Effects of Near-Field and Far-Field Earthquakes on Seismic Response of SDOF System Considering Soil Structure Interaction

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Abstract:
Ground motions close to a ruptured fault can be significantly different than those observed further away from the seismic source. It is well known that near-fault earthquake may contain distinct forward directivity pulse and fling step motion. These specifications of near-fault earthquake records make structural responses to be different from those expected in far-fault earthquakes. In addition, soil-structure interaction can have a major influence on the seismic response of buildings founded on soft soils. According to Wolf's approach, which has been presented in 1985, the SSI effect on the response of structures is studied through introducing a replacement single-degree-of-freedom system with longer period and usually higher damping. This paper addresses the influence of near-fault and far-fault earthquakes with considering soil-structure interaction on the maximum response of SDOF system. In some cases salient diversities have been seen in comparison to Wolf's results.

Keyword: Near-field earthquake, Far-field earthquake, soil structure interaction, SDOF system

1. Introduction

Ground motions consequent to an earthquake reflect the features of the seismic source, the rupture process, the source-site travel path, and local site conditions. Consequently, the characteristics of ground motion in the vicinity of an active fault can be significantly different from that of the far-field [8]. There is no well-defined distance over which a site may be classified as in near or far-field. A useful criterion to define the near-field zone is related to the comparison of the source dimension with the source to site distance [10].

When a structure founded on solid rock is subjected to an earthquake, the extremely high stiffness of the rock constrains the rock motion to be very close to the free-field motion. The same structure would respond differently if supported on a soft soil deposit. This process, in which the response of the soil influences the motion of the structure and the response of the structure influences the motion of the soil, is referred to as soil-structure interaction [2].

The SSI effect on the response of structures is studied by Wolf through introducing a replacement single-degree-of-freedom (SDOF) system with longer period and usually higher damping. For an artificial earthquake time history, taking soil-structure interaction into account will in general reduce the maximum structural distortion, while the maximum displacement of the structure relative to the free-field motion can be increased [1].

Moreover, the effect of Soil-Structure Interaction (SSI) when the structure is subjected to near-fault records has attracted much less attention. The effect of soil-structure interaction on SDOF system subjected to near-field ground motion with forward directivity effect which has been studied by Ghannad et al. indicated that the peaks of acceleration spectra become closer in the case of soil-structure systems in comparison to the corresponding fixed-base systems. This phenomenon is more pronounced for systems with lower soil-to-structure stiffness ratios [3].

2. Soil-structure interaction

2.1. Soil-structure model

Soil-structure interaction is, in most cases, studied assuming linear elastic behavior. In this section, the effects of SSI on response of linear structures subjected to near-field and far-field earthquake records have been investigated. For this purpose, a simplified discrete model shown in Fig.1 is used to represent the real soil-structure system. This model is based on the following assumptions:
(1) The structure is replaced by an equivalent elastic SDOF system.
(2) The foundation is replaced by a circular rigid disk.
(3) The soil beneath the foundation is considered as a homogeneous half-space.

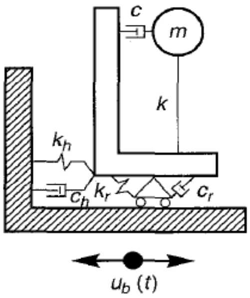


Figure 1. Idealized discrete system in which compliance of base is represented by translational and rotational springs and dashpots [1]

Actual foundation stiffness and damping coefficients are frequency dependent. To illustrate the effects of soil-structure interaction, however, the following 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 are evaluated using the following formula, respectively [1]:

$$k_h = \frac{8Ga}{2-\vartheta} \tag{2.1}$$

$$k_r = \frac{8Ga^3}{3(1-\vartheta)} \tag{2.2}$$

$$c_h = \frac{4.6}{2-\vartheta}\rho v_s a^2 \tag{2.3}$$

$$c_r = \frac{0.4}{1-\vartheta}\rho v_s a^4 \tag{2.4}$$

2.2. Dimensionless parameters

For a specific excitation, the response of the dynamic system will depend on the properties of the structure compared to those of the soil. For the model illustrated in Fig. 2 the following dimensionless parameters are introduced [1]:
1-The ratio of the stiffness of the structure to that of the soil:

$$\bar{S} = \frac{\omega_s h}{c_s} \tag{2.5}$$

2-The slenderness ratio

$$\bar{h} = \frac{h}{a} \tag{2.6}$$

Where “a” represents a characteristic length of the rigid base
3-The mass ratio

$$\bar{m} = \frac{m}{\rho a^3} \tag{2.7}$$

Where “ρ” represents the mass density of the soil

2.3. Equivalent one-degree-of-freedom system

In order to considering SSI effect, the SDOF system must be replaced with an equivalent system which has higher hysteretic damping ratio and less natural frequency [1].
1-Equivalent frequency:

$$\tilde{\omega}^2 = \frac{{\omega_s}^2}{1+\frac{\bar{m}\bar{s}^2}{8}[\frac{2-\vartheta}{\bar{h}^2}+3(1-\vartheta)]} \tag{2.8}$$

2-Equivalent hysteretic damping ratio:

$$\tilde{\zeta} = \frac{\tilde{\omega}^2}{{\omega_s}^2}\zeta + \left(1 - \frac{\tilde{\omega}^2}{{\omega_s}^2}\right)\zeta_g + \frac{\tilde{\omega}^3}{{\omega_s}^3}\frac{\bar{s}^3\bar{m}}{\bar{h}}[0.0036\frac{2-\vartheta}{\bar{h}^2} + 0.028(1-\vartheta)] \tag{2.9}$$

Where ζ is hysteretic structure material damping ratio and ζ_g is hysteretic soil material damping ratio.

2.4. Equations of motion

In this study the equations of motion for equivalent one-degree-of-freedom system with a rigid basement have been derived in the time domain by formulating the dynamic equilibrium of the mass point and the horizontal and rotational equilibrium equations of total system which leads to:

$$\ddot{u} + 2\tilde{\zeta}\tilde{\omega}\dot{u} + \tilde{\omega}^2 u = -\frac{\tilde{\omega}^2}{{\omega_s}^2}\ddot{u}_g \tag{2.10}$$

$$\frac{4.6\bar{h}}{(2-\vartheta)\bar{m}\bar{s}\omega_s}\dot{u}_0 + \frac{8\bar{h}^2}{(2-\vartheta)\bar{m}\bar{s}^2}u_0 = \frac{2\zeta}{\omega_s}\dot{u} + u \tag{2.11}$$

$$\frac{0.4}{(1-\vartheta)\bar{m}\bar{s}\bar{h}\omega_s}h\dot{\phi} + \frac{8}{3(1-\vartheta)\bar{m}\bar{s}^2}h\phi = \frac{2\zeta}{\omega_s}\dot{u} + u \tag{2.12}$$

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

$$u^{total} = u_0 + h\phi + u \tag{2.13}$$

3. Near-field ground motion

From the past observations, the near-field ground motions can produce ground motion characteristic different from that in the far-field because of the directivity and fling step effects. The direction of rupture propagation relative to the site, forward-directivity, and possible permanent ground displacements, fling step, are the major effects in near fault region [5]. Forward directivity occurs where the fault rupture propagates with a velocity close to the shear-wave velocity. Displacement associated with such a shear-wave velocity is largest in the fault-normal direction for strike-slip faults [6]. The fling step is the static component of the near-fault ground motion and is characterized by a ramp-like step in the displacement time-history and a one-sided pulse in the velocity time-history [5].

3.1. Ground motion database

The ground motion database compiled for numerical analyses in this study constitutes a representative number of far-fault and near-fault ground motions from a variety of tectonic environments. A total of 85 records were selected to cover a range of frequency content, duration, and amplitude. Near-fault records were chosen so as to consider the presence of both forward-directivity and fling-step effects. Hence the assembled database can be investigated in three sub–data sets. The first set contains 19 near-field ground motions characterized with forward directivity effect which is divided into normal and parallel component records. The second set includes 24 near-field ground motions records characterized with fling-step effect which were recorded from the 1999 (M_w7.4) Kocaeli (Turkey) and 1999 (M_w7.6) Chi-Chi (Taiwan) earthquakes. The third set consists of 26 ordinary far-fault ground motion records which is recorded within 92 Km of the causative fault plane. In this study the ground motion records have been extracted from PEER Strong Motion Database of Berkeley University.

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

No.	Earthquake	M_w	Station	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	Parkfield	6.19	Shandon array	31.04	0.475	75.01	22.4
2	San fernando	6.61	Pacima dam	11.86	1.45	115.66	30.46
3	Gazli	6.8	Karakyr	12.82	0.599	64.94	24.18
4	Tabas	7.35	Tabas	55.24	0.851	121.22	95.06
5	Coyote lake	5.74	Gillroy array	4.37	0.452	51.53	7.09
6	Imperial valley	6.53	Brawley airport	43.15	0.158	36.09	22.63
7	Coalinga	6.36	Pleasant valley	9.98	0.377	32.37	6.45
8	Morgan hill	6.19	Anderson dam	16.67	0.449	29.01	3.91
9	Nahanni	6.76	Site1	6.8	0.853	43.82	16.08
10	Palm spring	6.06	N.palm springs	10.57	0.669	73.55	11.87
11	Whittier narrows	5.99	Santa-fe springs	11.73	0.398	23.75	1.76
12	Superstition hill	6.54	Parachute test site	15.99	0.418	106.74	50.54
13	Loma pierta	6.93	Gillroy array	29.77	0.406	45.65	12.53
14	Sierra madre	5.61	Cogswell dam	18.77	0.297	15.01	2.05
15	Erzican	6.69	Erzican	8.97	0.486	95.4	32.09
16	Northridge	6.69	LA dam	11.79	0.576	77.09	20.1
17	Kobe	6.9	KJMA	18.27	0.854	95.75	24.56
18	Kocaeli	7.51	Sakarya	33.24	0.376	79.49	70.56
19	Chi-Chi	7.62	TCU065	26.67	0.831	129.55	93.85

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

No.	Earthquake	M_w	Station	Dist. (km)	PGA (g)	PGV (cm/s)	PGD (cm)
1	San fernando	6.61	Pacima dam	11.86	0.827	34.43	18.67
2	Gazli	6.8	Karakyr	12.82	0.71	71.05	24.7
3	Coyote lake	5.74	Gillroy array	4.37	0.333	27.14	4.48
4	Imperial valley	6.53	Brawley airport	43.15	0.21	35.85	14.61

5	Coalinga	6.36	Pleasant valley	9.98	0.284	19.02	2.47
6	Morgan hill	6.19	Anderson dam	16.67	0.276	29.52	6.44
7	Nahanni	6.76	Site1	6.8	1.17	36.53	4.36
8	N.palm spring	6.06	N.palm springs	10.57	0.615	29.2	3.52
9	Whittier narrows	5.99	Santa-fe springs	11.73	0.51	33.09	4.16
10	Superstition hill	6.54	Parachute test site	15.99	0.343	49.57	21.78
11	Loma pierta	6.93	Gillroy array	29.77	0.302	27.58	6.11
12	Sierra madre	5.61	Cogswell dam	18.77	0.261	9.19	0.85
13	Erzican	6.69	Erzican	8.97	0.419	45.29	16.52
14	Northridge	6.69	LA dam	11.79	0.415	40.74	16.01
15	Kobe	6.9	KJMA	18.27	0.548	53.38	10.27
16	Chi-Chi	7.62	TCU065	26.67	0.557	82.27	55.05

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

No.	Earthquake	M_w	Station	Dist. (km)	Comp.	PGA (g)	PGV (cm/s)	PGD (cm)
1	Chi-Chi-1999	7.6	TCU052	1.84	EW	0.35	178	493.5
2	Chi-Chi-1999	7.6	TCU052	1.84	NS	0.44	216	709.1
3	Chi-Chi-1999	7.6	TCU068	3.01	EW	0.5	277.56	715.8
4	Chi-Chi-1999	7.6	TCU068	3.01	NS	0.36	294.14	895.7
5	Chi-Chi-1999	7.6	TCU074	13.75	EW	0.59	68.9	193.2
6	Chi-Chi-1999	7.6	TCU074	13.75	NS	0.37	47.95	155.4
7	Chi-Chi-1999	7.6	TCU084	11.4	EW	0.98	140.43	204.6
8	Chi-Chi-1999	7.6	TCU129	2.21	EW	0.98	66.92	126.1
9	Kocaeli-1999	7.4	Yarimca	3.3	EW	0.23	88.83	184.8
10	Kocaeli-1999	7.4	Sakarya	3.2	EW	0.41	82.05	205.9
11	Chi-Chi-1999	7.6	TCU102	1.19	EW	0.29	84.52	153.9
12	Chi-Chi-1999	7.6	TCU089	8.33	EW	0.34	44.43	193.9
13	Chi-Chi-1999	7.6	TCU049	3.27	EW	0.27	54.79	121.8
14	Chi-Chi-1999	7.6	TCU067	1.11	EW	0.48	94.31	181.3
15	Chi-Chi-1999	7.6	TCU075	3.38	EW	0.32	111.79	164.4
16	Chi-Chi-1999	7.6	TCU076	3.17	EW	0.33	65.93	101.7
17	Chi-Chi-1999	7.6	TCU072	7.87	NS	0.36	66.73	245.3
18	Chi-Chi-1999	7.6	TCU072	7.87	EW	0.46	83.6	209.7
19	Chi-Chi-1999	7.6	TCU065	2.49	EW	0.76	128.32	228.4
20	Chi-Chi-1999	7.6	TCU079	10.95	EW	0.57	68.06	166.1
21	Chi-Chi-1999	7.6	TCU078	8.27	EW	0.43	41.88	121.2
22	Chi-Chi-1999	7.6	TCU082	4.47	EW	0.22	50.49	142.8
23	Chi-Chi-1999	7.6	TCU128	9.08	EW	0.14	59.42	91.05
24	Chi-Chi-1999	7.6	TCU071	4.88	NS	0.63	79.11	244.1

Table 4. Important characteristics of far field ground motions

No.	Earthquake	Station	M_w	Dist. (km)	Comp.	PGA (g)	PGV (cm/s)	PGD (cm)
1	Kern County	Taft Lincoln School	7.4	38.89	NS	0.156	15.31	9.21
2	Kern County	Taft Lincoln School	7.4	38.89	EW	0.177	17.47	8.84
3	Landers	Baker Fire Station	7.3	87.94	NS	0.107	9.32	6.25
4	Landers	Baker Fire Station	7.3	87.94	EW	0.105	11.01	7.91
5	N. Palm Springs	Hesperia	6.1	72.97	NS	0.041	2.32	0.71
6	N. Palm Springs	Hesperia	6.1	72.97	EW	0.036	1.71	0.91
7	Tabas, Iran	Ferdows	7.4	91.14	NS	0.087	5.63	4.52
8	Tabas, Iran	Ferdows	7.4	91.14	EW	0.107	8.55	9.53
9	Victoria, Mexico	SAHOP Casa Flores	6.3	39.3	NS	0.101	7.77	2.45
10	Victoria, Mexico	SAHOP Casa Flores	6.3	39.3	EW	0.068	8.99	2.06
11	Imperial Valley-06	Coachella Canal #4	6.5	50.1	NS	0.115	12.47	2.32
12	Imperial Valley-06	Coachella Canal #4	6.5	50.1	EW	0.128	15.62	2.94
13	Whittier Narrows-01	Canyon Country - W Lost Cany	6	48.18	NS	0.109	7.32	0.49
14	Whittier Narrows-01	Canyon Country - W Lost Cany	6	48.18	EW	0.103	6.94	0.85
15	Morgan Hill	San Juan Bautista, 24 Polk St	6.2	27.15	NS	0.043	4.31	1.72
16	Morgan Hill	San Juan Bautista, 24 Polk St	6.2	27.15	EW	0.035	4.41	1.52
17	Chalfant Valley-02	Convict Creek	6.2	31.19	NS	0.059	4.04	1.54
18	Chalfant Valley-02	Convict Creek	6.2	31.19	EW	0.071	3.84	1.07
19	San Fernando	2516 Via Tejon PV	6.6	55.2	NS	0.025	3.82	2.18
20	San Fernando	2516 Via Tejon PV	6.6	55.2	EW	0.041	4.21	3.07
21	Coalinga-01	Parkfield - Cholame 12W	6.4	55.77	NS	0.039	4.22	1.01
22	Coalinga-01	Parkfield - Cholame 12W	6.4	55.77	EW	0.052	5.52	1.56
23	Loma Prieta	Richmond City Hall	6.9	87.87	NS	0.124	17.34	2.58
24	Loma Prieta	Richmond City Hall	6.9	87.87	EW	0.105	14.16	3.87
25	Northridge-01	Huntington Bch - Waikiki	6.7	69.5	NS	0.086	5.01	1.63
26	Northridge-01	Huntington Bch - Waikiki	6.7	69.5	EW	0.068	7.38	1.86

4. Code verification procedure

In this study, a highly efficient numerical method which can be developed for linear system by interpolating the excitation over each time interval, has been used to solve the equations of motion for equivalent one-degree-of-freedom system in time domain. It is necessary to verify the numerical procedure which has been utilized. The only available corresponding reference is Wolf procedure, which has been presented in 1985. In that study an artificial time history, which is illustrated in Fig.3, has been normalized to 0.1g and then applied to the base of the single degree of freedom system to gain the maximum structural responses.

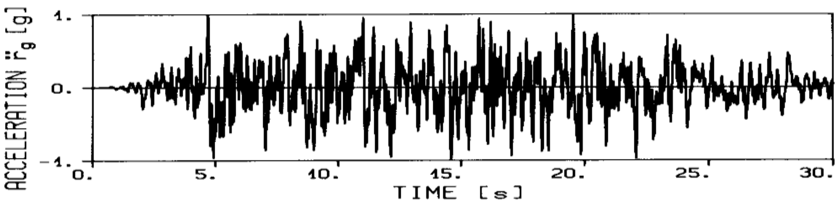
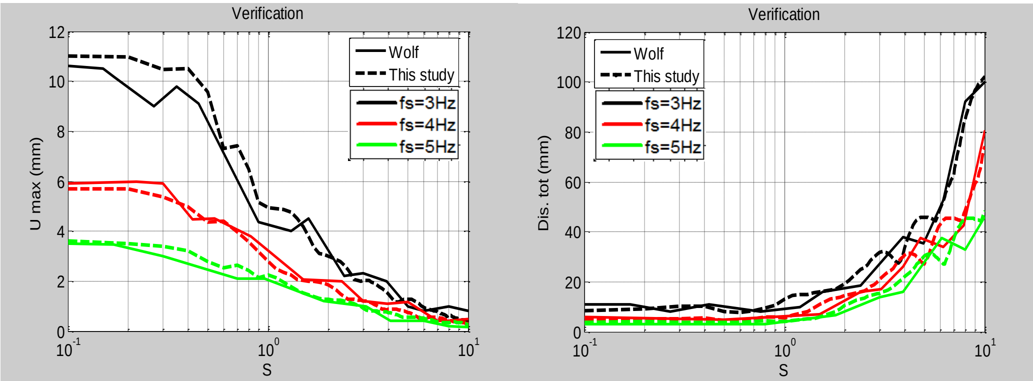


Figure 3. Artificial acceleration time history [1]

In order to verify this numerical study procedure, a similar artificial time history which has been normalized to 0.1g was used in a same way with Wolf's procedure. As an illustration, Fig.4 shows acceptable correspondence between this study's results to Wolf's one.



(a) (b)

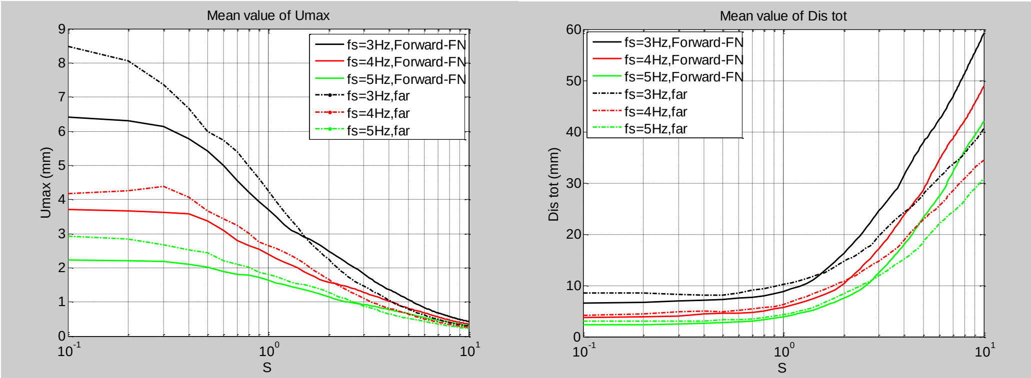
Figure 4. Maximum response, artificial time history ($\bar{h} = 1$, $\bar{m} = 3$, $\vartheta = 0.33$, $\xi = 0.025$, $\xi_g = 0.05$), varying fixed base frequency. (a) Structural distortion, (b) displacement of mass relative to free field

5. Analysis results

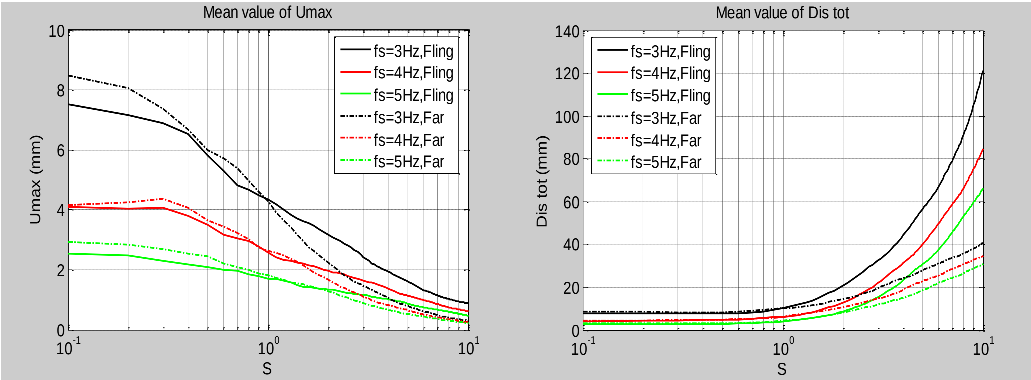
In this paper the effects of soil-structure interaction on maximum displacement of equivalent SDOF system for near-field ground motions with forward directivity and fling-step characteristics and far-field ground motions have been studied. The general procedure which presented by Wolf in 1985 have differed from this study's results in some near-field and far-field ground motions.

5.1. The mean value of maximum dynamic responses

In order to gain better perception about the general procedure of maximum displacement responses of equivalent SDOF system which subjected to various near-field and far-field ground motions, which all have been normalized to 0.1g, the mean values of maximum displacement responses has been studied.
The mean value of maximum dynamic responses of equivalent SDOF system subjected to far-field ground motions at low stiffness ratios are higher than fault normal component of near-field ground motions with forward directivity effect and near-field ground motions with fling-step effect (See Fig. 5). As expected, decreasing the stiffness of the soil ($\bar{S}$ increases) results in a decreasing of equivalent frequency [1]. On the other hand, large earthquakes produce greater low-frequency motions than do smaller ones [2]. Consequently, these results indicate that far field ground motions can produce greater maximum dynamic responses at low stiffness ratios in comparison of fault normal component of near-field ground motions with forward directivity effect and near-field ground motions with fling-step effect (See Fig.6).

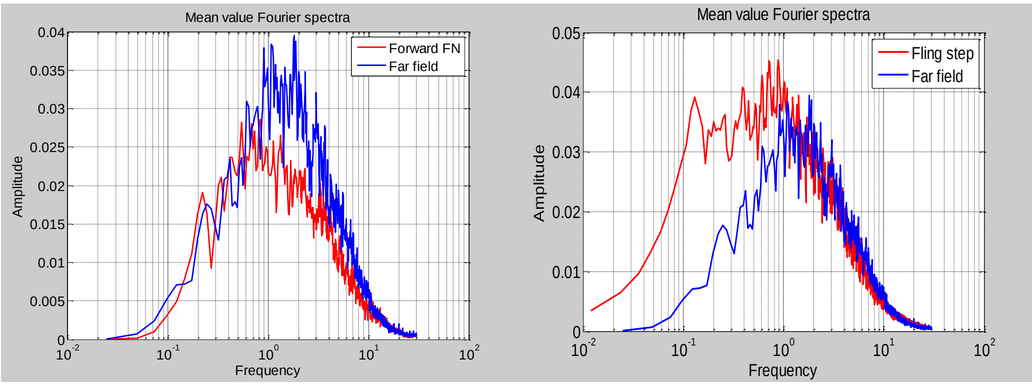


(a)



(b)

Figure 5. Comparison of maximum mean value dynamic response of equivalent SDOF system subjected to (a) fault normal component of near-field ground motions with forward directivity effect and far- field ground motions (b) near-field ground motions with fling-step effect and far- field ground motions, ($\bar{h} = 1$, $\bar{m} = 3$, $\vartheta = 0.33$, $\xi = 0.025$, $\xi_g = 0.05$)



(a) (b)

Figure 6. Comparison of mean value of Fourier acceleration spectra (a) fault normal component of near-field ground motions with forward directivity effect and far- field ground motions (b) near-field ground motions with fling-step effect and far- field ground motions

The mean value of maximum dynamic response of equivalent system subjected to fault parallel component of near-field ground motions with forward directivity and far-field ground motions show that at all stiffness ratios the maximum responses of system subjected to far-field are higher than responses that result from fault parallel component of near-field ground motion with forward directivity effect. Consequently, it is more conservative to consider far-field ground motions relative to fault parallel component of near-field ground motions for structure design at all stiffness ratios (See Fig.7).

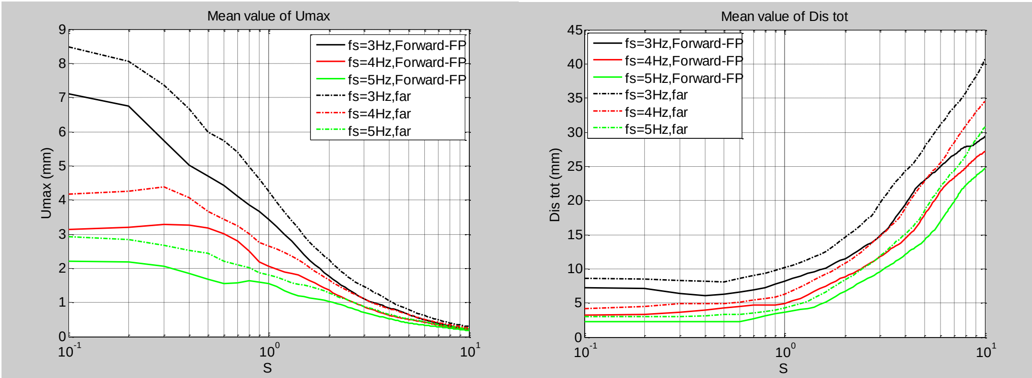


Figure 7. Comparison of maximum mean value dynamic response of equivalent SDOF system subjected to fault parallel component of near-field ground motions with forward directivity effect and far-field ground motions, ($\bar{h} = 1$, $\bar{m} = 3$, $\vartheta = 0.33$, $\xi = 0.025$, $\xi_g = 0.05$)

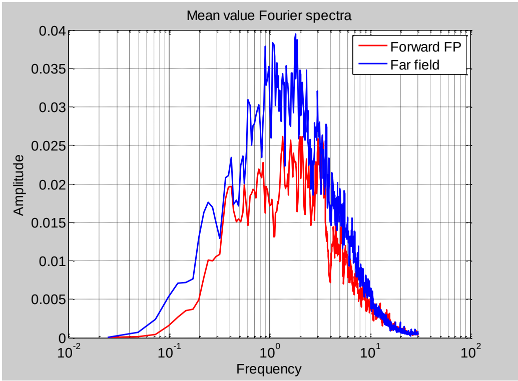
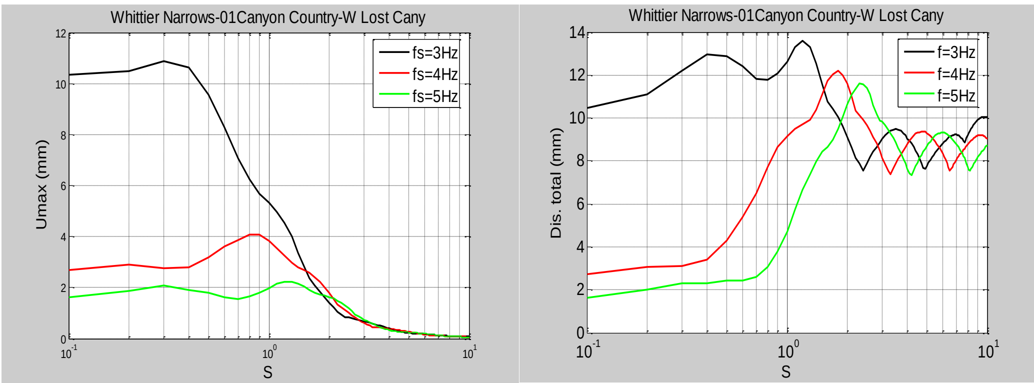


Figure 8. Comparison of mean value of Fourier acceleration spectra; Fault normal component of near-field ground motions with forward directivity effect and far- field ground motions

5.2. Unusual results of some input motions

According to the Wolf's results, for an artificial earthquake time history, considering soil structure interaction will reduce the maximum structural distortion, while the maximum displacement of the structure relative to the free-field motion can be increased. However, in this study 10 near-field and 3 far-field ground motions among all earthquakes, which have been introduced in section 3.1., cause different procedure from which has been presented by Wolf. For example, as it illustrated in Fig.9, considering soil structure interaction will increase the maximum structural distortion and will decrease the maximum displacement of the structure relative to the free-field motion at some stiffness ratios. In fact, results show that the response of soil–structure system depends on the applied excitation in addition to properties of the structure and the soil profile.



(a) (b)

Figure 9. The one example of unusual results due to Whittier Narrows-01earthquake; (a) maximum structural distortion; (b) maximum displacement of mass relative to free field

6. Conclusions

In this paper the effects of near-field and far-field earthquakes on seismic responses of SDOF system with considering soil structure interaction have been studied. For this purpose the equations of motion of equivalent SDOF system, which have been derived in time domain, have been solved with a numerical method by interpolating the excitation over each time interval. The following conclusions may be drawn:

(1) At low stiffness ratios, the mean value of maximum dynamic responses of equivalent SDOF system subjected to far-field ground motions are higher than fault normal component of near-field ground motions with forward directivity effect and near-field ground motions with fling-step effect.

(2) At all stiffness ratios, the mean value of maximum dynamic responses of equivalent SDOF system subjected to far-field ground motions are higher than responses that result from fault parallel component of near-field ground motions with forward directivity effect.

(3) For some near-field and far-field ground motions general procedure which has been mentioned by Wolf in 1985 about maximum structural displacements, may differ at some stiffness ratios.

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