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Inelastic displacement ratios for evaluation of stiffness degrading structures with soil structure interaction built on soft soil sites

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Abstract. In this study, inelastic displacement ratios are investigated for existing systems with known lateral strength considering soil structure interaction. For this purpose, SDOF systems for period range of 0.1-3.0 s with different hysteretic behaviors are considered for a number of 18 earthquake motions recorded on soft soil. The effect of stiffness degradation on 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. Soil structure interaction analyses are conducted by means of equivalent fixed base model 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. A new equation is proposed for inelastic displacement ratio of system with SSI with elastoplastic or degrading behavior as a function of structural period ($\tilde{T}$), 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; strength reduction factor; lateral strength; stiffness degradation; 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. In general, nonlinear time history analyses of structures may produce a good estimation of global and local deformation demands for a given acceleration time history. However these analyses are still considered unpractical for everyday design situations. Thus, simple, yet reliable methods for estimating lateral inelastic displacements demands on structures are needed for the design of new structures or during the seismic evaluation and rehabilitation of existing structures. Generally accepted standpoints of seismic design methodologies establish that structures should be

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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). A common and key step for the estimation of peak inelastic deformation demands is the use of inelastic displacement ratios (C_R) that allows the estimation of peak inelastic displacement demands from peak elastic displacement demands. 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, 2004, 2006), Decanini *et al.* (2003), 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 systems with SSI.

In addition, there are many other researches focusing on soil structure interaction concept. Hatzigeorgiou and Beskos presented a simple and effective method for the inelastic displacement ratio estimation of a structure under repeated or multiple earthquakes and obtained expressions for this ratio, in terms of the period of vibration, the viscous damping ratio, the strain-hardening ratio, the force reduction factor and the soil class (Hatzigeorgiou and Beskos 2009). Roy and Dutta examined the inelastic seismic response of low-rise buildings through adequate idealization of structure and sub-soil medium. It is 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). In another study an equivalent ductility factor for the combined structure and foundation is derived to determine the design strength (Aviles and Perez-Rocha 2011). 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 nonlinear interaction analysis of a two-bay ten-storey plane building frame- layered soil system under seismic loading has been carried out using the coupled finite-infinite elements (Agraval and Hora 2012). As an another research, performance-based framework for soil-structure systems using simplified rocking foundation models has been conducted and it is concluded that soil foundation system can inherently have deformation capacity well in excess of the demand and thus act as a source of energy dissipation that protects the structural integrity of the shear walls (Smith-Pardo 2011). 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 system with SSI with elastoplastic behavior, as a function of structural period, strength reduction factor or ductility and period lengthening ratio.

The aim of this study is to present the results of an investigation whose main goal was to provide more information on the soil structure interaction effects on inelastic displacement ratios for stiffness degrading structures with known lateral strength 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 six levels of known lateral strength (R = 1.5, 2, 3, 4, 5, 6); (2) focus on stiffness degrading structures with strain hardening ratios of α = 0, 2%, 5% and 10%; (3) analyze SDOF systems with SSI for five aspect ratios (h/r = 1, 2, 3, 4, 5); and (4) propose new equations for inelastic displacement ratio of system with SSI with elastoplastic and degrading behavior as a function of structural period ($\tilde{T}$), strength reduction factor (R) and period lengthening ratio ($\tilde{T}/T$).

2. Modelling of system with SSI

A 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.

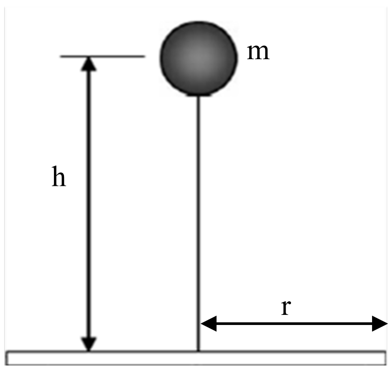


Fig. 1 SDOF system

For interacting case, the foundation is modeled as a circular rigid disk with 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 schematically view considering soil structure interaction modeling of supports is shown in Fig. 2. More details regarding the stiffness and damping coefficients for the horizontal and rocking modes can be found in (Wolf 1994).

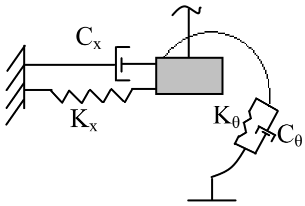


Fig. 2 Mathematical model of supports with soil structure interaction

3. Hysteretic models considered in this study

Load-deformation characteristics of RC structures subjected to reverse cyclic loading have been presented by many hysteretic models. 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. A trilinear model, commonly used and known as the Takeda model has been proposed based on experimental results of a number of medium-sized reinforced concrete members subjected to cyclic loading (Takeda *et al.* 1970). In the present study, the Modified Clough model is used to represent structures with stiffness degradation. 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, Borzi *et al.* 2001, Gupta and Krawinkler 1998, Gupta and Kunnath 1998). 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).

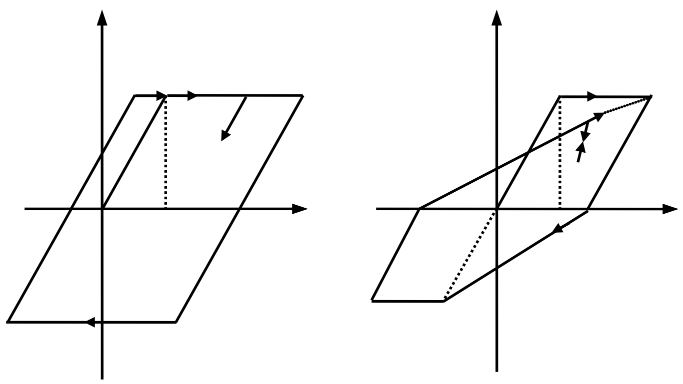
As FEMA guidelines proposed a series of coefficients C_1 to C_4 to evaluate inelastic displacement ratios, C_2 modification factor is defined to represent the effect of pinched hysteretic shape, stiffness degradation and strength deterioration on maximum displacement response without soil structure interaction. Values of C_2 modification factor for different framing systems and Structural Performance Levels shall be obtained from aforementioned guidelines. Alternatively, use of $C_2 = 1.0$ is permitted for nonlinear procedures (FEMA 356 2000, FEMA 440 2005). 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).

In a more recent study conducted by Chenouda and Ayoub, a newly developed model that incorporates degradation effects into seismic analysis of structures is presented and a new energy-based approach is used to define several types of degradation effects. Approximate methods are proposed for estimating maximum inelastic displacements of degrading systems for use in performance-based seismic code provisions (Chenouda and Ayoub 2008). Another research conducted by the same authors 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 (Ayoub and Chenouda 2009). In 2012, Erberik and co-workers studied on the inelastic displacements of reinforced concrete systems by employing an energy-based approach and developed a hysteresis model is that accounts for stiffness degradation, strength deterioration and pinching based on experimental data (Erberik *et al.* 2012). However, none of existing studies has considered the influence of soil structure interaction phenomenon. Therefore, the present study focuses on the effect of stiffness degradation on inelastic displacement ratios for soil structure interacting case. For this purpose, elastoplastic and Modified Clough hysteretic models shown in Fig. 3 are considered in this study.

4. Analysis method

For fixed-base case, dynamic time history analyses have been conducted for specified strength reduction factors 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 within a certain tolerance equal to the target ductility ratio, 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 system with SSI, analyses have been repeated for the same yield strength of the fixed -base case. Thus, inelastic displacement ratios ($\tilde{C}_R$) of systems with SSI 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). In the present study, the described soil-structure model is analyzed in time domain. For inelastic time history analyses, Newmark method for step by step time integration was adapted in an in-house computer program.



(a) (b)

Fig. 3 Load-deformation hysteretic models used in this study: (a) Elastoplastic; (b) Modified Clough

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)
Loma Prieta 18/10/89	7.1	Appel 2 Redwood City	1002	47.9	A02043	0.274	53.6	A02133	0.22	34.3
Northridge 17/01/94	6.7	Montebello	90011	86.8	BLF206	0.179	9.4	BLF296	0.128	5.9
Superstition Hills 24/11/87	6.6	Salton Sea Wildlife Refuge	5062	27.1	WLF225	0.119	7.9	WLF315	0.167	18.3
Loma Prieta 18/10/89	7.1	Treasure Island	58117	82.9	TRI000	0.1	15.6	TRI090	0.159	32.8
Kocaeli 17/08/99	7.8	Ambarli	-	78.9	ATS000	0.249	40	ATS090	0.184	33.2
Morgan Hill 24/04/84	6.1	Appel 1 Redwood City	58375	54.1	A01040	0.046	3.4	A01310	0.068	3.9
Düzce 12/11/99	7.3	Ambarlı	-	193.3	ATS030	0.038	7.4	ATS300	0.025	7.1
Kobe 16/01/95	6.9	Kakogawa	0	26.4	KAK000	0.251	18.7	KAK090	0.345	27.6
Kobe 16/01/95	6.9	Shin-Osaka	0	15.5	SHI000	0.243	37.8	SHI090	0.212	27.9

A set of earthquake acceleration time-histories recorded on soft soil used in this study 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 155520 of 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, six values of strength reduction factor (R = 1.5, 2, 3, 4, 5, 6), 18 ground motions, four strain hardening ratios (α = 0, 2%, 5%, 10%) and two types of hysteretic behavior (EP and SD).

4.1 Analogy of 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, Veletsos and Nair 1975, Veletsos 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 system with SSI is given by the equation below

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

Rearranging this equation gives the equivalent stiffness of the system with SSI as follows

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

Effective damping for the system with SSI is given by the equation below

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

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).

For elastic range, it is adequate to modify structural period and damping ratio of system with SSI 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 system with SSI has to be defined. Effective ductility of system with SSI 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 effective ductility of the system with SSI 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)

$$\tilde{\mu} = \left(\frac{T}{\tilde{T}}\right)^2(\mu-1)+1 \tag{4}$$

5. Results of statistical study

5.1 Mean inelastic displacement ratios

In Fig. 4, variations of mean inelastic displacement ratios against period are shown for cases with (dashed line) and without (solid line) interaction. Results are presented for systems with strength reduction factor of 1.5, 3 and 6 and aspect ratio of 3. The left graph shows the results for strain hardening ratio of 0% and the right graph shows the results for strain hardening ratio of 10%. It can be seen from the figure that, inelastic displacement ratios of fixed-base and interacting cases are very close to each other and approximately equal to unity for long period range. This behavior is in accordance with well-known "equal displacement rule" for long period range. Especially for short period region, inelastic displacement ratios of fixed-base and system with SSI are considerably different for increasing strength reduction factors.
Variations of mean inelastic displacement ratios against period for increasing values of aspect ratio are shown in Fig. 5. Results are presented for systems with strength reduction factor of 4 and strain

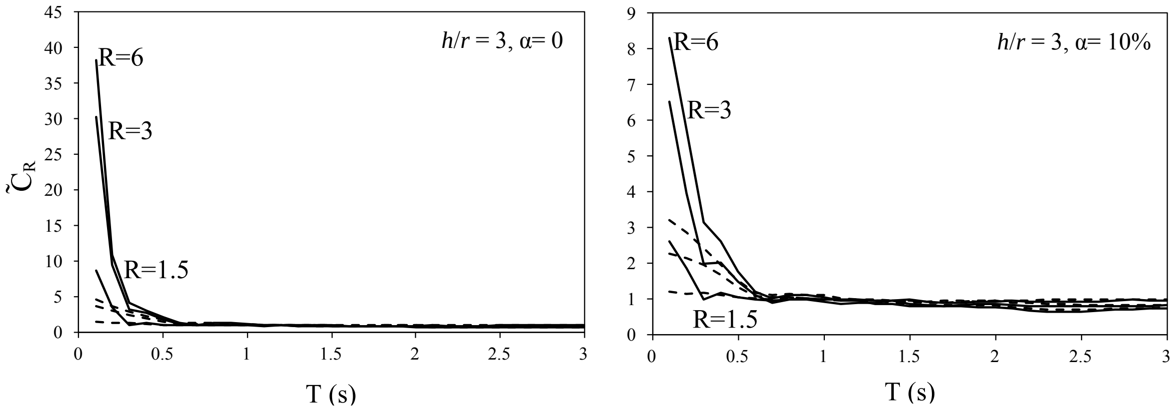


Fig. 4 Variations of mean inelastic displacement ratios against period with (dashed line) and without (solid line) interaction for α = 0 and 10%. Results correspond to a system with SSI for *h*/*r* = 3

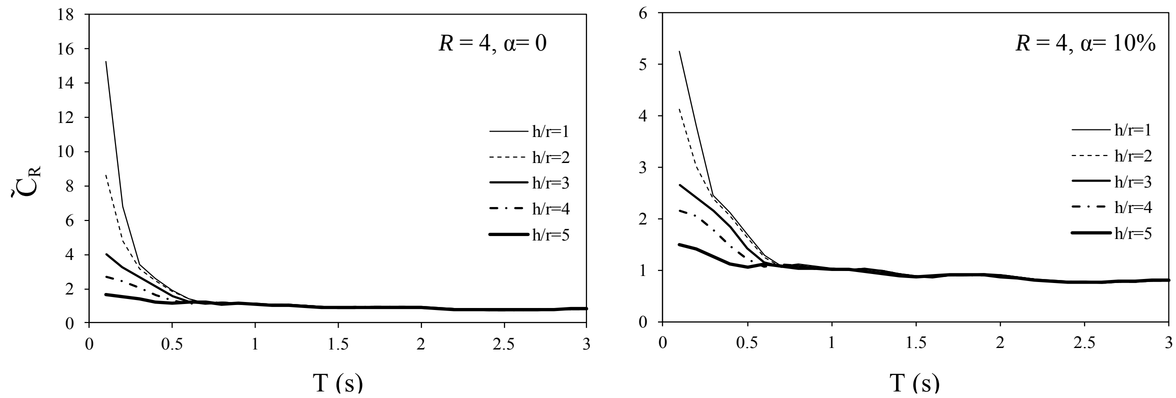


Fig. 5 Variations of mean inelastic displacement ratios against period and increasing values of aspect ratio for α = 0 and 10%. Results correspond to a system with SSI for *R* = 4.

hardening ratio of 0% and 10%. 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.

5.2 Effect of hysteretic behavior

Variations of mean inelastic displacement ratios with strength reduction factor for elastoplastic (dashed line) and Modified Clough (solid line) behavior are shown in Fig. 6. Results are presented for a system with SSI for α = 5% and h/r = 3. It is seen from Fig. 6 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 strength reduction factor value of 6 for period range before the mentioned certain period, this curve has the smallest inelastic displacement ratio values from this period point.

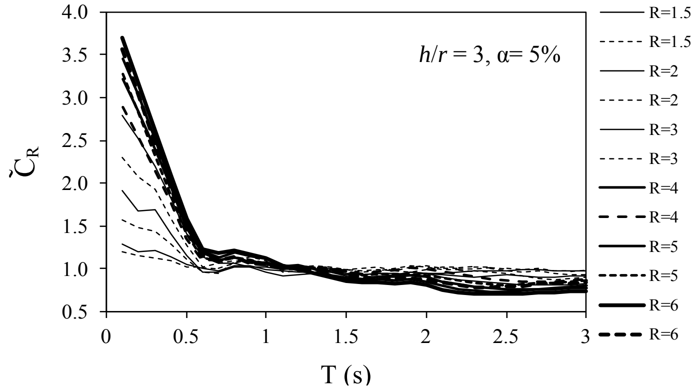


Fig. 6 Variations of mean inelastic displacement ratios for elastoplastic behavior (dashed line) and Modified Clough (solid line) behavior against period for α = 5%. Results correspond to a system with SSI for *h/r* = 3

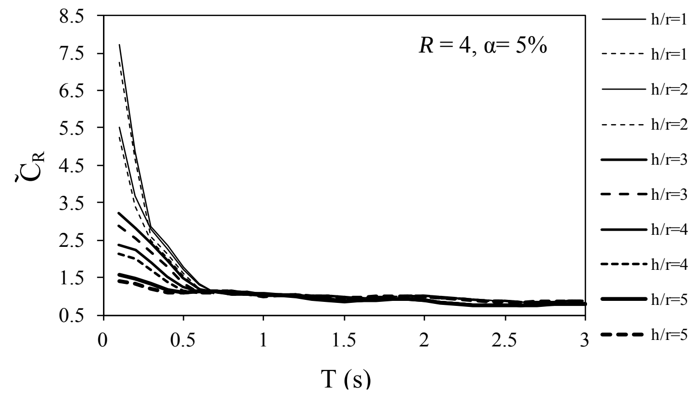


Fig. 7 Variations of mean inelastic displacement ratios for elastoplastic behavior (dashed line) and Modified Clough (solid line) behavior against period and increasing values of aspect ratio for α = 5%. Results correspond to a system with SSI for *R* = 4

In Fig. 7, variations of mean inelastic displacement ratios with aspect ratio for elastoplastic (dashed line) and Modified Clough (solid line) behavior for a system with SSI for α = 5% and strength reduction factor of 4 are given. It is seen from Fig. 7 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 displacement demands, non-degrading to degrading inelastic demand ratios were computed. Variation of these ratios is shown in Fig. 8. The graph shows the ratio of the inelastic displacement ratios in non - degrading system, $\tilde{C}_{R(EP)}$, to inelastic displacement ratios in stiffness degrading system, $\tilde{C}_{R\,(SD)}$.

It can be seen from Fig. 8 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 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 strength reduction factor increases.

Fig. 9 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 left graph shows the ratios for systems with elastoplastic behavior whereas the right graph shows the ratios for systems with Modified Clough behavior. The results demonstrate that fixed-base inelastic displacement ratios are greater than the corresponding ones of systems with SSI. Especially the considered ratios are much greater for systems with elastoplastic behavior. Although the maximum ratio of mean inelastic displacement ratio for cases with and without interaction is nearly 20 for Modified Clough behavior, this ratio becomes much more than 20 for elastoplastic behavior in the high frequency region. It can be seen from analysis results that the period, aspect ratio and strength reduction factor values corresponding to the highest value of the considered ratio, are found to be T = 0.1s, aspect ratio (h/r) of 5 and strength reduction factor (R) of 5 and 6. It can be emphasized that the main reason for such high ratios is due to the high values

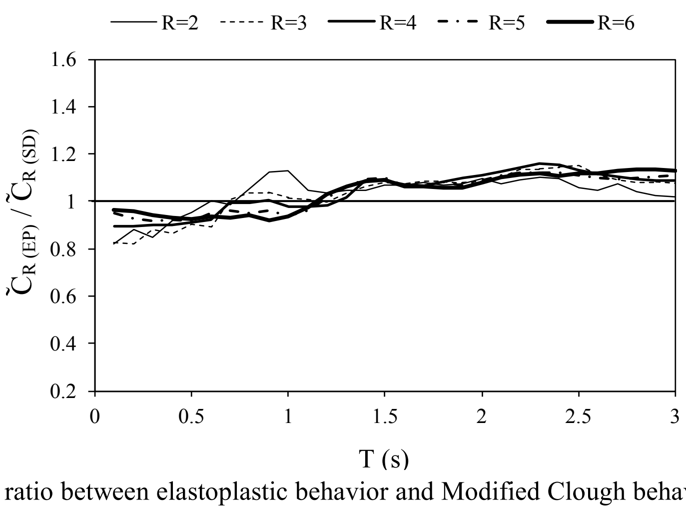


Fig. 8 Variation of the ratio between elastoplastic behavior and Modified Clough behavior against period for α = 5%. Results correspond to a system with SSI for *h/r* = 3

of inelastic displacement ratios for fixed-base rather than systems with SSI. For periods smaller than 0.5s, inelastic displacement ratios are strongly dependent on the period of vibration and on the lateral strength ratio. In general, in this spectral region maximum inelastic displacements become much larger than maximum elastic displacements as the strength reduction factor increases (i.e., as the lateral strength decreases with respect to the lateral strength required to maintain the system elastic) and as the period of vibration decreases. When soil structure interaction is considered, due to period elongation, the periods increase even for systems with small period values, which lead to lower inelastic displacement ratios than fixed-base systems. Furthermore, constant relative strength inelastic displacement ratios tend towards ∞ as the period of vibration tends to zero, which means that existing structures with very short periods may undergo very large inelastic displacement demands relative to their elastic counterparts unless they have lateral strengths that allow them to remain elastic or nearly elastic.

5.3 Effect of strain hardening ratio

Variations of mean inelastic displacement ratios with strain hardening ratio for systems with elastoplastic (left) and Modified Clough behavior (right) are shown in Fig. 10. Results are presented for a system with R = 6 and h/r = 5. As mentioned above, the considered strain hardening

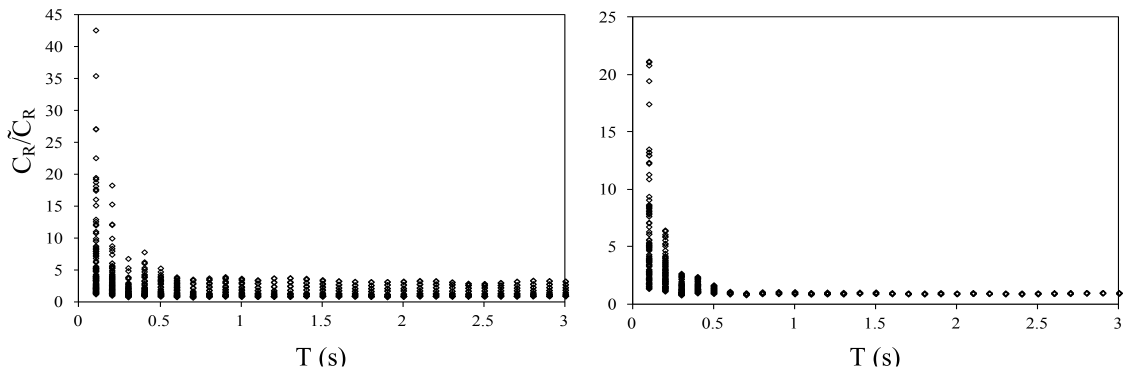


Fig. 9 Ratio of mean inelastic displacement ratios for cases with and without interaction for all strength reduction levels and aspect ratios

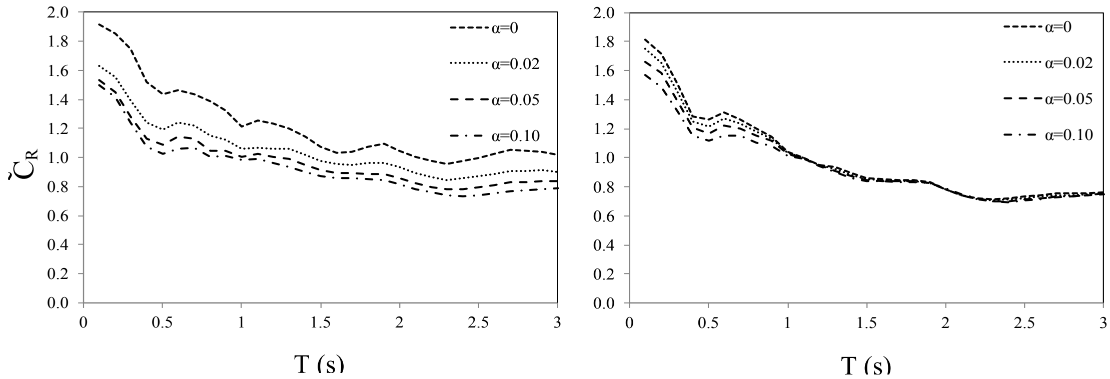


Fig. 10 Variations of mean inelastic displacement ratios with strain hardening ratio for elastoplastic (left) and degrading (right) systems. Results correspond to a system with R = 6 and h/r = 5

ratio values in analyses are α = 0, 2%, 5%, 10%, respectively. It is clearly seen from Fig. 10 that, there is a significant strain hardening effect on inelastic displacement demands. Especially, mean inelastic displacement ratios for systems with elastoplastic behavior are quite sensitive to strain hardening for almost entire period range. But, for stiffness degrading systems, effect of strain hardening ratio on inelastic displacement demands can be neglected for periods greater than 1.0 s. The figure illustrates that, for a given lateral strength, 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.

5.4 Nonlinear regression analysis

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

$$\tilde{C}_R = 1 + a\frac{(R-1)}{R}(R^b + \tilde{T}^c + d) \tag{5}$$

In Eq. (5), a, b, c and d are coefficients which take into account the influence of vibration period of system with SSI and period lengthening ratio. In this work, the aforementioned coefficients are given by the following empirical expressions

$$a = a_0 + a_1 \cdot \tilde{T} \tag{6}$$

$$b = b_0 + b_1 \cdot \tilde{T} \tag{7}$$

$$c = c_0 + c_1 \cdot \frac{\tilde{T}}{T} \tag{8}$$

$$d = d_0 + d_1 \cdot \frac{\tilde{T}}{T} + d_2 \cdot \tilde{T} \tag{9}$$

The coefficients *a, b, c* and *d* and correlation coefficient (r^2) are summarized in Table 2 for Modified Clough (SD) and elastoplastic (EP) hysteretic behaviors.

Fig. 11 shows the fitness of the regressed function of the mean $\tilde{C}_R$ factor with stiffness egrading behavior for different strain hardening ratios. In this figure, the dashed line represents the values obtained from the regressed function (Eq. 5) and the solid line represents the actual mean values of $\tilde{C}_R$ factors obtained from non-linear dynamic analyses. Results are presented for systems with SSI for R = 1.5 and h/r = 3 in top figures and R = 6 and h/r = 3 in bottom figures.

Fig. 12 shows the fitness of the regressed function of the mean $\tilde{C}_R$ factor with elastoplastic behavior for different strain hardening ratios. As in the previous figure, the dashed line represents the values obtained from the regressed function (Eq. 5) and the solid line represents the actual mean values of $\tilde{C}_R$ factors obtained from non-linear dynamic analyses. Results are presented for systems with SSI for R = 1.5 and h/r = 3 in top figures and R = 6 and h/r = 3 in bottom figures. In Figs. 11 and 12, coefficient C_2 defined in the FEMA guidelines (FEMA 356 and FEMA 440) is also shown with dotted line. As the coefficient C_2 defined in the FEMA guidelines is constant for different period range, this coefficient is almost always smaller than the calculated inelastic displacement ratios for high values of strength reduction factors.

Table 2 Parameter Summary for Eq. (5)

$$\tilde{C}_R = 1 + a\frac{(R-1)}{R}(R^b + \tilde{T}^c + d) \qquad \text{Eq. (5)}$$

Hys. beh.	Parameter		r^2	Hys. beh.	Parameter		r^2
SD	a_0	0.542	0.94	EP	a_0	0.316	0.94
	a_1	-0.095			a_1	-0.171	
	b_0	0.825			b_0	1.943	
	b_1	-0.535			b_1	-2.687	
	c_0	-1.407			c_0	-1.557	
	c_1	-0.035			c_1	0.025	
	d_0	-2.808			d_0	-1.666	
	d_1	-0.193			d_1	-0.085	
	d_2	0.6			d_2	0.857	

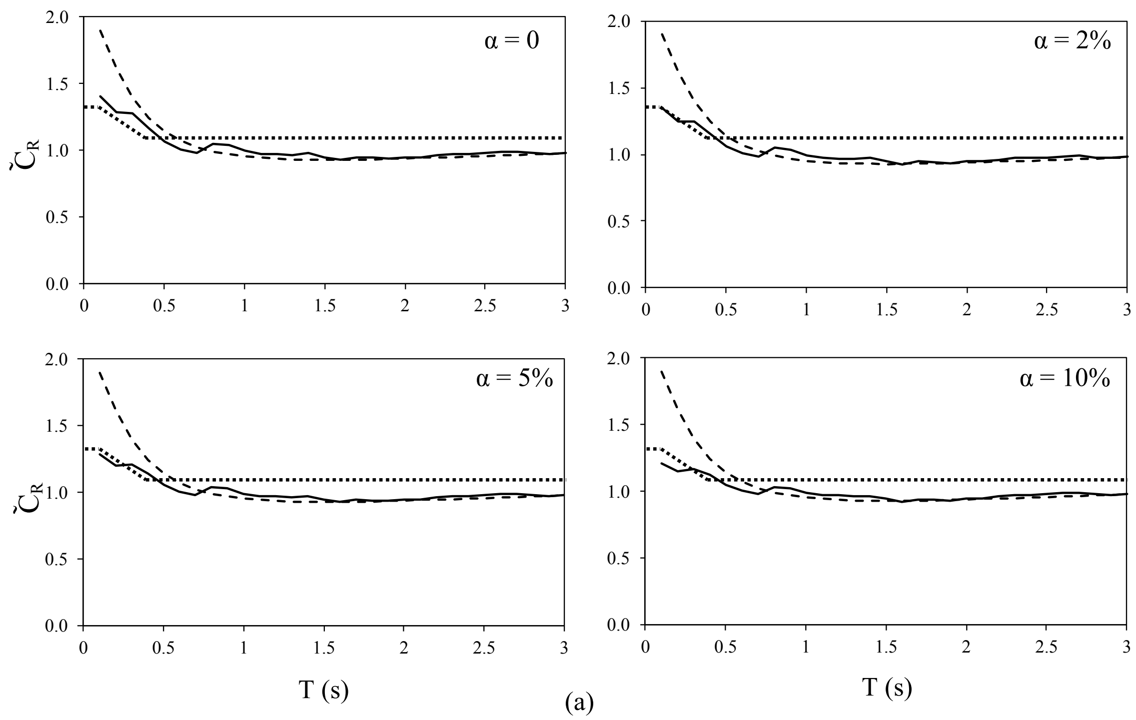


Fig. 11 For Modified Clough hysteretic behavior comparison of mean inelastic displacement ratios (solid line) with interaction to those computed with Eq. (5) (dashed line) for a system with SSI (a) R = 1.5 and h/r=3 (b) R = 6 and h/r=3. (Dotted line corresponds to coefficient C_2)

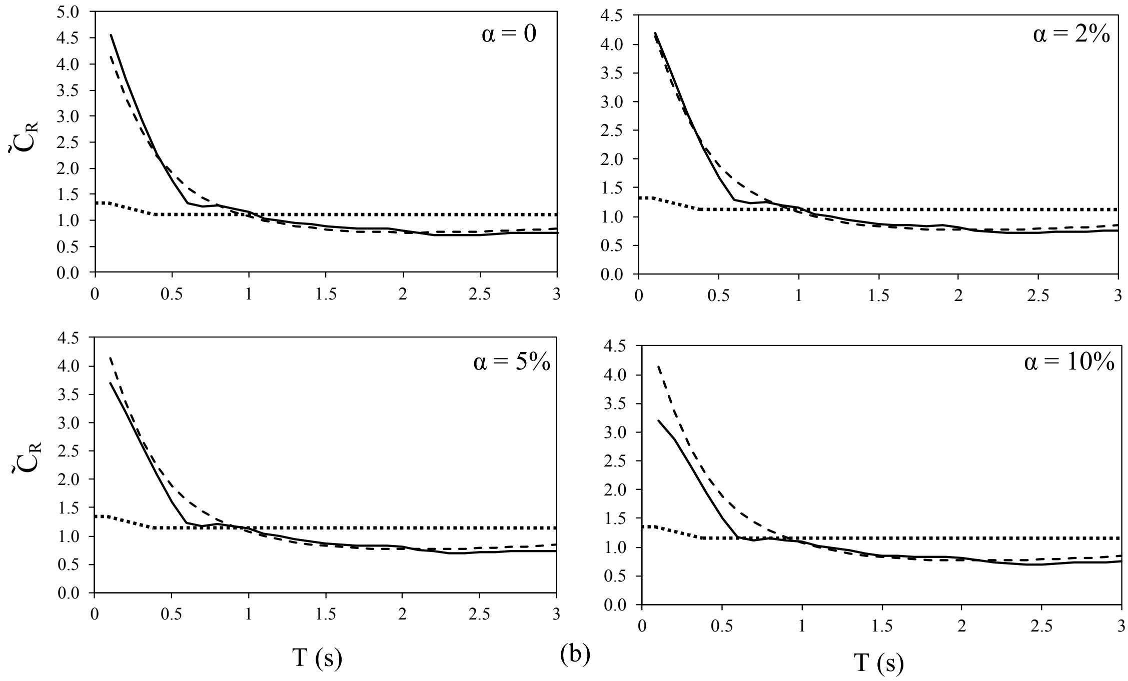


Fig. 11 Continued

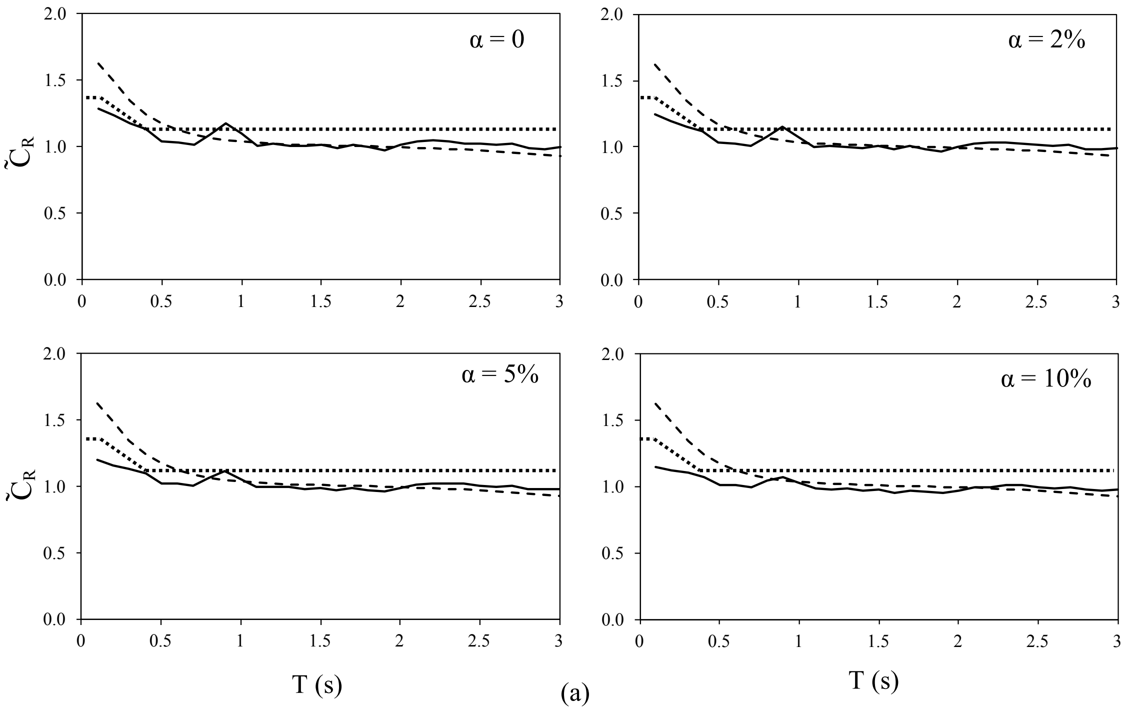
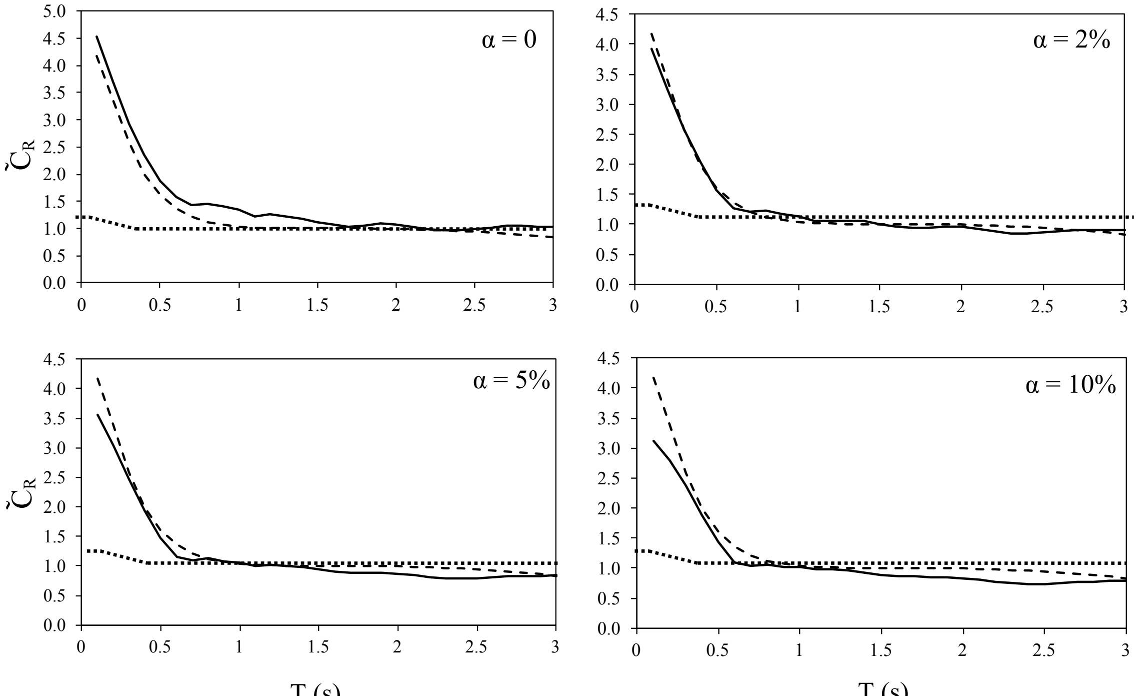


Fig. 12 For elastoplastic hysteretic behavior comparison of mean inelastic displacement ratios (solid line) with interaction to those computed with Eq. (5) (dashed line) for a system with SSI (a) R = 1.5 and h/r = 3 (b) R = 6 and h/r = 3 (Dotted line corresponds to coefficient C_2)



(b)

Fig. 12 Continued

6. Conclusions

In this study, inelastic displacement ratios 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 analyses are performed by using an analogy with an equivalent fixed base model defined by an effective ductility in addition to the effective period and damping of the system for the elastic condition and a limited number of 18 earthquake records. A new equation is proposed for mean inelastic displacement ratio of systems with degrading and non-degrading behavior of systems with SSI as functions of structural period ($\tilde{T}$), strength reduction factor (R) and period lengthening ratio ($\tilde{T}/T$). Based on the solution for an equivalent fixed base model the following conclusions can be drawn from the results of this study.

- Inelastic displacement ratios of fixed-base and interacting cases are very close to each other and approximately equal to unity for long period range. This behavior is in accordance with well-known "equal displacement rule" for long period range. Especially for short period region, inelastic displacement ratios of fixed-base system and system with SSI are considerably different for increasing strength reduction factors.
- 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.

• 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.

• 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.

• Fixed-base inelastic displacement ratios are greater than the corresponding ones of systems with SSI. Especially the considered ratios are much greater for systems with elastoplastic behavior.

• Especially, mean inelastic displacement ratios for systems with elastoplastic behavior are quite sensitive to strain hardening for almost all period range. But, for stiffness degrading systems, effect of strain hardening ratio on inelastic displacement demands can be neglected for periods greater than 1.0 s. For a given lateral strength, 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.

• A new equation (Eq. (5)) is proposed to represent the mean inelastic displacement ratios of elastoplastic and degrading behavior for all records, strength reduction factors, aspect ratios, strain hardening ratios and structural periods as a function of structural period of system with SSI ($\tilde{T}$), strength reduction factor (R) and period lengthening ratio ($\tilde{T}/T$). The proposed simplified expression provides a good approximation of mean inelastic displacement ratios of SDOF systems.

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