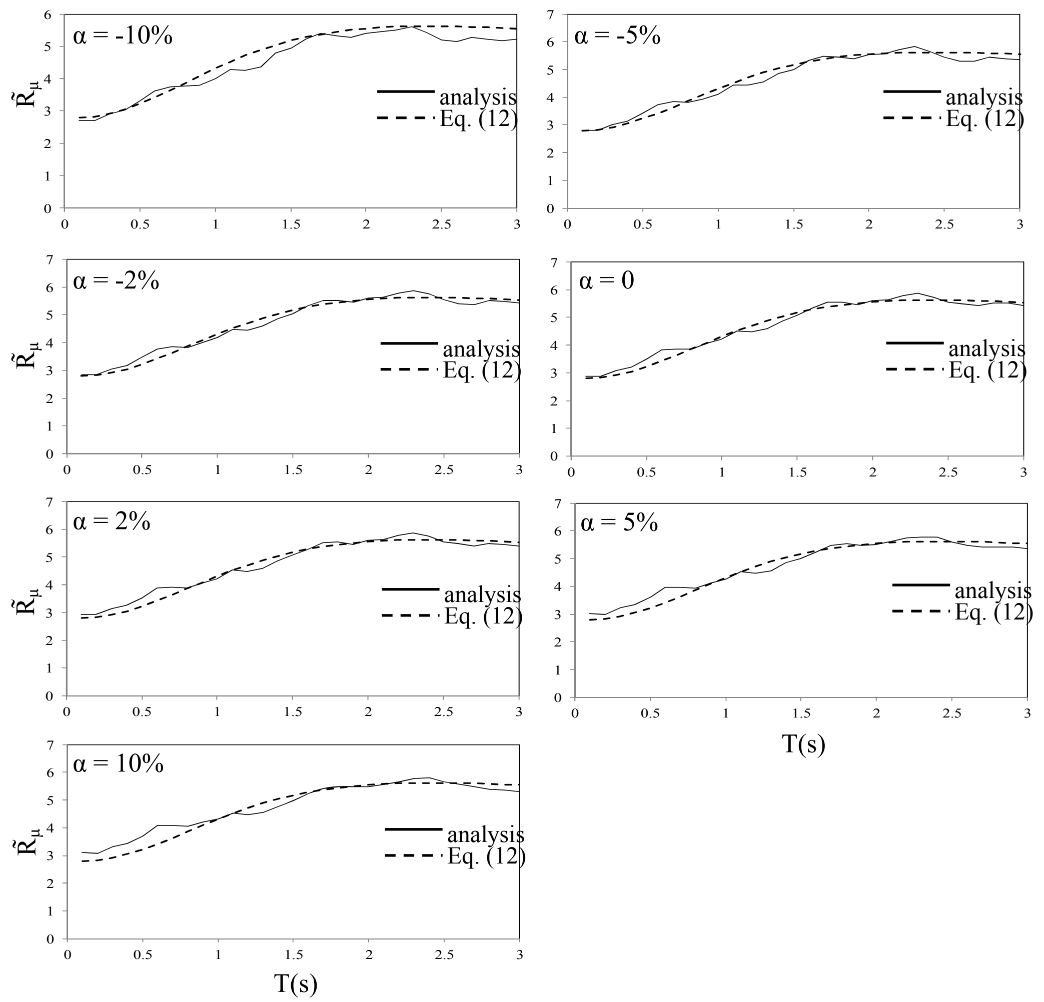


Fig. 16 Comparison of mean strength reduction factors (solid line) with interaction to those computed with Eq. (12) (dashed line). Results correspond to an interacting system with $\mu = 4$ and h/r = 3

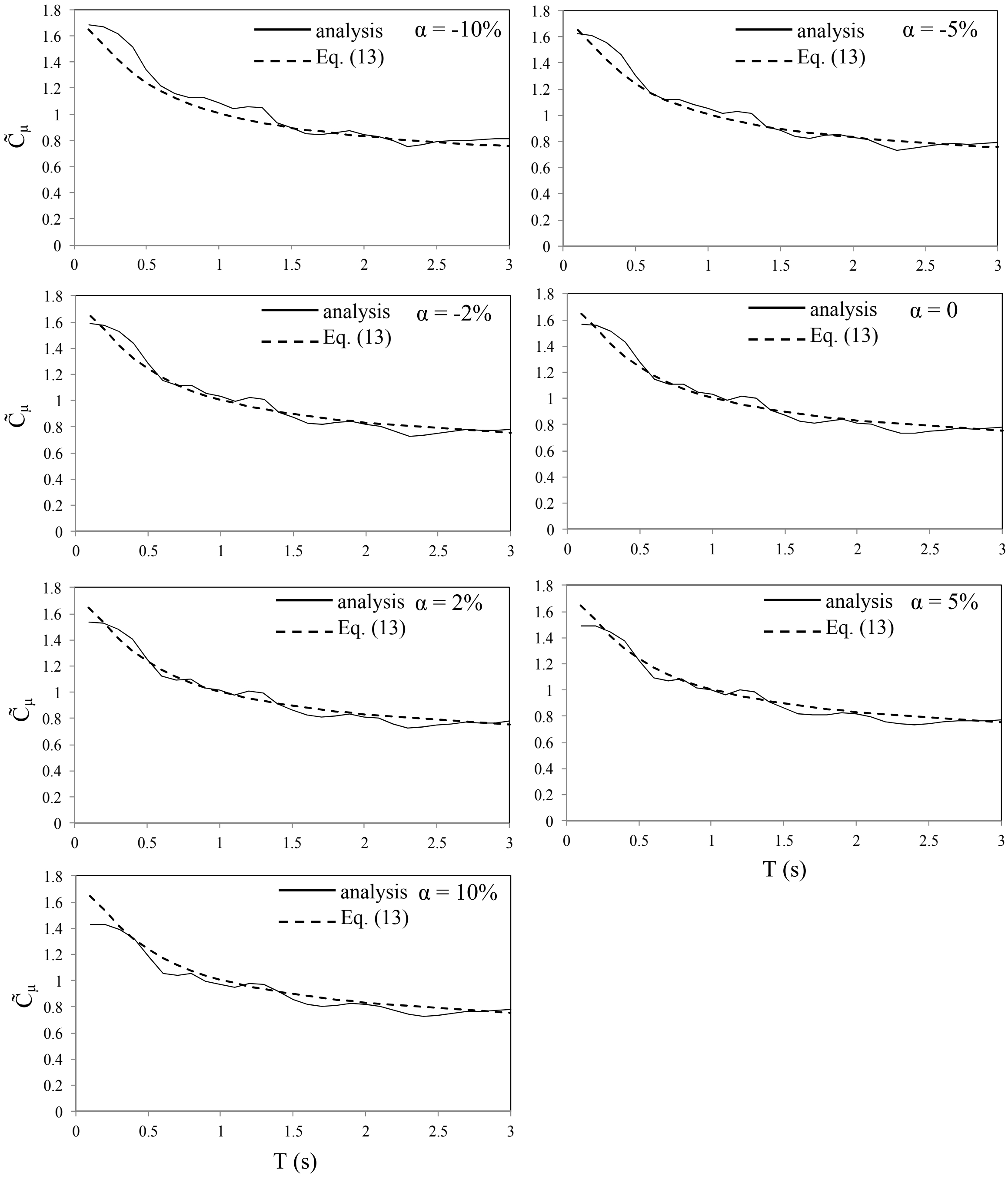


Fig. 17 Comparison of mean inelastic displacement ratios (solid line) with interaction to those computed with Eq. (13) (dashed line). Results correspond to an interacting system with $\mu = 4$ and $h/r = 3$

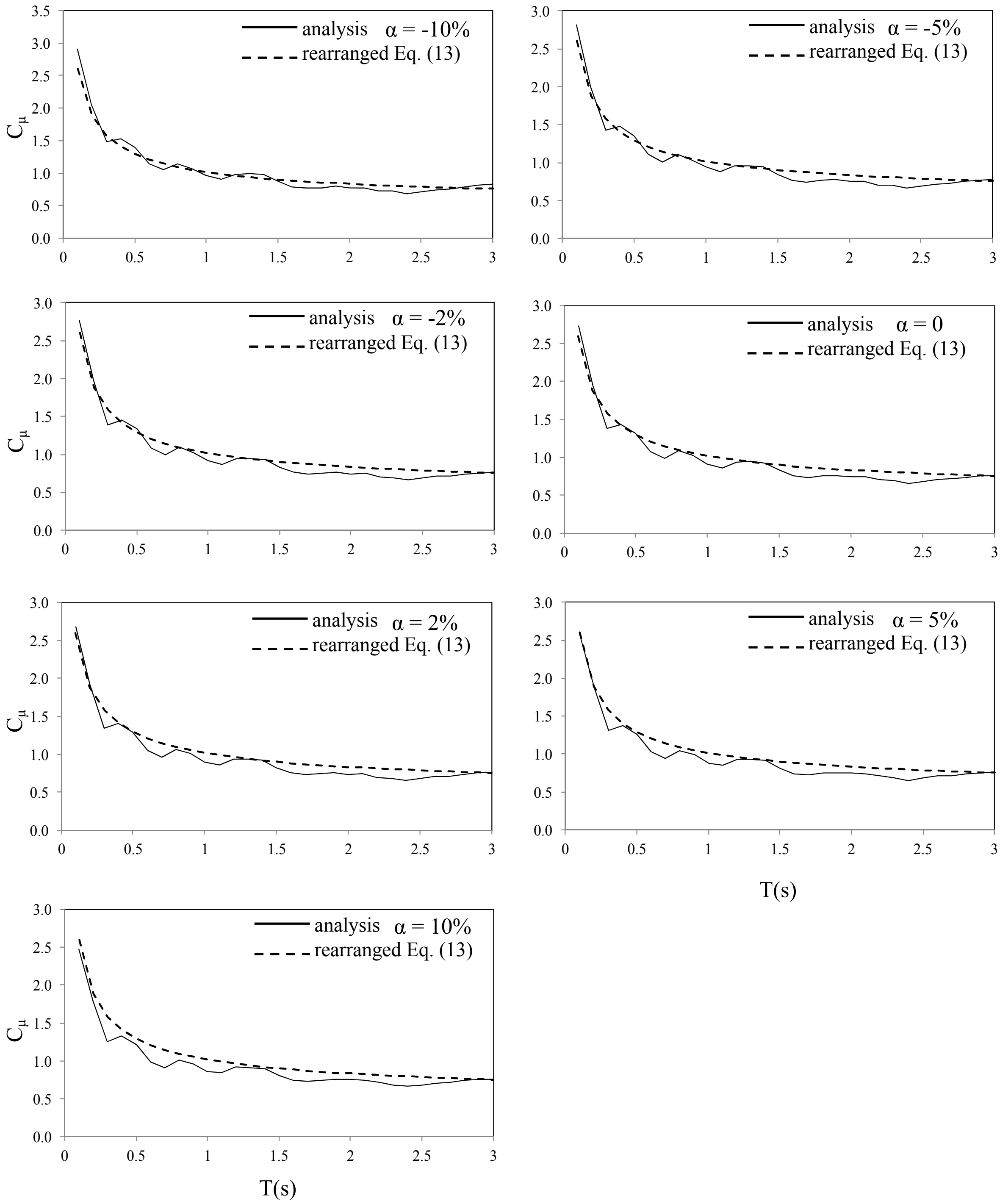


Fig. 18 Comparison of mean inelastic displacement ratios (solid line) for fixed-base case for $\mu = 4$ to those computed with rearranged Eq. (13) (dashed line)

Fig. 17 shows the fitness of the regressed function of the mean $\tilde{C}_\mu$ factor for different strain hardening ratios. In this figure, the dashed line represents the values obtained from the regressed function (Eq. 13) and the solid line represents the actual mean values of $\tilde{C}_\mu$ factors obtained from non-linear dynamic analyses. Results are presented for an interacting system with $\mu = 4$ and $h/r = 3$. Although Eq. (13) is derived for inelastic displacement ratios considering soil structure interaction, it is possible to use this function to obtain fixed-base inelastic displacement ratios. Replacing effective period of interacting system ($\tilde{T}$) with fixed base period (T), the fixed base inelastic displacement ratios can be obtained. Fitness of the rearranged function of the mean C_μ factor for fixed base case is shown in Fig. 18.

8. Conclusions

In this study, inelastic displacement ratios and strength reduction factors are investigated for SDOF systems with degrading and non-degrading behavior for period range of 0.1-3.0 s considering soil structure interaction for earthquake motions recorded on soft soil. For this purpose, the modified-Clough model is used to represent structures that exhibit significant stiffness degradation and the elastoplastic model is used to represent non-degrading structures. The effects of negative strain hardening on the demand and strength of structures are also investigated. New equations are proposed for mean inelastic displacement ratio and strength reduction factor of interacting systems as functions of structural period ($\tilde{T}$,T), ductility ratio (μ) and period lengthening ratio ($\tilde{T}/T$). The following conclusions can be drawn from the results of this study.

• Aspect ratio is an effective parameter for both inelastic displacement ratios and strength reduction factors in high frequency region for all strain hardening ratios. There is a decrease tendency for inelastic displacement ratios and an increase tendency for strength reduction factors up to a certain period, say 0.8 s, for increasing values of aspect ratio, but from this period point the effect of aspect ratio is negligible.

• Strength reduction factors of interacting systems are almost always smaller than the fixed-base strength reduction factors for both elastoplastic and Modified Clough behavior. Therefore, interaction effects should be considered for soft soil.

• The strength reduction factors against ductility for degrading systems are smaller than the corresponding ones of non-degrading systems up to period of nearly 0.8 s and from this period point vice versa. Mean inelastic displacement ratios against ductility for degrading systems are greater than the corresponding ones of non-degrading systems up to period of nearly 1.0 s and from this period point vice versa.

• Strain hardening / softening has a significant effect on seismic response and inelastic displacement demands. Mean strength reduction factors decrease as the strain hardening ratio values decrease (i.e. for systems with negative hardening). Therefore, the strength of systems with a negative hardening stiffness needs to be increased considerably compared to hardening systems in order to limit the inelastic deformations to the same ductility ratio. Also it is found that, for a given ductility, maximum inelastic deformation demands decrease as the level of post-yield stiffness ratio increases, and that the reduction in displacement demands depends on the spectral region.

• Two new equations (Eqs. (12) and (13)) are proposed to represent the mean strength reduction factors and inelastic displacement ratios for all records, ductility values, aspect ratios, strain hardening ratios and structural periods as a function of structural period of interacting system ($\tilde{T}$), ductility ratio (μ) and period lengthening ratio ($\tilde{T}/T$). The proposed simplified expressions provide a good approximation of mean strength reduction factors and mean inelastic displacement ratios of SDOF systems having degrading behavior.

• Although Eq. (13) is derived for inelastic displacement ratios considering soil structure interaction, it is possible to use this function to estimate fixed-base inelastic displacement ratios. Replacing effective period of interacting system ($\tilde{T}$) with fixed base period (T), the fixed base inelastic displacement ratios can be obtained. This simplification satisfies the mean C_μ factor for fixed base case.

References

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

Aviles, J. and Perez-Rocha, L.E. (2005), "Influence of foundation flexibility on R_μ and C_μ factors", *Journal of Structural Engineering, ASCE*, **131**, No.2.

Aviles, J. and Perez-Rocha, L.E. (2011), "Use of global ductility for design of structure–foundation systems", *Soil Dynamics and Earthquake Engineering*, **31**, 1018-1026.

Ayoub, A. and Chenouda, M. (2009), "Response spectra of degrading structural systems", *Engineering Structures*, **31**, 1393-1402.

Bates, D.M. and Watts, D.G. (1988), *Nonlinear regression analysis and its applications*, Wiley, New York.

Borzi, B., Calvi, G.M., Elnashai, A.S., Faccioli, E. and Bommer, J.J. (2001), "Inelastic spectra for displacement-based seismic design", *Soil Dyn. Earthquake Eng.*, **21**(1), 47-61.

Chopra, A.K. and Chintanapakdee, C. (2004) "Inelastic deformation ratios for design and evaluation of structures: Single-degree-of-freedom bilinear systems", *Journal of Structural Engineering*, **130**(9), 1309-1319.

Clough, R.W. and Johnston, S.B. (1966), "Effect of stiffness degradation on earthquake ductility requirements", *Proc. of the Japan Earthquake Engineering Symposium*, Tokyo, Japan.

Decanini, L., Liberatore, L. and Mollaioli, F. (2003), "Characterization of displacement demand for elastic and inelastic SDOF systems", *Soil Dynamics and Earthquake Engineering*, **23**,455-471.

Elghadamsi, F.E. and Mohraz, B. (1987), "Inelastic earthquake spectra", *Earthquake Engineering and Structural Dynamics*, **15**, 91-104.

Eser, M. and ve Aydemir, C. (2011), "The effect of soil-structure interaction on inelastic displacement ratio of structures", *Structural Engineering and Mechanics*, **39**(5), 683-701.

Eser, M., ve Aydemir, C. and ve Ekiz, İ. (2012), "Soil structure interaction effects on strength reduction factors", *Structural Engineering and Mechanics*, **41**(3), 365-378.

Eser, M., Aydemir, C. and ve Ekiz, İ. (2012), "Inelastic displacement ratios for structures with foundation flexibility", *KSCE Journal of Civil Engineering*, **16**(1), DOI: 10.1007/s12205-012-1266-5.

Federal Emergency Management Agency (2003), "Recommended provisions for seismic regulations for new buildings and other structures", Rep. FEMA-450, Federal Emergency Management Agency, Washington (DC).

Federal Emergency Management Agency (2009), "Effects of Strength and Stiffness Degradation on Seismic Response", FEMA P440A, Federal Emergency Management Agency, Washington (DC).

Ghannad, M.A. and Jahankhah, H. (2007), "Site-dependent strength reduction factors for soil-structure systems", *Soil Dynamics and Earthquake Engineering*, **27**, 99-110.

Gupta, A. and Krawinkler, H. (1998), "Effect of stiffness degradation on deformation demands for SDOF and MDOF structures." *Proc., 6th Natl. Conf. on Earthquake Engineering*, Earthquake Engineering Research Institute, Oakland, California.

Gupta, B. and Kunnath, S.K. (1998), "Effect of hysteretic model parameters on inelastic seismic demands", *Proc., 6th Natl. Conf. on Earthquake Engineering*, Earthquake Engineering Research Institute, Oakland, California.

Lai, S.P. and Biggs, J.M. (1980), "Inelastic response spectra for a seismic building design", *Journal of Structural Engineering*, *ASCE*, **106**, 1295-310.

Lee, L.H., Han, S.W. and Oh, Y.H. (1999), "Determination of ductility factor considering different hysteretic models", *Earthquake Engineering and Structural Dynamics*, **28**(9), 957-977.

Miranda, E. (1993), "Site dependent strength reduction factors", *Journal of Structural Engineering, ASCE*, **119**(12), 3503-3519.

Miranda, E. and Ruiz-Garcia, J. (2002), "Influence of stiffness degradation on strength demands of structures built on soft soil sites", *Engineering Structures*, **24**(10), 1271-128.

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.

Rahnama, M. and Krawinkler, H. (1993), "Effects of soft soil and hysteresis model on seismic demands", Rep. No. 108, John A. Blume Earthquake Engineering Center, Stanford Univ., Stanford, California.

Raychowdhury, P. (2011), "Seismic response of low-rise steel moment-resisting frame (SMRF) buildings incorporating nonlinear soil–structure interaction (SSI)", *Engineering Structures*, **33**, 958-967.

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 modification factors for earthquake resistant design of short period structures", *Earthquake Spectra*, **5**(3), 571-590.

Roy, R. and Dutta, S.C. (2010), "Inelastic seismic demand of low-rise buildings with soil-flexibility", *International Journal of Non-Linear Mechanics*, **45**, 419-432.

Ruiz-Garcia, J. and Miranda, E. (2004), "Inelastic displacement ratios for design of structures on soft soils sites", *Journal of Structural Engineering*, *ASCE*, **130**(12), 2051-2061.

Ruiz-Garcia, J. and Miranda, E. (2006), "Inelastic displacement ratios for evaluation of structures built on soft soils sites", *Earthquake Engineering and Structural Dynamics*, **35**, 679-694.

StatSoft 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", *Proc. of the Second World Conference on Earthquake Engineering*, Tokyo, 895-912.

Veletsos, A.S., Newmark, N.M. and Chelapati, C.V. (1965), "Deformation spectra for elastic and elastoplastic systems subjected to ground shock and earthquake motions", *Proc. of the Third World Conference on Earthquake Engineering*, **7**, New Zealand.

Veletsos, A.S. and Meek, J.W. (1974), "Dynamic behavior of building–foundation systems", *Earthquake Engineering and Structural Dynamics*, **3**, 121-138.

Veletsos, A.S. and Nair, V.V.D. (1975), "Seismic interaction of structures on hysteretic foundations", *Journal of Structural Engineering*, *ASCE*, **101**(1), 935-956.

Veletsos, A.S. (1977), "Dynamics of structure–foundation systems", *Structural Geotechnical Mechanics*, Ed. W.J. Hall, Prentice-Hall, Englewood Cliffs, N.J., 333-361.

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

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

Wolf, J.P. and Somaini, D.R. (1986), "Approximate dynamic model of embedded foundation in time domain", *Earthquake Engineering and Structural Dynamics*, **14**, 683-703.