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Assessment of near-field and far-field strong ground motion effects on soil-structure SDOF system

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Abstract

The distinctive characteristics of near-field earthquake records can lead to different structural responses from those experienced in far-field ones. Furthermore, soil-structure interaction (SSI) can have a crucial influence on the seismic response of structures founded on soft soils; however, in most of the time has been neglected nonchalantly. This paper addresses the effects of near-field versus far-field earthquakes on the seismic response of single degree of freedom (SDOF) system with considering SSI. A total 71 records were selected in which near-field ground motions have been classified into two categories: first, records with a strong velocity pulse, (i.e. forward-directivity); second, records with a residual ground displacement (i.e. fling-step). Findings from the study reveal that pulse-type near-field records generally produce greater seismic responses than far-field motions especially at high structure-to-soil stiffness ratios. Moreover, the importance of considering SSI effects in design of structures is investigated through an example. Finally, parametric study between Peak Ground Velocity to Peak Ground Acceleration ratio (PGV/PGA) of pulse-like ground motions and maximum relative displacement indicate that with increase in structure-to-soil stiffness ratios, earthquakes with higher PGV/PGA ratio produce greater responses.

Keywords: *Soil-structure interaction, SDOF system, Near-field earthquake, Far-field earthquake, PGV/PGA.*

1. Introduction

Ground motions result from an earthquake mirror the characteristics of the seismic source such as the rupture process, the source-to-site travel path, and local site conditions. Therefore, the features of ground motions in the vicinity of an active fault are significantly different from the far-fault ones that severely affect the damage potential of these earthquakes [1].

In the near-field zone, the ground motions may be distinguished by short-duration impulsive motions, permanent ground displacement and high-frequency content, which have attracted much attention as the critical factors in the design of structure in the near-field zone [2-4]. Thus, in order to provide quantitative knowledge to consider the salient effects of near field earthquakes on seismic performance of various elastic and inelastic systems and to develop appropriate design guidelines, much effort has been devoted [5-13].

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It should be noted that the seismic analysis of engineering structures is often conducted based on an assumption that the structure is founded on a rigid semi-space, while in most situations the structures are supported by soil deposits. Under based-rigid condition, the base motion of structure is restricted to be very close to the free-field motion (FFM) due to the extremely high stiffness of the substructure. In all other cases, presence of the soil can cause two distinct effects on the response of the structure, first, alteration of the FFM at the base of the structure, and second, inducing a deformation from dynamic response of the structure into the supporting soil. The former is referred to as kinematic soil-structure interaction (KSSI), while the latter is known as inertial soil-structure interaction (ISSI) and the whole process is identified as SSI. As a result, SSI effects should be taken into account to evaluate effectively the seismic performance of various systems [14-17].

Various procedures have been proposed to consider SSI effects in the seismic analysis of structures. A proposed classification is presented according to the selection of the models which are used in studies. Some studies followed the classic methods (i.e. impedance functions, lumped-parameter models, Cone models, beam-column analogy). The others used the modern methods (i.e. direct method, substructure method) [18].

The necessity of considering SSI effects and distinct features of near-fault strong motions was revealed to

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develop appropriate design codes and provisions. Therefore, some researchers tried to analysis and evaluate the seismic performance of different soil-structure systems subjected to such excitations. In this regards some contributions found in literature using various SSI methods, which are briefly presented in following.

Ghannad et al. [19] studied the seismic response of soil-structure system, based on the concept of Cone models, subjected to near-fault ground motions with forward-directivity effect. They used moving average filtering to decompose near-fault ground motions into two components possess different frequency content: "A Pulse-Type Record (PTR) that having long period pulses, and a relatively high frequency Background Record (BGR)". The results showed that considering SSI causes the peaks of acceleration spectra for the original near-fault records and their decomposed parts become closer compared to the corresponding fixed-base systems especially at low structure-to-soil stiffness ratios. Zhang and Tang [20] investigated the dynamic responses of the soil-foundation-structure interaction (SFSI) through a lumped 2DOF system subjected to pulse-type near-fault ground motions by introducing dimensionless parameters. Their numerical simulations revealed that "SSI effects highly depend on the pulse-to-structure frequency ratio, the foundation-to-structure stiffness ratio, the foundation rocking, and the development of nonlinearity in structure". Azarhoosh and Ghodrati Amiri [21] carried out a parametric study on the elastic response of different soil-structure systems having shallow foundations, based on the concept of Cone models, subjected to synthetic pulses and near-fault motions. They found out that considering SSI have negligible effects on the dynamic responses of structures having very low or very large period ratios ($T_{structure}$ /T_{Pulse}). Additionally, under SSI effects, synthetic pulses and near fault motions produced elastic structural seismic demands with clear similarities. Minasidis et al. [22] examined SSI effect on the inelastic seismic response of two-dimensional steel frames subjected to near-fault earthquakes by using springs and dashpots to consider flexibility of soil at the soil-foundation interface. They found that SSI generally results in greater maximum inter-story drift ratios and lesser floor accelerations in comparison with the case of stiff soil. Gelagoti et al. [23] studied the seismic performance of rocking-isolated frame structures by employing nonlinear Finite Element modeling to consider SSI. The near-source seismic records were considered to investigate the margins of safety against toppling collapse of the 2-storey frame structure. Their results revealed that the important role of maximum impact pulse velocity (V_{impact} (max)) and the number of strong motion cycles in addition to PGA in toppling potential of earthquakes.

In previous studies, some characteristics of near-fault earthquakes have been investigated generally by applying restricted number of records. The SSI effects also have been brought to consideration through describing limited soil-structure parameters which can be representative of rather restricted situations. Thus, it seems to be necessary to investigate the outstanding effects of near-field ground motions versus far-field records at wide range of soil-structure conditions to gain better perception about the SSI effects on seismic responses of structures [24]. In this paper, the elastic response of soil-structure SDOF systems subjected to a large diversity of near-field and far-field ground motions is studied at various structure-to-soil stiffness ratios. In addition, the probable crucial role of considering SSI is presented through an example of unexpected trend of structural responses relative to stiff soil condition. At last, a parametric study is conducted to present a relationship between maximum displacement responses of equivalent SDOF system and PGV/PGA ratios of various ground motions.

2. Soil-Structure Model

The SSI effects rely on the properties of both structure and supporting soil, which may alter widely. Although different models can be adapted to consider SSI effects, a linear soil-structure SDOF system with a longer natural period and mostly a higher damping ratio can be employed as a simple model [14].

In present study, the effects of SSI have been investigated on elastic response of linear surface structure which is subjected to horizontal seismic excitations. A simplified discrete model as shown in Fig. 1 is used to represent the real soil-structure system. This model is based on the following assumptions [14]:

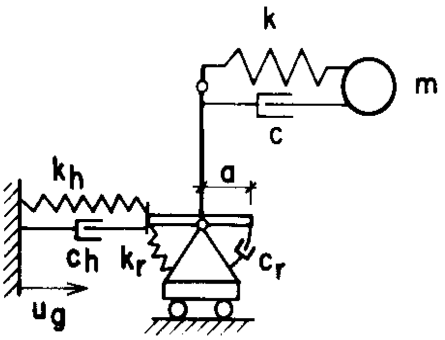

Fig. 1 Soil-structure model [14]

- An equivalent linear SDOF system introduced as a structure.
- A massless circular rigid disk applied as a foundation.
- The soil beneath the foundation is considered as a homogeneous half-space.

Actual foundation stiffness and damping coefficients are frequency dependent. However, to illustrate the SSI effects the simplified frequency independent expressions can be used to estimate the stiffness and damping coefficients. The coefficients of springs and dashpots for the sway and rocking motions can be evaluated using the following formula, respectively [14]:

$$k_h = \frac{8Ga}{2-\vartheta} \tag{1}$$

$$k_r = \frac{8Ga^3}{3(1-\vartheta)} \tag{2}$$

$$c_h = \frac{4.6}{2-\vartheta}\rho V_s a^2 \tag{3}$$

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$$c_r = \frac{0.4}{1-\vartheta}\rho V_s a^4 \quad (4)$$

Where ϑ, ρ, G and V_s are respectively Poisson's ratio, the mass density, shear modulus and the shear-wave velocity of the soil. Moreover, "a" represents a characteristic length of the rigid base.

3. Equations of Motion of Equevalent Sdof System

For a specific excitation, the response of a dynamic system relies on the characteristics of the structure relative to those of soil. The following dimensionless parameters can describe the effect of SSI effectively [14]:

- Structure-to-soil stiffness ratio:

$$\bar{S} = \frac{\omega_s h}{V_s} \quad (5)$$

Where "ω_s" is fixed-base frequency of structure and "h" is height of the structure.

- The slenderness ratio:

$$\bar{h} = \frac{h}{a} \quad (6)$$

- The mass ratio:

$$\bar{m} = \frac{m}{\rho a^3} \quad (7)$$

- Poisson's ratio of the soil "ϑ"
- Hysteretic material damping ratios of the soil "ζ_g" and the structure "ζ".

To consider SSI effect, a SDOF system must be replaced with an equivalent system which has higher hysteretic damping ratio and less natural frequency [14]:

- Equivalent frequency:

$$\tilde{\omega}^2 = \frac{{\omega_s}^2}{1+\frac{\bar{m}\bar{S}^2}{8}\left(\frac{2-\vartheta}{\bar{h}^2}+3(1-\vartheta)\right)} \quad (8)$$

- Equivalent damping ratio:

$$\tilde{\zeta} = \frac{\tilde{\omega}^2}{{\omega_s}^2}\zeta + \left(1-\frac{\tilde{\omega}^2}{{\omega_s}^2}\right)\zeta_g + \frac{\tilde{\omega}^3}{\omega_s^3}\frac{\bar{S}^3\bar{m}}{\bar{h}}\left(0.0036\frac{2-\vartheta}{\bar{h}^2}+0.028(1-\vartheta)\right) \quad (9)$$

In this study, the equations of motion for equivalent one-degree-of-freedom system with a rigid basement were derived in the time domain. The formulation of dynamic equilibrium of the mass point as well as the horizontal and rotational equilibrium equations of total system lead to [25]:

$$\ddot{u} + 2\tilde{\zeta}\tilde{\omega}\dot{u} + \tilde{\omega}^2 u = -\frac{\tilde{\omega}^2}{\omega_s^2}\ddot{u_g} \quad (10)$$

$$\frac{4.6\bar{h}}{(2-\vartheta)\bar{m}\bar{S}\omega_s}\dot{u}_0 + \frac{8\bar{h}^2}{(2-\vartheta)\bar{m}\bar{S}^2}u_0 = \frac{2\zeta}{\omega_s}\dot{u} + u \quad (11)$$

$$\frac{0.4}{(1-\vartheta)\bar{m}\bar{S}\bar{h}\omega_s}h\dot{\phi} + \frac{8}{3(1-\vartheta)\bar{m}\bar{S}^2}h\phi = \frac{2\zeta}{\omega_s}\dot{u} + u \quad (12)$$

Where "u" is lateral displacement of mass, "u_0" is lateral displacement of base and "ϕ" is rocking amplitude.

$$u_{total} = u_0 + h\phi + u \quad (13)$$

4. Near-Field Ground Motion

The Near-fault zone is typically considered to be within a distance of about 20-60 km from the fault rupture. However, there is no universal definition for it over which a site may be classified as in near or far-field [26]. Moreover, forward-directivity effect and fling-step effect are two well-known specifications of near-field ground motions [3]. Forward-directivity pulses, which can be distinguished best in velocity time history, occur where the rupture propagation velocity is close to the shear-wave velocity. These pulses, due to the radiation pattern of the fault, are mainly oriented in the fault-normal direction. However, the fault parallel direction may contain strong pulses as well [27]. Moreover, fling-step motion is a result of the development of static permanent ground displacements due to tectonic deformation associated with fault rupture. It is generally characterized by a one-sided large-amplitude velocity-pulse and a ramp-like step in the displacement time history [28]. It should be noted that these pulse-like near-field ground motions can lead to higher seismic demands and must be taken into account for design or retrofit of structures in the near-field zone [29-30].

5. Ground Motion Database

In this study, the ground motion database compiled for numerical analyses consists of a large number of far-field and near-field ground motions to cover a range of frequency content, duration, and amplitude. Near-field records are classified based on the presence of forward-directivity effect and fling-step effect. Moreover, near-field ground motions recorded within 30 km. In three sub-data sets the assembled database can be investigated. The first set contains 15 near-field ground motions characterized with forward-directivity effect and is divided into normal and parallel component records given in Tables 1 and 2. The second set includes 19 near-field ground motions records characterized with fling-step effect given in Table 3. Due to inaccessibility to various near-field ground motions database with fling-step effect, the fling records were generally selected from the 1999 (M_w 7.6) Chi-Chi (Taiwan) earthquake that has provided one the rich data sets including significant permanent tectonic displacement records. The third set consists of 22 ordinary far-field ground motions recorded within 92 Km of the causative fault plane given in Table 4. All the time histories are recorded on soil classified as type C or D, according to the NEHRP site classification. Selecting these soil conditions is required to consider SSI effects properly. The whole ground motion records were extracted from PEER Strong Motion Database of Berkeley University [31].

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Table 1 The characteristics of near-field ground motions with forward-directivity effect (The normal component)

No.	Earthquake	Year	Station	M_w	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	San fernando	1971	Pacoima Dam-Left Abutment	6.61	11.86	1.45	115.66	30.46
2	Gazli	1976	Karakyr	6.8	12.82	0.599	64.94	24.18
3	Coyote lake	1979	Gilroy Array #6	5.74	4.37	0.452	51.53	7.09
4	Coalinga	1983	Pleasant Valley P.P. - bldg	6.36	9.98	0.377	32.37	6.45
5	Morgan hill	1984	Anderson dam(Downstream)	6.19	16.67	0.449	29.01	3.91
6	Nahanni, Canada	1985	Site1	6.76	6.8	0.853	43.82	16.08
7	N. Palm Springs	1986	North Palm Springs	6.06	10.57	0.669	73.55	11.87
8	Whittier Narrows-01	1987	Santa Fe Springs - E.Joslin	5.99	11.73	0.398	23.75	1.76
9	Superstition Hills-02	1987	Parachute Test Site	6.54	15.99	0.418	106.74	50.54
10	Loma Prieta	1989	Gilroy Array #2	6.93	29.77	0.406	45.65	12.53
11	Sierra Madre	1991	Cogswell Dam-Right Abutment	5.61	18.77	0.297	15.01	2.05
12	Erzican, Turkey	1992	Erzican	6.69	8.97	0.486	95.4	32.09
13	Northridge-01	1994	LA dam	6.69	11.79	0.576	77.09	20.1
14	Kobe	1995	KJMA	6.9	18.27	0.854	95.75	24.56
15	Chi-Chi	1999	TCU065	7.62	26.67	0.831	129.55	93.85

Table 2 The characteristics of near-field ground motions with forward-directivity effect (The parallel component)

No.	Earthquake	Year	Station	M_w	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	San fernando	1971	Pacoima Dam-Left Abutment	6.61	11.86	0.827	34.43	18.67
2	Gazli	1976	Karakyr	6.8	12.82	0.71	71.05	24.7
3	Coyote lake	1979	Gilroy Array #6	5.74	4.37	0.333	27.14	4.48
4	Coalinga	1983	Pleasant Valley P.P. - bldg	6.36	9.98	0.284	19.02	2.47
5	Morgan hill	1984	Anderson dam(Downstream)	6.19	16.67	0.276	29.52	6.44
6	Nahanni, Canada	1985	Site1	6.76	6.8	1.17	36.53	4.36
7	N. Palm Springs	1986	North Palm Springs	6.06	10.57	0.615	29.2	3.52
8	Whittier Narrows-01	1987	Santa Fe Springs - E.Joslin	5.99	11.73	0.51	33.09	4.16
9	Superstition Hills-02	1987	Parachute Test Site	6.54	15.99	0.343	49.57	21.78
10	Loma Prieta	1989	Gilroy Array #2	6.93	29.77	0.302	27.58	6.11
11	Sierra Madre	1991	Cogswell Dam-Right Abutment	5.61	18.77	0.261	9.19	0.85
12	Erzican, Turkey	1992	Erzican	6.69	8.97	0.419	45.29	16.52
13	Northridge-01	1994	LA dam	6.69	11.79	0.415	40.74	16.01
14	Kobe	1995	KJMA	6.9	18.27	0.548	53.38	10.27
15	Chi-Chi	1999	TCU065	7.62	26.67	0.557	82.27	55.05

Table 3 The characteristics of near-field ground motions with fling-step effect

No.	Earthquake	Year	Station	Comp.	M_w	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Chi-Chi	1999	TCU074	EW	7.6	13.75	0.59	68.9	193.2
2	Chi-Chi	1999	TCU074	NS	7.6	13.75	0.37	47.95	155.4
3	Chi-Chi	1999	TCU084	EW	7.6	11.4	0.98	140.43	204.6
4	Chi-Chi	1999	TCU129	EW	7.6	2.21	0.98	66.92	126.1
5	Kocaeli	1999	Yarimca	EW	7.4	3.3	0.23	88.83	184.8
6	Kocaeli	1999	Sakarya	EW	7.4	3.2	0.41	82.05	205.9
7	Chi-Chi	1999	TCU102	EW	7.6	1.19	0.29	84.52	153.9
8	Chi-Chi	1999	TCU089	EW	7.6	8.33	0.34	44.43	193.9
9	Chi-Chi	1999	TCU049	EW	7.6	3.27	0.27	54.79	121.8
10	Chi-Chi	1999	TCU067	EW	7.6	1.11	0.48	94.31	181.3
11	Chi-Chi	1999	TCU075	EW	7.6	3.38	0.32	111.79	164.4
12	Chi-Chi	1999	TCU076	EW	7.6	3.17	0.33	65.93	101.7
13	Chi-Chi	1999	TCU072	NS	7.6	7.87	0.36	66.73	245.3
14	Chi-Chi	1999	TCU072	EW	7.6	7.87	0.46	83.6	209.7
15	Chi-Chi	1999	TCU065	EW	7.6	2.49	0.76	128.32	228.4
16	Chi-Chi	1999	TCU079	EW	7.6	10.95	0.57	68.06	166.1
17	Chi-Chi	1999	TCU078	EW	7.6	8.27	0.43	41.88	121.2
18	Chi-Chi	1999	TCU082	EW	7.6	4.47	0.22	50.49	142.8
19	Chi-Chi	1999	TCU128	EW	7.6	9.08	0.14	59.42	91.05

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Table 4 The characteristics of far-field ground motions

No.	Earthquake	Year	Station	Comp.	M_w	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Kern County	1952	Taft Lincoln School	NS	7.4	38.89	0.156	15.31	9.21
2	Kern County	1952	Taft Lincoln School	EW	7.4	38.89	0.177	17.47	8.84
3	San Fernando	1971	2516 Via Tejon PV	NS	6.6	55.2	0.025	3.82	2.18
4	San Fernando	1971	2516 Via Tejon PV	EW	6.6	55.2	0.041	4.21	3.07
5	Tabas, Iran	1978	Ferdows	NS	7.4	91.14	0.087	5.63	4.52
6	Tabas, Iran	1978	Ferdows	EW	7.4	91.14	0.107	8.55	9.53
7	Imperial Valley06	1979	Coachella Canal #4	NS	6.5	50.1	0.115	12.47	2.32
8	Imperial Valley06	1979	Coachella Canal #4	EW	6.5	50.1	0.128	15.62	2.94
9	Victoria, Mexico	1980	SAHOP Casa Flores	NS	6.3	39.3	0.101	7.77	2.45
10	Victoria, Mexico	1980	SAHOP Casa Flores	EW	6.3	39.3	0.068	8.99	2.06
11	Coalinga-01	1983	Parkfield-Cholame 12W	NS	6.4	55.77	0.039	4.22	1.01
12	Coalinga-01	1983	Parkfield-Cholame 12W	EW	6.4	55.77	0.052	5.52	1.56
13	N. Palm Springs	1986	Hesperia	NS	6.1	72.97	0.041	2.32	0.71
14	N. Palm Springs	1986	Hesperia	EW	6.1	72.97	0.036	1.71	0.91
15	WhittierNarrows1	1987	Canyon Country-W Lost	NS	6	48.18	0.109	7.32	0.49
16	WhittierNarrows1	1987	Canyon Country-W Lost	EW	6	48.18	0.103	6.94	0.85
17	Loma Prieta	1989	Richmond City Hall	NS	6.9	87.87	0.124	17.34	2.58
18	Loma Prieta	1989	Richmond City Hall	EW	6.9	87.87	0.105	14.16	3.87
19	Landers	1992	Baker Fire Station	NS	7.3	87.94	0.107	9.32	6.25
20	Landers	1992	Baker Fire Station	EW	7.3	87.94	0.105	11.01	7.91
21	Northridge-01	1994	Huntington Bch-Waikiki	NS	6.7	69.5	0.086	5.01	1.63
22	Northridge-01	1994	Huntington Bch-Waikiki	EW	6.7	69.5	0.068	7.38	1.86

6. Method of Analysis

In order to analysis the soil-structure SDOF model directly in time domain, a highly efficient numerical method is used based on interpolation of excitation to solve the equations of motion for equivalent one-degree-of-freedom systems (see Equations 10, 11, 12). This method can be developed for linear systems by interpolating the excitation over each time interval. The linear interpolation is essentially perfect when the excitation is defined at exact spaced time intervals, i.e. earthquake ground acceleration [32].

The SSI effects are studied through comparing maximum displacement responses of equivalent SDOF systems. For this purpose, a group of 600 soil–structure systems consist of 6 SDOF system with six different fixed-base structural frequencies (*fs* = 0.5, 1, 2, 3, 4 and 5 Hz) are investigated for all introduced 71 input ground motions. The selection of these six structural frequencies makes it possible to consider a wide suite of typical structures which they can be representative of high-rise, mid-rise and low-rise buildings [33]. The key non-dimensional parameters of the soil-structure systems are considered to be as follows $\bar{h}$=1, $\bar{m}$=3, ϑ=0.33, ζ=0.025 and ζ_g=0.05. The responses of equivalent SDOF system are calculated for a broad range of structure-to-soil stiffness ratio ($\bar{S}$=0.01 to 10).

7. Verification of the Analysis Procidure

In this section, the code verification is carried out through the only available corresponding reference which was presented by Wolf in 1985 [14]. In order to consider SSI effects straightforwardly on the seismic response of structures, Wolf introduced an equivalent SDOF system (as shown in Fig. 1). Fig. 2 presents an artificial time history corresponds with the US NRC Regulatory Guide 1.6 spectrum [34] which was used by Wolf to gain maximum displacement responses of equivalent SDOF system.

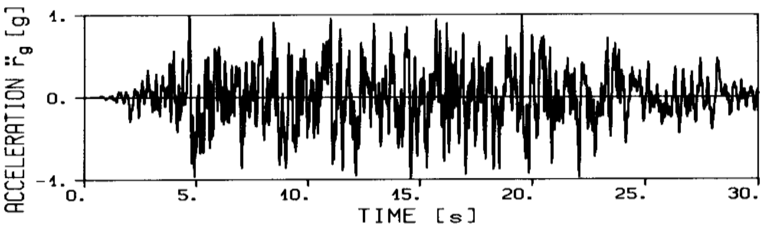

Fig. 2 Artificial acceleration time history [34]

The digitized artificial time history normalized to 0.1g as same as Wolf procedure, and then applied to base of soil-structure SDOF system (Fig. 1). The maximum of the relative displacement "U_{max}" and of the total displacement "$(u + u_o + h\phi)_{max}$" are plotted as a function of the stiffness ratio ($\bar{S}$) for three different fixed-base structural frequencies. The results of these two studies are plotted in Fig. 3 simultaneously.

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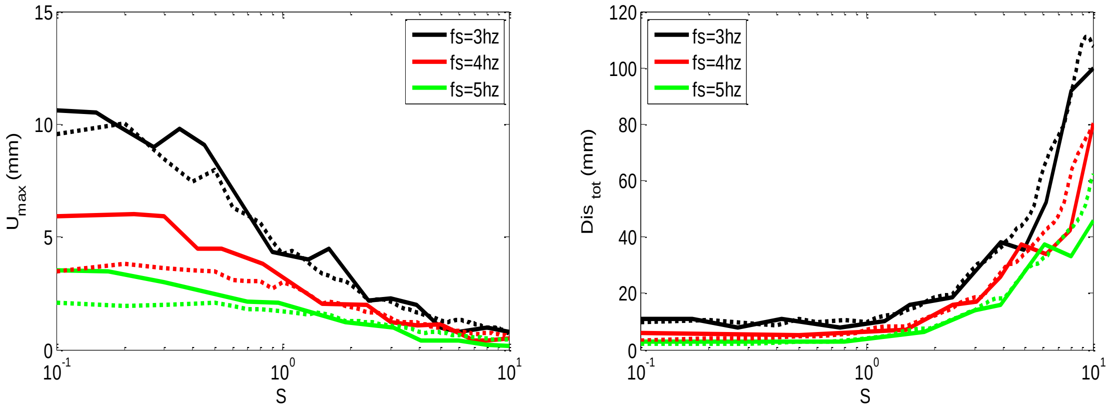


(a) (b)

Fig. 3 Maximum displacement responses of soil-structure SDOF system due to an artificial time history, ($\bar{h}$=1, $\bar{m}$=3, ϑ=0.33, ζ=0.025 and ζ_g=0.05), (a) relative displacement, (b) total displacement, (Noted the results of Wolf study and this study are presented by solid and dashed lines, respectively)

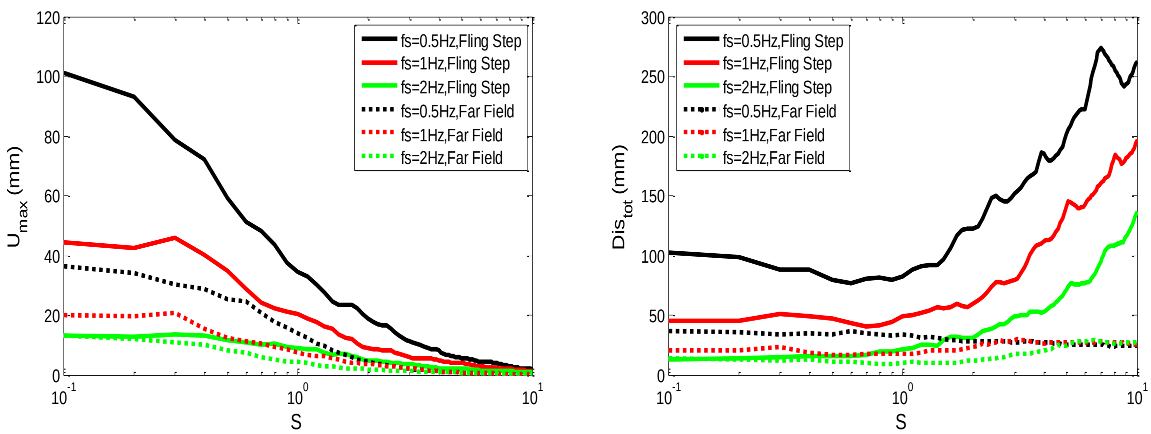
As can be seen, the trend of figures presents satisfactory correspondence with each other; however, there are quantitative discrepancies to some extent. The main reason of these variances in results can be addressed to differences between two digitized accelerograms used as input motions in each study. One of the discernible errors, which is more common in manual digitization, is "low-pass-filtering" of high frequency peaks that most likely taken place here. This matter leads to results be lower at low stiffness ratios and greater at high stiffness ratios than Wolf's one.

8. Seismic Response Analysis of Soil-Structure System

In order to gain further perception about the SSI effects on seismic responses of equivalent SDOF systems with 6 fixed-base structural frequencies, the median values of maximum displacement responses caused by various near-field and far-field ground motions are presented. These can be considered as representative of the general characteristics observed. In first place, the structural responses due to near-field records will be compared with far-field ones. Afterwards, structural responses due to various near-field ground motions with different characteristics will be compared with each other. Finally, the frequency content of input ground motions will be investigated as an effective factor on structural responses.

9. Near - Field Versus Far - Field Structural Responses

The comparison of the median values of maximum dynamic responses of equivalent SDOF systems shows that at all stiffness ratios the fling-step and fault-normal component of forward-directivity records produce greater displacement responses in SDOF systems with low fixed-base structural frequencies than far-field records. However, in the case of high fixed-base structural frequencies at stiff soils (i.e. at less stiffness ratios) far-field motions can produce higher responses than fling-step and fault-normal component of forward-directivity records. In addition, the maximum responses of systems subjected to far-field ground motions are generally higher than responses caused by fault-parallel component of near-field ground motion with forward-directivity effect. It should be noted that in the case of mid-rise structural frequencies this procedure can become reverse especially at low stiffness ratios (See Figs. 4-5).



(a)

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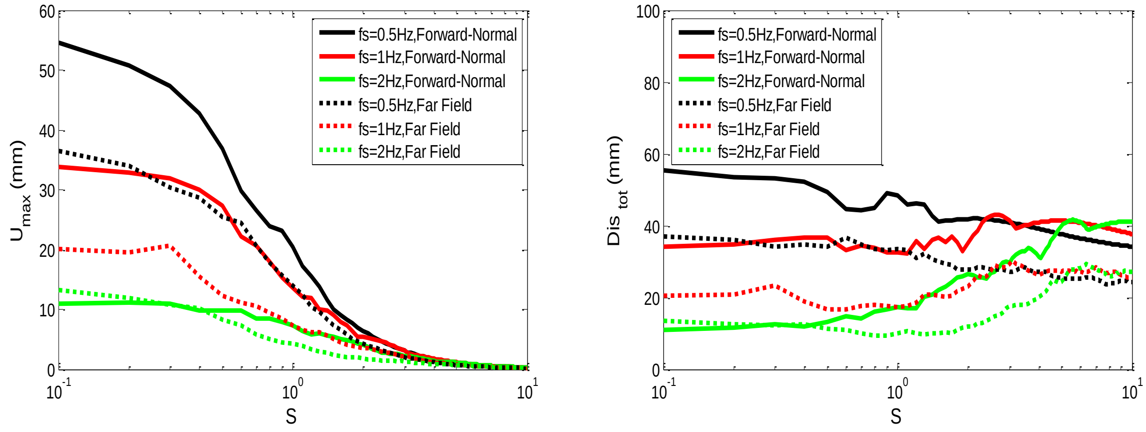
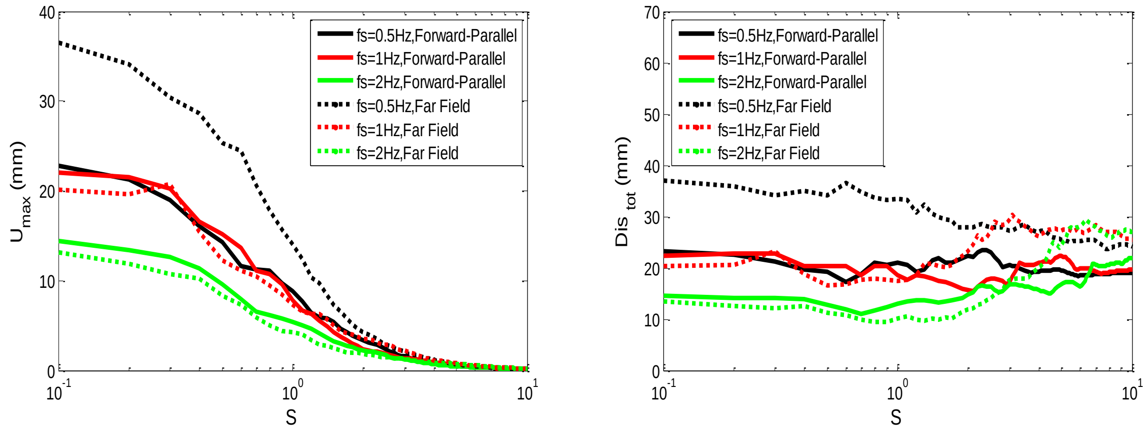
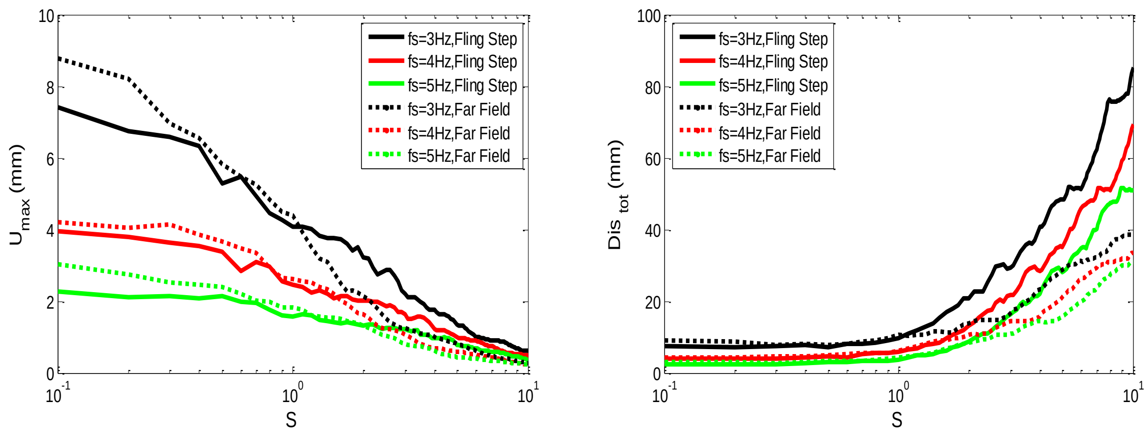


(b)

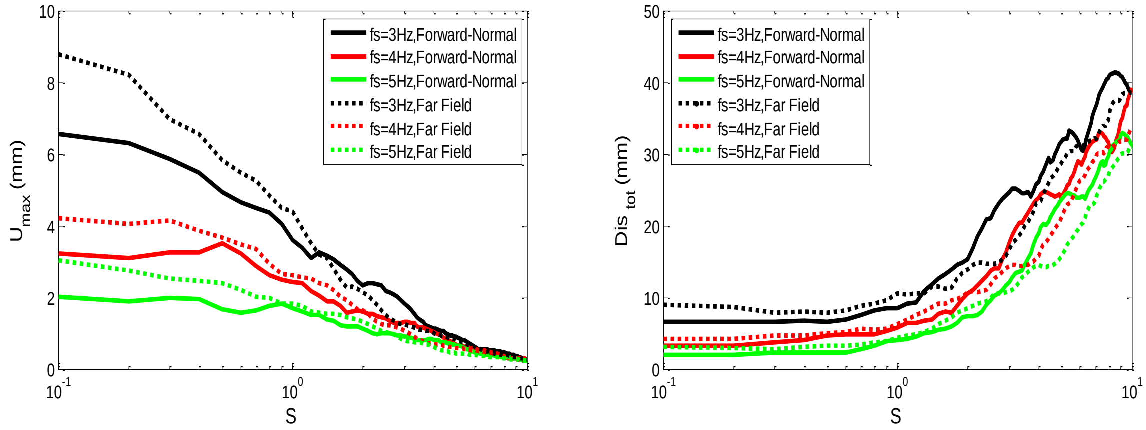


(c)

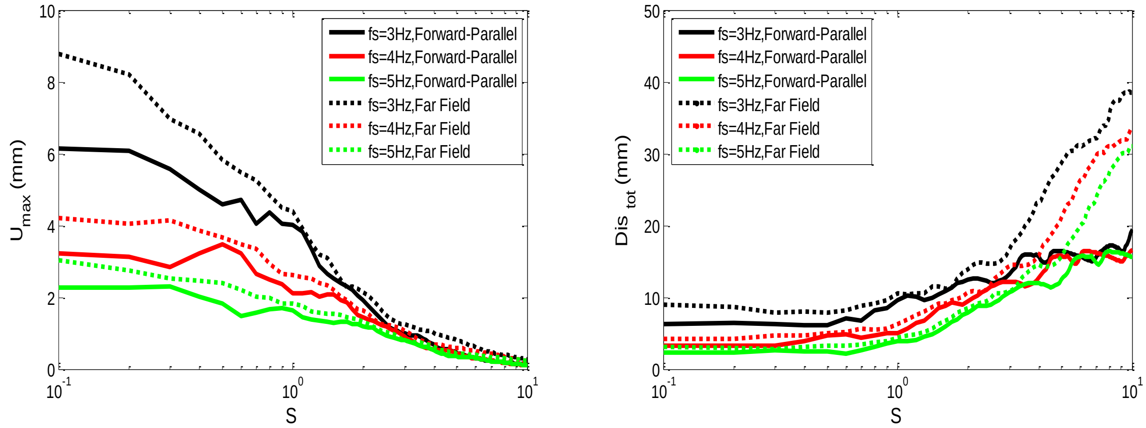
Fig. 4 Comparison of median values of maximum dynamic responses of equivalent SDOF system with high structural frequency subjected to (a) near-field ground motions with fling-step effect versus far-field ground motions, (b) fault-normal component of near-field ground motions with forward-directivity effect versus far-field ground motions, (c) fault-parallel component of near-field ground motions with forward-directivity effect versus far-field ground motions, ($\bar{h}$=1, $\bar{m}$=3, ϑ=0.33, ζ=0.025 and ζ_g=0.05)



(a)



(b)

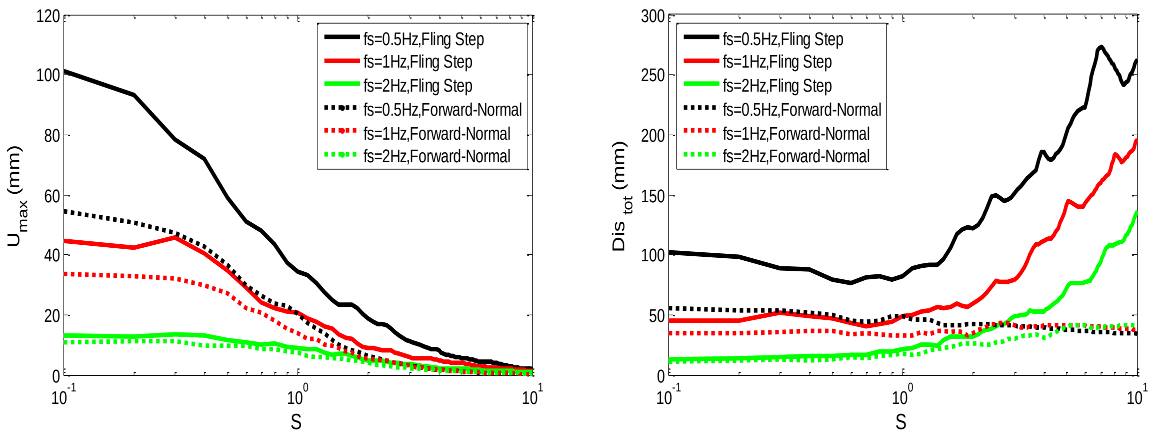


(c)

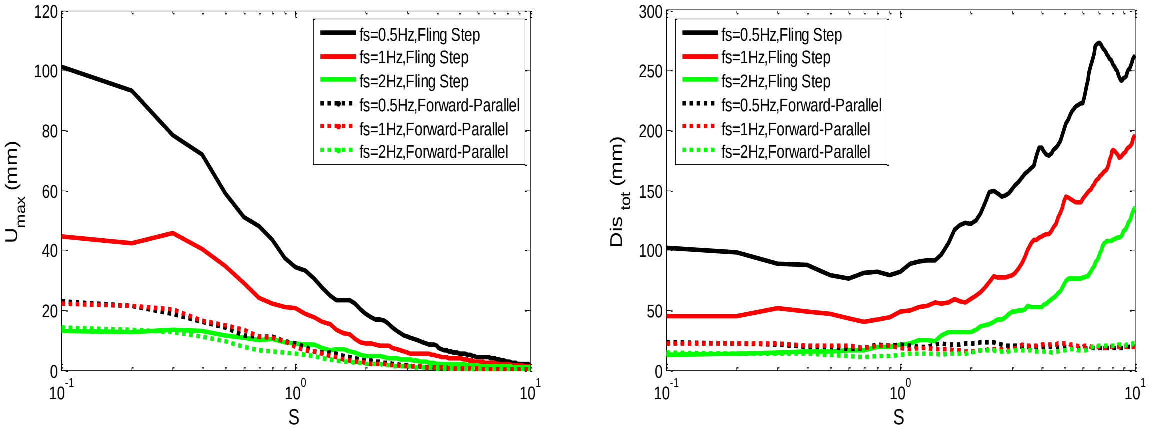
Fig. 5 Comparison of median values of maximum dynamic responses of equivalent SDOF system with low structural frequency subjected to (a) near-field ground motions with fling-step effect versus far-field ground motions, (b) fault-normal component of near-field ground motions with forward-directivity effect versus far-field ground motions, (c) fault-parallel component of near-field ground motions with forward-directivity effect versus far-field ground motions, ($\bar{h}$=1, $\bar{m}$=3, ϑ=0.33, ζ=0.025 and ζ_g=0.05)

10. Fling - Step Versus Forward - Directivity Structural Responses

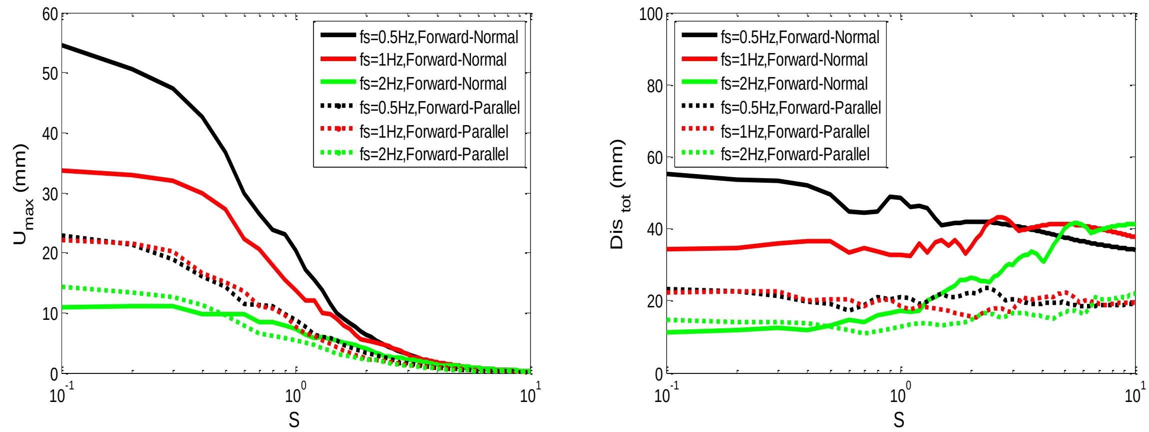
The comparison of the median values of maximum dynamic responses due to near-field ground motions with different characteristics demonstrates that records with fling-step effects and fault-normal component of forward-directivity records cause generally higher responses in structural systems with low fixed-base frequencies at all range of structure to soil stiffness ratios than fault-parallel component of records with forward-directivity effect. With increasing soil stiffness, fault-parallel component of forward-directivity records can cause predominant responses in low-rise stiff SODF systems (See Figs. 6-7).



(a)

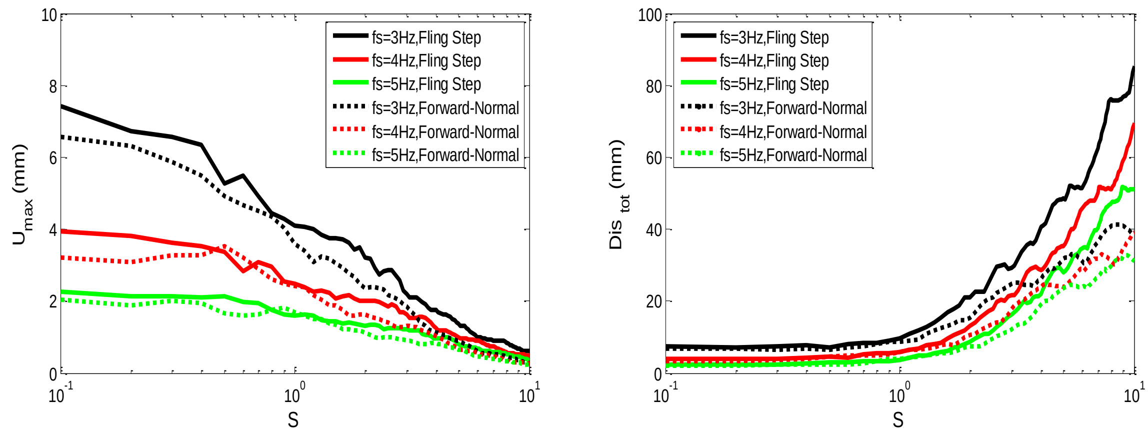


(b)



(c)

Fig. 6 Comparison of maximum dynamic response (median values) of the equivalent SDOF system with high structural frequency subjected to 19 fling-step and 30 forward-directivity records (a) fling-step versus fault-normal component of forward-directivity, (b) fling-step effect versus fault-parallel component of forward-directivity, (c) fault-normal component of forward-directivity versus fault-parallel component of forward-directivity, ($\bar{h}$=1, $\bar{m}$=3, ϑ=0.33, ζ=0.025 and ζ_g=0.05)



(a)

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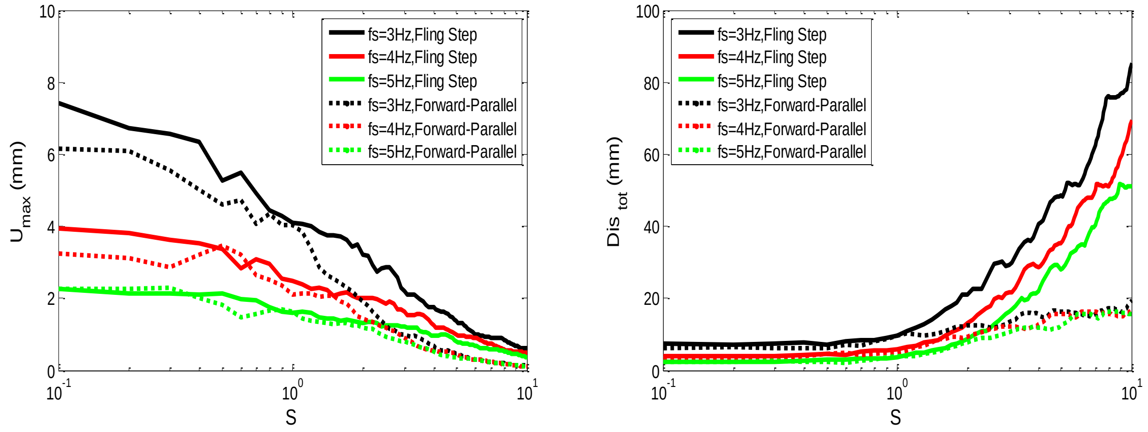

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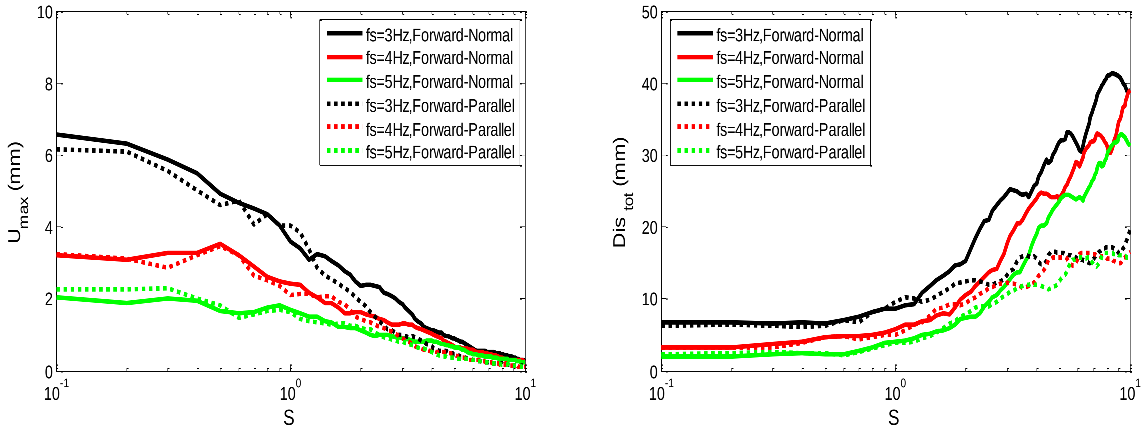


(c)

Fig. 7 Comparison of maximum dynamic response (median values) of the equivalent SDOF system with low structural frequency subjected to 19 fling-step and 30 forward-directivity records (a) fling-step versus fault-normal component of forward-directivity, (b) fling-step effect versus fault-parallel component of forward-directivity, (c) fault-normal component of forward-directivity versus fault-parallel component of forward-directivity, ($\bar{h}$=1, $\bar{m}$=3, ϑ=0.33, ζ=0.025 and ζ_g=0.05)

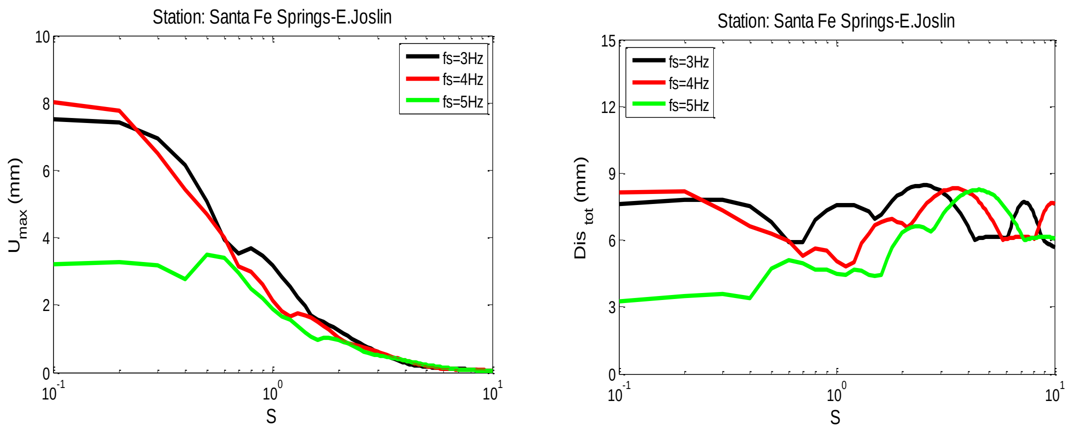
It is significant to note that among all applied earthquakes, which are introduced in ground motion database section, 10 near-field and 3 far-field ground motions produce apparently different trends in structural responses from common expectations. It has been conventionally considered that SSI has beneficial effect on the seismic response of a structure which tends to reduce the demands on structure. However, because the foundation can translate and rotate, overall displacement of the structure relative to the free-field motion increases. This perception, indeed, can be accurate for a large number of structures and seismic environments but not always. This beneficial role of SSI effect is an over-simplification that may lead to unsafe design for both the superstructure and the foundation [17].

For instance, as illustrated in Fig. 8, considering SSI may increase the maximum relative displacement and will decrease the maximum displacement of the structure in comparison to stiff soils, which is close to fixed-base conditions, at some structure-to-soil stiffness ratios. Thus, these unexpected structural responses refute the beneficial role of considering SSI in all situations and accentuate the importance of taking into account SSI effects to be on the safe side.

11. Consideration of Ground Motions Frequency Content

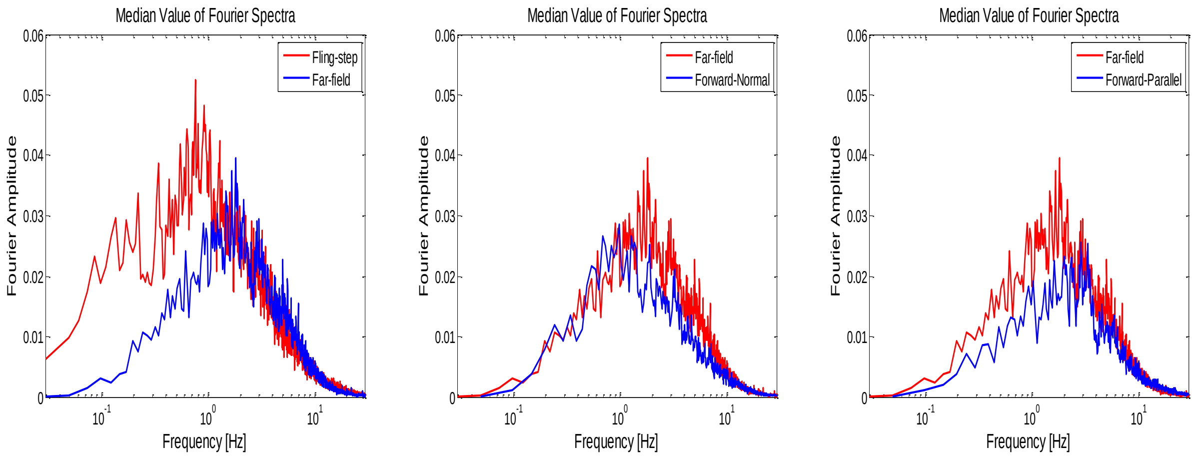
It should be noted that considering soil-structure interaction, makes a structure more flexible and lead to decrease in the natural frequency of the structure compared to the corresponding one supported by rigid soil. Moreover, the dynamic response of structures is very sensitive to the frequency at which they are loaded [14-15]. In this section, the characterization of dynamic responses of various soil-structure systems is completed by consideration of frequency content of input ground motions.

In the frequency domain, as can be seen in Figs. 9 (a), (b) and (c), the maximum Fourier amplitudes of far-field ground motions and fault-parallel component of forward-directivity records are distributed at higher frequencies than (mainly beyond 1Hz) the maximum Fourier amplitudes of near-field ground motions with fling-step and fault-normal component of forward-directivity records (generally at frequencies less than 1Hz).



(a) (b)

Fig. 8 Example of unexpected trend in structural responses due to normal-fault component of Whittier Narrows-01 earthquake, (a) maximum relative displacement, (b) maximum total displacement



(a) (b) (c)

Fig. 9 Comparison of median values of Fourier acceleration spectra, (a) near-field ground motions with fling-step effect and far- field ground, (b) fault-normal component of near-field ground motions with forward-directivity effect and far-field ground motions, (c) fault-parallel component of near-field ground motions with forward-directivity effect and far- field ground motions

The higher Fourier amplitudes of far-field ground motions in comparison with near-field records with fling-step and fault-normal component of forward-directivity records can cause greater maximum dynamic responses at low stiffness ratios in SDOF systems with high structural frequencies. Moreover, far-field ground motions generally cause greater responses than fault-parallel component of near-field records with forward-directivity because of stronger Fourier amplitudes.

As can be seen in Figs. 10 (a), (b) and (c) in the frequency domain, the comparison of median values of Fourier spectra of near-field ground motions shows that records with fling-step have generally stronger Fourier amplitudes relative to two components of records with forward-directivity effects. However, at some frequencies beyond 1Hz, higher Fourier amplitudes of especially fault-parallel component of forward-directivity records can produce greater responses at low stiffness ratios in SDOF systems with high structural frequencies. The fault-normal component of near-field ground motions with forward-directivity effect possesses relatively stronger low frequency content than fault-parallel components.

12. Parametric Study

In the near-field zone, pulse-like motions play vital roles in the design of structures. In order to find a dependable intensity measure for design of civil structures, much effort has been devoted to analysis and to evaluate seismic performance of various systems subjected to such excitations. In some studies, the role of high ground velocities was accentuated to the extent that peak ground velocity (PGV) is often considered as the effective indicator of damage potential [7-8]. On the other hand, some other studies indicated that acceleration pulses are in general leading engineering demand parameters for most civil structures than velocity pulses [35-37].

Although PGA and PGV are very useful intensity measures for seismological studies, none of them can provide any information on the frequency content or duration of the motion. There is the agreement among the researchers concerning the influences of frequency content on seismic responses of civil structures. Consequently, PGA and PGV have to be completed by additional information for the proper characterization of a ground motion [15]. The ratio of PGV to PGA is a ground motion

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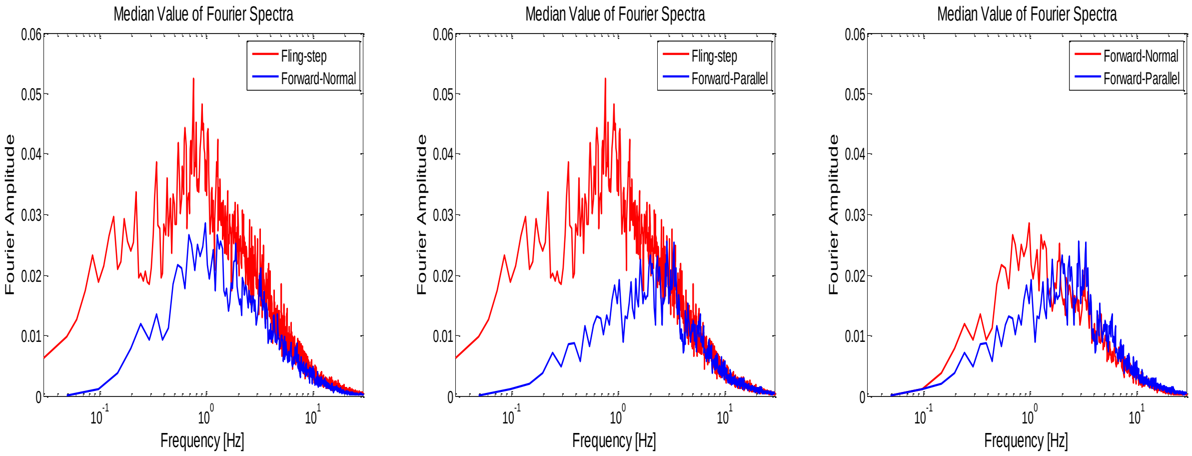
parameter which provides information about frequency content of the input motion. Since PGA and PGV are usually associated with motions of different frequencies [38-39]. Moreover, in pulse-like ground motions, the coherent long-period pulses may lead to the PGV/PGA ratio of ground motions become larger (Fig. 11) [26]. Hence, the PGV/PGA ratio is a very important parameter to characterize the damage potential of near-fault ground motions and indicated as being a measure of destructiveness [40]. The ground motions with higher PGV/PGA values have larger damage potential [41-42].



(a) (b) (c)

Fig. 10 Comparison of Fourier acceleration spectra (median values) of 19 fling-step and 30 forward-directivity records, (a) fling-step versus fault-normal component of forward-directivity, (b) fling-step effect versus fault-parallel component of forward-directivity, (c) fault-normal component of forward-directivity versus fault-parallel component of forward-directivity

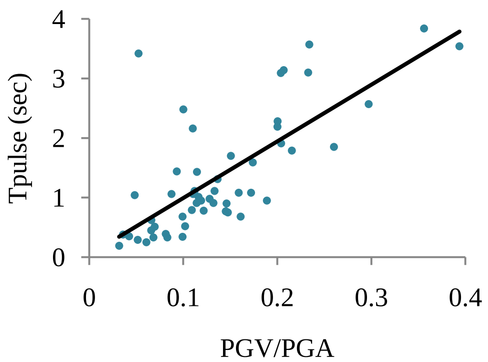
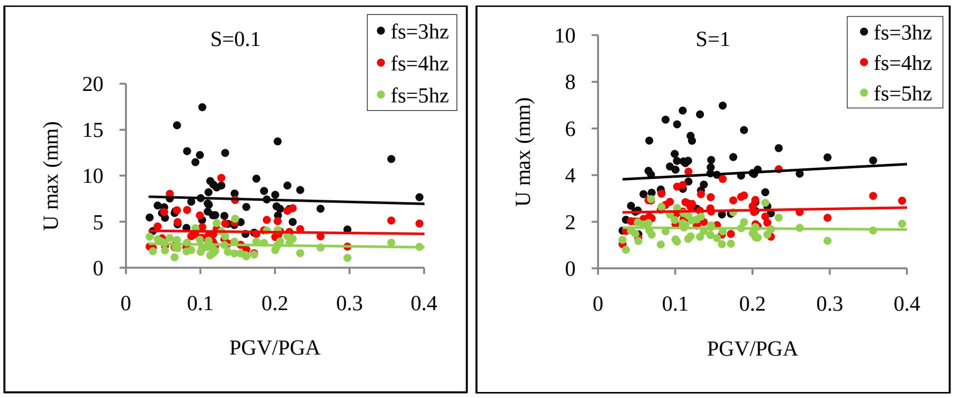


Fig. 11 Relationship between the pulse period of near-field ground motions and PGV/PGA ratios

As regards previous studies, the main goal of this section is to present the relationship between the PGV/PGA ratio, as a compound intensity index, and maximum relative displacement of soil-structure SDOF system caused by pulse-like ground motions in four different stiffness ratios ($\bar{S}$=0.1, 1, 5 and 10). Each straight line is the result of linear curve fitting. From limitations of space and same trends of different fixed-base structural SDOF systems subjected to pulse-type motions, only the figures related to three structural frequencies which is representative of low-rise stiff buildings will be mentioned (i.e. f_s=3hz, 4hz, 5hz).

Fig. 12 shows that increasing in stiffness ratios result in the maximum distortion of structure subjected to ground motion with higher PGV/PGA ratios (typically pulse-type ground motions with high period pulse) becomes predominant. It should be noted that, as can be seen in Fig. 12, scattering of data points are considerable, especially at low stiffness ratios, which can affect curve fitting approach in this section to some extent.



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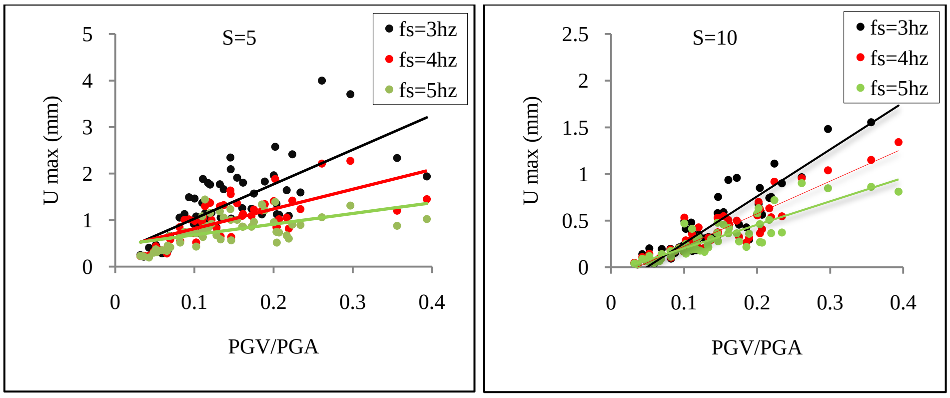

Fig. 12 Relationship between the relative displacement of soil-structure SDOF system with high structural frequency and PGV/PGA ratio

13. Conclusions

In this paper, the maximum elastic displacement responses of soil–structure systems produced by a large number of near-field and far-field ground motions were studied parametrically for assessing the effects of SSI. The results show that:

- Far-field ground motions cause greater maximum seismic responses in comparison with pulse-like near-field ground motions in SDOF systems with high fixed-base structural frequencies (i.e. $f_s = 3, 4, 5\ Hz$) where the soil is stiff enough relative to structure ($\bar{S} >> 1$).
- Due to concentration of maximum Fourier amplitudes of earthquakes associated with fling-step and fault-normal component of forward-directivity effects mainly at frequencies less than 1Hz generally lead to higher displacements in low structural frequency systems relative to far-field earthquakes.
- At all stiffness ratios conditions, near-field ground motions with fling-step effect generate most likely higher maximum dynamic responses compared to fault-normal and fault-parallel component of near-field ground motions with forward-directivity pulses.
- Fault-parallel component of forward-directivity records by possessing higher frequency content relative to fling-step and fault-normal component of forward-directivity effects, generally greater than 1Hz, can cause severer responses in massive low-rise buildings where structure found on stiff soil condition than the others seismic records.
- Unexpected structural response which has been presented in this study, for instance, accentuate this point that the response of structure depends substantially on the applied excitation in addition to properties of the structure and the soil profile and negligence of the effect of each of them can lead to unsafe design.
- Earthquakes with higher PGV/PGA ratios tend to produce greater maximum dynamic responses at higher stiffness ratios than the ones with lower ratios.

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