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RESPONSE OF ISOLATED RC BUILDINGS UNDER BI-DIRECTIONAL NEAR-FAULT GROUND MOTIONS

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ABSTRACT

Nonlinear response history analyses of an isolated 3-story RC building were carried out under bi-directional earthquake excitations considered as near-fault records. Two sets of eleven near-fault ground motion records were used. These ground motions are classified according to site classes they were recorded (stiff and soft soil). Selected near-fault ground motions were used to investigate the variation of the absolute top floor acceleration, isolator displacement, and base shear of the isolated RC buildings. The responses of the isolated RC building were represented considering different parameters such as yield strength of LRB (Q/W ratio), isolation period, and site classes where ground motions are recorded. Analysis results showed that the amount of contribution of orthogonal horizontal ground motion component is higher at stiff soil records than soft soil records. Consideration of bi-directional response of isolated structures is observed that it may lead to more efficient design strategies for the superstructure.

Introduction

When multi-component ground motion is of concern, most of the design codes recommend two approaches to consider the effects of orthogonal ground motions on the response of structures. First one is the square-root-of-sum-of-squares (SRSS) rule, and the other is percentage rule. The percentage rule is simply the application of 100%+30% combination. This method is first recommended by Rosenblueth and Contreras (1977). In their study, Rosenblueth and Contreras (1977) made linear approximation during the modeling of orthogonal ground motion components in terms of elastic spectral accelerations. The suggested 30% increment in the response of structures is implied to cover the errors initiated by the linear approximation (Menun and Der Kiureghian 1998).

The percentage rule for combination of effect of multi-component ground motions do not consider neither the dynamic characteristics of response of structure (linear or nonlinear) nor the soil conditions (rock, soft soil). However, some recent studies made an emphasis on the response of isolation systems under soft soil and near-fault conditions (Pavlou and Constantinou 2004; Chung

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et al. 1999). Jangid and Kelly (2001) studied the response of linear isolation systems to near-fault motions under bi-directional earthquake excitations and concluded that the resultant displacement of the isolators can be obtained simply by increasing the displacement under uni-directional excitation by 5% to incorporate the effect of orthogonal component. However, Mosqueda et al. (2004) and Warn and Whittaker (2004) showed that degree of contribution of orthogonal components may be higher than 5%. Similarly, Colunga and Osornio (2006) show that average amplification in isolator displacements due to bi-directional earthquake excitations is almost 10%, regardless of the level of seismicity. However, all of the considered ground motions were recorded in rock or firm soil and limited to a specific region which is Mexican Pasific Coast (Colunga and Osornio 2006).

In this study, seismic response of an isolated 3-story reinforced concrete (RC) building was investigated by nonlinear response history analyses (NRHA) considering bilinear force-deformation relation for isolators. The isolator hysteretic model is coupled in the two directions of motion. The study reported herein concentrated on motions with near-fault characteristics but implemented a selection and scaling approach that is consistent with contemporary practices in the representation of site-specific response spectra by ground motion assemblies. The resultant isolator displacements under bi-directional excitations were compared with isolator displacements obtained under uni-directional excitations. Comparisons were carried out for two different site classes (stiff and soft soil) to clarify the effect of orthogonal horizontal components on resultant isolator displacement at different site classes. The response of superstructure was also studied in terms of base shear and top floor acceleration to determine the variation due to bi-directional earthquake excitations. It is believed that the results will lead the engineers to more efficient design of both isolation systems and superstructures.

Near-Fault Ground Motions

Twenty two pairs of near-fault ground motion records were used to carry out NRHA. These ground motions are grouped into two bins according to site class they were recorded namely, stiff soil (NEHRP B and C) and soft soil (NEHRP D). Each bin contains 11 ground motion pairs. Ground motions used in this study were extracted from previous studies carried out by Pavlou and Constantinou (2004), Somerville et al. (1997), Akkar and Gulkan (2002), and Metin (2006). The ground motion records were taken from PEER Strong Motion Database (2009) and their main characteristics are given in Tables 1 and 2. The magnitudes of the considered motions are in between 6.0 and 7.6, while the distances (closest distance) to the fault rupture are in between 2 and 15 km.

Scaling of Ground Motions

Scaling of the selected ground motion pairs were carried out in two levels. In the first level, an amplitude scaling method was used. Scaling of ground motions was carried out so that the difference between the geometric mean of the square root of sum of the squares (SRSS) of spectral accelerations of each component and the target spectra gets minimum. Details of this method can be found in Huang (2008). In the second level, each pair of motions was further scaled such that the average of the SRSS spectra from all ground motion pairs does not fall below 1.3 times the corresponding ordinate of the design response spectrum by more than 10%

(ASCE 2005). The final scaling factors equal to multiplication of factors obtained in two levels.

Table 1. Near-fault ground motions recorded at stiff soil.

Earthquake	**Station**	**Magnitude (M_w)**	**d (km)**	**Component**	**PGA (g)**	**PGV (cm/sec)**	**PGD (cm)**
Chi Chi (CC057)	TCU057	7.6	11.8	N	0.09	42.6	56.2
				W	0.12	35.2	56.7
Cape Mendocino (CMP)	Petrolia	7.0	8.2	0	0.59	48.4	21.7
				90	0.66	89.7	29.6
Duzce (DB)	Bolu	7.1	12	0	0.73	56.4	23.1
				90	0.82	62.1	13.6
Gazli (GK)	Karakyr	6.8	5.5	0	0.61	65.4	25.3
				90	0.72	71.6	23.7
Kocaeli (KG)	Gebze	7.5	10.9	0	0.24	50.3	42.7
				270	0.14	29.7	27.5
Kocaeli (KI)	Izmit	7.5	7.2	180	0.15	22.6	9.8
				90	0.22	29.8	17.1
Landers (LL)	Lucerne	7.3	2.2	275	0.72	97.6	70.3
				0	0.79	31.9	16.4
Northridge (NN)	Newhall	6.7	5.9	90	0.58	75.5	17.6
				360	0.59	97.2	38.1
Northridge (NR)	Rinaldi	6.7	6.5	228	0.84	166.1	28.8
				318	0.47	73.0	19.8
Northridge (NS)	Sylmar	6.7	5.4	52	0.61	117.4	53.5
				142	0.90	102.8	47.0
Tabas (TT)	Tabas	7.4	2.1	LN	0.84	97.8	36.9
				TR	0.85	121.4	94.6

Table 2. Near-fault ground motions recorded at soft soil.

Earthquake	**Station**	**Magnitude (M_w)**	**d (km)**	**Component**	**PGA (g)**	**PGV (cm/sec)**	**PGD (cm)**
Chi Chi (CC101)	TCU101	7.6	2.1	N	0.25	49.4	35.1
				W	0.20	67.9	75.4
Erzincan (EE)	Erzincan	6.7	4.4	NS	0.52	83.9	27.4
				EW	0.50	64.3	22.8
Imperial Valley (IVA4)	Array 4	6.5	7.1	140	0.49	37.4	20.2
				230	0.36	76.6	59.0
Imperial Valley (IVA5)	Array 5	6.5	4.0	140	0.52	46.9	35.4
				230	0.38	90.5	63.0
Imperial Valley (IVA6)	Array 6	6.5	1.4	140	0.41	64.9	27.7
				230	0.44	109.8	65.9
Imperial Valley (IVA10)	Array 10	6.5	6.2	50	0.17	47.5	31.1
				320	0.22	41.0	19.4
Kocaeli (KD)	Duzce	7.5	15.4	180	0.31	58.8	44.1
				270	0.36	46.4	17.6
Kocaeli (KY)	Yarimca	7.5	4.8	60	0.27	65.7	57.0
				330	0.35	62.1	51.0
Loma Prieta	Corralitos	6.9	3.9	0	0.64	55.2	10.9
				90	0.48	45.2	11.4

(LPCor)							
Loma Prieta (LPSar)	Saratoga	6.9	8.5	0	0.51	41.2	16.2
				90	0.32	42.6	27.5
Parkfield (PC)	Cholame 2	6.0	14.3	90	0.60	63.3	14.1
				360	0.37	44.1	8.9

Considered design spectra for two different site conditions were taken from Turkish Earthquake Code (TEC) (2007). The design spectra given in TEC for maximum considered earthquake (MCE) correspond to the probability of exceedance of 2% in 50 years. The design spectra for 5% damping and mean SRSS of twenty two ground motions are given in Fig. 1 for both site classes. Final scaling factors are presented in Table 3.

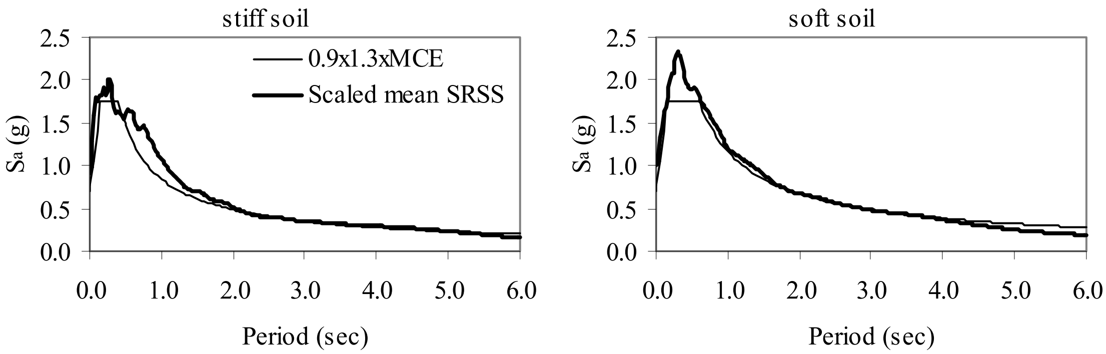

Figure 1. Final scaling of ground motion records for stiff and soft soil conditions.

Table 3. Scale factors for stiff and soft soil records.

Stiff Soil		**Soft Soil**	
Ground Motion	**Scale Factor**	**Ground Motion**	**Scale Factor**
CC057	2.31	CC101	2.43
CMP	1.10	EE	1.24
DB	0.93	IVA4	1.75
GK	1.31	IVA5	1.48
KG	2.60	IVA6	1.24
KI	2.69	IVA10	2.70
LL	1.71	KD	1.74
NN	0.93	KY	1.39
NR	0.68	LPCor	2.20
NS	0.60	LPSar	2.41
TT	0.90	PC	1.73

Modeling of Isolation System

The bilinear force-deformation relation of base isolators (Fig. 2) are defined by three parameters: (i) the post yield stiffness k_d, (ii) the characteristic strength Q, (iii) initial stiffness k_e. In a lead rubber bearing, k_d and Q represent the stiffness of rubber and yield strength of the lead core, respectively. F_y and D_y are the yield force and yield displacement, respectively. As being a representative value, 10mm is assigned to D_y, for lead-rubber isolation systems. However, the value of D_y does not have any important effect on the response of isolation systems (Makris and Chang 2000). The considered hysteretic model for isolators is coupled in the two directions of motion as described in Park et al. (1986) and Nagarajaiah et al. (1989).

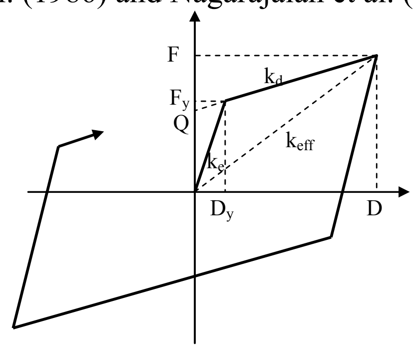

Figure 2. Bilinear force-deformation relation of a base isolator.

Table 4. Parameters for isolation systems considered in this study.

Period, *T* (sec)	3.0, 3.5, 4.0 (for stiff soil) 3.5, 4.0, 4.5 (for soft soil)
Strength to Weight Ratio, *Q*/*W*	0.04, 0.06, 0.08, 0.10 (for stiff soil) 0.08, 0.10, 0.12, 0.14 (for soft soil)

Results are presented for the range of parameters given in Table 4. In this table, the parameters used are the Q/W ratio and the period T (Eqn. (1)) based on the post-elastic stiffness. Parameters tabulated in Table 4 are selected such that the base shears of the isolation systems are not more than 30% of the weight of the superstructure for MCE according to equivalent lateral force (ELF) procedure described in the codes (ASCE 2005, AASHTO 1999). Application of the ELF procedure requires calculation of the effective stiffness k_{eff} and effective damping β_{eff} of a single-degree-of-freedom representation of the isolated structure. These quantities are given by the Eqns. (2) and (3) where D is the maximum design displacement of the isolation system:

$$T = 2 \cdot \pi \sqrt{\frac{W}{k_d \cdot g}} \tag{1}$$

$$k_{eff} = k_d + \frac{Q}{D} \tag{2}$$

$$\beta_{eff} = \frac{4 \cdot Q \cdot (D - D_y)}{2 \cdot \pi \cdot k_{eff} \cdot D^2} \tag{3}$$

The simplified analysis starts with an assumption for displacement D, followed by calculation of effective stiffness k_{eff} and effective damping β_{eff}. The calculated effective stiffness is used to obtain the effective period T_{eff} by Eqn. (4). The process is iterative until the assumed value and the calculated value of displacement by Eqn. (5) are sufficiently close.

$$T_{eff} = 2 \cdot \pi \sqrt{\frac{W}{k_{eff} \cdot g}} \tag{4}$$

$$D = \frac{g S_a T_{eff}^2}{4\pi^2 B} \tag{5}$$

Modeling of Superstructure

The modeled 3-D reinforced concrete (RC) structure is designed according to a recent study carried out by Yakut (2008). In his study, Yakut presented the characteristics of RC structures in Istanbul, Turkey. Author stated the average plan area, column orientation through the plan, and number of bays in both long and short directions of the plan. 3-D model is given in Fig. 3 for 3-story (3S) isolated RC building. Structure has longitudinal reinforcement with yield strength (f_{yk}) of 420 MPa, while the concrete compressive strength (f_{ck}) is 25 MPa. Column dimensions of the superstructure are 35^{cm}x50^{cm} and their orientations are presented in Fig. 3a. The distributed dead and live load values are 500 kg/m^2 and 200 kg/m^2, respectively (TEC 2007). In Table 5, the first six fixed-base periods of the mode shapes are presented for the considered 3S RC frame.

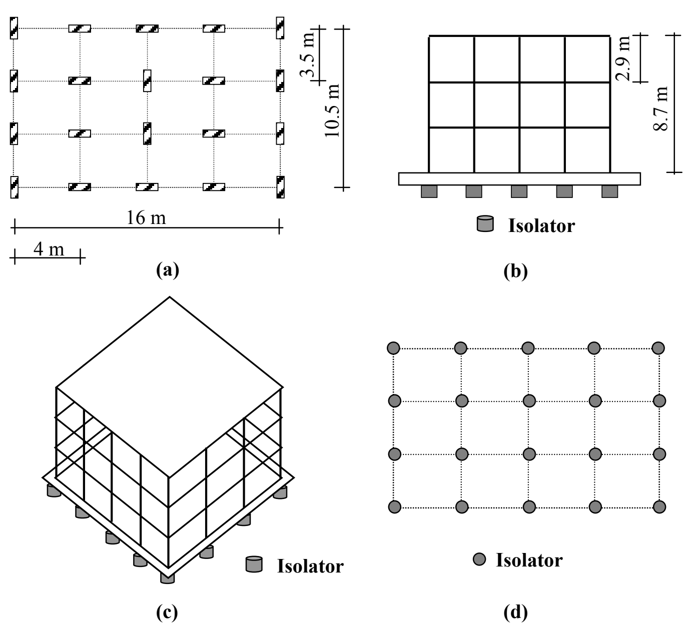

Figure 3. 3-D model of 3-story isolated RC building: (a) plan, (b) elevation, (c) 3D layout, and (d) isolation system.

Table 5. Periods of the first six fixed-base mode shapes.

MODE	PERIOD (sec.)	MODE	PERIOD (sec.)
1 (Translation X)	0.195	4 (Translation X)	0.064

2 (Translation Y)	0.195	5 (Translation Y)	0.064
3 (Rotation)	0.187	6 (Rotation)	0.061

Modeling of isolated structure was performed by structural analysis program SAP2000 (Computers and Structures. Inc, 2009). The linearly modeled superstructure has damping values of 2% for the first three modes and 5% for the rest. On the other hand, isolators were modeled nonlinearly using the bilinear force-deformation relation (Fig. 2). Isolators are positioned under each column at the foundation level.

Results

To compare the response of isolated structure under uni-directional and bi-directional earthquake excitations, a total of 792 NRHA were conducted. First, each component of ground motion records was applied unidirectional and the maximum responses obtained from those two analyses were recorded. Then, both components were applied simultaneously and resultant responses were calculated by taking SRSS at each time step. Comparisons are done considering two different site classes namely, stiff and soft soil. The influence of both isolation period and *Q*/*W* ratio on the response of isolated structure was examined through the isolator displacements (D), base shears (V), and top floor accelerations (A) of the superstructure. All the results presented in this section are the average of each ground motion bins.

Isolator Displacements

Comparison of isolator displacements under uni-directional (D_{uni}) and bi-directional (D_{bi}) earthquake excitations for both of the soil conditions are presented in Fig. 4. In each of these plots, the vertical axis stands for the ratio of D_{bi} to D_{uni}, and horizontal axis represent *Q*/*W* ratios. The solid lines in Fig. 4 represent the ratio of D_{bi}/D_{uni} calculated in accordance with 100%+30% rule, that is, it is $\sqrt{1^2 + 0.3^2} \approx 1.045$.

The results presented in Fig. 4 revealed that the contribution of orthogonal components of ground motions in stiff soil records is higher than soft soil records. For stiff soil motions, D_{bi}/D_{uni} ratio vary in between 1.1 – 1.15 band. At lower *Q*/*W* ratios D_{bi}/D_{uni} ratio tends to increase as *Q*/*W* ratio increases. However, as *Q*/*W* ratios get higher values, D_{bi}/D_{uni} ratio starts to decrease with further increase in *Q*/*W* ratio. For soft soil records, D_{bi}/D_{uni} ratio changes in the range of 1.05 – 1.1 and gradually decreases with increasing *Q*/*W* ratio. Another deduction from Fig. 4 is that isolation period has negligible effects on D_{bi}/D_{uni} ratio with the exception of lower *Q*/*W* ratios for both of the soil classes. As it is clearly seen in Fig. 4, all the data is above the solid line that represents the 100%+30% rule defined by the codes. This indicates that ~5% increment is not good enough to capture the relation between uni-directional and bi-directional responses under near-fault excitations. Fig. 4 also shows that amount of increment should be dependent of the soil class.

Base Shears

Fig. 5 presents the ratio of base shears obtained by uni-directional (V_{uni}) and bi-directional (V_{bi}) earthquake excitations for both of the soil classes. V_{uni} and V_{bi} are the maximum shear forces in any direction of the structure (x or y) under uni-directional and bi-directional excitations, respectively. The solid lines in Fig. 5 stand for the case where V_{bi}/V_{uni} is equal to 1.

V_{bi}/V_{uni} is observed to be less than 1 in almost all of the considered cases in Fig. 5 with the exception of isolation system with Q/W = 0.04 at stiff soil class. As the Q/W ratio increases, V_{bi}/V_{uni} ratio decreases gradually. The maximum amount of reduction in base shear due to bi-directional excitation is 7% for stiff soil bin while it is 8% for soft soil bin. Fig. 5 also states that, although it is very limited, the effect of isolation period on V_{bi}/V_{uni} ratio in stiff soil bin is more than that of soft soil bin.

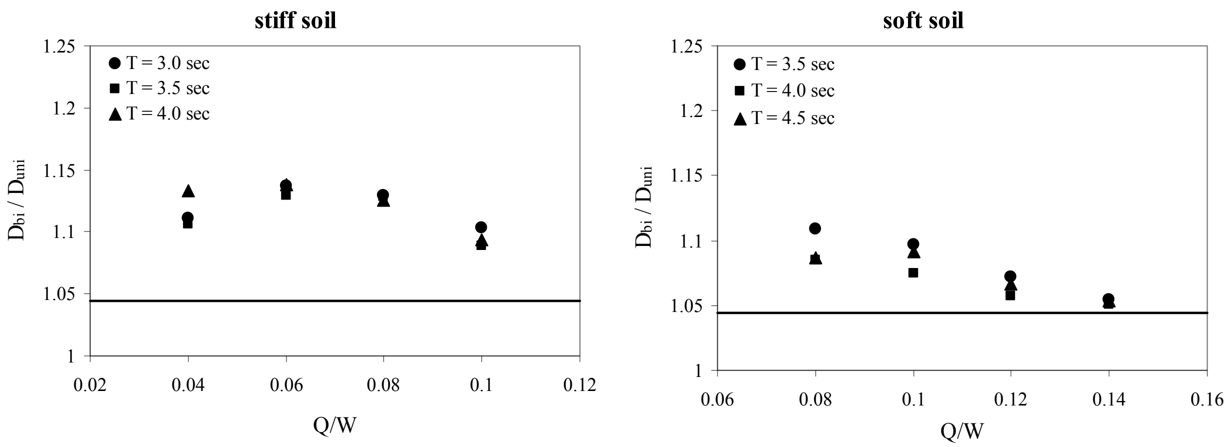

Figure 4. D_{bi}/D_{uni} ratios versus Q/W ratios for a range of isolation periods.

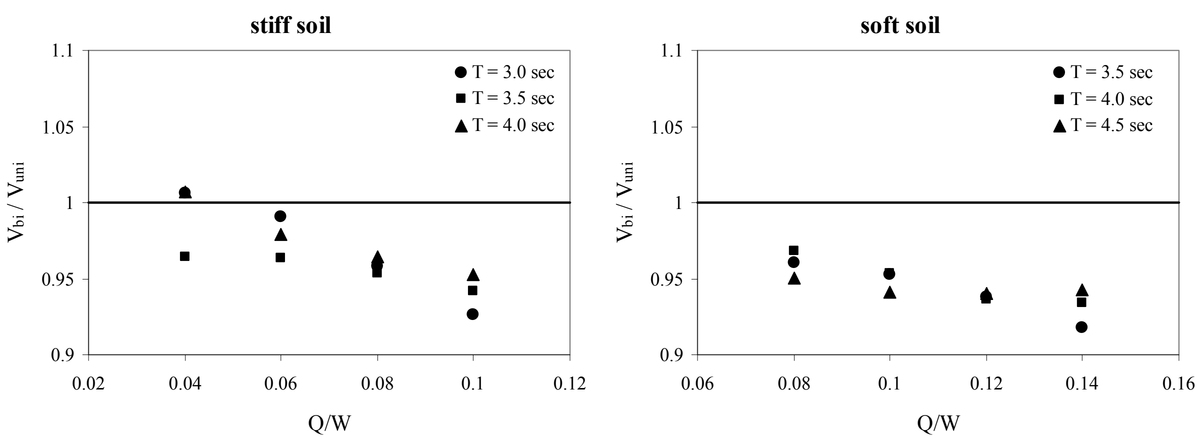

Figure 5. V_{bi}/V_{uni} ratios versus Q/W ratios for a range of isolation periods.

Top Floor Accelerations

Change in A_{bi}/A_{uni} ratio is presented for various Q/W ratios and isolation periods in Fig. 6. Variation of A_{bi}/A_{uni} ratio depending on Q/W ratio is almost the opposite for stiff and soft soil conditions. While A_{bi}/A_{uni} ratio is substantially affected by the change in isolation period at higher *Q/W* ratios for stiff soil bin, isolation period becomes more dominant at lower *Q/W* ratios for soft soil bin. The amount of increment in top floor accelerations may be up to 10 % for stiff soil bin and decreases with increasing *Q/W* ratio. On the other hand, there is not any increase in uni-directional top floor accelerations due to bi-directional excitations in soft soil bin. Instead, there is a gradual decrease in A_{bi}/A_{uni} ratio with increasing *Q/W* ratio. Results revealed that the reduction in A_{uni} may be as much as 10% and 15% for stiff and soft soil conditions, respectively.

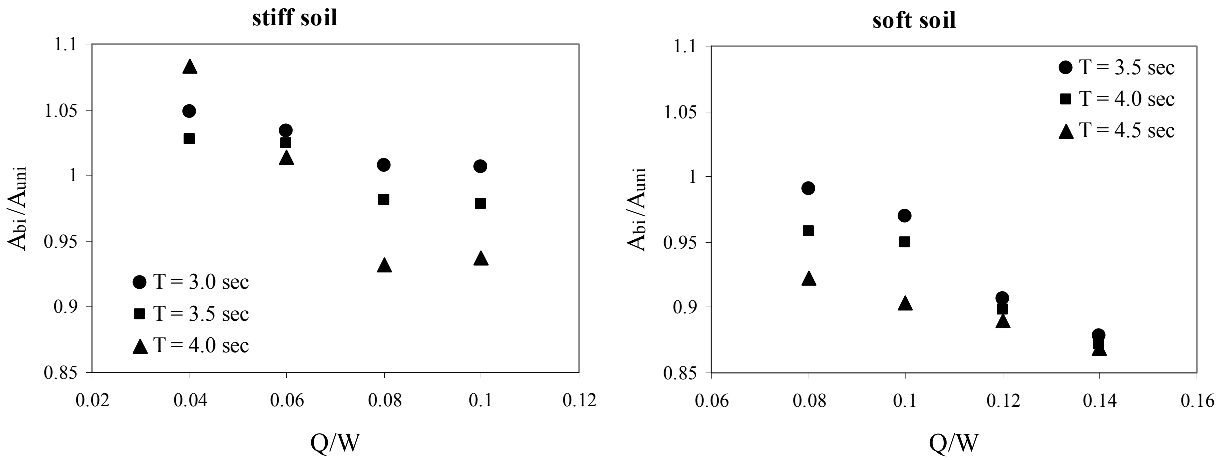

Figure 6. A_{bi}/A_{uni} ratios versus Q/W ratios for a range of isolation periods.

Conclusions

In this study, NTHA of an isolated RC building with three stories were carried out under bi-directional earthquake excitations considered as near-fault records. Two sets of near-fault ground motion records were used, and each set have eleven records. These two sets of ground motions are classified according to site classes they were recorded (stiff and soft soil). Selected near-fault ground motions were used to investigate the difference in response of isolation systems when ground motion is applied as uni-directional or bi-directional. The following conclusions can be revealed from the results of the present study:

1. 100%+30% combination rule (~1.045xD_{uni}) for determining the maximum displacement of isolators by simplified method of analysis is not enough to consider the contribution of orthogonal horizontal component of near-fault excitations. Moreover, soil conditions where ground motions were recorded affect that contribution (15% and 10% for stiff and soft soil conditions, respectively).
2. Base shears under bi-directional excitations are observed to be less then the ones under uni-directional excitations for almost all of the cases considered, regardless of the soil type. Likewise, a reduction in top floor accelerations is observed for both of the soil conditions. These reductions may lead the engineers for more efficient design strategies for isolated structures.

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