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Residual displacement estimation of simple structures considering soil structure interaction

Müberra Eser Aydemir* and Cem Aydemir[a]

Department of Civil Engineering, Istanbul Aydin University, Istanbul, Turkey

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Abstract. As the residual displacement and/or drift demands are commonly used for seismic assessment of buildings, the estimation of these values play a very critical role through earthquake design philosophy. The residual displacement estimation of fixed base structures has been the topic of numerous researches up to now, but the effect of soil flexibility is almost always omitted. In this study, residual displacement demands are investigated for SDOF systems with period range of 0.1-3.0 s for near-field and far-field ground motions for both fixed and interacting cases. The elastoplastic model is used to represent non-degrading structures. Based on time history analyses, a new simple yet effective equation is proposed for residual displacement demand of any system whether fixed base or interacting as a function of structural period, lateral strength ratio and spectral displacement.

Keywords: residual displacement; soil structure interaction; spectral displacement; lateral strength ratio

1. Introduction

Current earthquake-resistant design provisions allow the nonlinear response of structures because of economic factors, although it would be preferable to design a structure that behaves elastically in the event of severe earthquake motions. Seismic design procedures aim at controlling earthquake damage to structural elements and many types of nonstructural elements by limiting lateral deformations on structures. Structural performance is usually estimated using peak deformation demands. However, the past earthquakes have shown that the residual (permanent) deformation or drift demand of a system -in addition to peak demands- is one of the most critical parameters for seismic assessment. To determine whether the structural system can continue its function or the system should be strengthened/repaired or the system should be rebuilt, residual displacement/drift demands are required. This necessity to consider the residual displacements and residual drifts in seismic performance assessment is addressed in (Vision 2000, 1995, FEMA356, 2000 and FEMA P-58, 2012) guidelines. Therefore, it is important to estimate residual structural displacement demands for the evaluation and rehabilitation of structures.

Residual displacement ratios have been the topic of several investigations so far. The first well-known studies on residual displacement were conducted by Riddell and Newmark (1979a, b) pointing out that the magnitude of residual displacements is strongly affected by the unloading- reloading rules of the hysteresis model. Mahin and Bertero investigated the dispersion of the residual displacements of SDOF systems assuming a peak-ductility for each SDOF system (1981). MacRae and Kawashima (1997) studied on SDOF systems with ductility demands of 2, 4 and 6 for 11 ground motions. They concluded that post-yield stiffness has an important effect on the residual displacement levels. Another study conducted by Kawashima *et al*. (1998), focused on a residual displacement response spectrum and residual displacement response ratio spectrum proposed based on 63 ground motions in order to evaluate residual displacements of structures subjected to large ground motions. Besides, an application of the residual displacement response spectrum to bridges supported by cantilever column was presented. Similarly, to these previous studies, Pampanin and his co-workers studied on residual displacement ratios for equivalent SDOF systems for 20 earthquake motions and three different hysteretic models (2002). Ruiz Garcia and Miranda conducted the most extensive researches on residual displacement ratios for both SDOF and multistory structures (2005, 2006a, b, 2008). They proposed simplified expressions to estimate mean residual displacement ratios of existing structures and also, they reported that the amplitude and heightwise distribution of residual drift demands depend on the frame mechanism, structural overstrength and hysteretic behavior. Hatzigeorgiou *et al*. (2011) conducted parametric studies on SDOF systems to derive empirical equations for maximum displacement from residual displacements. Ramirez and Miranda (2012) proposed a new approach that incorporates the influence of residual drifts by accounting for the possibility of having to demolish a building as a result of excessive residual interstorey drifts, where the probability of demolition is computed as a function of the maximum residual drift in the building. More recently, Liossatou and Fardis (2014)

*Corresponding author, Associate Professor
E-mail: muberraaydemir@aydin.edu.tr
[a]Associate Professor
E-mail: cemaydemir@aydin.edu.tr

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investigated the effects of hysteresis rules representing the cyclic degradation of stiffness and strength and the energy dissipation of typical RC structures on residual displacement ratios whereas D'Ambrisi and Mezzi (2015) proposed a method to evaluate the residuals of the response parameters of a reinforced concrete plane frame. As recent studies, Ruiz Garcia and Guerrero (2017) presented a technical note on a new functional form to estimate mean residual displacement ratios for soft soil sites, and Dai *et al*. (2017) presented a seismic assessment procedure to predict the peak drift from the residual drift. Ji *et al*. (2018) presented a technical note to quantify the residual displacement of structural systems with varying stiffness, strength and hysteretic behavior experience when subjected to earthquake motions recorded on soft soil conditions. All these mentioned studies provide the results of researches on fixed base systems, in other words, soil structure interaction or soil flexibility is always ignored. With respect to authors' knowledge soil structure interaction effects on residual displacement has not been considered, yet, thus this study is intended to focus on the effects of soil flexibility on residual displacements.

It has been known for many years that SSI affects the elastic strength demand of structures and, generally, elastic strength demand is reduced due to SSI. This is mainly because the soil-structure system has longer period and, usually, higher damping ratio in comparison to the fixed base structure (Veletsos 1977). In 1970s, many researchers put effort into estimating the SSI effect on elastic response of structures (Chopra and Gutierrez 1974, Novak 1974). During last decade, Aviles and Perez-Rocha studied on soil-structure interaction phenomenon widely (2003, 2005a, b, 2011). They concluded that for soft/deep soil deposits, the SSI effects in yielding structures may result in either increase or decrease of the fixed-base strengths and displacements, depending primarily on the period ratio of the structure and site. The higher the structural ductility, the smaller becomes these effects. Also, Ghannad and co-workers studied on soil-structure interaction effects on strength reduction factors and ductility demands (2002, 2004, 2006, 2007). They showed that both ductility and strength demanded by the structure may experience considerable variations under the effect of SSI. It has been shown that the interaction between the soil and structure also affects the hysteretic energy dissipation of the structure under earthquake loading. The effect of soil-structure interaction on inelastic displacement ratio and strength reduction factors of structures has been also studied by authors (Eser *et al*. 2012 a, b, Eser 2013). They proposed a new equation for inelastic displacement ratio of interacting system, as a function of structural period of interacting system, strength reduction factor and period lengthening ratio.

The objective of this study is to present the results of an investigation conducted to provide more information on the residual displacement demands of fixed base and interacting case systems with known lateral strength built on soft soils when subjected to near-field and far-field earthquake ground motions. In particular, this study tried to: (1) study on SDOF systems with period range of 0.1-3.0s and six levels of known lateral strength (R=1.5, 2, 3, 4, 5, 6); (2) analyze SDOF systems with SSI for five aspect ratios which is a key parameter for especially SSI systems defined as the ratio of effective height (h) to radius of the equivalent circular foundation (r) to express the slenderness ratio (h/r=1, 2, 3, 4, 5); (3) use a set of near-field and far-field ground motions and (4) propose a new equation for residual displacement demands of SDOF systems as a function of spectral displacement (S_d), structural period (T) and lateral strength ratio (R). The lateral strength ratio is the ratio of the structural strength demand required for a system to remain elastic, to the lateral strength capacity in the literature. Considering an idealized elasto-plastic SDOF system this factor is defined as follows

$$R = F_e / F_y \tag{1}$$

where F_e is the elastic strength demand of structure and F_y is the supplied strength.

2. Analysis procedure

2.1 Methodology and SSI modelling

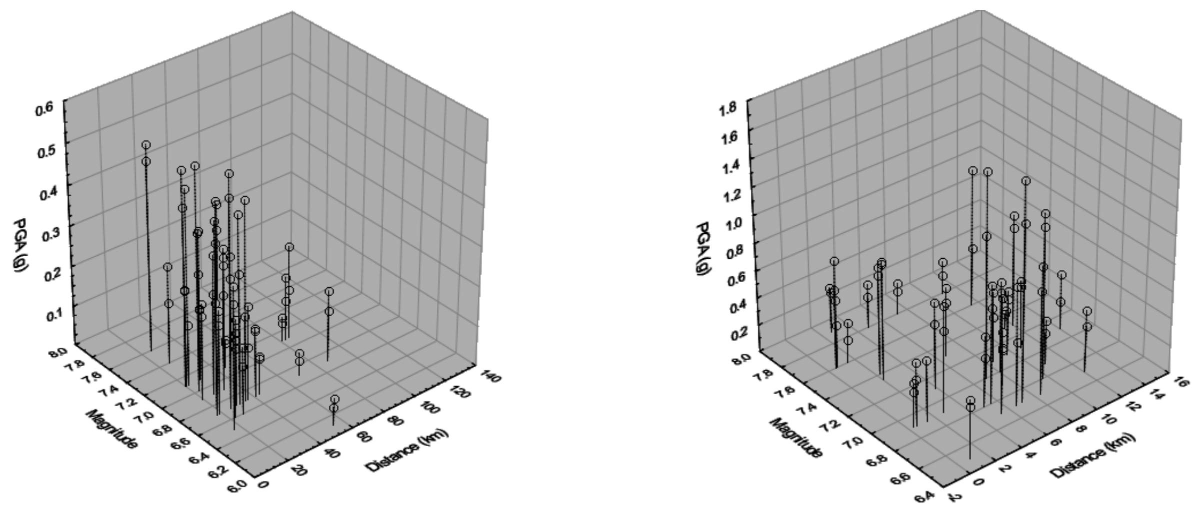
The present study focuses on residual displacement demands of SDOF systems. The dynamic equation of motion of an SDOF system is given by Eq. (2)

$$m\ddot{u} + c\dot{u} + f_s(u) = -m\ddot{u}_g \tag{2}$$

where m is the mass, u is the relative displacement, c is the viscous damping coefficient, $f_s(u)$ is the resisting force and $\ddot{u}_g$ is the acceleration of ground motion. Newmark's step by step time integration method is adapted in an in-house computer program for inelastic time history analyses. As the time-integration step size was found to be a critical and effective parameter to predict the residual displacements by Yazgan and Dazio (2011), time history analyses were carried out with the time step selected as the minimum of:

- Original earthquake ground motion time step,
- 1/25 of structural period,
- 0.01 s.

As many of these previous studies mainly focus on the normalized residual displacement ratios, the main difference lies in the definition of these ratios. For the case of residual displacements, several normalization alternatives have been proposed by various researchers. Mahin and Bertero (1981), Farrow and Kurama (2003) used yield displacement to normalize residual displacement and they called this ratio as the residual displacement ductility. MacRae and Kawashima (1997) used maximum possible residual displacement demand for normalization. Pampanin *et al*. (2002), Ruiz Garcia (2004), Ruiz Garcia and Miranda (2005), Borzi *et al*. (2001) used the ratio of residual displacement to maximum inelastic displacement as the key parameter. Similarly, the ratio of residual displacement to elastic spectral displacement is used by Ruiz Garcia and Miranda (2005, 2006a, b, 2008); this ratio is called residual displacement ratio. Among these several normalization alternatives for residual displacement demands, for simplicity, it is generally appropriate to normalize the residual displacements (D) with respect to elastic spectral



(a) Far field ground motions (b) Near field ground motions

Fig. 1 Magnitude-source distance-PGA relation for the used ground motions

displacement (S_d) of a SDOF system subjected to same acceleration time history which is called as residual displacement ratio and expressed as follows

$$D_s = \frac{D}{S_d} \tag{3}$$

Thus, the results of conducted study have been presented in the terms of residual displacement demands (D) and residual displacement ratios (D_s), respectively.

For soil structure interaction, the most common approach to consider elastic SSI effects has not changed over the years. This approach involves the usage of a replacement oscillator represented by the effective period and damping of the system. The mass of this equivalent oscillator is taken to be equal to that of the actual structure. Under harmonic base excitation, it is imposed that the resonant period and peak response of the interacting system be equal to those of the replacement oscillator. Eurocode 8 obligates to take the effects of dynamic soil-structure interaction into account for structures where P-δ (2nd order) effects play a significant role; structures with massive or deep-seated foundations, such as bridge piers, offshore caissons, and silos; slender tall structures, such as towers and chimneys; and structures supported on very soft soils, with average shear wave velocity less than 100 m/s (EC8, 1994). Effective period and damping of the interacting system are given below

$$\tilde{T} = T\sqrt{1 + \frac{k}{K_x}\left(1 + \frac{K_x h^2}{K_\theta}\right)} \tag{4}$$

$$\tilde{\beta} = \beta_0 + \frac{0.05}{\left(\dfrac{\tilde{T}}{T}\right)^3} \tag{5}$$

where β_o denotes the foundation damping factor and values for this factor should be read from the figure given in current U.S. codes (ATC 1984, FEMA 2003). The stiffness coefficients for the horizontal (K_x) and rocking modes (K_θ) of soil medium are defined as follows (Wolf 1994)

$$K_x = \frac{8 \cdot \rho \cdot V_s^2 \cdot r}{2 - \upsilon} \tag{6}$$

$$K_\theta = \frac{8 \cdot \rho \cdot V_s^2 \cdot r^3}{3 \cdot (1 - \upsilon)} \tag{7}$$

More details regarding equivalent fixed-base model can be found in (Eser *et al.* 2012a, b).

2.2 Seismic input

Seismic excitation consists of real near-field and far-field earthquakes. A set of 70 near-field and 70 far-field acceleration time-histories are used in this study. The selection of near field and far field ground motions are based on the earthquakes given in ATC documents (1996, 2008). Details of selected ground motions are listed in Tables 1 and 2. The soil categorization is based on classification system presented in NEHRP provisions which corresponds to shear wave velocity higher than 1500 m/s for Soil Class A, between 760-1500 m/s for Soil Class B, 360-760 m/s for Soil Class C, 180-360 m/s for Soil Class D and lower than 180 m/s for Soil Class E. Also, Figure 1 shows the magnitude-source distance-PGA relation for the aforementioned 140 ground motions. These accelerograms are downloaded from the strong motion database of the Pacific Earthquake Engineering Research Center (Last access 2018). Near-field seismic ground motions are usually characterized by intense velocity and displacement pulses; besides, forward directivity and permanent translation are generally the two main causes for the velocity pulses observed in near-field regions. Near-fault ground motions containing strong velocity pulses are of interest in the fields of seismology and earthquake engineering because of imposing extreme demands on structures that not predicted by typical measures such as response spectra. Thus, the near-fault ground motion data set is evaluated in detail to distinguish records that contain pulse-like signal effects, i.e.

Table 1 Far field ground motions used in analyses

Earthquake	Station/No	M	Dist. (km)	Comp. 1	PGA (g)	PGV (cm/s)	Comp. 2	PGA (g)	PGV (cm/s)	Site class
Loma Prieta 18/10/89	Coyote Lake Dam/57217	7.1	21.8	CYC195	0.151	16.2	CYC285	0.484	39.7	C
Loma Prieta 18/10/89	Monterey City Hall/47377	7.1	44.8	MCH000	0.073	3.5	MCH090	0.063	5.8	C
Loma Prieta 18/10/89	SC Pacific Heights/58131	7.1	80.5	PHT270	0.061	12.8	PHT360	0.047	9.2	B
Northridge 17/01/94	Lake Hughes 9/127	6.7	28.9	L09000	0.165	8.4	L09090	0.217	10.1	C
Northridge 17/01/94	Wrightwood - Jackson Flat/23590	6.7	68.4	WWJ090	0.056	10	WWJ180	0.037	7	C
Northridge 17/01/94	Sandberg Bald Mtn/24644	6.7	43.4	SAN090	0.091	12.2	SAN180	0.098	8.9	C
Northridge 17/01/94	MT Wilson-Cit Sta./24399	6.7	36.1	MTW000	0.234	7.4	MTW090	0.134	5.8	C
Loma Prieta 18/10/89	Anderson Dam Downstream/1652	7.1	20	AND250	0.244	20.3	AND340	0.24	18.4	C
Northridge 17/01/94	Castaic Old Ridge/24278	6.7	25.4	ORR090	0.568	52.1	ORR360	0.514	52.2	C
Northridge 17/01/94	LA Century City North/24389	6.7	18.3	CCN090	0.256	21.1	CCN360	0.222	25.2	D
Cape Mendocino 1992	Rio Dell Overpass/89324	7	22.7	RIO270	0.39	43.9	RIO360	0.55	42.4	D
Loma Prieta 18/10/89	Golden Gate Bridge/1678	7.1	85.1	GGB270	0.233	38.1	GGB360	0.123	17.8	C
Northridge 17/01/94	Ucla Grounds/24688	6.7	16.8	UCL090	0.278	22	UCL360	0.474	22.2	C
Northridge 17/01/94	LA Univ. Hospital/24605	6.7	34.6	UNI005	0.493	31.1	UNI095	0.214	10.8	D
Landers 28/06/92	Yermo Fire Station/22074	7.4	26.3	YER270	0.245	51.5	YER360	0.152	29.7	D
Friuli, Italy-01, 1976	Tolmezzo/8012	6.5	16	TMZ000	0.35	22	TMZ270	0.31	30.8	C
Loma Prieta 18/10/89	Foster City - APEEL 1/58375	7.1	43.9	A01000	0.26	31.9	A01090	0.28	46.3	E
Loma Prieta 18/10/89	Hollister - South & Pine/47524	7.1	28.8	HSP000	0.371	62.4	HSP090	0.177	29.1	D
Northridge 17/01/94	Downey-Birchdale/90079	6.7	40.7	BIR090	0.165	12.1	BIR180	0.171	8.1	D
Northridge 17/01/94	LA-Centinela/90054	6.7	30.9	CEN155	0.465	19.3	CEN245	0.322	22.9	D
Imperial Valley 15/10/79	Delta/6605	6.9	32.7	DLT262	0.238	26	DLT352	0.351	33	D
Loma Prieta 18/10/89	APEEL 2- Redwood City/1002	7.1	47.9	A02043	0.274	53.6	A02133	0.22	34.3	E
Northridge 17/01/94	Montebello/90011	6.7	86.8	BLF206	0.179	9.4	BLF296	0.128	5.9	D
Superstition Hills 24/11/87	Salton Sea Wildlife Refuge/5062	6.6	27.1	WLF225	0.119	7.9	WLF315	0.167	18.3	D
Loma Prieta 18/10/89	Treasure Island/58117	7.1	82.9	TRI000	0.1	15.6	TRI090	0.159	32.8	E

Table 1 Continued

Earthquake	Station/No	M	Dist. (km)	Comp. 1	PGA (g)	PGV (cm/s)	Comp. 2	PGA (g)	PGV (cm/s)	Site class
Kocaeli 17/08/99	Ambarli/-	7.8	78.9	ATS000	0.249	40	ATS090	0.184	33.2	E
Morgan Hill 24/04/84	Appel 1 Redwood City/58375	6.1	54.1	A01040	0.046	3.4	A01310	0.068	3.9	E
Düzce 12/11/99	Ambarlı/-	7.3	193.3	ATS030	0.038	7.4	ATS300	0.025	7.1	E
Kobe 16/01/95	Kakogawa/0	6.9	26.4	KAK000	0.251	18.7	KAK090	0.345	27.6	D
Northridge 17/01/94	Beverly Hills – Mulhol/522	6.7	17.2	MUL009	0.42	58.9	MUL279	0.52	62.7	D
Kobe 16/01/95	Shin-Osaha/932	6.9	19.2	SHI000	0.24	37.8	SHI090	0.21	27.9	D
Loma Prieta 18/10/89	Capitola/47125	7.1	20.1	CAP000	0.53	35	CAP090	0.44	29.2	D
San Fernando 1971	LA - Hollywood Stor FF/326	6.6	22.8	PEL090	0.211	18.9	PEL180	0.171	14.9	D
Chi – Chi Taiwan 1999	HWA003/-	7.6	56.1	HWA003-N	0.14	19.1	HWA003-W	0.05	10.4	A
Chi – Chi Taiwan 1999	TCU045/1018	7.6	26	TCU045-E	0.47	50.05	TCU045-N	0.51	46.4	C

Table 2 Near field ground motions used in analyses

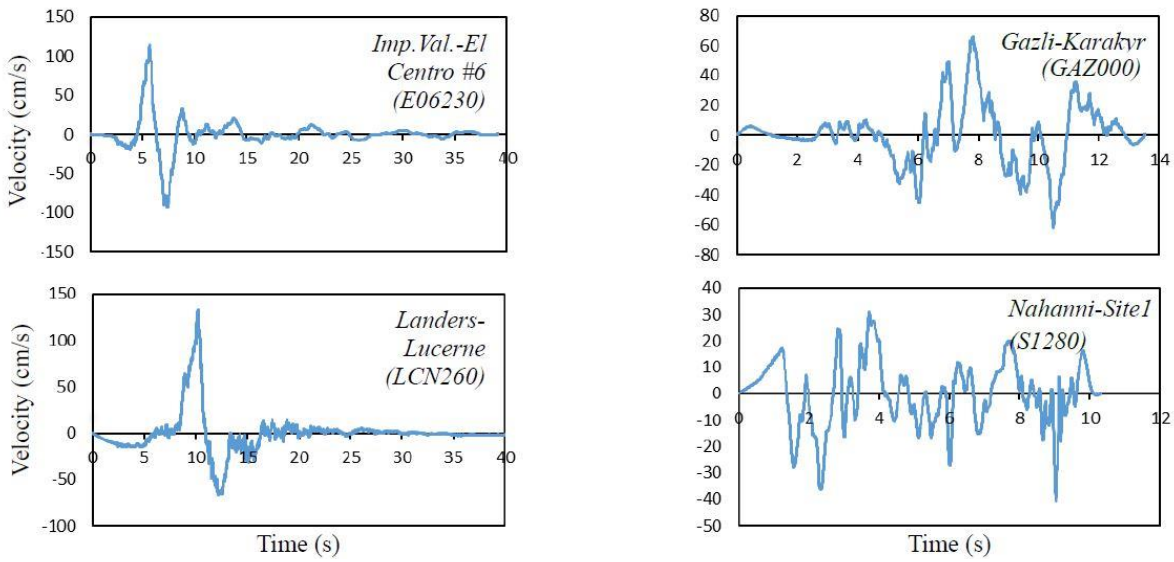
Earthquake	Station/No	M	Dist. (km)	Comp. 1	PGA (g)	PGV (cm/s)	Comp. 2	PGA (g)	PGV (cm/s)	Site class	Pulse Type*
Imperial Valley 15/10/79	El Centro Array #6/230	6.9	1.35	E06140	0.45	67	E06230	0.45	113.5	D	P
Imperial Valley 15/10/79	El Centro Array #7/200	6.9	0.56	E07140	0.34	51.7	E07230	0.47	113.1	D	P
Irpinia, Italy 1980	Sturno/935	6.9	10.8	STU000	0.23	36.9	STU270	0.32	71.9	C	P
Superstition Hills-02 1987	Parachute Test Site/5051	6.5	0.95	PTS225	0.43	134.3	PTS315	0.38	53.1	D	P
Loma Prieta 18/10/89	Saratoga Aloha/58065	7.1	8.5	STG000	0.51	41.6	STG090	0.33	45.9	C	P
Imperial Valley 15/10/79	Chihuahua/6621	6.9	7.3	CHI012	0.27	24.9	CHI282	0.254	30.1	D	NP
Cape Mendocino 1992	Petrolia/89156	7	8.1	PET000	0.59	49.6	PET090	0.66	88.6	C	P
Landers 28/06/92	Lucerne/260	7.4	2.2	LCN260	0.73	133.5	LCN345	0.79	28.2	B	P
Loma Prieta 18/10/89	Gilroy Array #4/57382	7.1	14	G04000	0.417	38.8	G04090	0.212	37.9	D	NP

*P: Pulse, NP: No Pulse

Table 2 Continued

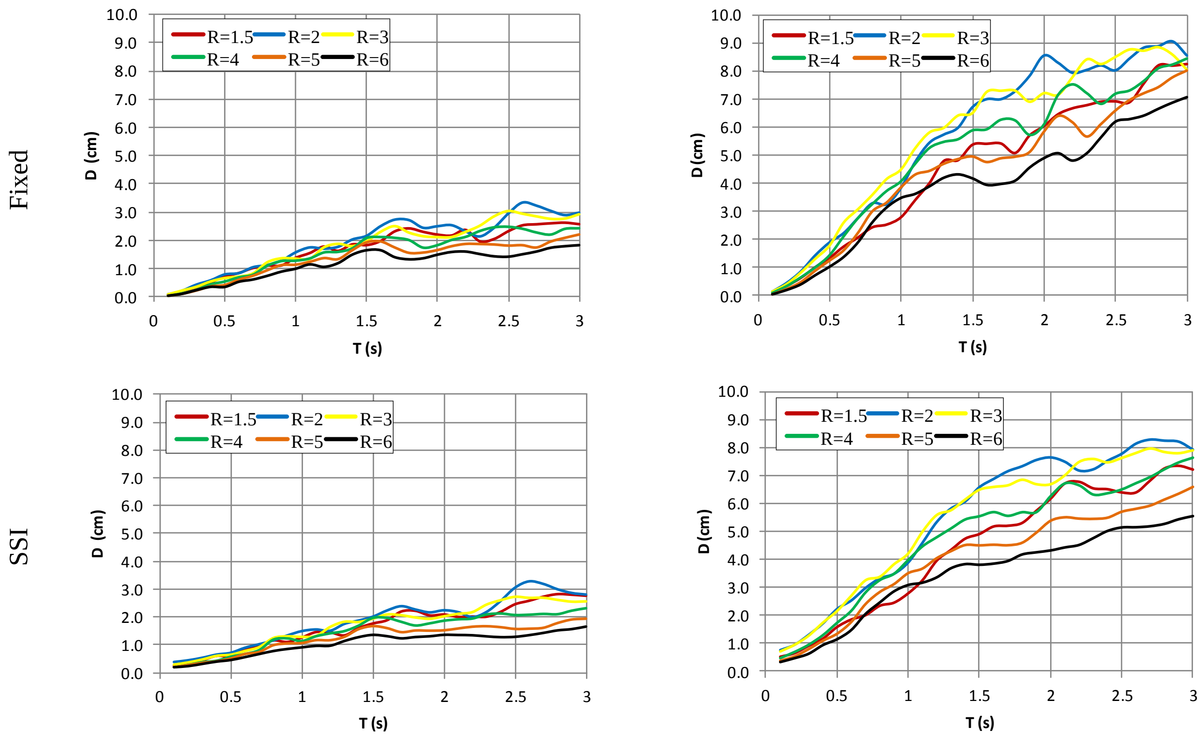
Earthquake	Station/No	M	Dist. (km)	Comp. 1	PGA (g)	PGV (cm/s)	Comp. 2	PGA (g)	PGV (cm/s)	Site class	Pulse Type*
Düzce 12/11/99	Bolu/Bolu	7.3	12	BOL000	0.728	56.4	BOL090	0.822	62.1	D	NP
Kocaeli 17/08/99	Gebze/-	7.8	10.9	GBZ000	0.244	50.3	GBZ270	0.137	29.7	B	NP
Düzce 12/11/99	Lamont 1061/1061	7.3	11.4	1061-E	0.107	11.5	1061-N	0.134	13.7	C	NP
Northridge 17/01/94	Rinaldi Receiving Station/77	6.7	6.5	RRS228	0.87	148.1	RRS318	0.47	74.8	D	P
Northridge 17/01/94	Sylmar Olive View/24514	6.7	5.3	SYL090	0.6	77.6	SYL360	0.84	129.6	C	P
Kocaeli 17/08/99	İzmit/-	7.8	7.2	IZT090	0.23	38.28	IZT180	0.17	22.33	B	P
Chi – Chi Taiwan 1999	TCU065/-	7.6	0.57	TCU065-E	0.79	125.3	TCU065-N	0.58	92.1	D	P
Loma Prieta 18/10/89	Gilroy Array #1/47379	7.1	9.64	G01000	0.41	31.6	G01090	0.47	33.9	B	NP
Chi – Chi Taiwan 1999	TCU102/-	7.6	1.49	TCU102-E	0.3	91.67	TCU102-N	0.17	66.4	C	P
Düzce 12/11/99	Düzce/-	7.3	6.58	DZC180	0.4	71.12	DZC270	0.51	84.2	D	P
Gazli, USSR, 1976	Karakyr/9201	6.8	5.46	GAZ000	0.7	66.2	GAZ090	0.86	67.7	D	NP
Imperial Valley 15/10/79	Bonds Corner/5054	6.9	2.66	BCR140	0.6	46.7	BCR230	0.78	44.9	D	NP
Nahanni, Canada, 1985	Site 1/6097	6.8	9.6	S1010	1.11	43.9	S1280	1.2	40.6	C	NP
Nahanni, Canada, 1985	Site 2/6098	6.8	4.93	S2240	0.52	29.6	S2330	0.36	31.9	C	NP
Loma Prieta 18/10/89	Bran/13	7.1	10.72	BRN000	0.46	51.4	BRN090	0.5	44.5	C	NP
Loma Prieta 18/10/89	Corralitos/57007	7.1	3.85	CLS000	0.64	56	CLS090	0.48	47.5	C	NP
Cape Mendocino 1992	Cape Mendocino/89005	7	6.96	CPM000	1.49	124.6	CPM090	1.04	42.5	C	NP
Northridge 17/01/94	Sepulveda VA/637	6.7	8.44	SPV270	0.75	77.6	SPV360	0.93	76.3	C	NP
Northridge 17/01/94	Saticoy/90003	6.7	12.09	STC090	0.34	31.47	STC180	0.46	60.1	D	NP
Kocaeli 17/08/99	Yarımca/-	7.8	4.83	YPT060	0.23	69.7	YPT150	0.32	71.9	D	NP
Chi – Chi Taiwan 1999	TCU067/-	7.6	0.62	TCU067-E	0.5	92.02	TCU067-N	0.32	51.3	C	NP
Chi – Chi Taiwan 1999	TCU084/-	7.6	11.48	TCU084-E	1.01	128.8	TCU084-N	0.43	48.1	C	NP
Denali, Alaska, 2002	TAPS Pump Sta. #10/Ps10	7.9	2.74	PS10-047	0.33	115.7	PS10-317	0.3	65.9	D	NP
Northridge 17/01/94	Pacoima Dam (upper left)/24207	6.7	7.01	PUL104	1.58	55.7	PUL194	1.29	104	A	P
Tabas, Iran, 1978	Tabas/9101	7.35	2.05	TAB-T1	0.86	123.5	TAB-L1	0.85	99.1	B	NP
Imperial Valley 15/10/79	Aeropuerto Mexicali/6616	6.9	0.34	AEP045	0.33	42.8	AEP315	0.26	24.8	D	P

*P: Pulse, NP: No Pulse



(a) Pulse records (b) No pulse records

Fig. 2 Pulse and no pulse records



(a) Far field (b) Near field

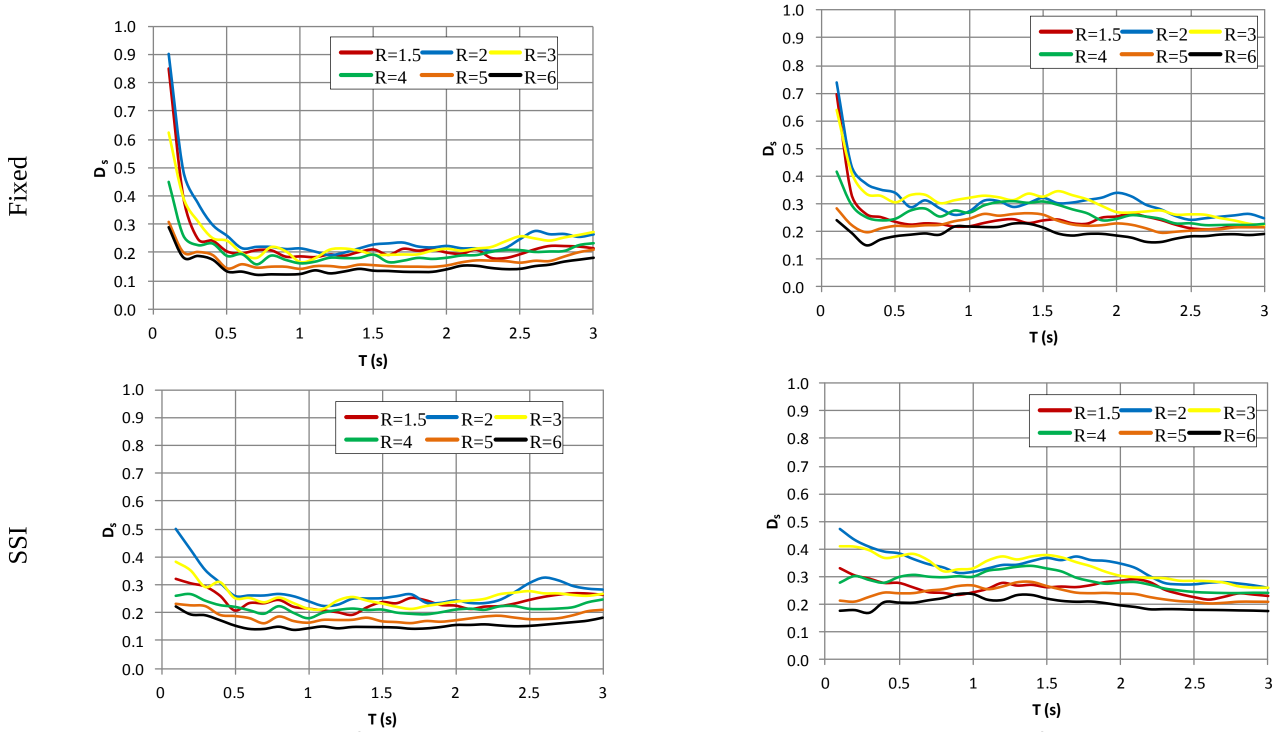
Fig. 3 Variations of mean residual displacements with fault distance

records with strong velocity pulses are categorized as "the pulse like earthquake records", These "pulse" records are selected based on the near field record set given in ATC 63 (2008) document and study of Baker (2007). An explanatory plot is presented in Fig. 2 for pulse and no-pulse records suggested in ATC 63 document (2008). The near-field ground motion set used for the presented study consists of 30 records with pulse signal and 40 records without pulse signal. The residual displacement demands are described separately for near-fault records that either do or do not contain pulse signals.

A total of 151200 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 lateral strength (*R*=1.5, 2, 3, 4, 5, 6) and 140 ground motions.

3. Results and discussion

3.1 Effect of ground motions



(a) Far field (b) Near field

Fig. 4 Variations of residual displacement ratios with fault distance

3.1.1 Effect of fault distance

The effects of fault distance on residual displacement demands are shown in Fig. 3. The top graphs represent the analysis results of fixed base case whereas the bottom graphs show the results of interacting systems with an aspect ratio of 3. It can be seen from the figures that; residual displacement demands for near field ground motions are much greater than the ones for far field ground motions. This condition is almost always valid for all values of lateral stiffness. Especially for period range greater than 1.5s, residual displacement demands for near field ground motions are nearly three times greater than the corresponding ones of far field ground motions

Fig. 4 shows the effects of fault distance on residual displacement ratio (D_s). Analysis results of fixed base case and interacting systems with an aspect ratio of 3 are presented in top and bottom graphs, respectively. In contrast to residual displacement demands, the difference between residual displacement ratios because of fault distance is less noticeable. Especially for period range greater than 0.5s, residual displacement ratios do not vary significantly with fault distance.

3.1.2 Effect of pulse like features

The effect of pulse like features on residual displacement demands is also investigated. In Fig. 5, variations of mean residual displacement demands for far field, pulse and no pulse type records are presented for fixed and flexible systems for two different values of lateral strength. As it is seen from the figures, pulse like features have an obvious effect on residual displacement demands for both lateral strength ratios. Although the same behaviour is valid for other lateral strength ratios, they are not included in the figures for the sake of clarity.

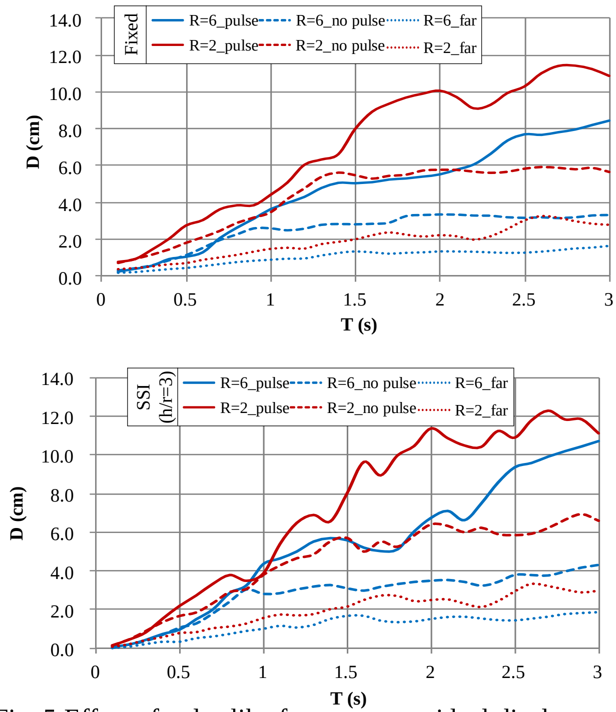


Fig. 5 Effect of pulse like features on residual displacement demands

The effect of pulse like features on mean residual displacement ratio for fixed and flexible systems is also investigated. In Fig. 6, variations of mean residual displacement ratios (D_s) for far field, pulse and no pulse type records are presented. It can be said from the figures that, the effects of pulse like features on mean residual

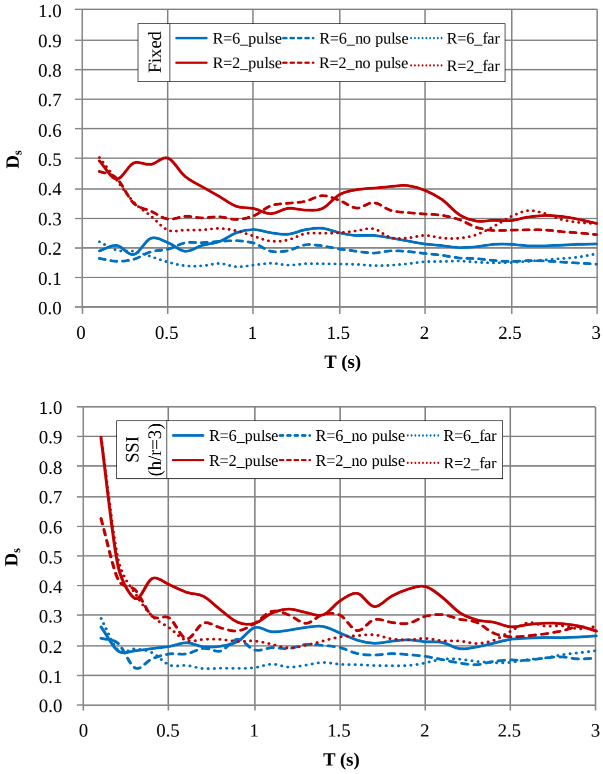


Fig. 6 Effect of pulse like features on residual displacement ratios

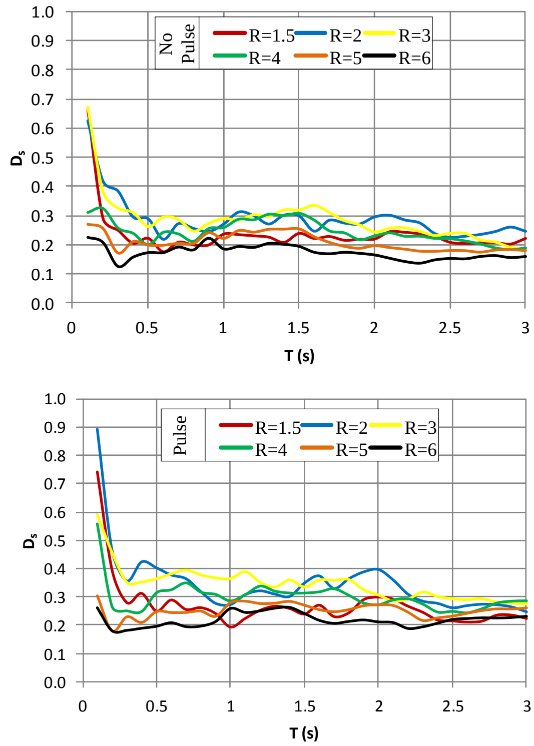


Fig. 8 Variation of residual displacement ratios with pulse like features

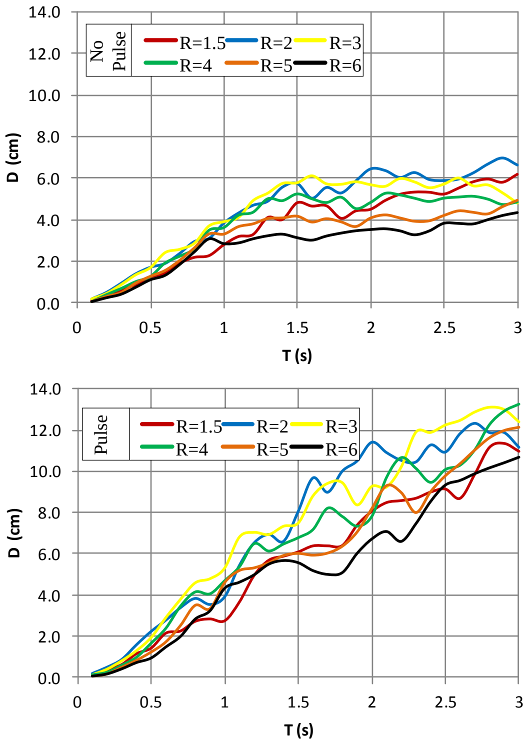


Fig. 7 Variation of residual displacement demands with pulse like features

displacement ratios are still remarkable but not as marked as on residual displacement demands.

Residual displacement demands and residual displacement ratios of fixed base case with pulse and no pulse earthquake records for various values of lateral strength are presented in Figs. 7 and 8, respectively.

Graphs axes are intentionally drawn with the same scales to express the variation and effects of pulse type records. As it is seen from the figures, pulse like features have a very remarkable effect on especially residual displacement demands for all values of lateral strength whereas the same judgement can be valid for residual displacement ratios only for period range smaller than 0.5s.

3.2 Effect of soil flexibility

In Fig. 9, effect of soil flexibility on residual displacement demands against period is presented. The results are given for far field (top) and near field (bottom) ground motions. It is seen from the both figures that, residual displacement demands generally decrease as the soil flexibility is taken into consideration. Residual displacement ratio variation with soil flexibility is shown in Fig. 10. It is observed that residual displacement ratios remain nearly constant for T>0.5 s. For T<0.5 s, there is a decrease tendency for residual displacement ratio for increasing values of lateral strength.

The effect of aspect ratio of flexible systems on residual displacement demands and residual displacement ratios is presented in Figs. 11 and 12, respectively. The results are given for far field and near field ground motions. It is seen from the both figure that, from a certain structural period, residual displacement demands and residual displacement ratios almost always remain constant. However, for period range shorter than approximately 1.0s, mentioned

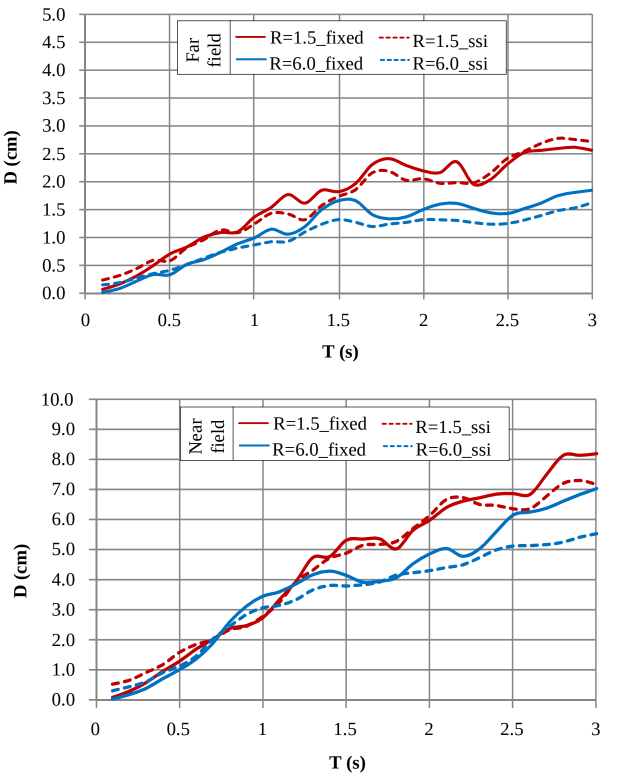


Fig. 9 Effect of soil flexibility on residual displacement demands

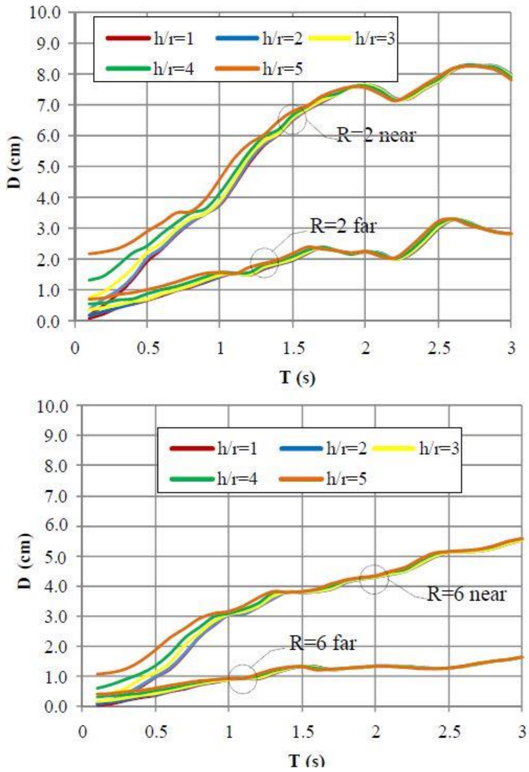


Fig. 11 Effect of aspect ratio on residual displacement demands

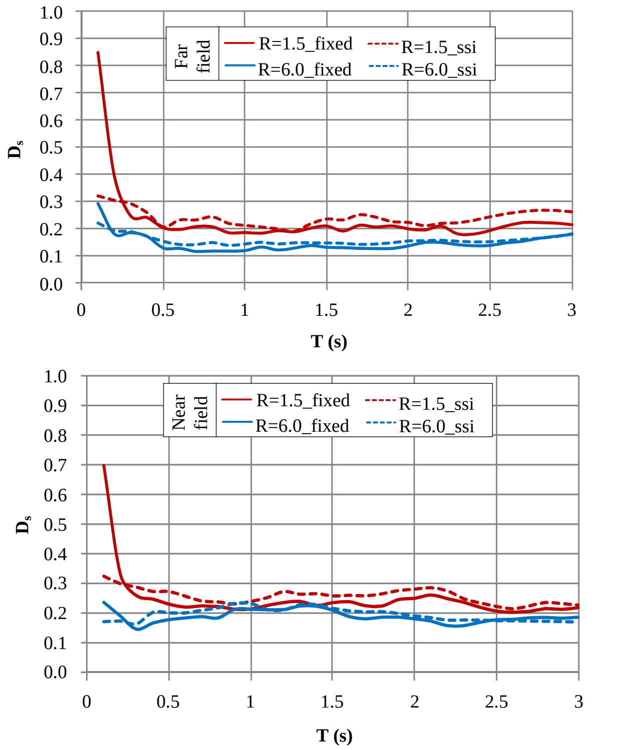


Fig. 10 Effect of soil flexibility on residual displacement ratios

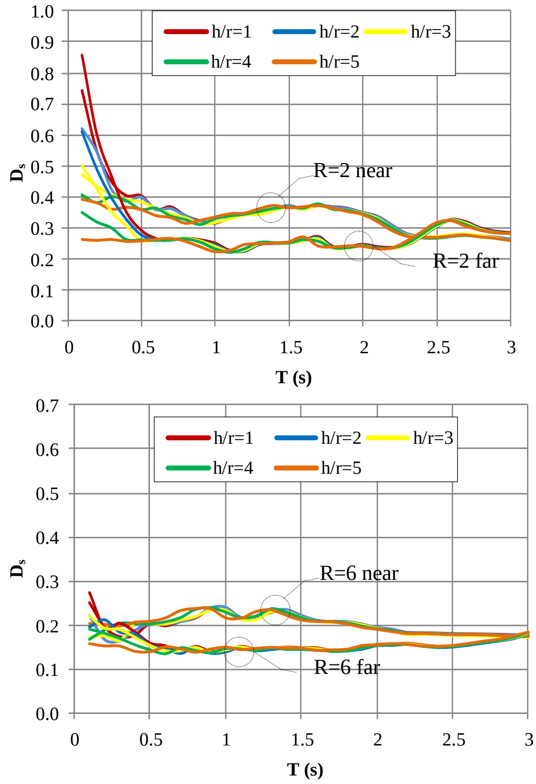


Fig. 12 Effect of aspect ratio on residual displacement ratios

parameters vary significantly. For this period range, residual displacement demands increase as the aspect ratio increases, whereas residual displacement ratios exhibit an opposite tendency. It should also be noted that, as the lateral strength increases both residual displacement demands and residual displacement ratios decrease.

4. Simplified equation to estimate residual displacements

As it is mentioned above, residual displacement / drift demand is a critical key parameter to determine structural performance and seismic assessment. Thus, a simplified equation to predict residual displacement both for fixed base and flexible systems would be very useful and effective through seismic design. The most effective parameters on residual displacement are found to be spectral displacement, lateral strength and structural period. Thus, a simplified equation to predict residual displacement would include these parameters as variables.

Using the Levenberg-Marquardt method (More 1977) in the regression module of STATISTICA (StatSoft 1995), nonlinear regression analyses were conducted to derive simplified expressions for estimating mean residual displacements for both fixed-base and interacting cases, respectively. The resulting regression formula is appropriately simplified and expressed as

$$D = D_s \cdot S_d \tag{8}$$

where D_s is given by

$$D_s = a_0 + a_1 * a_2 \tag{9}$$

In Eq. (9), a_0 is a constant whereas a_1 and a_2 parameters depend on lateral strength, R and structural period, *T*. The definition of a_1 and a_2 parameters are given by Eqs. (10) and (11).

$$a_1 = b + c*R + d/(R*T) + e/R \tag{10}$$

$$a_2 = R^{(f+g*T)} + T^{(h+k*T)} \tag{11}$$

The proposed equation is also valid for residual displacement demands of interacting systems. The main difference between the equations of fixed and flexible base cases lies in the definition of structural period. For residual displacement demand estimation of systems without interaction, fixed base structural period is used whereas flexible period is used for interacting case, so the rearranged equation form is given by

$$a_1 = b + c*R + d/(R*\tilde{T}) + e/R \tag{12}$$

$$a_2 = R^{(f+g*\tilde{T})} + \tilde{T}^{(h+k*\tilde{T})} \tag{13}$$

For all cases, parameter estimates and coefficients are summarized in Table 3.

Fig. 13 shows the fitness of the regressed function of the mean residual displacement ratios for fixed base and interacting systems for both near field and far field records, all lateral strength ratios and periods. The vertical axis shows the observed/calculated values whereas the horizontal axis shows the corresponding values obtained with proposed equation Eq. (9).

Two commonly used measures of "goodness of fit" of the nonlinear regression analyses results are computed for the proposed equation. The standard error and the correlation coefficient values calculated for the cases considered are reported in Table 4. From these measures, it can be concluded that the proposed equation to estimate residual displacements provide good results.

Figs. 14 and 15 demonstrate the fitness of the proposed function for the mean residual displacement ratios for far field and near field ground motions, respectively. In these figures, the top graphs represent the comparisons of calculated and predicted values for fixed base systems whereas the bottom graphs represent the comparisons of results for and flexible case systems with rearranged version of proposed equation.

5. Conclusions

In this study, residual displacement demands are investigated for both fixed and flexible base SDOF systems with period range of 0.1-3.0s under near-field and far-field ground motions. The elastoplastic model is used to represent non-degrading structures. For soil structure interaction, a replacement oscillator represented by the effective period and damping of the system is used. The mass of this equivalent oscillator is taken to be equal to that of the actual structure. Based on nonlinear regression analyses, not only conceptually simple but also effective new equation is proposed for residual displacement demand of both fixed and flexible base systems as a function of structural period (T or $\tilde{T}$), lateral strength ratio (R) and spectral displacement (S_d). With respect to authors' knowledge soil structure interaction effects on residual

Table 4 Computed measures of "goodness of fit" for Eq. (9)

Base/Record Set	Standard Error, SE	Correlation Coefficient, *R*
Fixed / FF*	0.02064	0.98
Fixed / NF	0.02317	0.95
SSI / FF	0.01962	0.95
SSI / NF	0.02148	0.95

*FF: Far field; NF: Near field.

Table 3 Parameter Summary for Eq. (9)

Base/Record Set	Coefficients of derived equation								
	a_0	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*k*
Fixed / FF*	0.124	0.184	-0.0252	0.019	-0.173	-0.863	-0.144	-0.675	0.518
Fixed / NF	4.04	-1.25	0.03	0.06	-0.849	0.433	0.004	-0.083	0.027
SSI / FF	0.132	0.226	-0.0308	0.0117	-0.196	-0.916	0.029	-0.768	0.445
SSI / NF	-1.59	1.634	-0.032	0.131	-0.965	-0.119	-0.424	0.344	-0.04

*FF: Far field; NF: Near field.

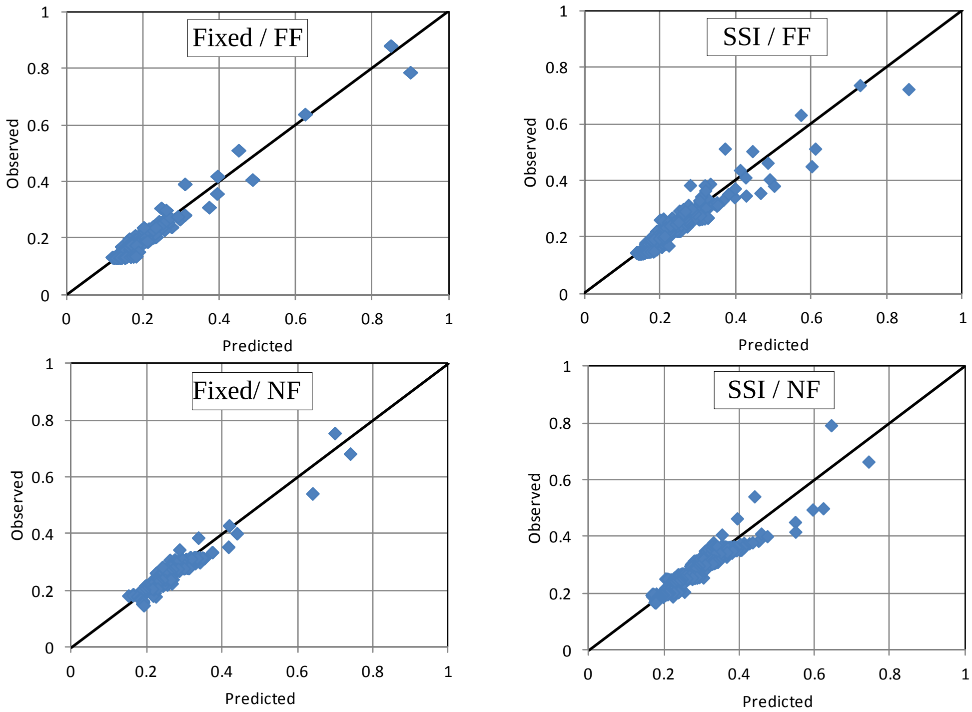


Fig. 13 Comparison of calculated residual displacements with corresponding values obtained with proposed equation Eq. (9)

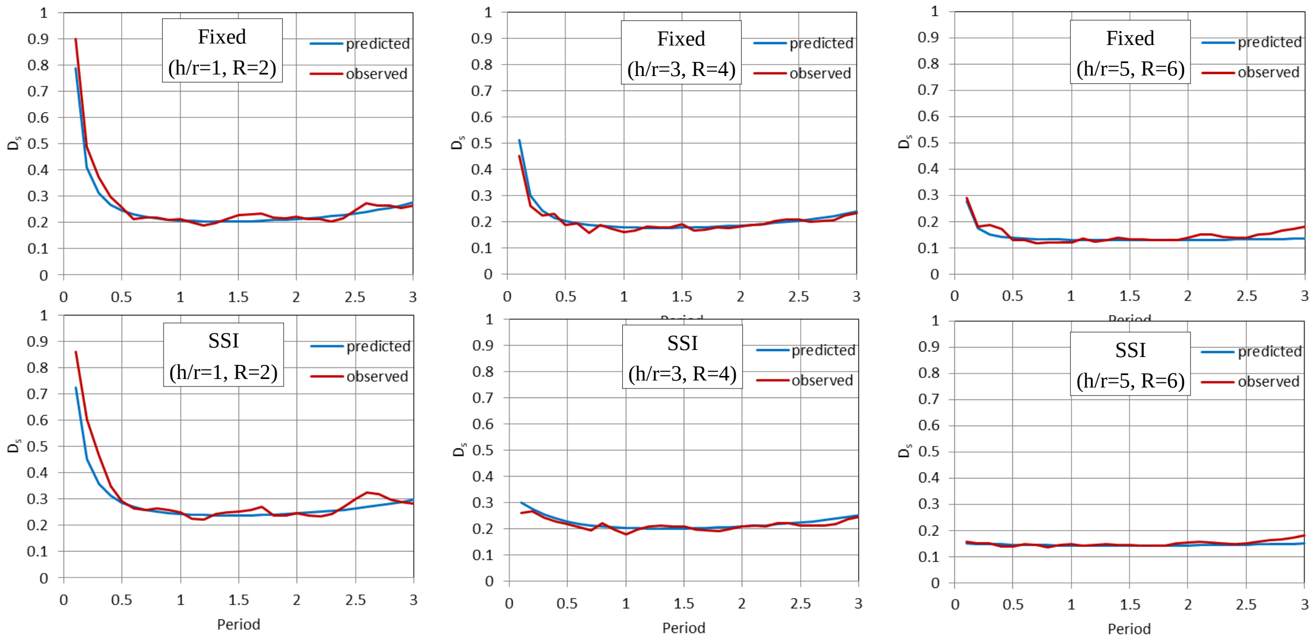


Fig. 14 Comparison of calculated residual displacement ratios with those computed with Eq. (9) for far field records

displacement has not been considered, yet, thus this study is intended to focus on the effects of soil flexibility on residual displacements. The following conclusions can be drawn from the results of this study.

• Residual displacement demands for near field ground motions are much greater than the ones for far field ground motions. This condition is almost always valid for all values of lateral stiffness. Especially for period range greater than 1.5s, residual displacement demands for near field ground motions are nearly three times greater than the corresponding ones of far field ground motions.

• In contrast to residual displacement demands, the variation on residual displacement ratios because of fault distance is less noticeable. Especially for period range greater than 0.5s, residual displacement ratios do not vary significantly with fault distance.

• Pulse like features have an obvious effect on residual

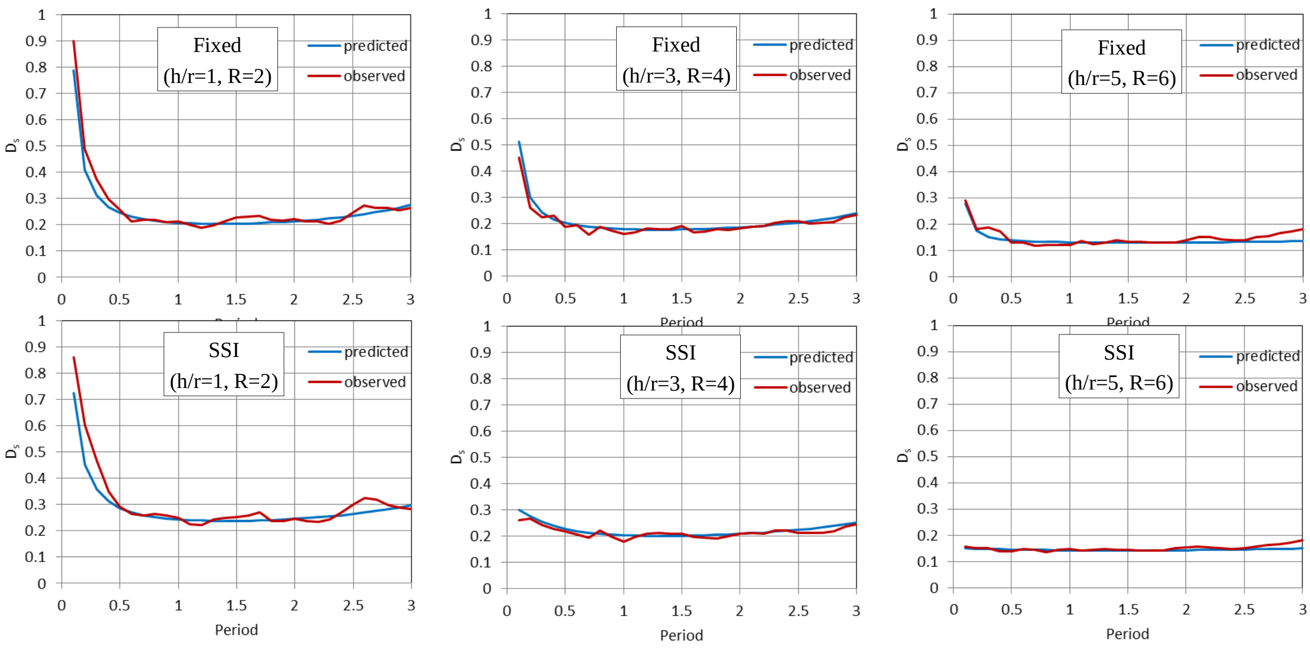


Fig. 15 Comparison of calculated residual displacement ratios with those computed with Eq. (9) for near field records

displacement demands for all lateral strength ratios. Pulse type ground motions require higher residual displacement demands.

• The effects of pulse like features on mean residual displacement ratios are still remarkable but not as marked as on residual displacement demands. The effects are clear only for period range smaller than 0.5s.

• Residual displacement demands generally decrease as the soil flexibility is taken into consideration. It is observed that residual displacement ratios remain nearly constant for T>0.5 s. For T<0.5 s, there is a decrease tendency for residual displacement ratio for increasing values of lateral strength.

• Residual displacement demands and residual displacement ratios almost always remain constant from a certain structural period. However, for period range shorter than approximately 1.0 s, mentioned parameters vary significantly. For this period range, residual displacement demands increase as the aspect ratio increases, whereas residual displacement ratios exhibit an opposite tendency. It should also be noted that, as the lateral strength increases both residual displacement demands and residual displacement ratios decrease.

• New equations (Eqs. (8)-(9)) are proposed to represent the mean residual displacement demands for considered records, lateral strengths, and structural periods. The proposed simplified expression provides a good approximation of mean residual displacement ratios of SDOF systems having non-degrading behavior. Eqs. (10) and (11) present the form of equations for residual displacements of fixed base case whereas Eqs. (12) and (13) present the results for interacting case. The major contribution and originality of this study lies in the fact that, the proposed equation is also valid for flexible base systems with the replacement of fixed base structural period to interacting period.

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