

Seismic demands and analysis of site effects in the Marmara region during the 1999 Kocaeli earthquake

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Abstract The characteristics of the strong ground motion accelerograms from the 1999 Kocaeli earthquake are investigated in detail in this study. The emphasis is on the comparison of the response spectra for the fault normal (FN) and fault parallel (FP) components of the ground motions. The results show that the near-fault records with directivity effects characterize themselves with increased base shear demands rather than increased displacement demands for both the FN and FP components and a narrower velocity sensitive region for the FN component. This study also shows that the effectiveness of base isolation may vary from site to site and for a given site, from component to component. The site effects in the Marmara region during the 1999 Kocaeli earthquake are examined. Site amplifications are predicted by the classical spectral ratio (CSR) and the receiver function (RF) methods. The CSR method gives higher estimates for the site amplifications compared to the RF method and is in better conformity with the observed damage during the Kocaeli earthquake. The districts of Istanbul that are especially susceptible to site amplification hazard are determined. It is apparent from the results that the site amplification hazard risk is the highest for Avcilar and Bakirkoy districts. This study also shows that for sites which have the risk of soil amplification for long-period structures, liquefaction may not be beneficial as a natural base isolator, and may result in shifting the eigenperiod of the low- and mid-rise structures to the critical periods with high site amplifications. This may be especially the case for Avcilar and Bakirkoy districts. In Fatih, Bakirkoy, and Cekmece districts, the predominant period of the ground motion is calculated to be very close to the eigenperiods of the typical residential buildings. Therefore, these three districts are expected to experience heavier damages in future earthquakes due to resonance effects.

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1 Introduction

The Kocaeli earthquake hit Turkey on 17 August 1999 at 03:01:37 a.m. local time. The moment magnitude was 7.4 (United States Geological Survey 2006). The earthquake affected the entire Marmara region, where 17 million people live according to the National Statistics Institute (1997), and where the major industry is established (Bakir and Boduroglu 2002). The Kocaeli earthquake caused high casualties and significant structural damage. There were 18,000 officially reported deaths, 1 million people were trapped under debris. According to the Ministry of Public Works and Settlement, 94,000 buildings had either collapsed or were heavily damaged after these earthquakes. One hundred five thousand buildings had partially collapsed and 113,000 buildings had suffered slight damage. The number of people left homeless after the Kocaeli earthquake amounted to 600,000. It has been reported by the public and private sectors that total monetary losses as a result of the Kocaeli earthquake were 16 billion USD. The losses in the industrial facilities alone were estimated between 1.1 billion USD and 4.5 billion USD (Bibbee et al. 2000). Comprehensive reviews of the Duzce and Kocaeli earthquakes can be found in Bakir and Boduroglu (2002) and Bakir (2004). The most common residential building types in the area are three–seven storey reinforced concrete structures with hollow brick infills and with fundamental natural vibration periods between 0.3 and 1 s.

To process and analyze the data in this study, a complete seismic analysis and strong motion signal processing toolbox SPIDER (signal processing in digital earthquake recordings) is developed in MATLAB (2006) by the first author. The strong motion data set used for this publication is shown in Table 1. Except for the KUT record provided by Earthquake Research Department (ERD), the majority of the data used in this study is provided by Kandilli observatory of Bosphorus University, KOERI (2006). The locations of the recording stations of KOERI are given in Fig. 1. The NS, EW, and Vertical (V) components of the Kocaeli earthquake processed by the toolbox SPIDER are shown in Figs. 2, 3, and 4.

The ARC record in the database is a near-fault record and is obtained from the ARC station which was located off the western end of the fault during the Kocaeli earthquake. Only about 25% of the fault ruptured towards this site, producing moderate rupture directivity characteristics. No static residual displacements were observed in the displacement time history of this record.

One very important phenomenon observed during the 1999 Kocaeli earthquake was site amplification. In this study, the site effects observed during the Kocaeli earthquake are investigated using the strong motion data set shown in Table 1. Two different methods are employed for quantifying the site amplifications. The first is the classical spectral acceleration ratio, in which spectra obtained at soft soil sites are divided by the spectra obtained at a reference rock site in Istanbul. The result of this division is also known as “amplification functions”. The second method is the receiver function method, where the site amplifications are investigated for a

Table 1 Ground motion characteristics for the Kocaeli earthquake

Station	Component	Operator	f_c	f'_c	PGA [g]	PGV [m/s]	PGD [m]	PGV/PGA	PGD/PGV	Distance [km]	Site conditions	T_g
ARC	N-S	KOERI	0.02	40	0.215	0.152	0.366	0.072	2.41	17	B	0.1845
ARC	E-W	KOERI	0.02	35	0.135	0.44	0.503	0.332	1.41	17	B	3.9010
ARC	V	KOERI	0.03	45	0.0851	0.0853	0.0923	0.102	1.0821	17	B	a
ATS	N-S	KOERI	0.05	15	0.258	0.364	0.261	0.144	0.72	79	D	0.87
ATS	E-W	KOERI	0.04	20	0.189	0.352	0.21	0.190	0.60	79	D	0.87
ATS	V	KOERI	0.025	35	0.0814	0.1073	0.0694	0.134	0	79	D	a
BUR	N-S	ERD	0.05	15	0.103	0.18	0.148	0.178	0.82	63.1	D	0.66
BUR	E-W	ERD	0.08	18	0.102	0.18	0.102	0.18	0.51	63.1	D	1.24
BUR	V	ERD	0.03	10	0.0452	0.0989	0.0645	0.223	0.65	63.1	D	a
DHM	N-S	KOERI	0.02	18	0.092	0.252	0.299	0.279	1.19	69.4	D	0.495
DHM	E-W	KOERI	0.025	15	0.086	0.166	0.147	0.197	0.89	69.4	D	0.85
FAT	N-S	KOERI	0.07	50	0.188	0.173	0.114	0.094	0.66	64.5	D	0.55
FAT	E-W	KOERI	0.02	40	0.164	0.153	0.128	0.095	0.84	64.5	D	0.52
FAT	V	KOERI	0.025	18	0.0898	0.0877	0.07	0.0996	0.7982	64.5	D	a
HAS	N-S	KOERI	0.06	18	0.052	0.079	0.082	0.155	1.04	43.6	C	0.57
HAS	E-W	KOERI	0.04	15	0.113	0.298	0.355	0.269	1.19	43.6	C	0.82
HAS	V	KOERI	0.09	10	0.1375	0.175	0.103	0.13	0.59	43.6	C	a
CNA	N-S	KOERI	0.02	20	0.181	0.172	0.21	0.097	1.22	76.1	C	0.197
CNA	E-W	KOERI	0.03	20	0.135	0.103	0.069	0.078	0.67	76.1	C	0.669
CNA	V	KOERI	0.025	15	0.566	0.0664	0.0508	0.12	0.7651	76.1	C	a
KUT	N-S	ERD	0.07	10	0.061	0.161	0.099	0.269	0.61	144.6	C	0.485
KUT	E-W	ERD	0.06	10	0.051	0.047	0.013	0.094	0.28	144.6	C	0.86
KUT	V	ERD	0.035	3	0.0234	0.055	0.0284	0.24	0.52	144.6	C	a
BOT	N-S	KOERI	0.02	17	0.089	0.11	0.157	0.126	0.143	136.4	D	0.82
BOT	E-W	KOERI	0.025	15	0.0997	0.119	0.045	0.122	0.38	136.4	D	0.95
BOT	V	KOERI	0.01	4	0.0195	0.0398	0.0384	0.21	0.96	136.4	D	0
YKP	N-S	KOERI	0.02	18	0.0417	0.093	0.117	0.227	1.26	62.6	A	2.52
YKP	E-W	KOERI	0.08	14	0.036	0.049	0.037	0.139	0.76	62.6	A	0.19
YKP	V	KOERI	0.02	4	0.02	0.061	0.065	0.306	1.06	62.6	A	a

Note: f_c is the corner frequency for the high pass Butterworth, f'_c is the corner frequency for the low pass Butterworth filter

^a T_g is the predominant period of the ground motion (only calculated for the horizontal components here)

A is rock, B is stiff soil, C is deep narrow soil, D is deep broad soil, Distance is the Joyner-Boore distance which is the closest distance from the station to the surface projection of the fault



Fig. 1 Strong ground motion stations in Istanbul and the Marmara region operated by KOERI (2006)

frequency range of 0.05–10 Hz. Further details on determining site amplifications by receiver function method can be found in Langston (1979). The predominant period of the ground motions are also calculated from the smoothed Fourier Amplitude Spectrums. The smoothing is performed via a moving averaging filter.

This study has three main contributions. First, the response spectral characteristics of strong ground motion associated with the Kocaeli earthquake with special focus on the fault normal (FN) and fault parallel (FP) components are described. Second, the seismic demands for buildings in Istanbul and the Marmara region during the 1999 Kocaeli earthquake are analyzed and interpreted. Third, the site effects and soil amplifications are determined by receiver function method and through amplification functions.

2 Response spectra

The response spectra are calculated by the piecewise exact method as suggested by Nigam and Jennings (1968). The pseudo spectral velocity (PSV), pseudo spectral acceleration (PSA), and the spectral displacement (SD) are related to each other by Eq. 1.

$$\text{PSA} \left(\frac{T}{2\pi} \right)^2 = \text{PSV} \left(\frac{T}{2\pi} \right) = \text{SD} \quad (1)$$

Boore has stated that the elastic response spectra is insensitive to the processing scheme used, for periods less than 20 s for recordings of Chi–Chi earthquake in Taiwan (Boore 1999). Therefore, the sensitivity of the strong ground motion records to the processing scheme adopted is investigated first. The seismic demands are then

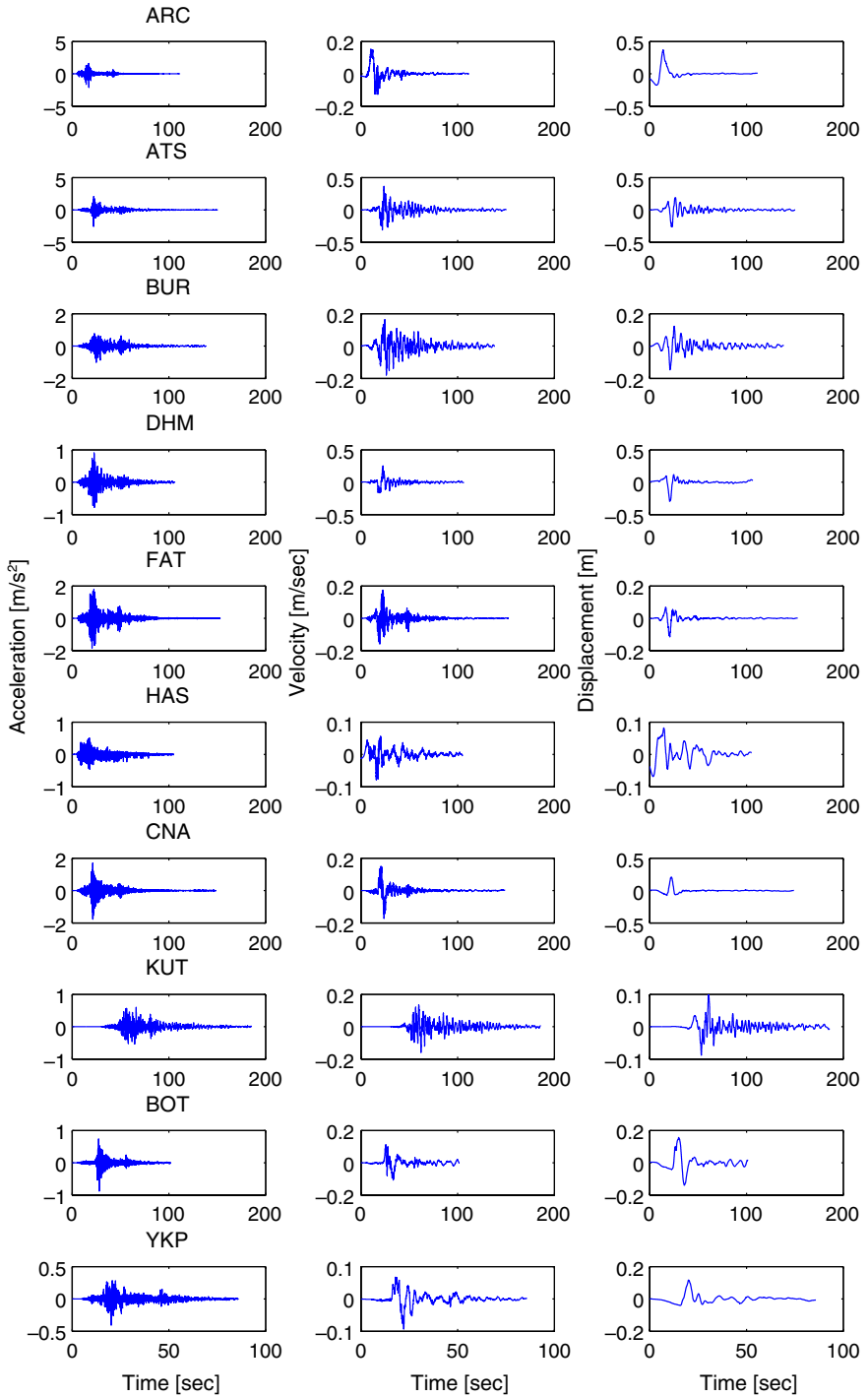


Fig. 2 The NS components of the records obtained during the Kocaeli earthquake processed by the toolbox SPIDER developed by the first author

determined based on the response spectra and acceleration–displacement response spectra obtained from records that are processed in a consistent manner.

It should hereby be stated that a building does not show a single deterministic period value. During the earthquake motion, the period of the building varies within a band. The bounds of this band change according to the duration of the earthquake and the history of the cumulative damage. In this study, within that band an effective and approximate period value of 0.1 N is used for parametric studies where N is the number of stories. The choice for this period value is also recommended by Crowley and Pinho (2004) as well as by Bertero et al. (1988).

2.1 The effects of signal processing on the response spectra

Signal processing methodology used for strong ground motions is explained in detail in previous publications of the authors (Bakir et al. 2005, 2006). In this study, although not shown here, a parametric study is carried out which showed the influence of the causality of the Butterworth filters on the response spectra for the DHM record of the Kocaeli earthquake ($\xi = 5\%$). This study showed that the two spectra obtained from high pass Butterworth filters with different causalities match each other closely up to a period of 25 s. This important result which shows that the choice of the causality of the filters does not affect the dynamic response of structures, is also confirmed previously by Boore and Bommer (2005).

Figure 5 shows the response spectra for the EW component of the ARC record of the Kocaeli earthquake processed by acausal Butterworth filters with different high pass corner frequencies. It is apparent from the figure that the different spectra match each other up to only 2.5 s. For periods greater than 2.5 s, the differences become very pronounced. The choice of the corner frequency affects the response of structures more than the causality of the filters. For the dynamic analysis of typical residential structures in the Marmara region, this difference does not pose any problem, as the eigenperiods of these structures are much below the 2.5 s threshold. It should be noted here that the high pass filter corner of 0.02 Hz in the figure is the only frequency that is obtained from the f^2 source model of Brune (1970).

Figure 6 shows the influence of the high pass corner frequency of causal Butterworth filters, on the response spectra of the EW component of the ARC record of the Kocaeli earthquake. The spectra obtained from different corner frequencies match each other closely for a period of up to 3 s. For periods greater than 3 s, the spectra differ significantly. This means that the dynamic analysis for structures with eigenperiods up to 3 s will not be affected from the corner frequency chosen for the Butterworth filter. However, for high-rise structures and bridges, the results of the dynamic analysis will depend to a great extent on the corner frequency adopted for processing strong ground motions.

These parametric studies show that the dynamic response of typical buildings in the Marmara region is independent of the causality of the filters. Therefore, whether the signals from the strong ground motion are processed by causal Butterworth filters or acausal Butterworth filters may be irrelevant. What may be relevant on the other hand, is the corner frequency chosen for the high pass filters. A careful review of Fourier amplitude spectrum (FAS) and strict adherence to the f^2 source model of Brune is necessary. It has long been suggested among earthquake engineers that the sensitivity to the choice of the corner frequency is higher in the case of causal filters compared to the acausal filters. This study on the other hand, shows that the spectra

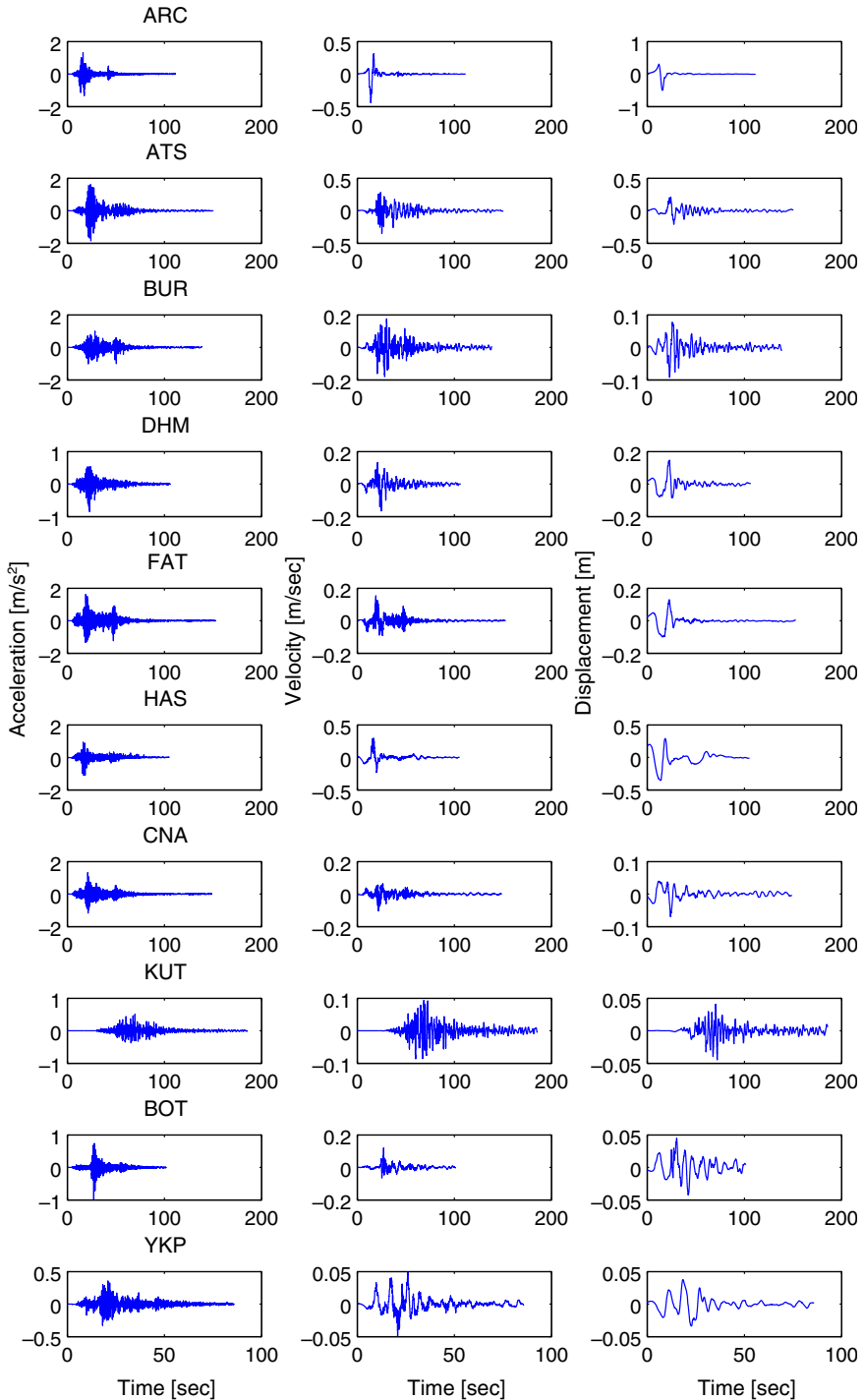


Fig. 3 The EW components of the records obtained during the Kocaeli earthquake processed by the toolbox SPIDER developed by the first author

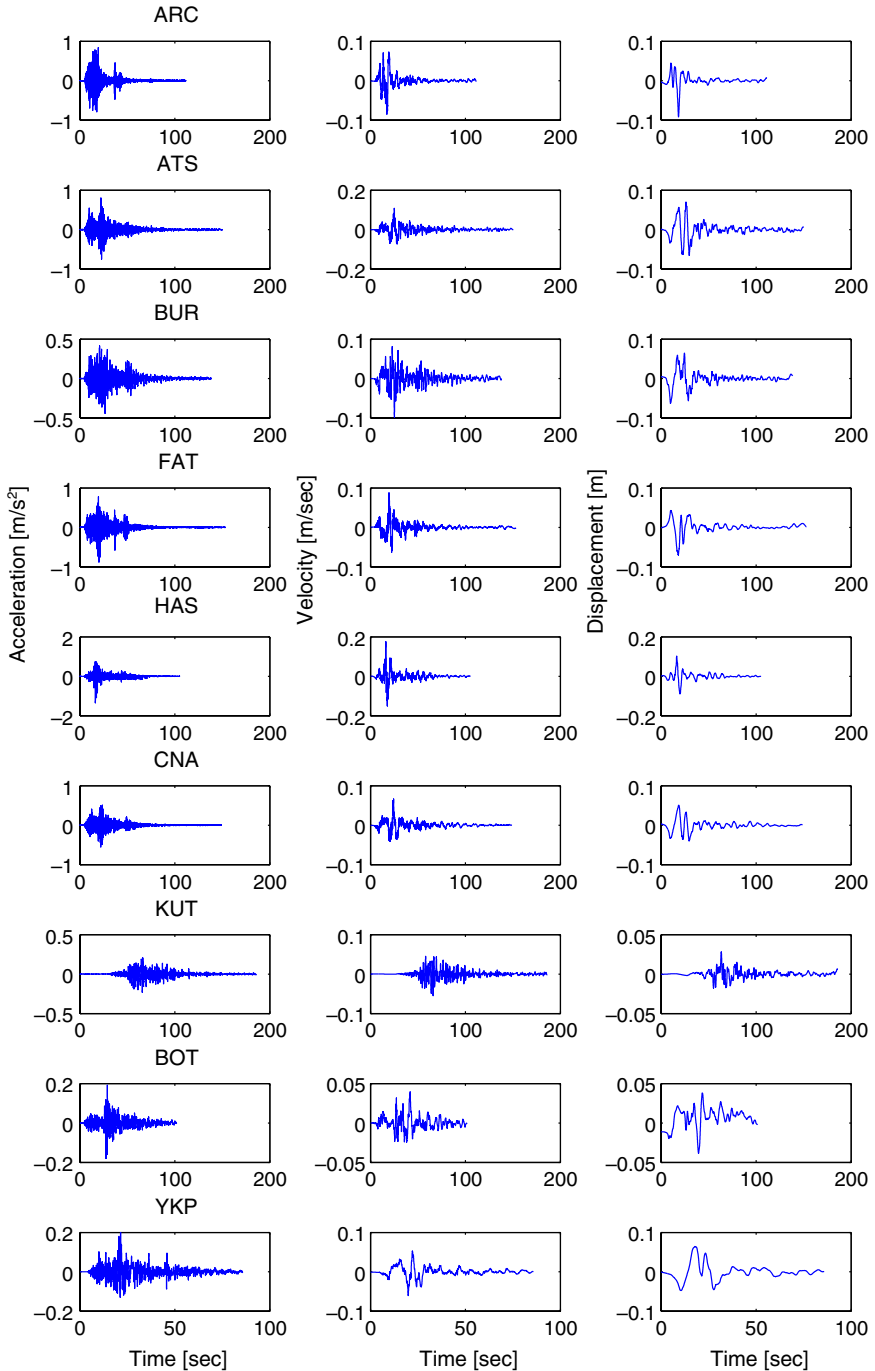


Fig. 4 The vertical components of the records obtained during the Kocaeli earthquake processed by the toolbox SPIDER developed by the first author

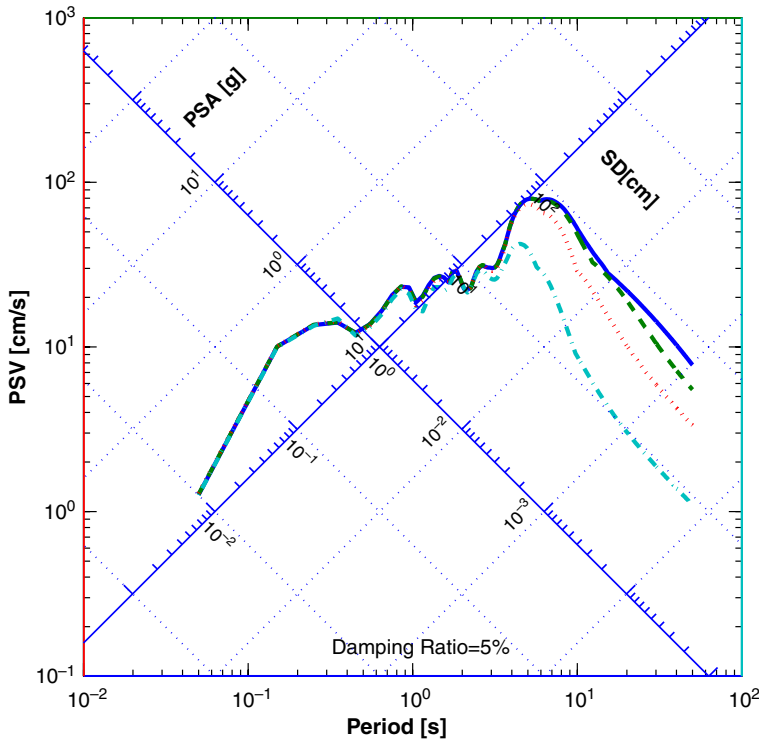


Fig. 5 Response spectra for the EW component of the ARC record of the Kocaeli earthquake processed by acausal filters with different corner frequencies: $f_c = 0.02$ Hz (solid line), $f_c = 0.05$ Hz (dashed line), $f_c = 0.14$ Hz (dotted line), and $f_c = 0.2$ Hz (dashed dotted line)

obtained from different corner frequencies match each other closely up till 3 s irrespective of the causality of the filters. Thus, both types of filters are affected from the choice of the corner frequency to the same extent.

2.2 Response spectra and its implications on buildings in the Marmara region

Malhotra (1999) states that the boundaries of the spectral regions are to a great extent dependent on the PGV/PGA and PGD/PGV ratios. The higher the PGV/PGA ratio is, the wider is the acceleration sensitive region. On the contrary, the lower the PGD/PGV ratio is, the wider is the displacement sensitive region. If the acceleration sensitive region of a ground motion is wider, greater number of buildings behave in a stiff manner with increased base shear demands. Greater number of modes fall in to the acceleration sensitive region for long-period structures such as high-rise buildings and bridges. This results in increased base shear and displacement demands for these structures. A wider acceleration sensitive region decreases the higher mode effects due to the fact that the fundamental mode of even a high-rise structure falls within the acceleration-sensitive region of the spectrum resulting in a reduction of the relative contributions of the higher modes with respect to the fundamental vibration period.

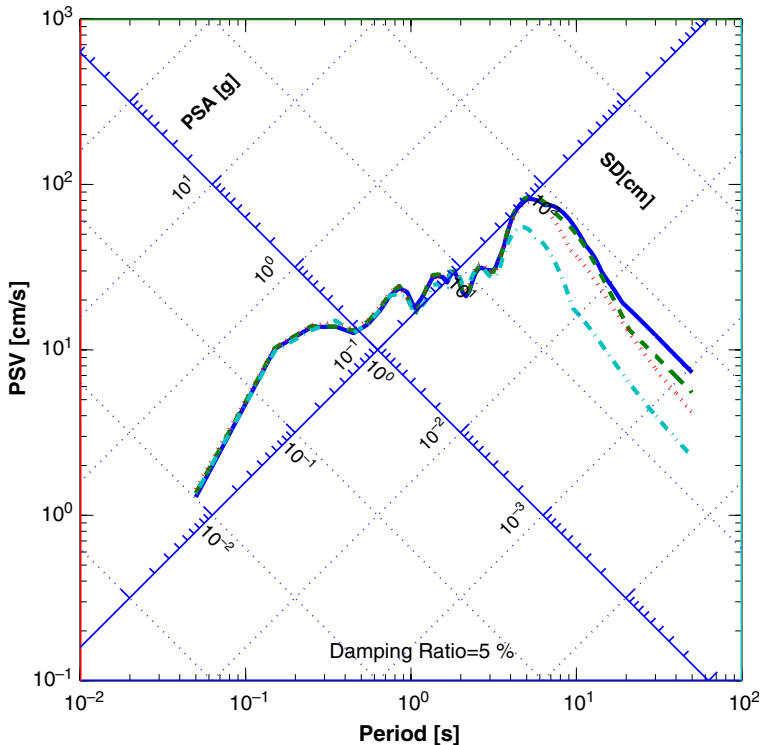


Fig. 6 Response spectra for the EW component of the ARC record of the Kocaeli earthquake processed by causal filters with different corner frequencies: $f_c = 0.02$ Hz (solid line); $f_c = 0.05$ Hz (dashed line), $f_c = 0.1$ Hz (dotted line), and $f_c = 0.2$ Hz (dashed dotted line)

The response spectra for a 5% damped structure are shown in Fig. 7 for the NS components of the records obtained in Istanbul. It is apparent from this figure that the DHM record which is obtained at Yesilkoy has the widest acceleration-sensitive region. This means that many structures in Yesilkoy had increased base shear and drift demands. The observed damage in structures during the 1999 earthquakes confirms the above findings. Many structures had to be evacuated or demolished in Yesilkoy after the 1999 Kocaeli earthquake, although the district was 69.3 km to the surface projection of the fault.

The response spectra for a 5% damped structure are shown in Fig. 8 for the EW components of the records obtained in other cities in the Marmara region. Figure 8 shows that the EW component of the ARC record has the widest acceleration sensitive region amongst the other records obtained in the region. This means that more number of structures behaved in a stiff manner when subjected to the EW component of the ARC record during the Kocaeli earthquake. Therefore, the relative effect of higher modes with respect to the fundamental mode is reduced and the base shear demand is increased in these structures. The predominant period of the ground motion for each of the horizontal accelerograms are calculated as shown in Table 1. It is apparent from this table that the FAT, DHM, and the CNA records have predominant periods of ground motion which are very close to the eigenperiods of the typical residential buildings in these regions. Therefore, typical residential

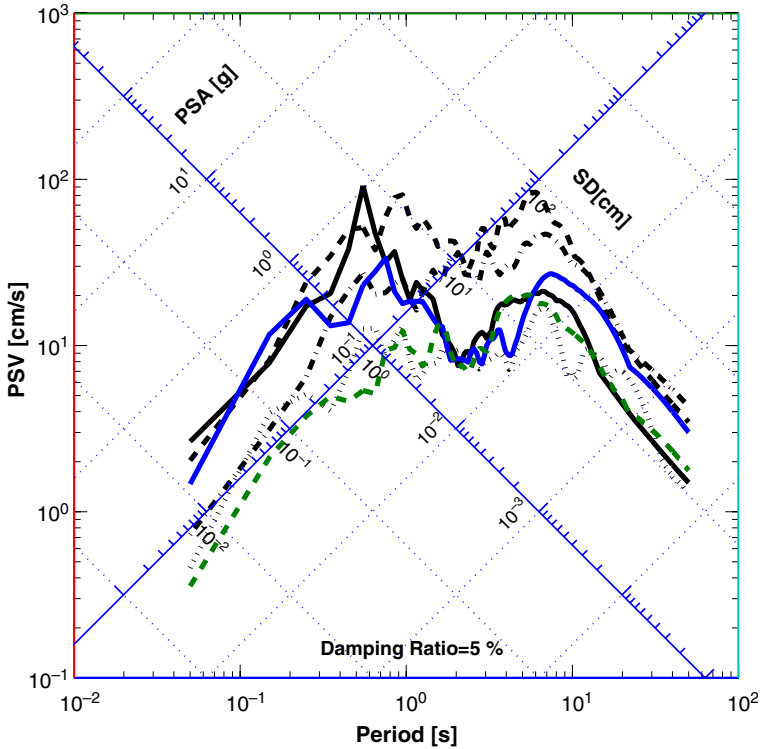


Fig. 7 Response spectra ($\xi = 5\%$) for the NS components of the ATS (black dashed line), DHM (dashed dotted line), FAT (black solid line) HAS (dotted line), CNA (solid line), and YKP (dashed line) records

buildings in Fatih, Cekmece, and Bakirkoy districts are expected to experience heavier damages due to quasi-resonance effects in future earthquakes.

2.3 Acceleration–displacement response spectra

Acceleration–displacement response spectra are plots frequently used in pushover analysis and nonlinear static procedures recommended in codes (Applied Technology Council 1996; EN 1998; Federal Emergency Management 1997). These plots are also used in performance-based design and they typically show the base shear demand in the ordinate against the displacement demand in the abscissa. The acceleration–displacement response spectra are shown in Fig. 9 for the EW components of the records from the Kocaeli earthquake obtained in other cities in the Marmara region and in Fig. 10 for the NS components of the records obtained in Istanbul.

The acceleration–displacement response spectra for the FN and FP components of the ARC record for the Kocaeli earthquake and the Bolu record of the Duzce earthquake in 1999 are shown in Figs. 11 and 12. Several observations are available from these figures. First, for the FN component of the Bolu record, increasing the eigenperiod from 0.3 to 1 s does not decrease the base shear demand much, but increases the displacement demand substantially. Thus, base isolation whose overall

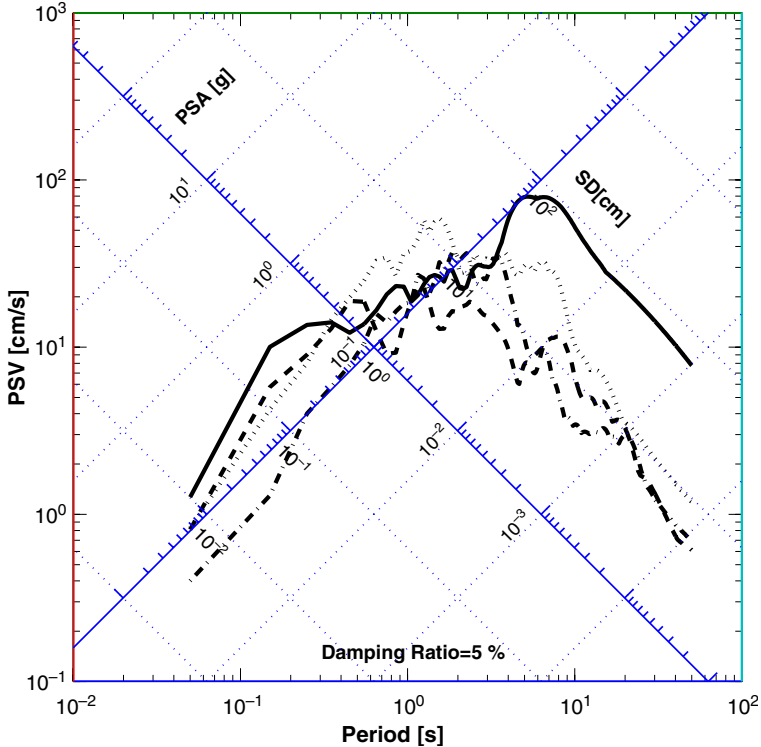


Fig. 8 Response spectra ($\xi = 5\%$) for the EW components of the ARC (solid line), BUR (dashed line) KUT (dashed dotted line) and BOT (dashed line) records

effect is to increase the eigenperiods of structures, is not beneficial for structures subjected to this record. For the FP component on the other hand, increasing the eigenperiod of the structure from 0.3 to 1 s decreases the base shear substantially without increasing the displacement demand much. Therefore, rehabilitating low- and medium-rise structures subjected to this record by base isolation would be very effective (Bakir et al. 2006). For the ARC record, increasing the eigenperiod of the structure from 0.5 s to 2 s, decreases the base shear demand substantially for the FN component of the ARC record compared to the FP component. Base isolation would be very effective for short-period structures subjected to the FN component of the ARC record. For long-period structures subjected to the FN and FP components of the ARC record on the other hand, base isolation would result in substantial increases in the displacement demands of structures without decreasing the base shear demands. Therefore base isolation would not be effective for high rise structures or bridges in the region.

The base shear demands due to the FN and FP components of the Bolu record of the Duzce earthquake, are substantially higher than the base shear demands due to the FN and FP component of the ARC record of the Kocaeli earthquake. However, for long-period structures, ARC record imposes very high displacement demands, more so, for the FP component. The differences in the demands of the Bolu and ARC records are associated with the fact that the directivity effects are not present

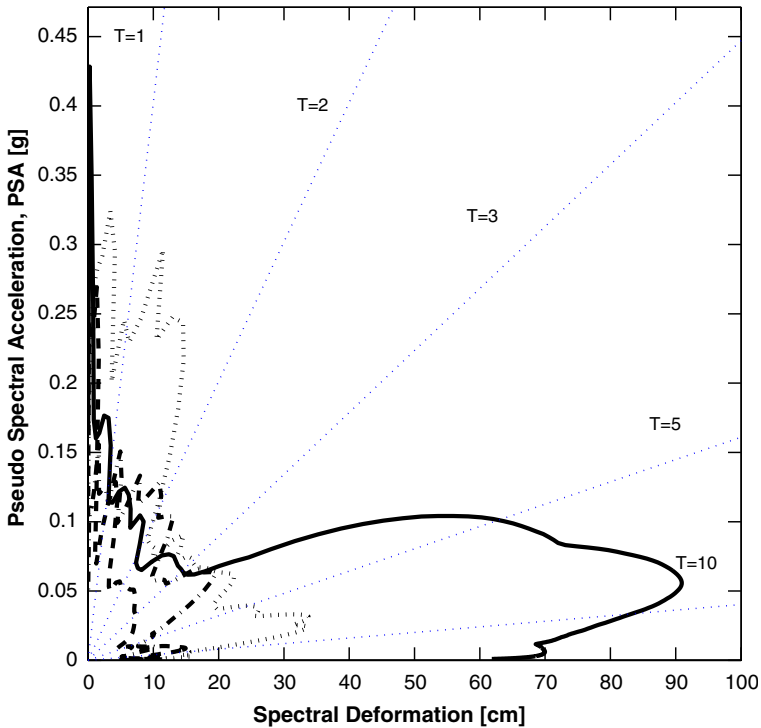


Fig. 9 Acceleration–displacement response spectra ($\zeta = 5\%$) for the EW components of the ARC (solid line), BUR (dashed line) KUT (dotted line) and BOT (dashed dotted line) records

in the ARC record. Both of these records are near-fault records of about 18 km to the surface projection of the fault. The Bolu record had received considerable amounts of directivity effects as the fault had ruptured towards this site in the Duzce earthquake. However, only 25% of the fault had ruptured towards the ARC station in the Kocaeli earthquake. Therefore, directivity effects were not dominant in the ARC record. Moreover, ARC record was obtained on stiff soil, whereas Bolu record was obtained on soft soil. This is also one of the reasons behind the high base shear demands in the Bolu station during the Duzce earthquake.

3 Site amplifications in Istanbul

It is apparent from the response spectra of both the NS and EW components of the records obtained in Istanbul that the frequency contents and the spectral acceleration responses are different for the YKP record obtained at a stiff site compared to the other records obtained in soil sites. The site amplifications are estimated at Istanbul, by both the classical spectral ratio (amplification functions) and the receiver function methods. In the classical spectral ratio method, the spectral acceleration of the record obtained on a soft site is divided by the spectral acceleration of a reference record obtained on rock. In this study, the YKP record obtained in Istanbul is taken as the reference site and all the other spectral

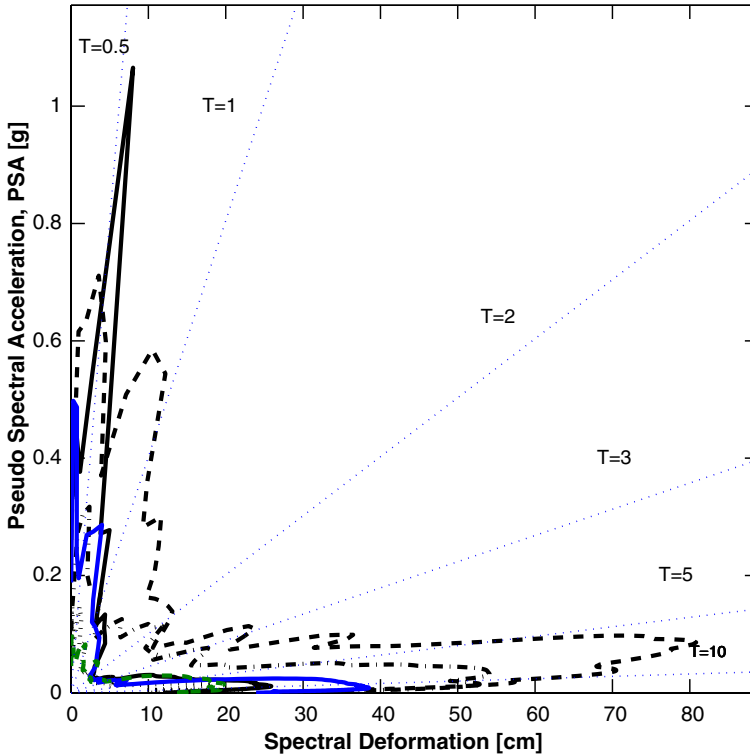


Fig. 10 Acceleration–displacement response spectra ($\zeta = 5\%$) for the NS components of the ATS (black dashed line), DHM (dashed dotted line), FAT (black solid line), HAS (dotted line), CNA (solid line), and YKP (dashed line) records

accelerations from other records are divided by the spectral acceleration obtained from this site. In the receiver function method, the FAS is computed for each horizontal and the vertical accelerogram. The average horizontal spectrum is calculated by taking the square root of the sum of the squares of each spectra in the horizontal direction. The spectra are then smoothed by a moving average filter before taking their ratios in the frequency domain. A typical frequency range from 0.05 Hz to 10 Hz is used as the frequency range of interest.

3.1 Results obtained by classical spectral ratio method

Spectral acceleration ratios for the NS and EW components of the strong ground motions are presented in Figs. 13 and 14.

Several observations are available from these figures. First, in the NS direction, the ATS record which is obtained at Ambarli thermoelectric power plant in the Avclar district shows that the spectral accelerations for the typical structures in the region with fundamental natural vibration periods of 0.3–1 s. are increased by a factor varying between 6 and 11 with respect to the same type of structures on rock site during the Kocaeli earthquake. The EW component of the same record shows 5–25 times site amplification in this region. This finding confirms the observed damage in this region during the Kocaeli earthquake. ATS accelerogram is recorded very close to the district

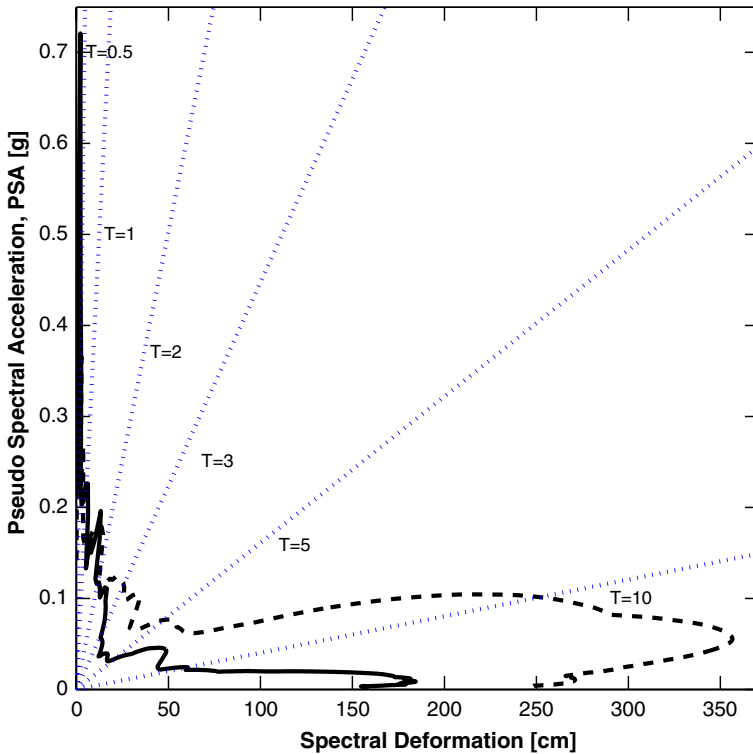


Fig. 11 Acceleration–displacement response spectra ($\xi = 5\%$) for the FN (solid line) and FP (dashed line) components of the ARC record of the Kocaeli earthquake

Avcilar in Istanbul, where, at least 1000 people were killed under pan cake-type collapsed buildings. Avcilar is a district in west Istanbul and almost 79 km to the fault. The building quality is not different from the other districts of Istanbul such as Bakirkoy, Gungoren, or Bahcelievler that sustained very little damage. The only explanation for such severe damage is the seismic wave amplification. According to Meremonte and others (Cranswick et al. 1999), the damage observed at Avcilar during the Kocaeli and Duzce earthquakes is mainly due to the inclined topography of the district, which is located on an east and south-dipping hillside that falls sharply to the Sea of Marmara in the south and to Kucuk Cekmece in the east. This topography converts the body waves generated during the earthquake to surface waves which are more detrimental. In the EW direction, the site amplification at Ambarli increased to as high as 40 for a period range of 1–1.5 s. This shows that the site amplifications were even worse for the long-period structures. Recent research at Istanbul Technical University (Yuzer et al. 1997) and Bosphorus University (Bal et al. 2002) shows that Avcilar may be vulnerable to liquefaction hazard. Therefore, the eigenfrequencies of typical midrise structures in the region may be shifted to the critical periods of 1–1.5 s, where the site amplifications are the highest.

In Yesilkoy neighborhood of Bakirkoy district, where the DHM record was obtained, many of the residential buildings constructed before 1970’s on soft soils experienced heavy damage and a few even had to be demolished although there were no fatalities in this district. The devastation in Avcilar was not observed in

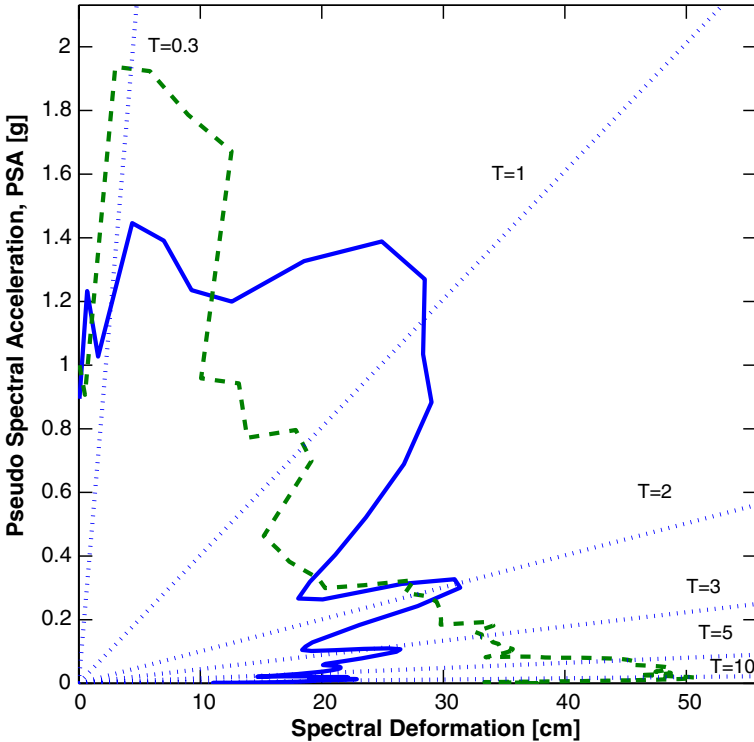


Fig. 12 Acceleration–displacement response spectra ($\xi = 5\%$) for the FN (solid line) and FP (dashed line) components of the Bolu record of the Duzce earthquake

Yesilkoy in spite of the fact that the two districts were at similar distances to the epicenter. In the NS direction, the site amplifications are 2–5, whereas in the EW direction, the amplifications are between 2.5 and 7. In the EW direction, the amplifications rise up to 10 for structures whose fundamental vibration periods are between 1.25 and 1.75 s. Yesilkoy is an area that may be prone to liquefaction-hazard in earthquakes. Although liquefaction is a potential hazard to the stability of sites, it may be beneficial to structures by providing a natural base isolation. This was the reason why many structures at Adapazari were subjected to liquefaction induced foundation displacements without serious structural damage. The liquefaction increases the eigenperiod of the structure resulting in considerable reductions in the spectral accelerations. However, for the case of Yesilkoy, which is susceptible to liquefaction hazard, increases in the eigenperiod of structures will result in higher site amplifications. Therefore, liquefaction may not be beneficial as a natural base isolator in this case and may result in shifting the eigenperiod of the structure to the critical periods with high site amplifications as is the case of Avclar.

The site amplifications for the FAT record, which is obtained from the historical district Fatih shows that in the NS and EW directions, the site amplifications are varying between 2 to 17 and 2 to 9, respectively for typical structures with fundamental periods varying between 0.3 and 1 s. In the NS direction, there is a very clear peak at 0.5–0.6 s. which corresponds to four or five storey structures. In the NS direction, the amplifications are negligible for long-period structures. However, in

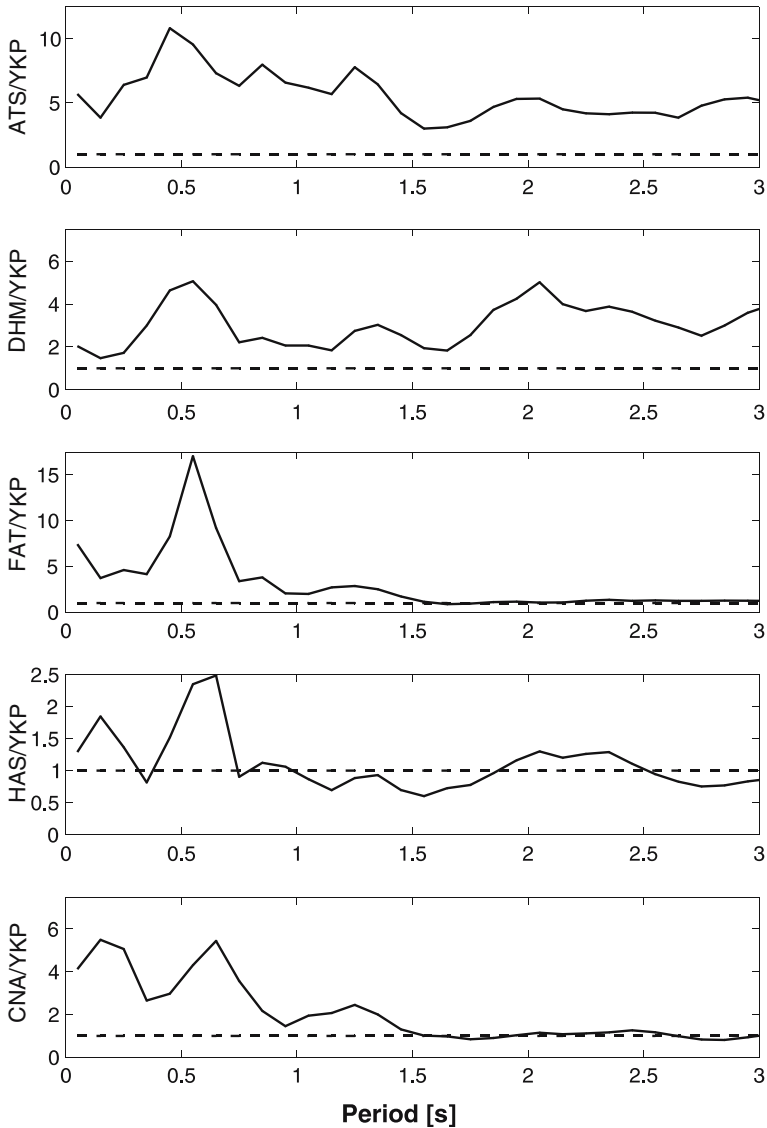


Fig. 13 Spectral acceleration ratios for the NS components of the records with respect to YKP record (from top to bottom): ATS, DHM, FAT, HAS, and CNA

the EW direction, the amplifications may again rise up to 4 at 1.3 s. For higher periods, the amplifications are insignificant.

The HAS record is obtained from one of the Prince Islands. The typical residential structures in this region are two to three storey timber historical mansions. The site amplifications for typical structures in the region are varying between 3 and 5 for the EW direction and 0.8 and 2.5 for the NS direction. For the EW component of the HAS record, a long-period site amplification having a value up to 13 is observed. However, this period is outside the engineering periods of interest for this region.

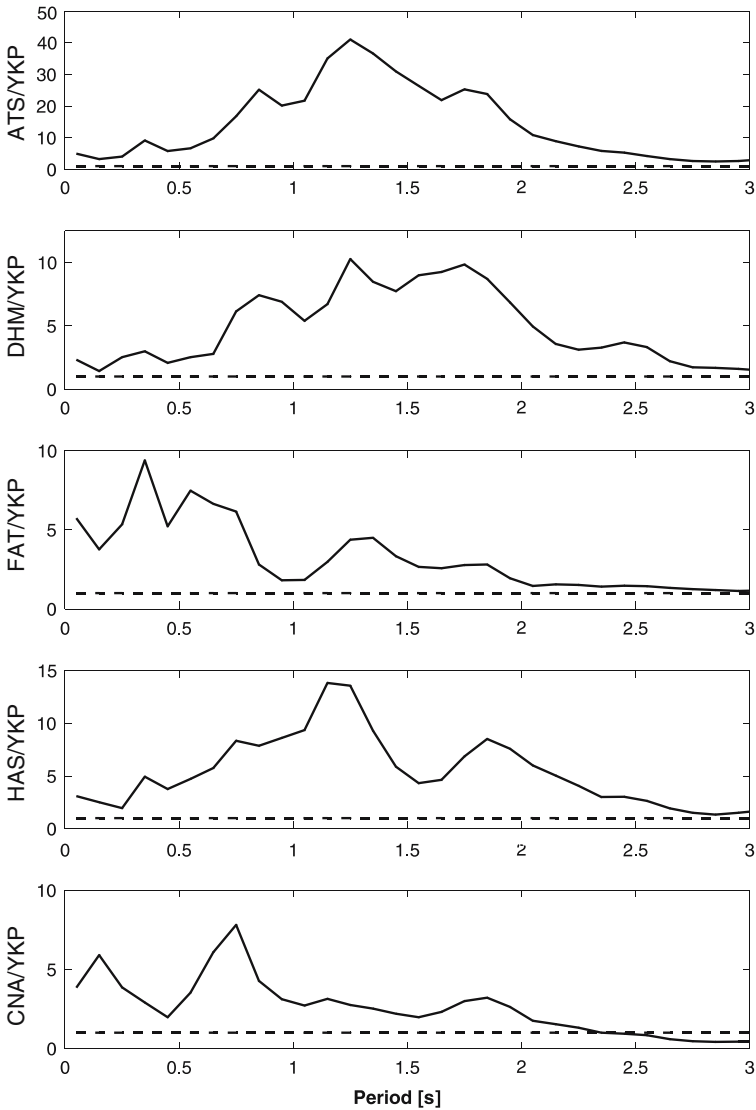


Fig. 14 Spectral acceleration ratios for the EW components of the records with respect to YKP record (from top to bottom): ATS, DHM, FAT, HAS, and CNA

3.2 Results obtained by receiver function method

The site amplifications during the 1999 Kocaeli earthquake have also been evaluated by the receiver function method except for the DHM record, where the vertical accelerogram had a very low signal to noise ratio. Figure 15 shows the site amplifications for all the records.

ATS station was located on soft soil at 79 km to the surface projection of the fault. It is apparent from the figure that the highest amplifications may rise up to 7 around 1 Hz and later around 2.5 Hz. Between 0.5 and 3 Hz, the amplifications are higher

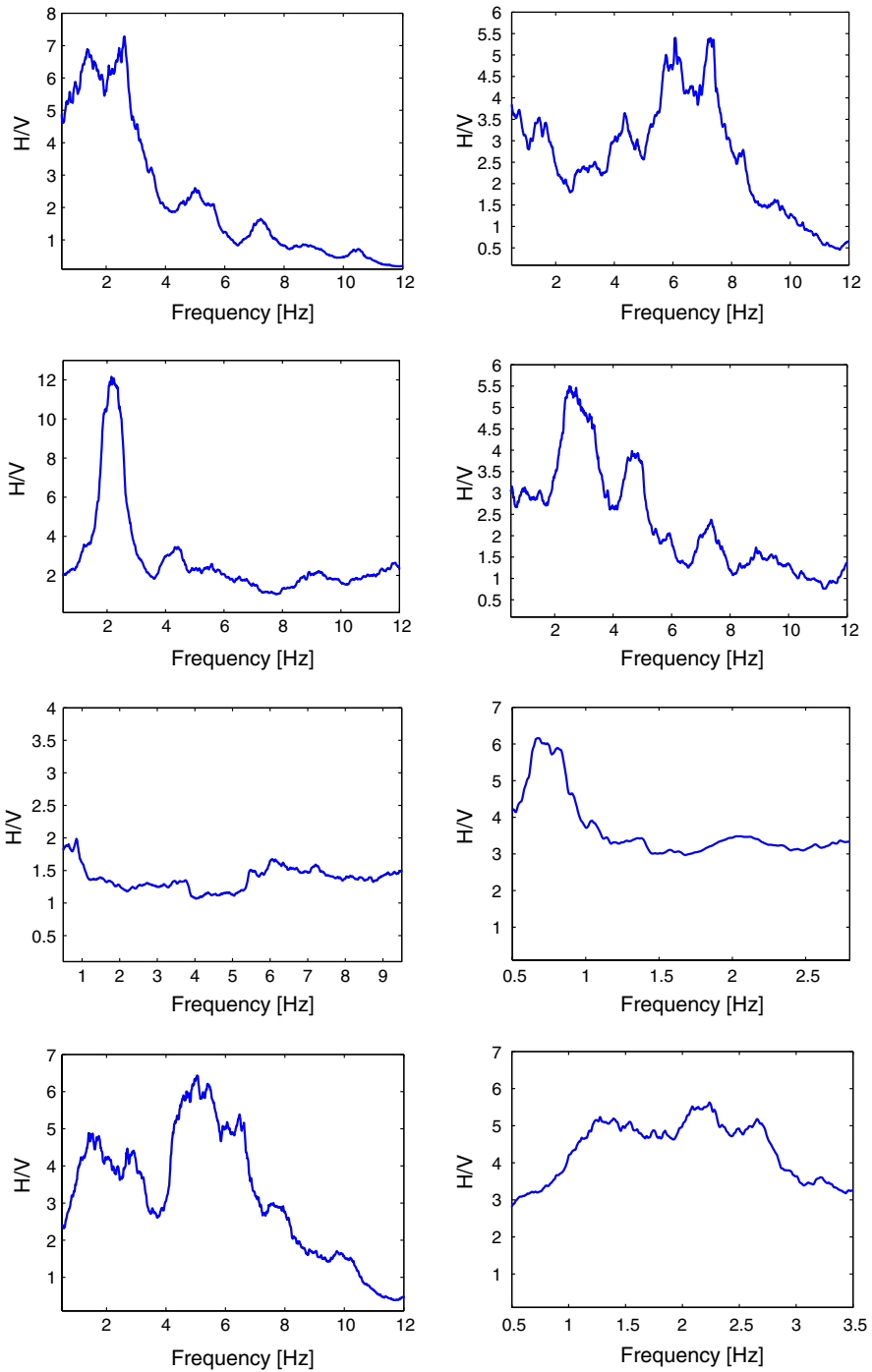


Fig. 15 Site amplifications obtained by the receiver function method, (left hand side from top to bottom): ATS, FAT, HAS, CNA and (right hand side from top to bottom): ARC, BUR, KUT, BOT

than five and decrease rapidly for increasing frequencies. This frequency range corresponds to the eigenfrequencies of typical residential buildings in this region. A comparison between the ARC and ATS records in Fig. 15 shows that the amplifications are higher in the ATS record and are shifted to lower frequencies compared to the ARC record which is only 17 km to the surface projection of the fault.

FAT station was located on soft soil at 64.5 km to the surface projection of the fault. FAT record distinguishes itself with an amplification of 12 around 2 and 2.5 Hz. This frequency corresponds to the eigenfrequency of a four or five storey typical residential building in the region.

HAS station was located on stiff soil at 43.6 km to the surface projection of the fault. It is apparent from the figure that site amplification phenomenon is not likely in the Prince Islands where, the HAS record is recorded. A slight amplification around 2 is obtained alone for frequencies less than 1. The eigenfrequencies of buildings in the Prince Islands are higher than this range, therefore no serious site amplification should be expected in this region if another earthquake strikes in the future.

CNA station was located on soft soil at 76.1 km to surface projection of the fault in the Cekmece districts. It is apparent from the figure that the site amplifications are between 4 and 5 for a frequency range of 1–3 Hz. This is the range for the eigenfrequencies of typical structures in this region. At 5 Hz, the H/V ratio peaks to 6.5.

4 Site amplifications outside Istanbul

For the records obtained in other cities in the Marmara region, there were no transparent reference rock site available that had no complexity of its own. Therefore, the amplification functions could not be used and the site amplifications outside of Istanbul were estimated by receiver function approach alone.

ARC station was located on stiff soil at 17 km to the surface projection of the fault. The figure shows that the amplifications were the highest from 6 to 8 Hz, approaching a value of 5.5. For the frequency range of 1–2 Hz, and around 4 and 5 Hz, another amplification of 3.5 is observed. For typical residential buildings in the region with eigenfrequencies of 2–3 Hz, site amplifications were between 1.5 and 2.5 Hz.

BUR station was located on soft soil at 63 km to the surface projection of the fault. It is apparent that there is an amplification of 5.5 around 3 Hz and there is another amplification of 4 around 5 Hz.

KUT station was located on soft soil at 144.6 km to the surface projection of the fault. The H/V ratio has a peak of 6 around 0.75 Hz, where the eigenfrequencies of many high-rise structures and bridges fall. For 1 Hz and greater frequencies, the amplifications have a constant value around 3 and 3.5 up to 3 Hz. The vertical component of the KUT record had a very low signal to noise ratio for frequencies higher than 3 Hz. Therefore, higher frequencies could not be included in the site amplification study for this record.

BOT station was located on stiff soil at 136.4 km to the surface projection of the fault. For all frequencies between 0.5 and 3 Hz, the amplifications are higher than 3. For the frequency range between 1.25 and 2.5 Hz, the amplifications peak to 5 and 6. This is the frequency range for typical buildings in the region, therefore site amplifications should be expected in this area in future earthquakes. The vertical

component of the BOT record had a very low signal to noise ratio for frequencies higher than 3.5 Hz. Therefore, these frequencies are not included in the site amplification study for this record.

5 Conclusions

In this study, the characteristics of the strong ground motion and seismic demands from the Kocaeli earthquake are investigated in detail using the seismic analysis and signal-processing toolbox SPIDER developed in MATLAB by the first author. Seismic demands on the existing buildings in the Marmara region are investigated. The risk of site amplification hazard for Istanbul is evaluated. The results can be summarized as follows:

- (1) The results of this study showed that the near-fault records with directivity effects characterized themselves with increased base shear demands rather than increased displacement demands for both the FN and FP components and a narrower velocity sensitive region of the response spectra for the FN component.
- (2) This study shows that the effectiveness of the base isolation depends on the ground motion and changes from record to record and even from component to component.
- (3) The results of the dynamic analysis are more sensitive to the chosen high pass corner frequency for Butterworth filters rather than the causality of the filters. Previous studies have claimed that this sensitivity was more pronounced in the case of causal filters rather than the acausal filters. However, this study shows that both causal and acausal filters are sensitive to the corner frequency to the same extent.
- (4) The site amplifications are investigated by both the classical spectral acceleration and the receiver function methods. The site amplification predictions of the receiver function method are smaller than the classical spectral ratio technique and nearly all available records from the Kocaeli earthquake show site amplifications.
- (5) For the Cekmece, Bakirkoy, and Fatih districts of Istanbul, the predominant period of the ground motions calculated are very close to the eigenperiods of the typical residential buildings in the region. Therefore, these structures are expected to experience heavier damages in the future earthquakes due to the resonance effects. Site amplification studies by the receiver function method also shows that the strong ground motion recorded in Fatih distinguishes itself with an amplification of 12 around 2 and 2.5 Hz. In Istanbul, many structures in Yesilkoy had increased base shear demands due to the fact that this record had the widest acceleration sensitive region amongst all.
- (6) It has been argued following the main shock of Kocaeli earthquake that although liquefaction is a potential hazard to the stability of sites, it may be beneficial by providing a means of natural base isolation and decreasing the spectral amplitudes for structures. However, this study shows that for sites which have the risk of soil amplification for long-period structures, this beneficial effect may be counterweighted and liquefaction may result in shifting the eigenperiod of the structures to the critical periods with high site

amplifications. This may be especially the case for Avclar and Bakirkoy districts in future earthquakes.

- (7) These site amplification studies clearly underline the importance of detailed microzonation analysis for Istanbul in each district. Dense instrumentation of buildings is crucial for earthquake risk mitigation in Istanbul. The results of this study, may be of value to the insurance sector, building officials and municipalities for earthquake planning, preparedness, and risk mitigation.

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