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The effect of soil-structure interaction on inelastic displacement ratio of structures

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Abstract. In this study, inelastic displacement ratios and ductility demands are investigated for SDOF systems with period range of 0.1-3.0 s. with elastoplastic behavior considering soil structure interaction. Earthquake motions recorded on different site conditions such as rock, stiff soil, soft soil and very soft soil are used in analyses. Soil structure interacting systems are modeled 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 inelastic displacement ratio of interacting system ($\tilde{C}_R$) as a function of structural period of interacting system ($\tilde{T}$), strength reduction factor (R) and period lengthening ratio ($\tilde{T}/T$). The proposed equation for $\tilde{C}_R$ which takes the soil-structure interaction into account should be useful in estimating the inelastic deformation of existing structures with known lateral strength.

Keywords: soil-structure interaction; inelastic displacement ratio; ductility demand; lateral strength; seismic analysis

1. Introduction

Current performance-based seismic design methods use displacements rather than forces as basic demand parameters for the design, evaluation and rehabilitation of structures. Performance-based seismic design methodologies 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 structural system elements and nonstructural components. Thus, implementation of displacement-based seismic design criteria into structural engineering practice requires simplified analysis procedures to estimate seismic demands by applying the nonlinear static procedure or pushover analysis presented in FEMA273 (1997), FEMA356 (2000), or ATC-40 guidelines (1996). With this purpose, inelastic displacement ratio (C_R) is used to estimate peak inelastic displacement demand from peak elastic displacement demand.

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Inelastic displacement ratio 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.

Inelastic displacement ratios have been the topic of several investigations so far. The first well-known studies 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. Recently, Miranda *et al*. (2000, 2003, 2004, 2006), Aydınoğlu and Kaçmaz (2002), 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. Aviles and Perez-Rocha (2005) investigated 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 addition to these researches, there are 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, inelastic displacement ratios are investigated for SDOF systems having elastoplastic behavior with period range of 0.1-3.0 s for five different aspect ratios (h/r = 1, 2, 3, 4, 5) and following strength reduction factors R = 1.5, 2, 3, 4, 5 and 6 considering soil structure interaction. Aspect ratio is defined as the ratio of height to foundation radius of system whereas strength reduction factor used in seismic design codes is the ratio of elastic base shear to the one required for a target ductility level. In analyses 64 ground motions recorded on different site conditions such as rock, stiff soil, soft soil and very soft soil are used. 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, initial stiffness, k, and strength, f_y 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.

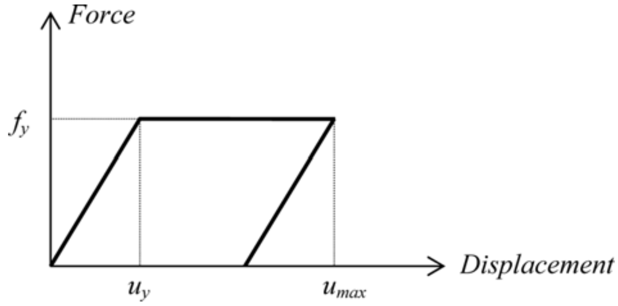

Fig. 1 Elastoplastic model of an SDOF system

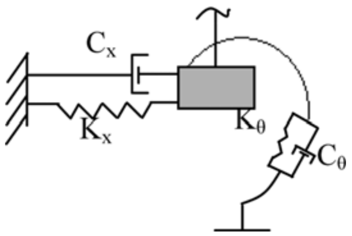

Fig. 2 Mathematical model of support with soil structure interaction

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

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

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

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

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). A schematical view considering soil structure interaction modeling of supports is shown in Fig. 2.

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)

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

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

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

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

3. Analysis method

A total of 69120 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), six strength reduction factors (R = 1.5, 2, 3, 4, 5, 6) and 64 ground motions.

For fixed-base case, dynamic time history analyses have been conducted for specified strength reduction factors and ductility demands (μ) and inelastic displacement ratios (C_R) are computed for the constant relative strength. Unlike the constant ductility inelastic displacement ratio (C_μ) that has to be computed through iteration on the lateral strength until the computed displacement ductility demand is equal to the target ductility ratio within a certain tolerance, the constant relative strength inelastic displacement ratio (C_R) can be computed without any iteration and thus, for a given acceleration time history, it is significantly faster to compute. For soil structure interacting case, analyses have been repeated for the same yield strength of the fixed-base case. Thus, ductility demands ($\tilde{\mu}$) and inelastic displacement ratios ($\tilde{C}_R$) of interacting systems are computed for the constant yield strength.

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 (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 described soil-structure model is analyzed in time domain. The dynamic equation of motion of an SDOF system is given by

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

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 (ATC-40 1996, ATC-63 2008). Details of selected ground motions are listed in Table 1. Site classes given in tables 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 A, between 360-750 m/s for site B, 180-360 m/s for site C and lower than 180 m/s for site class D. Soil - structure interacting systems are assumed to be located on soil profiles with shear velocities of 750 m/s for site A, 400 m/s for site B, 250 m/s for site C and 150 m/s for site D in analyses.

3.1 Equivalent fixed-base model

The main effects of soil structure interaction on elastic behavior of structures is to increase the natural period of system and, usually, to increase effective damping ratio. For this reason, the most common approach to consider soil structure interaction effects is to use a single degree of freedom replacement oscillator with effective period and effective damping for the system. Constant coefficients for springs and dampers are used in developing equivalent models. The first well-known studies on the use of replacement oscillator were conducted by Veletsos and his co-workers (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). The mass of this equivalent oscillator is taken to be equal to that of the actual structure. Under harmonic base

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	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

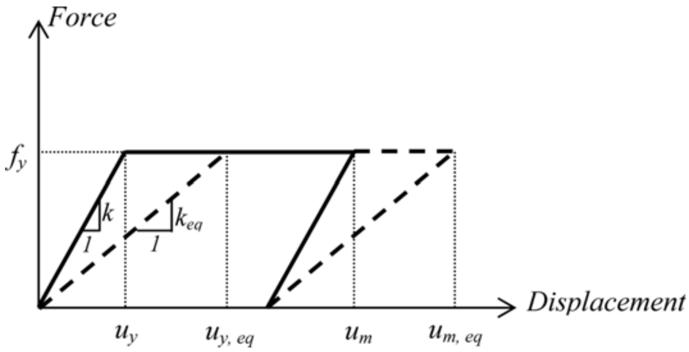

Fig. 3 Force-displacement relationships for the actual structure (solid line) and equivalent fixed-base model (dashed line) (Aviles and Perez-Rocha 2003)

excitation, it is imposed that the resonant period and peak response of the interacting system be equal to those of the replacement oscillator. 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 for the interacting system is given by the equation below

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

where β_0 denotes the foundation damping factor and values for this factor should be read from the figure given in current U.S. codes (ATC-3-06 1984, FEMA-450 2003).

The force-displacement relationship for the actual structure and equivalent fixed-base model is shown in Fig. 3.

4. Statistical study for inelastic displacement ratios

The relation of the inelastic displacement ratio of interacting system versus the structural period and strength reduction factor is regressed for the series of the aforementioned 69120 analyses in such a way 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 inelastic displacement ratio of interacting system is a function of structural period of interacting system ($\tilde{T}$), strength reduction factor (R) and period lengthening ratio ($\tilde{T}/T$).

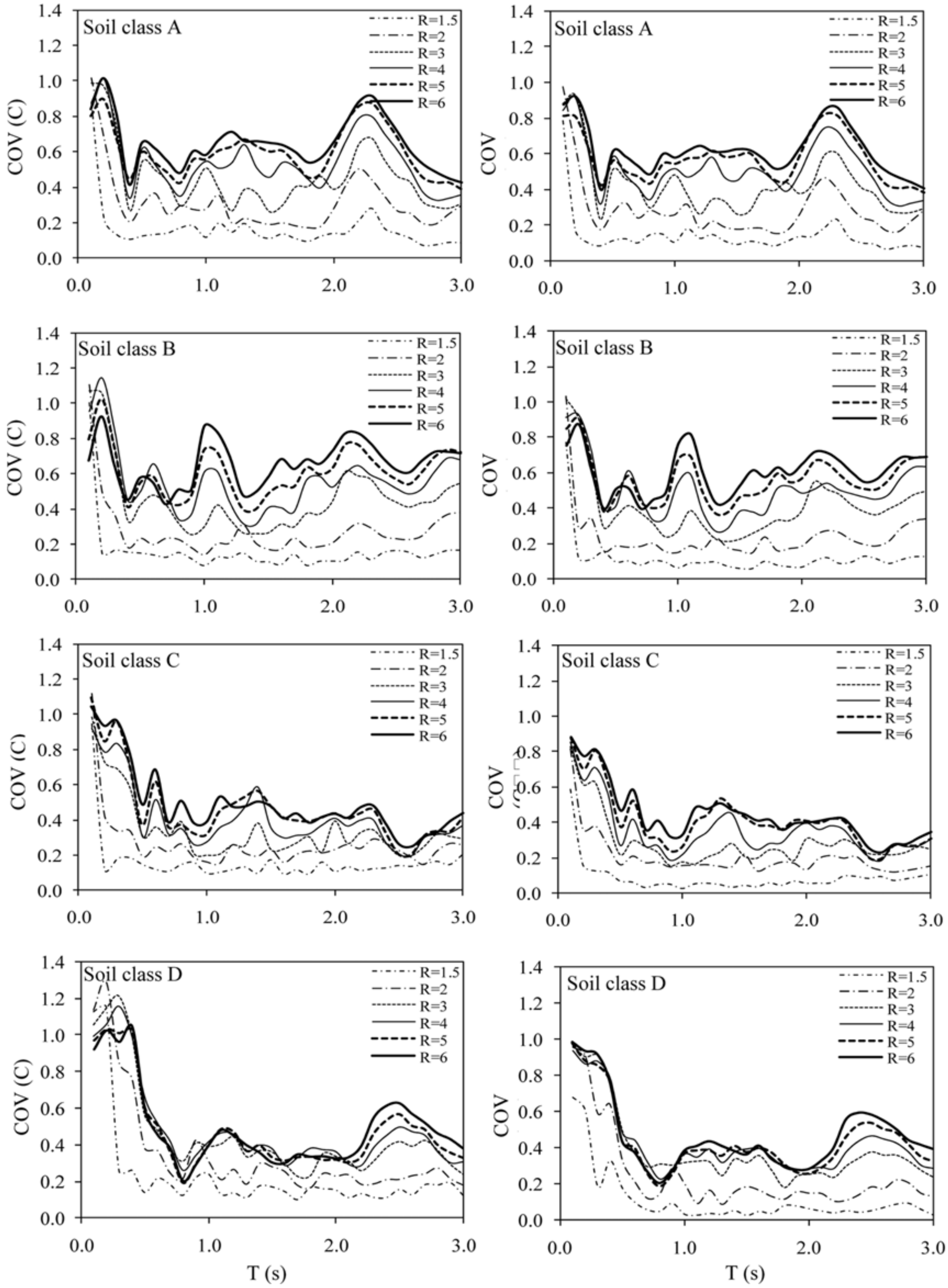

Fig. 4 COVs of inelastic displacement ratios of fixed base and interacting cases

4.1 Dispersion

Although mean inelastic displacement ratios are very important to be representative of what can be expected on average, it is also important to quantify the level of dispersion in C_R. 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 COVs of inelastic displacement ratios of fixed base and interacting cases for all ground motions and all aspect ratios considered herein. It can be seen that, the dispersion in inelastic displacement ratios for both fixed base and interacting cases, increases with increasing strength reduction factor. Dispersion is particularly high for periods of vibration shorter than 0.5 s regardless of the lateral strength ratio. For site classes A and B, dispersion in inelastic displacement ratios is larger than the dispersion of site classes of C and D.

4.2 Site effects on mean inelastic displacement ratios

In Fig. 5, variations of mean inelastic displacement ratios against period on different soil types are shown for cases with (solid line) and without (dashed line) interaction for an interacting system with strength reduction factor of 1.5 and 6 and aspect ratio of 3. It can be seen from the figure that, interaction effect is negligible for site classes A and B, whereas this effect should be considered for site classes C and especially D. Especially for short period region, inelastic displacement ratios of fixed-base and interacting system are considerably different for increasing strength reduction factors. For site classes C and D, there is an increase tendency for periods shorter than 0.5 s.

Variations of mean inelastic displacement ratios against period on different soil types for increasing values of *h/r* and strength reduction factors of 2 and 6 are shown in Fig. 6. It can be seen from the figure that, aspect ratio is an effective parameter for inelastic displacement ratios in high frequency region for all site classes and all strength reduction factors but especially for site classes C and D and strength reduction factor of 6. There is a decrease tendency up to a certain period, say 0.5 s, for increasing values of aspect ratio, but from this period point the effect of aspect ratio on inelastic displacement ratios is negligible.

Fig. 7 shows the ratio of mean inelastic displacement ratios for cases with and without interaction against structural period for all strength reduction factor levels and aspect ratios. The results demonstrate that fixed-base inelastic displacement ratios are greater than the corresponding ones of interacting systems. Although the maximum ratio of mean inelastic displacement ratio for cases with and without interaction is nearly 2.5 for site class A, this ratio becomes more than 20 for site class D in the high frequency region. These ratios increase for site class C and D remarkably.

4.3 Site effects on ductility demands

In Fig. 8, variations of mean ductility demands against period on different soil types are shown for cases with (solid line) and without (dashed line) interaction for an interacting system with strength reduction factor of 1.5 and 6 and aspect ratio of 3. It can be seen from the figure that, interaction effect is negligible for site classes A and B, whereas this effect should be considered for site classes C and especially D. Especially for short period region, ductility demands of fixed-base

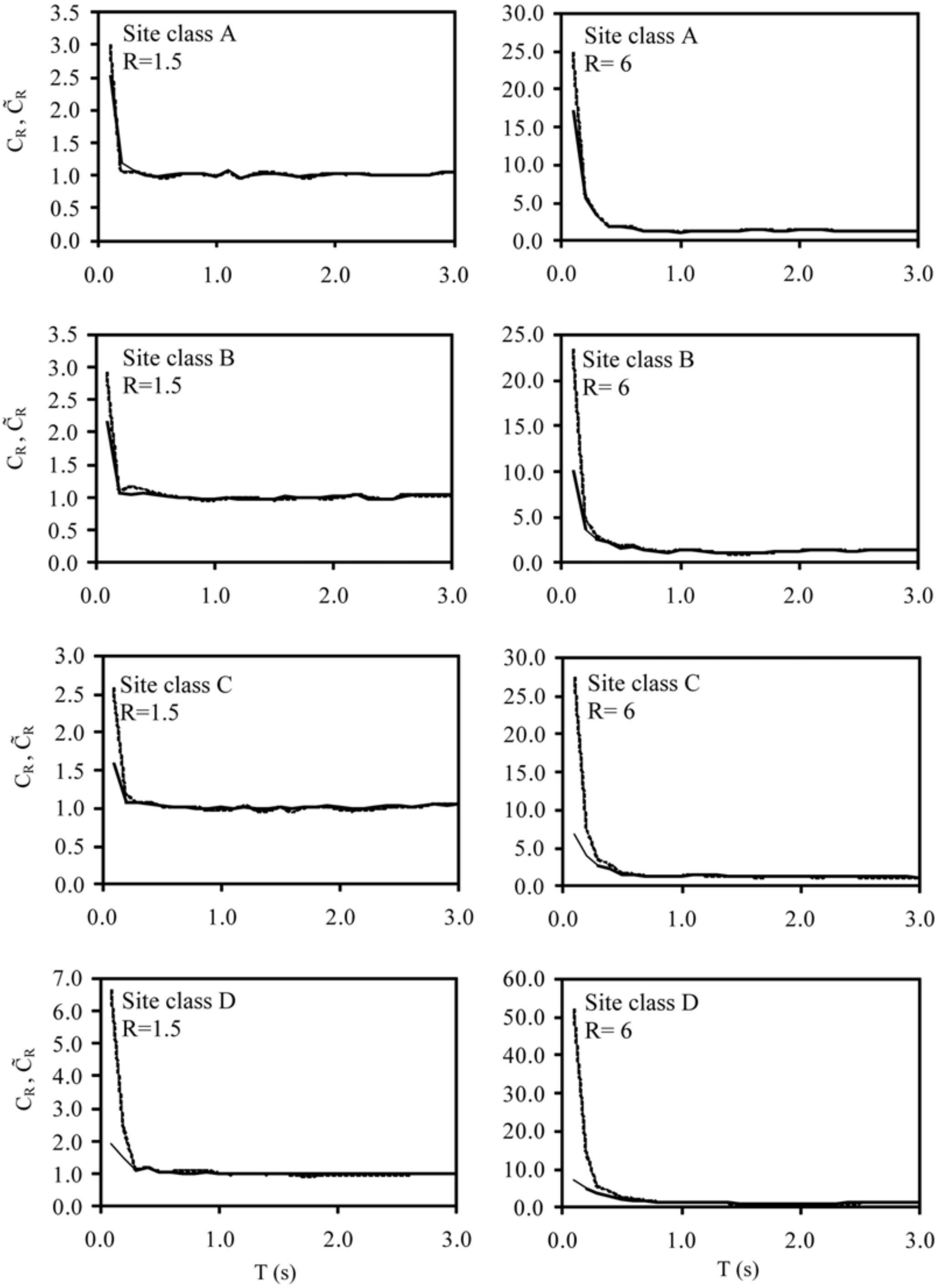

Fig. 5 Variations of mean inelastic displacement ratios against period on different soil types are shown for cases with (solid line) and without (dashed line) interaction for an interacting system with R = 1.5 and 6 and with h/r = 3

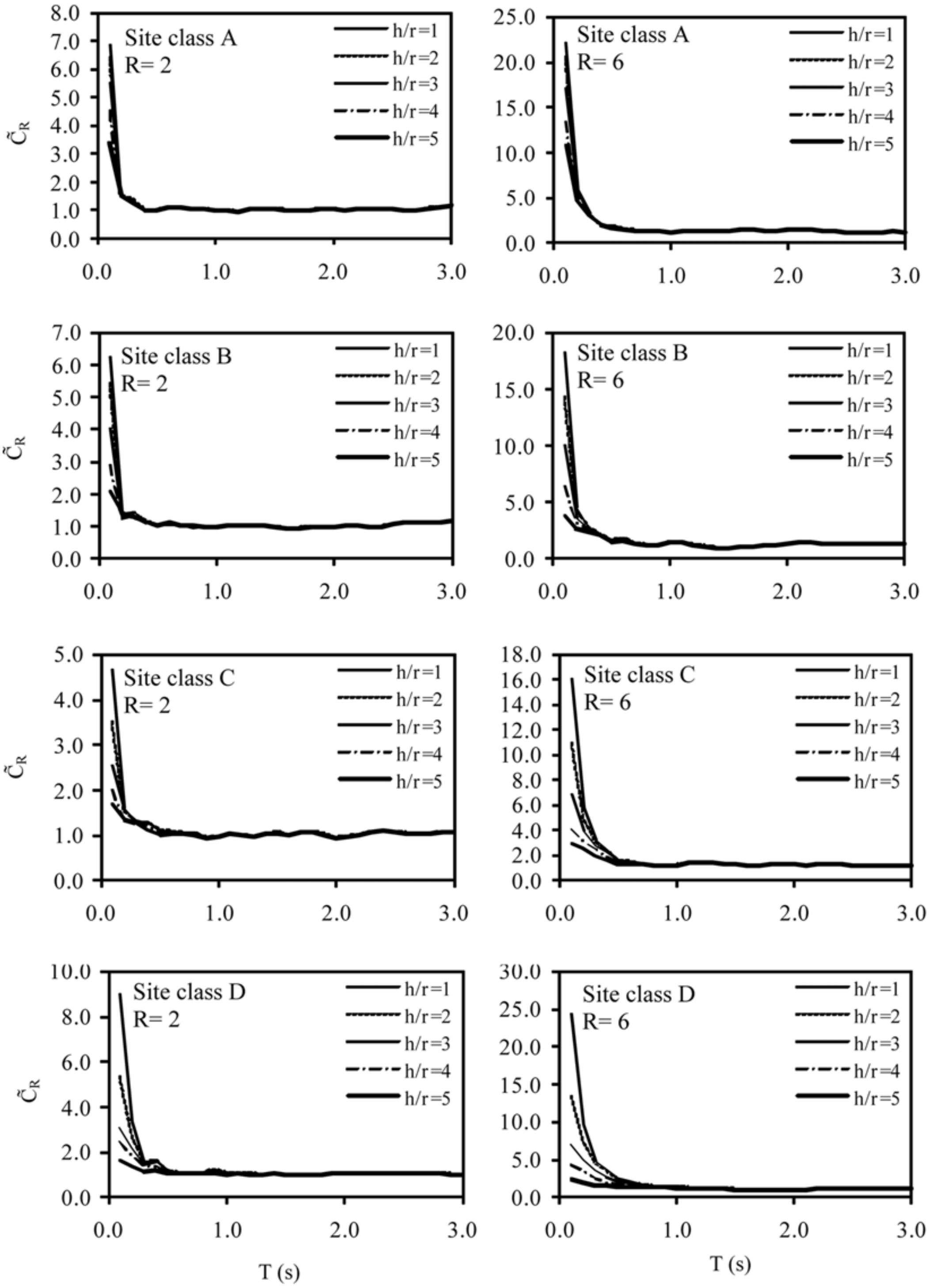

Fig. 6 Variations of mean inelastic displacement ratios against period on different soil types for increasing values of *h/r*. Results correspond to an interacting system with R = 2 and 6

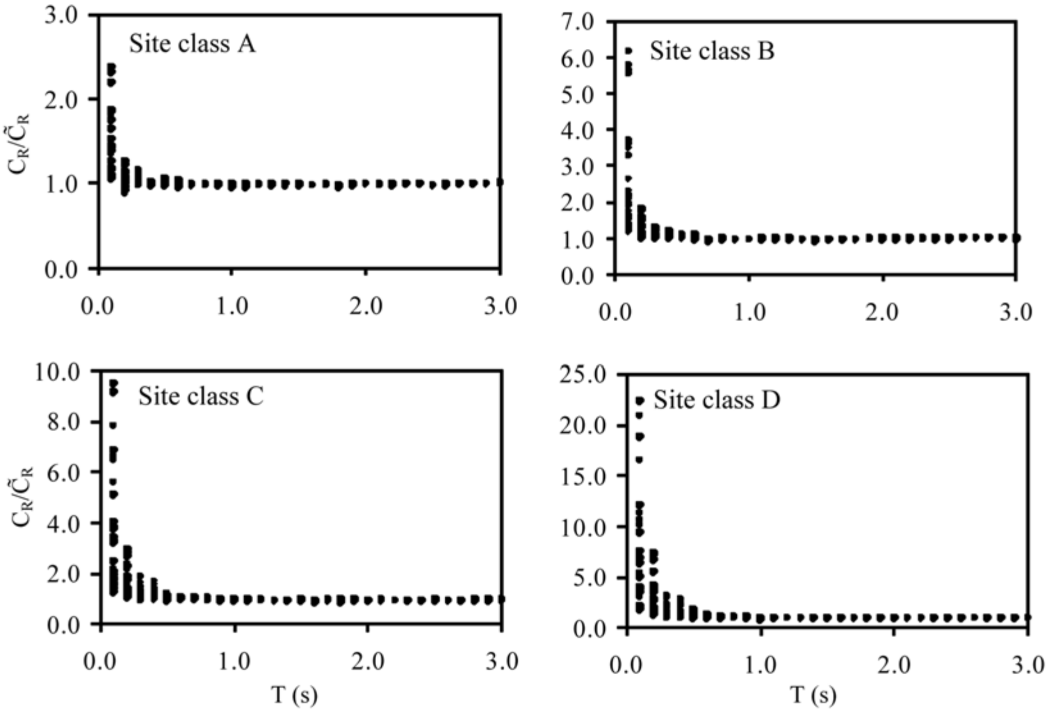

Fig. 7 Ratio of mean inelastic displacement ratios for cases with and without interaction for all strength reduction levels and aspect ratios

and interacting system are considerably different for increasing strength reduction factors. For site classes C and D, there is an increase tendency for periods shorter than 0.5 s.

Variations of mean ductility demands against period on different soil types for increasing values of *h/r* and strength reduction factors of 2 and 6 are shown in Fig. 9. It can be seen from the figure that, aspect ratio is an effective parameter for ductility demands in high frequency region for all site classes and all strength reduction factors but especially for site classes C and D and strength reduction factor of 6. There is a decrease tendency up to a certain period, say 0.5 s, for increasing values of aspect ratio, but from this period point the effect of aspect ratio on ductility demands is negligible.

Fig. 10 shows the ratio of mean ductility demands for fixed-base and with interaction against structural period for all strength reduction factor levels and aspect ratios. The results demonstrate that fixed-base ductility demands are greater than the corresponding ones of interacting systems. The maximum ratio of mean ductility demand for cases without and with interaction is nearly 16 in the high frequency region whereas this ratio decreases for higher period values.

4.4 Nonlinear regression analysis

In order to obtain an appropriate formula to represent the mean inelastic displacement ratios of interacting systems for all records, strength reduction factors, aspect ratios and structural periods combined, nonlinear regression analyses are carried out. Using the Levenberg-Marquardt method

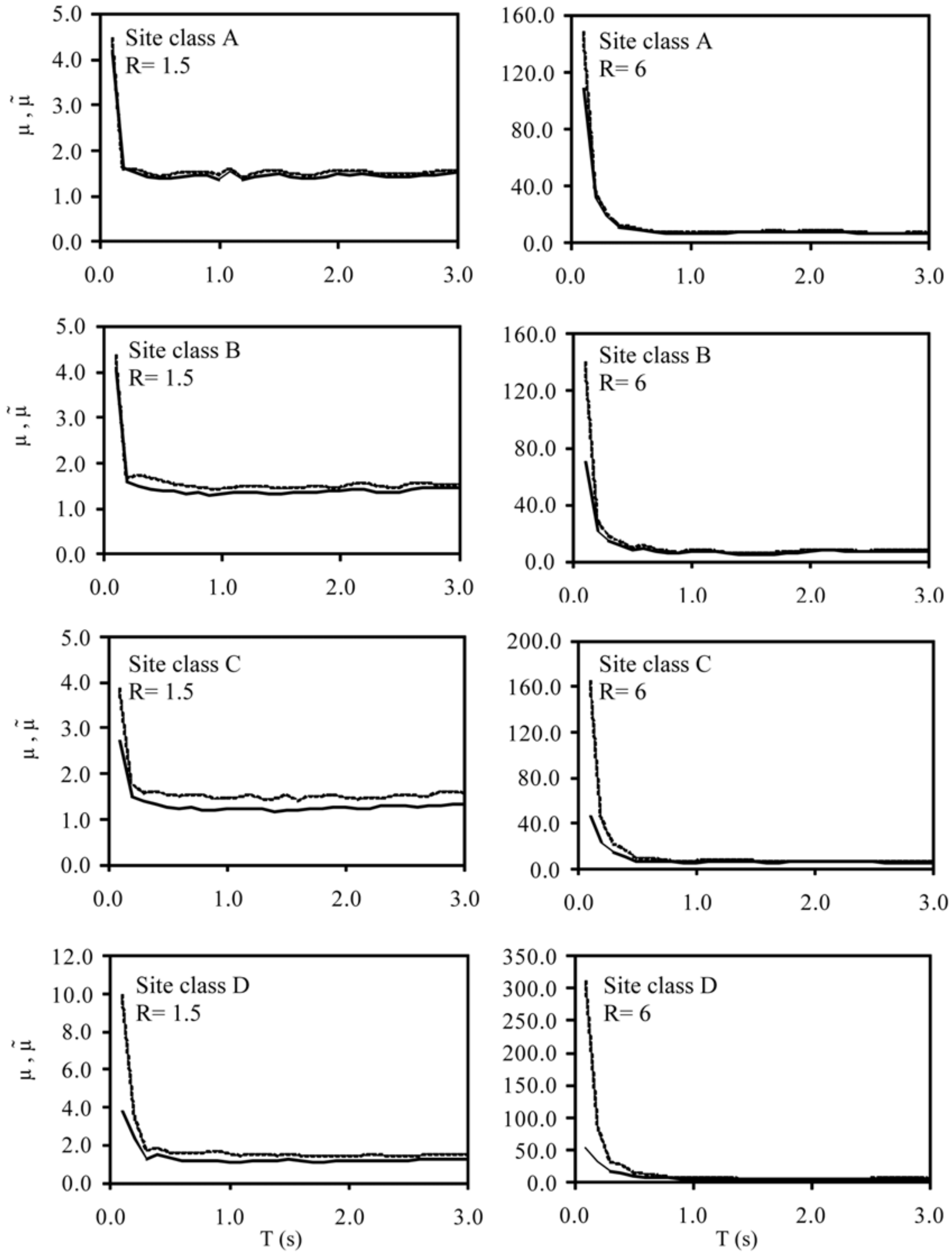

Fig. 8 Variations of mean ductility demands against period on different soil types are shown for cases with (solid line) and without (dashed line) interaction for an interacting system with R = 1.5 and 6 and with h/r = 3

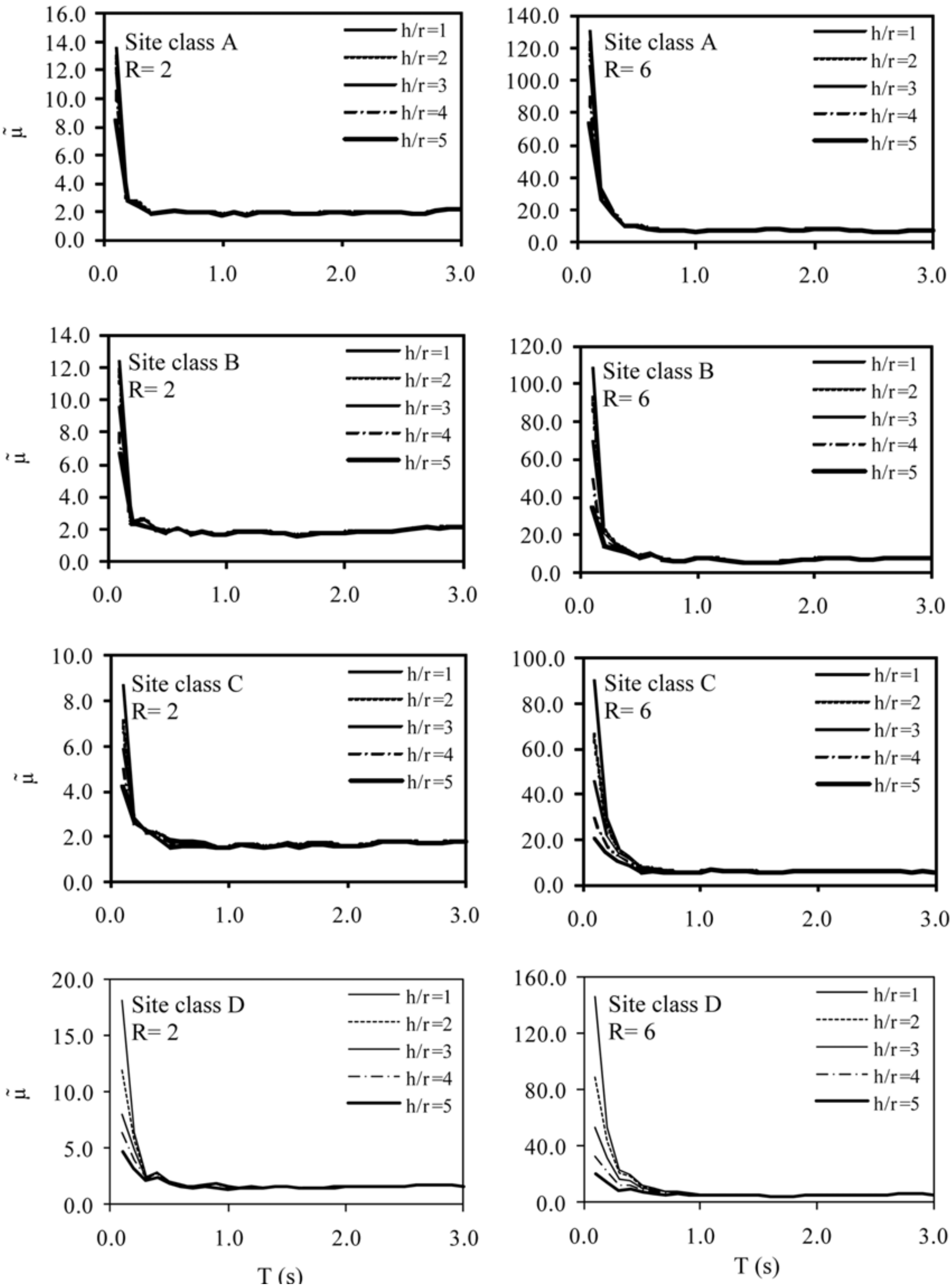

Fig. 9 Variations of mean ductility demands against period on different soil types for increasing values of *h/r*. Results correspond to an interacting system with R = 2 and 6

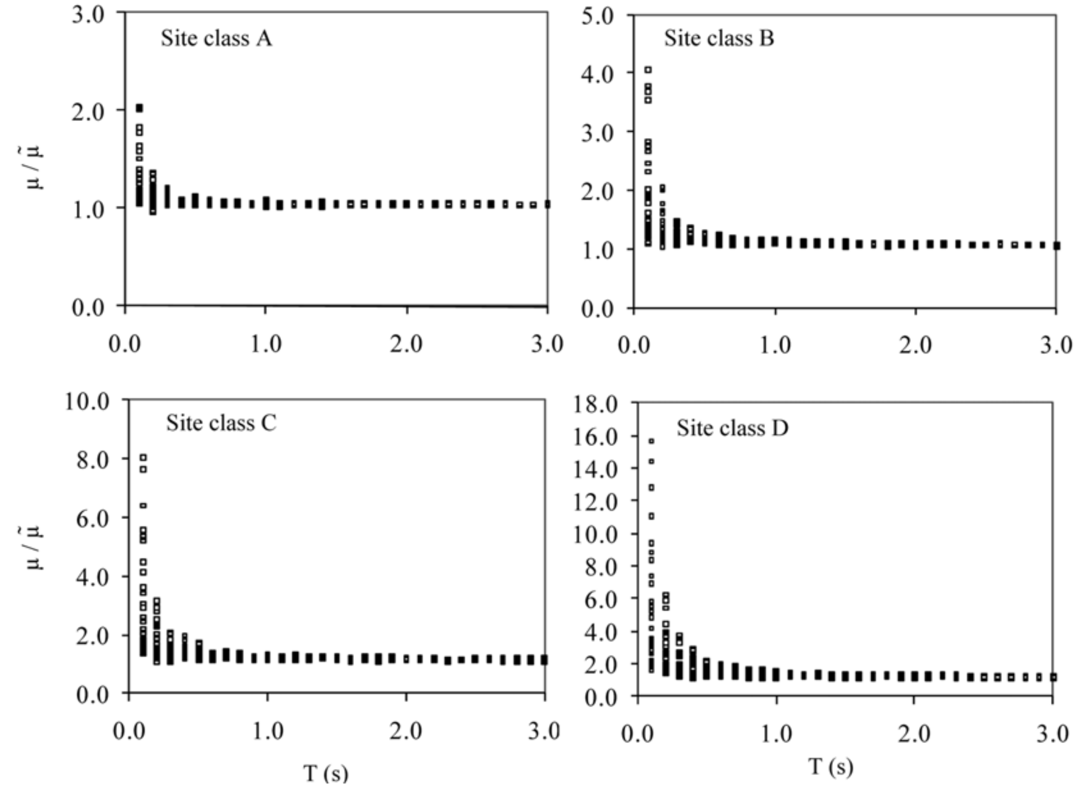

Fig. 10 Ratio of mean ductility demands for cases with and without interaction for all strength reduction levels and aspect ratios

(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 inelastic displacement ratios of interacting systems. The resulting regression formula is appropriately simplified and expressed as

$$\tilde{C}_R = 1 + a(R-1)(R^b + \tilde{T}^c) \tag{11}$$

In Eq. (11), *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 2 for different soil classes individually and also for complete sample space regardless of soil class.

Fig. 11 shows the fitness of the regressed function of the mean $\tilde{C}_R$ factor for different soil classes. In this figure, the solid line represents the values obtained from the regressed function Eq. (11) and the dashed line represents the actual mean values of $\tilde{C}_R$ factors obtained from non-linear dynamic analyses of an interacting system with strength reduction factor of 1.5 and 6 and aspect ratio of 3.

The proposed equation (Eq. (11)) also can be valid for inelastic displacement ratios of fixed-base systems. Replacing effective period of interacting system ($\tilde{T}$) with fixed base period (*T*), and equalizing period lengthening ratio to unity for fixed base case in Eq. (11), the fixed base inelastic

Table 2 Parameter Summary for Eq. (11)

Soil class	Parameters of Eq. (11)			Correlation coefficient
	a	*b*	*c*	
A	0.024	$0.34\frac{\tilde{T}}{T}$	$-2.14-0.15\frac{\tilde{T}}{T}$	0.99
B	0.019	$0.35\frac{\tilde{T}}{T}$	$-2.22-0.11\frac{\tilde{T}}{T}$	0.98
C	0.035	$-0.17\frac{\tilde{T}}{T}$	$-1.88-0.14\frac{\tilde{T}}{T}$	0.99
D	0.087	$-1.74\frac{\tilde{T}}{T}$	$-1.77-0.15\frac{\tilde{T}}{T}$	0.98
All sample	0.014	1	$-2.14-0.36\frac{\tilde{T}}{T}$	0.95

displacement ratios can be obtained. Fitness of the rearranged function of the mean C_R factor for fixed base case is shown in Fig. 12. Also the comparison with other equations presented in literature (Ruiz-Garcia and Miranda 2003, Vidic *et al.* 1994, FEMA 356 2000, Aydınoğlu and Kaçmaz 2002) for the evaluation of the inelastic displacement ratio is shown in figure.

It should be noted that the proposed and rearranged equation is valid for fixed-base and interacting SDOF systems having elastoplastic behavior. The choice of different hysteretic models for SDOF systems may influence the results.

5. Conclusions

In this study, structural parameters such as inelastic displacement ratios and ductility demands are investigated for SDOF systems with period range of 0.1-3.0 s with elastoplastic behavior considering soil structure interaction for 64 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 mean inelastic displacement ratio of interacting system as a function of structural period of system ($\tilde{T}$), strength reduction factor (R) and period lengthening ratio ($\tilde{T}/T$). The proposed equation is also valid for fixed-base systems with elastoplastic behavior. The fitness of the regressed function of the inelastic displacement ratios for fixed-base and interacting cases is shown in Figs. 11 and 12, respectively. The following conclusions can be drawn from the results of this study.

Soil structure interaction effect on inelastic displacement ratios and ductility demands is negligible for site classes A and B, whereas this effect should be considered for site classes C and especially D. Especially for short period region, inelastic displacement ratios and ductility demands of fixed-

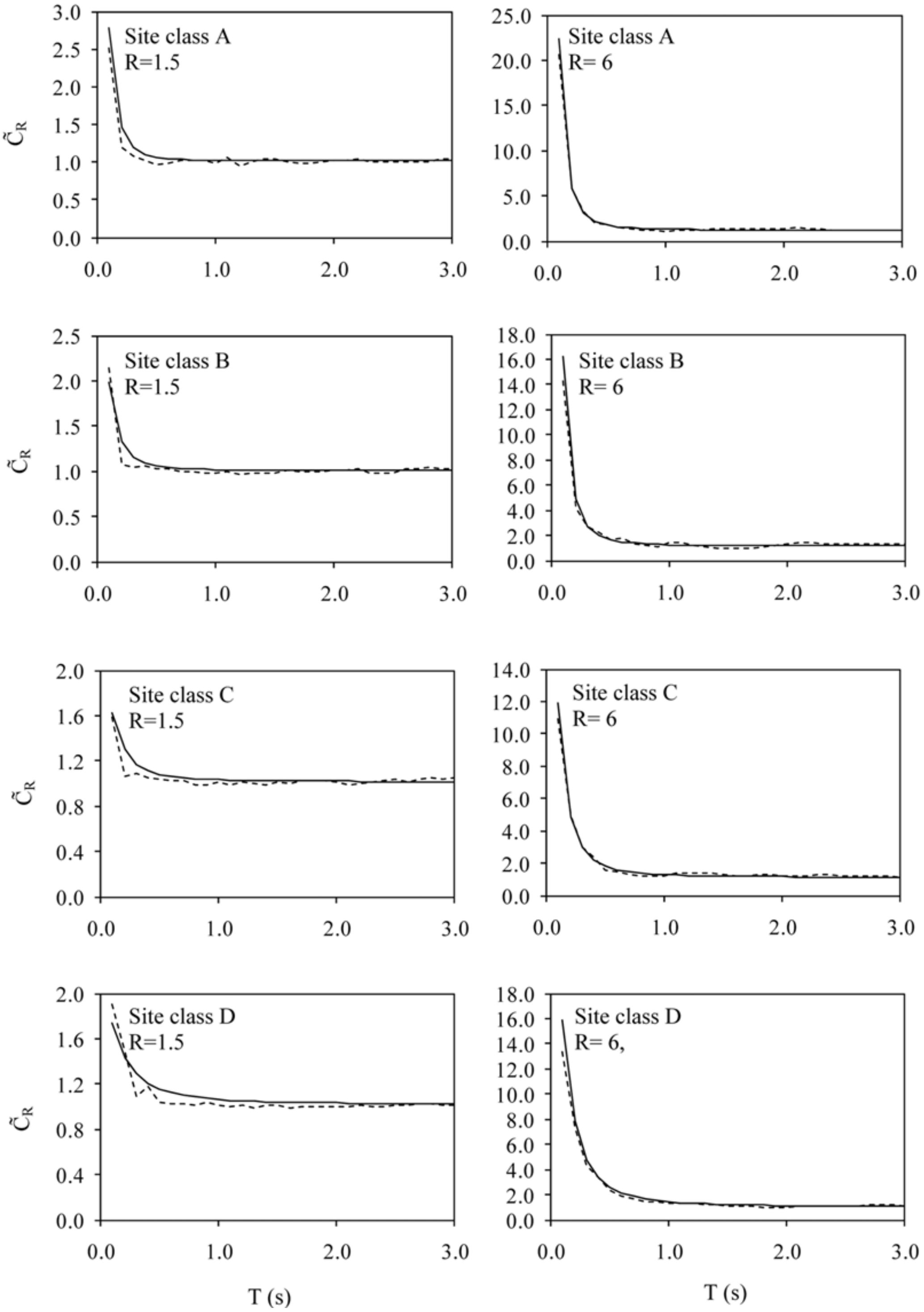

Fig. 11 Comparison of observed (dashed line) and calculated (solid line) mean inelastic displacement ratios (Eq. (11)) of interacting system with h/r = 3 for different soil classes

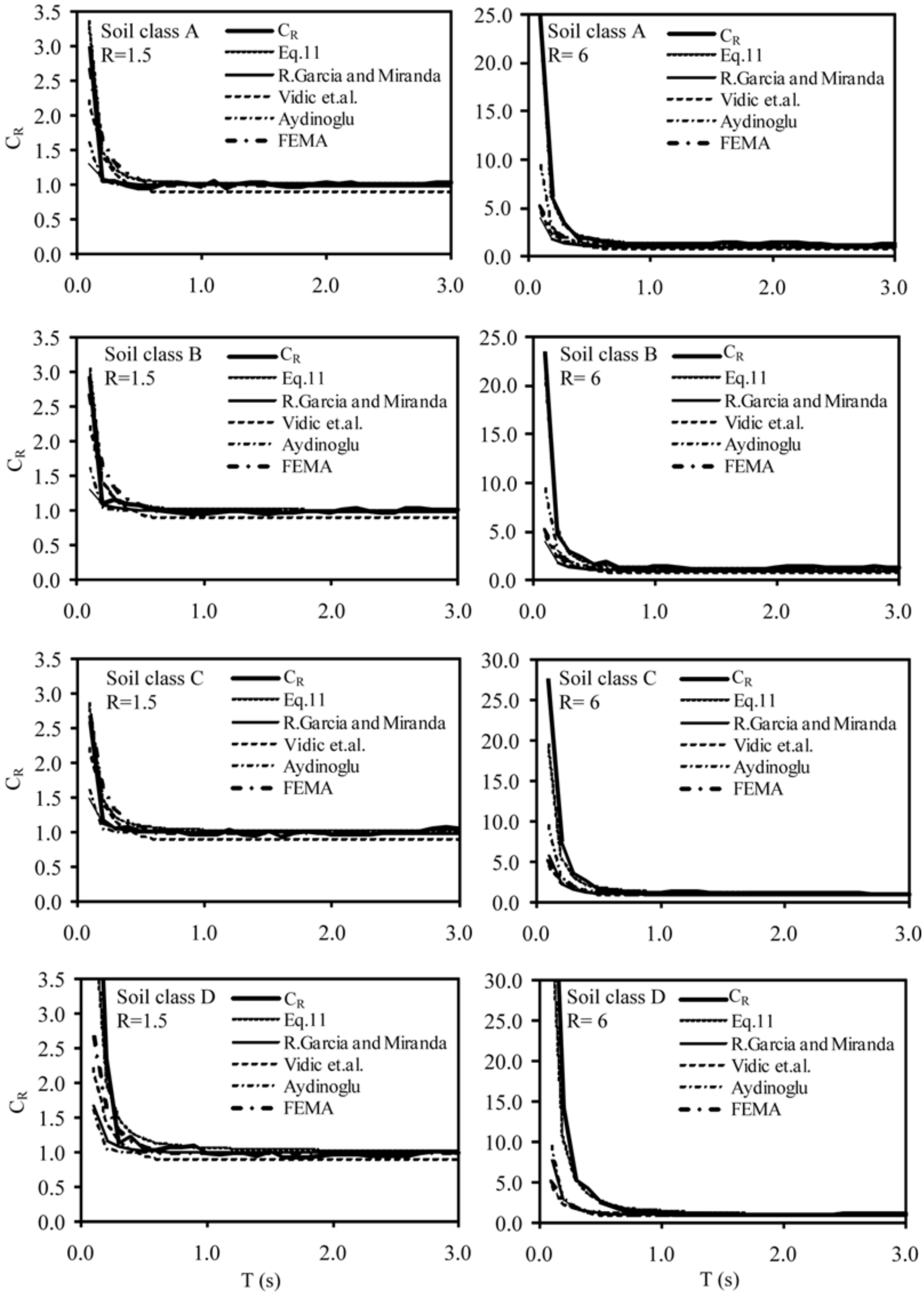

Fig. 12 Comparison of mean inelastic displacement ratios of fixed-base case to those computed with rearranged (Eq. (11)) and other equations in literature

base and interacting system are considerably different for increasing strength reduction factors. For site classes C and D, there is an increase tendency for periods shorter than 0.5 s.

Aspect ratio is an effective parameter for inelastic displacement ratios and ductility demands in high frequency region for all site classes and all strength reduction factors but especially for site classes C and D and strength reduction factor of 6. There is a decrease tendency up to a certain period, say 0.5 s, for increasing values of aspect ratio, but from this period point the effect of aspect ratio on inelastic displacement ratios and ductility demands is negligible.

The ratio of mean inelastic displacement ratios for cases with and without interaction against structural period for all strength ratios and aspect ratios are shown in Fig. 7. The results demonstrate that fixed-base inelastic displacement ratios are greater than the corresponding ones of interacting systems. Although the maximum ratio of mean inelastic displacement ratio for cases with and without interaction is 2.5 for site class A, this ratio becomes as high as 20 for site class D in the high frequency region. These ratios increase for site class C and D remarkably.

Fig. 10 presents the ratio of mean ductility demands for fixed-base and with interaction against structural period for all strength reduction factor levels and aspect ratios. The results demonstrate that fixed-base ductility demands are greater than the corresponding ones of interacting systems. The maximum ratio of mean ductility demand for cases without and with interaction is nearly 16 in the high frequency region whereas this ratio decreases for higher period values.

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

Although Eq. (11) is derived for inelastic displacement ratios considering soil structure interaction, it is possible to use this equation to estimate fixed-base inelastic displacement ratios. Replacing effective period of interacting system ($\tilde{T}$) with fixed base period (T), and equalizing period lengthening ratio to unity for fixed base case in Eq. (11), the fixed base inelastic displacement ratios can be obtained. This simplification satisfies the mean C_R factor for fixed base case. The regressed equation for C_R and $\tilde{C}_R$ should be useful in estimating the inelastic deformation of existing structures with known lateral strength for both fixed-base and interacting cases.

The equivalent fixed-base model and proposed simplified equation is valid for SDOF systems having elastoplastic behavior. The choice of different hysteretic models for SDOF systems may influence the results. Consequently, there is a need for additional research on effects of other hysteretic models on structural response of interacting systems in future.

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