Strong ground motion characteristics from the 17 August 1999 Kocaeli, Turkey earthquake

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(Received July 2, 2001; accepted December 21, 2001)

Abstract - The 17 August 1999 Kocaeli, Turkey earthquake (M_w = 7.4, USGS) occurred in the western part of the North Anatolian Fault Zone about 80 km east of Istanbul. The mechanism of the main event was almost a pure right-lateral strike-slip, and the aftershock distribution indicates that the rupture was located toward the western end of the North Anatolian Fault Zone. The earthquake affected a wide area in the Marmara region, as well as the city of Istanbul. Most of the damage and fatalities occurred in towns located on the narrow, flat shoreline of the Sea of Marmara. Since the broken fault segment traversed the densely populated and industrialized east Marmara region, damage was enormously high. Widespread liquefactions caused bearing capacity losses and consequent foundation failures in the Adapazari region, as well as extensive subsidence along the shoreline in Gölcük (Gulf of Izmit) and Sapanca. The earthquake struck also the western suburbs of Istanbul, the Avcilar region, causing severe damage on buildings even though the distance from the epicenter was about 80 km. In this study, we discuss the ground motion characteristics, as well as directivity and soil effects of recorded ground acceleration of the Kocaeli earthquake. Strong-motion data were obtained from the networks managed by the Bogaziçi University, Kandilli Observatory and Earthquake Research Institute and by the General Director of Disaster Affairs, Earthquake Research Department. Although the distribution of the accelerometers deployed in the epicentral area seems sparse, the Izmit earthquake generated approximately twenty strong-motion records within 200 km of the fault. Maximum peak ground acceleration reached 0.41g in Adapazarı, 40 km east from the epicenter and 3 km from the fault rupture. This value is rather small, only half of the value observed in various large earthquakes, e.g., 0.8 g in the 1995 Kobe, Japan earthquake and 0.9 g in the 1999 Chi-Chi, Taiwan, earthquake, while the maximum ground velocity was about 0.8 m/s, that is comparable to the typical value observed in large earthquakes.

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1. Introduction

The region around the western North Anatolian Fault Zone (NAFZ), Turkey, is subject to a substantial level of seismic hazard. Across most of Turkey (east of about longitude 31° E), the North Anatolian fault is a relatively simple, narrow, right-lateral strike-slip fault zone. It is obviously defined by surface ruptures along almost its entire length (1000 km) that are associated with a series of large earthquakes between 1939 and 1967. In the vicinity of the Sea of Marmara, the NAFZ splits into several fault strands, so that deformation and surface faulting become distributed over an ~120 km broad zone.

An earthquake of M_w = 7.4 (USGS) occurred on the northern branch of the NAFZ on August 17, 1999, at 03:02 a.m. local-time. The epicenter of the earthquake was located at 40.70° N, 29.91° E, according to the Earthquake Research Department (ERD) of the Directorate for Disaster Affairs of the Ministry of Public Works and Settlement. This is about 7 km southeast of the city of Izmit and 15 km east of the town Gölcük. The earthquake nucleated at a depth of 15.9 km. The isoseismals of the event had an E-W direction reaching the intensity X in the epicentral area, which is also the most densely populated part of Turkey (ERD web page, http:\\www.deprem.gov.tr). The focal mechanism and the fault surface rupture indicate a right-lateral strike-slip motion (Taymaz, 1999, 2000). The rupture propagated for 45 s both to the west and to the east side of the Gulf of Izmit (Bouchon et al., 2000; Yagi and Kikuchi, 2000). According to field observations, the total length of the rupture was about 110 km, starting from Degirmendere to Golyaka. Maximum horizontal and vertical displacement measured on the surface were 4.5 m and 2 m, respectively (Emre et al., 1999).

The strong motion network is managed by two institutions in Turkey: the ERD and the Bogaziçi University, Kandilli Observatory and Earthquake Research Institute (KOERI). Approximately 24 strong ground motion records of the August 17, 1999 Izmit earthquake were available within 200 km of the fault plane. All the observed peaks of ground acceleration were less than 0.5 g, with the highest maxima recorded by the three strong-motion stations closest to the fault (within 7.5 km of the rupture). Peak ground-motion was significantly smaller than expected for an M_w 7.4 event (Holzer, 2000). Recordings of the earthquakes at the other stations close to the fault (Sakarya station, SKR) indicate a damaging velocity pulse of long duration (4-5 s). Moreover, the intensity of ground motion at short distances (less than 20 km from the fault) was lower than predicted by current attenuation relationships (Boore et al., 1997; Campell, 1997; Sadigh et al., 1997). While rock sites fell below the prediction curves, most soil sites fell above them, indicating that ground motion amplification due to soil conditions was important in these areas. Since M_s = 5.7 aftershock of 13 September 1999 at a temporary station, Tepetarla, near Izmit, showed peak acceleration of 0.6 g, larger than any peak recorded during the main shock (Çelebi et al., 2000), nonlinear effects of soils, including ground failures, were very important in the area close to the bay, where buildings were tilted and settled.

The sparse strong-motion network in the epicentral area makes it difficult to define the characteristics of ground shaking in detail and, therefore, the need for a denser coverage of accelerometers in urban areas is clear.

2. Historical seismicity

NAFZ is an intra-continental transform fault that bounds the Eurasian plate to the north, and the Anatolian block to the south. It is a large-scale, right-lateral strike-slip fault, which runs for about 1400 km, from the Karliova triple junction in the east to the Aegean extensional domain in the west. Between 1939-1967, six large earthquakes occurred along the fault zone (Table 1), in a westward migrating sequence along a 900 km - long zone of continuous surface ruptures, from Erzincan to the western end of the Mudurnu Valley (Ambraseys, 1970, 1975; Barka, 1992, 1996; Stein et al., 1997). The NAFZ is not a single fault and consists of many fault traces, branching into three strands in the western 650 km (the Kocaeli, Izmit, 1999 earthquake occurred on the northern, west strand). The long-term seismicity, GPS measurements and geological data suggest that the northern strand of the fault zone is more active, giving a slip rate of approximately 10-15 mm/y (Straub and Kahle, 1995). Historical and paleoseismological data indicate that the recurrence interval of clusters of large earthquakes is 1200 years old in the Izmit bay area. The return period for large earthquakes south of Istanbul varies between 100 and 1000 years, depending on the size of the earthquakes. The last major earthquake on this section was probably in 1509 A.D. (Barka, 1992, 1997). The sequential westward progression of $M_w > 6.7$ earthquakes along the NAFZ during the 20th century was studied by Stein et al. (1997) and Nalbant et al. (1998), who showed that the earthquakes were induced by changes in stress on adjacent fault segments. Before the Kocaeli earthquake, Stein et al. (1997) calculated the stress changes, and estimated a 15% probability of a $M_w > 6.7$ earthquake east of Erzincan and 12% probability for a large event south of the city of Izmit during the interval from 1997 to 2027 on the Izmit segment of the NAFZ. On August 17, 1999, the Kocaeli earthquake ruptured the Izmit segment. Applications of this technique, to evaluate the effect of the Kocaeli earthquake on other faults, show that the area of increased stress to the east included the Düzce fault, which ruptured just after the Kocaeli earthquake (12 November, 1999, $M_w = 7.1$). To the west, the 80 km - long Yalova segment, southeast of Istanbul, and the Northern Boundary fault, immediately south of Istanbul, are thought to be closer to failure (Hubert-Ferrari et al., 2000). Stein et al. (1997) also introduced a way to quantify the transient growth of the likelihood of a new earthquake induced by stress changes due to adjacent large earthquakes on the NAFZ.

Table 1 - Historical earthquakes after 1900 occurred over NAFZ from east to west.

Date	Magnitude	Surface rupture (km)	Locality
1939.12.26	8.0	360	Erzincan
1942.12.20	7.1	50	Erbaa
1943.11.26	7.6	280	Tosya
1944.02.01	7.3	165	Bolu-Gerede
1957.05.26	7.0	30	Abant
1967.07.22	7.1	80	Mudurnu
1999.08.17	7.4	110	Izmit (Kocaeli)

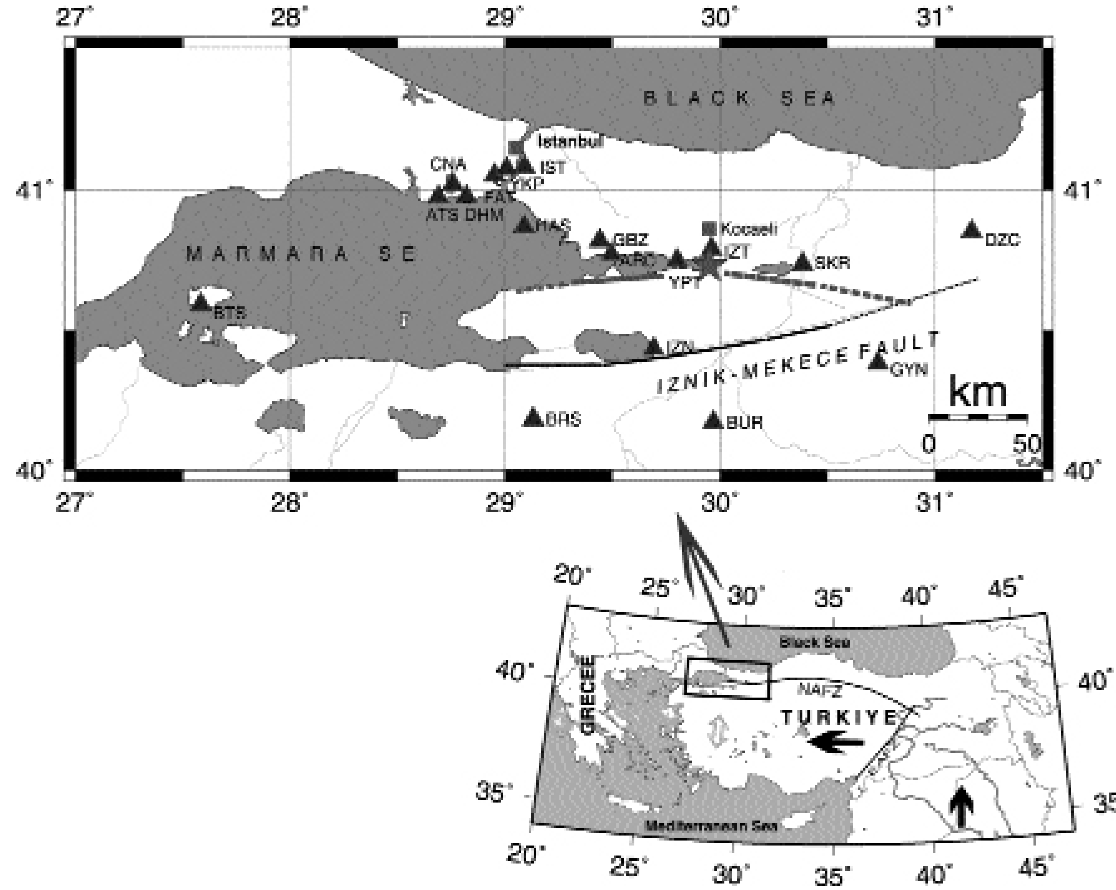

Fig. 1 - Map of the Marmara region showing the locations of the strong motion stations, that belong to ERD and KOERI (triangles) and the mainshock of the 17 August 1999 (M_w = 7.4) Izmit earthquake (star), used in this study. Dashed lines indicate the surface rupture of the Izmit earthquake, a solid line indicates the Iznik-Mekece Fault.

3. Data

The largest network operator in Turkey ERD has aimed at deploying strong motion instruments in every major city within the major seismic areas of Turkey. This systematic effort by the ERD, supplemented by strong motion stations deployed by the KOERI and the Istanbul Technical University (ITU) in Istanbul, Marmara Region, have produced very important recordings that will be useful for studying seismic hazard and for planning the rebuilding efforts. Strong motion data used in this study are obtained from both the KOERI and the ERD (http://kandilli.koc.net/earthquake.html, and http://angora.deprem.gov.tr /recentquakes. html). Recordings are made available on the web in digital form. The maximum peak ground accelerations (PGAs) of the two horizontal components are shown in Table 2. In this study, some ground motion recordings available from 19 mainshocks of the Kocaeli earthquake were analyzed. Fig. 1 shows the location of the events, whereas in Table 2 the coordinates of the stations used and the simplified description of the shallow geology at each site (the soil conditions beneath the stations are not well documented in Turkey) are indicated. Most of the stations are housed in buildings, some of which are more than two stories high. The accelerometers were three-component SM2, SMA-1, and GR-16 with a flat response between 0.2-30 Hz, DC-25 and DC-50 Hz, respectively (Table 2).

Table 2 - Stations which recorded the mainshock of the 17 August 1999 Kocaeli earthquake.

STATION	LON. °E	LAT. °N	INST.	OWNER	R (km)	SITE CLASS	PGA (Gal)
ARC ARCELIK	29.20	40.60	GSR-16	KOERI	17	Stiff Soil	211.4
ATS AMBARLI TERMIK SANT.	28.689	40.975	GSR-16	KOERI	78	Soft Soil	252.2
BTS BOTAS	27.584	40.593	GSR-16	KOERI	136	Stiff Soil	98.9
BUR BURSA TOFAS FABRIKASI	29.970	40.171	GSR-16	KOERI	67	Soft Soil	110.8
CNA CEKMECE	28.755	41.022	GRS-16	KOERI	76	Stiff Soil	177.3
DHM HAVA ALANI	28.819	40.976	GSR-16	KOERI	69	Stiff Soil	90.2
FAT FATIH	28.950	41.052	GSR-16	KOERI	65	Soft Soil	189.4
HAS HEYBELIADA SENATORYUM	29.087	40.868	GSR-16	KOERI	20	Rock	110.2
YKP YAPI KREDI	29.007	41.075	GSR-16	KOERI	63	Rock	41.1
YPT YARIMCA	29.800	40.750	GSR-16	KOERI	4	Soft Soil	322.2
DZC DUZCE	31.170	40.850	SMA-1	ERD	14	Unknown (Soft)	373.3
GBZ GEBZE	29.440	40.820	SMA-1	ERD	17	Unknown (Stiff)	264.8
GYN GOYNUK	30.734	40.385	SMA-1	ERD	35	Unknown (Soft)	137.7
IST ISTANBUL	29.090	41.080	GSR-16	ERD	60	Unknown (Rock)	60.7
IZT IZMIT	29.960	40.790	SMA-1	ERD	7	Unknown (Soft)	224.9
BRS BURSA SIVIL SAVUNMA	29.131	40.183	GSR-16	ERD	66	Unknown (Soft)	54.3
SKR SAKARYA	30.384	40.737	GSR-16	ERD	3	Stiff Soil	407.0
IZN IZNIK	29.691	40.437	SMA-1	ERD	30	Unknown (Soft)	123.3
KUT KUTAHYA	29.997	39.419	GSR-16	ERD	144	Unknown	59.7

Table 3 - Soil group definitions from the 1997 Turkish Building Code.

Site Class	General Description	Soil Group and Topmost Layer Thickness (h_1)
Z1	Rock	Group A soils, Group B soils with h1 < 15 m
Z2	Shallow Stiff Soil	Group B soils with h1 > 15 m, Group C soils with h1 < 15 m
Z3	Stiff Soil	Group C soils with 15 < h1 < 50 m, Group D soils with h1 < 10 m
Z4	Soft Soil	Group C soils with h1 > 50 m, Group D soils with h1 > 10 m

4. Observed ground motion

The Kocaeli earthquake generated a large number of ground motion recordings within 200 km of the fault rupture plane (twenty-four). The available recordings as well as the station locations and the observed fault rupture are shown in Fig. 1. The list of stations along with the closest distance to the fault rupture within 150 km and the preliminary site classifications are listed in Table 2. Site classifications are made based on the 1997 Turkish Buildings Code, which takes into account both the shear-wave velocity profile and the soil depth (Tables 3 and 4).

First of all, we compared the recorded horizontal PGAs according to the site conditions (free-field rock and shallow, stiff and soft soil sites) with the attenuation relationships proposed by Boore et. al. (1997), Campell (1997), Sadigh et. al. (1997), for an M_w = 7.4 strike-slip event. Assuming the fault dipping 90 degrees, the surface fault rupture was used to evaluate the closest distances to the recording stations. Horizontal PGAs from the Kocaeli earthquake for the 24 stations, 19 of which within 150 km of the fault rupture plane (Table 2) are compared to the values predicted by the empirical attenuation relation proposed by Boore et al. (1997), Campell (1997) and Sadigh et al. (1997) in Fig. 2 for a rock site and a soil site, respectively. Their attenuation relationships, which predict how PGA decreases with distance from the fault

Table 4 - Site Class Definitions from 1997 Turkish Building Code.

Soil Group	Description of Soil Group	Shear Wave Velocity (m/s)
A	1. Unweathered Rock 2. Very dense sand, gravel 3. Hard clay, silty clay	> 1000 > 700 > 700
B	1. Soft Rock 2. Dense sand, gravel 3. Very stiff clay, silty clay	700 - 1000 400 - 700 300 - 700
C	1. Higly weathered soft rocks 2. Medium dense sand and gravel 3. Stiff clay, silty clay	400 - 700 200 - 400
D	1. Soft, deep alluvial layers 2. Loose sand 3. Soft clay, silty clay	< 200 < 200 < 200

rupture, are based on regression analyses of PGAs recorded in western North America. Fig. 2 indicates that each of the attenuation relationships overpredicts accelerations at distances of less than about 15 km. At greater distances from the fault, PGAs are generally higher at soil sites than at rock sites, whereas they were smaller than expected on competent soil. However, the majority of data from both stiff and soft soil sites are above the prediction curve. For example, Ambarly (ATS), Fatih (FAT), Atakoy (ATK) sites recorded unusually large accelerations. These stations are situated on soft soils. Since site conditions beneath the stations in Turkey have not been thoroughly investigated and properly documented, the effects of soil conditions on peak amplitudes could not be discussed in detail. However, a considerable number of stations are in buildings that are more than two stories high and should not be included in the comparative curves. For example, the largest PGA was recorded at the Adapazarı (SKR) station, which was deployed at the basement of a six-story building. Maximum amplitudes of accelerations recorded by the three strong-motion stations that are closest to the fault rupture, within 7 km of the rupture (IZT, SKR and YPT), were smaller than usually generated by a M_w = 7.4 event, e.g., 0.8 g in the Kobe, Japan, earthquake and 0.9 g in the Chi-Chi, Taiwan, earthquake. However peak ground velocities are usually high. Unfortunately, there were no observations in the fast-growing urban areas of the Adapazarı basin and Gölcük where damage was enormously high. Only one record was retrieved from the SKR station, which was on stiff soil in the undamaged part of Adapazarı. I expected to find that the PGAs observed in the Adapazarı basin to be very different from those recorded at the stiff soil site.

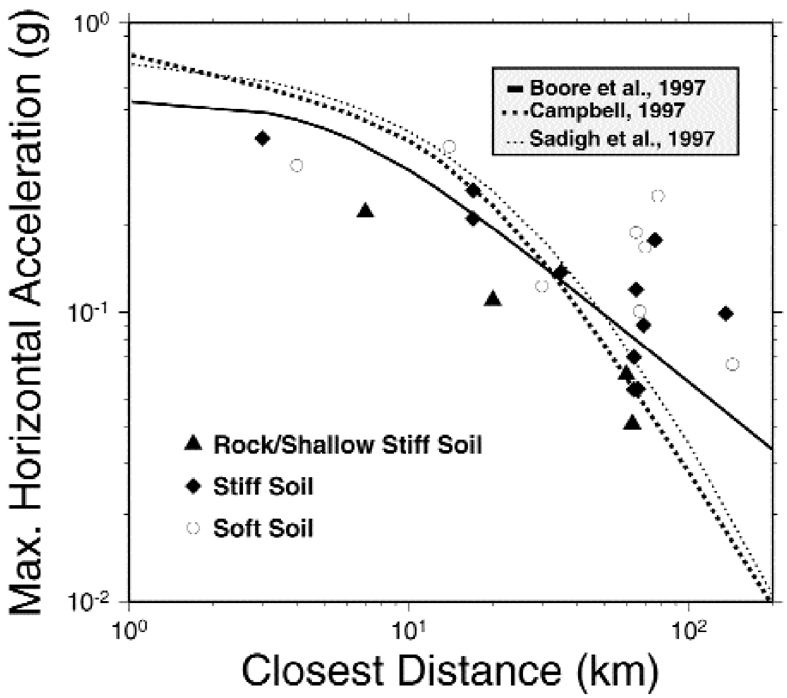

Fig. 2 - Comparison of horizontal PGA (g) values of Izmit earthquake (M_w=7.4) at rock (open circle), stiff (triangle) and soft sites (closed circle) and hard-rock predictions of Sadigh et al. (1997), Boore et al. (1997), and Campell (1997).

I calculated velocity and displacement time histories for six different sites (DZC, YPT, SKR, GBZ, IZT, ARC; see Table 2), which were recorded within 20 km of the fault plane. The SAC2000 (Seismic Analysis Codes) is used to obtain the velocity and displacement time histories. A Butterworth high-pass filter (0.05 Hz) was used in the time domain to eliminate the long period noise of the recordings and a baseline correction was applied to the data. The acceleration, velocity, and displacement time histories, as well as the Husid plots for the transverse and the radial components of ground motion at these stations are plotted in Figs. 3, 4, 5. Unfortunately, the radial component of the SKR instrument malfunctioned during the earthquake and did not record any ground shaking.

It is important to understand the process of fault rupture of the Kocaeli earthquake to evaluate the effect of directivity on the near-fault ground motions. Forward directivity occurs when a significant portion of the fault ruptures towards a site. Forward directivity can produce enhanced radiated energy in the forward strike direction, fault-normal components of ground motion larger than fault parallel components, and shorter duration ground motions (Somerville

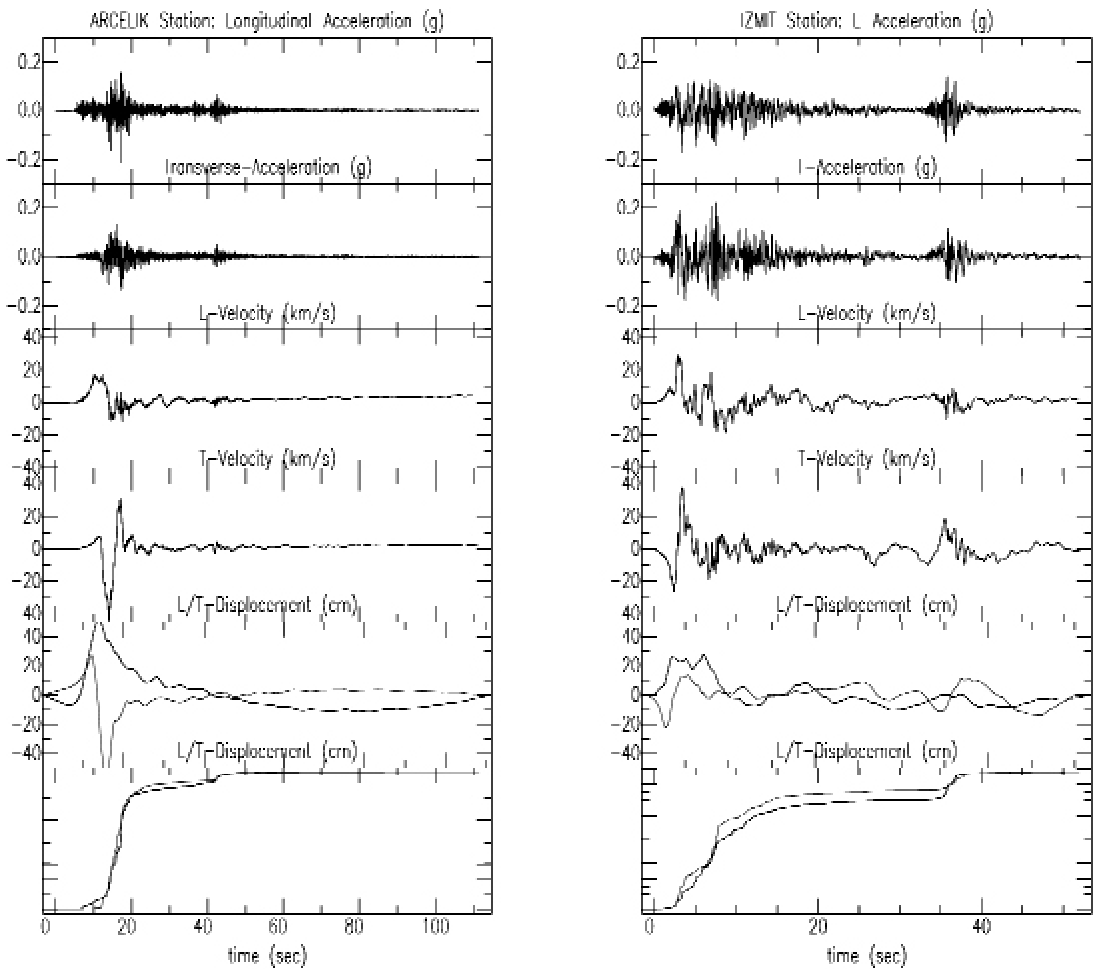

Fig. 3 - Horizontal acceleration, velocity, and displacement time histories and Husid plots for ARC, IZT, as east-west and south-north components.

et al., 1997). Back directivity (i.e. when a significant portion of the fault ruptures away from a site) can produce less intense ground motions with longer duration. The rupture characteristics of the Kocaeli earthquake were studied by Yagi and Kikuchi (2000), Bouchon et al. (2000), Tibi et al. (2001). Since their results suggest that a multiple strike-slip rupture process occurred in a propagating fashion along both directions (about 60-80 km to the east and approximately 40 km to the west), forward directivity may be observed both at the eastern and western ends of the fault. SKR and DZC stations are located east of the epicentral point, which may present strong forward directivity effects since they lie directly in the direction of the fault rupture. The DZC station is located on soft soil (14 km far from the fault rupture) and displays both the short and long-period energy; moreover, in long periods the fault-normal component of the ground motion is greater than the fault-parallel one, as expected for forward directivity motions (Fig. 6). This large ground motion may be a result of forward directivity, or of the combination of the two effects: site conditions and directivity. Although we suspect that the transverse component of the SKR stations (located on stiff soil) shows a forward directivity effect (Fig. 5), it is dif-

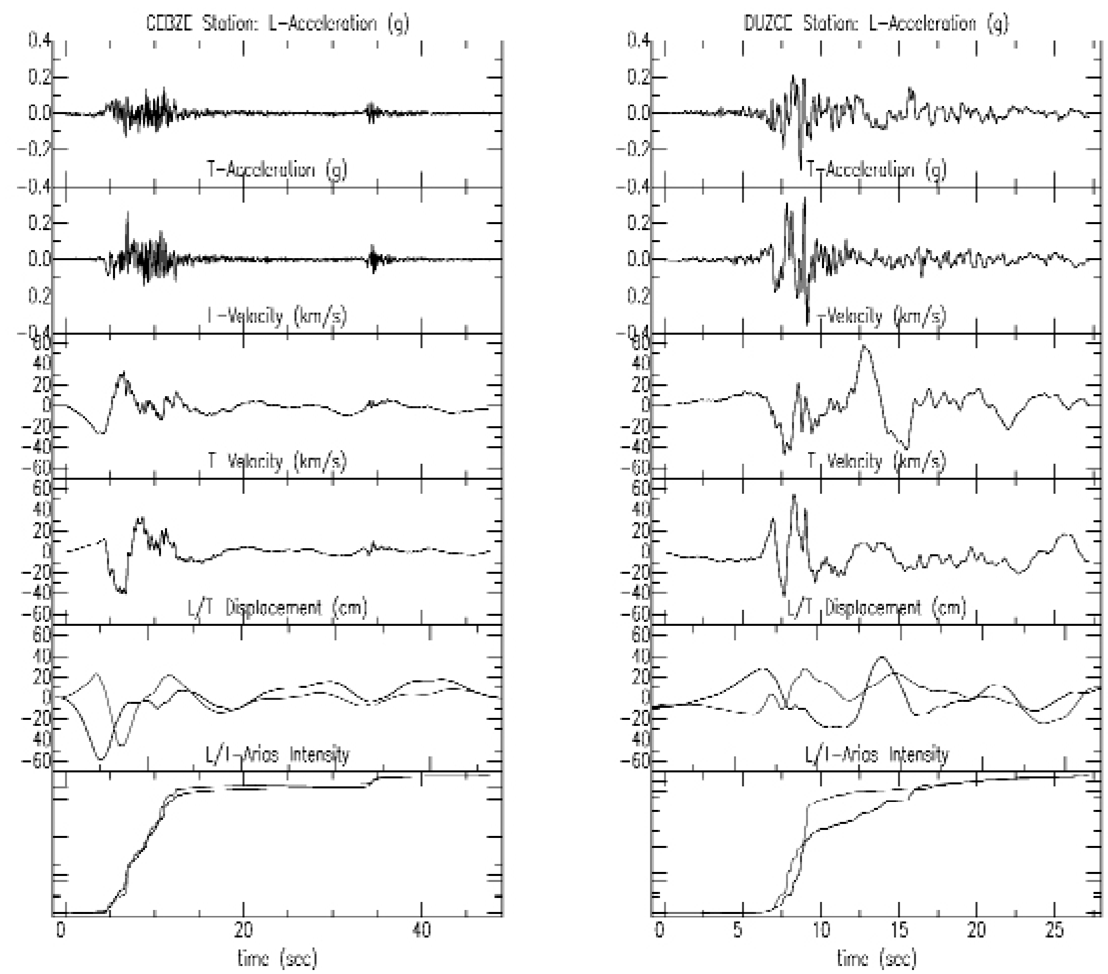

Fig. 4 - Horizontal acceleration, velocity, and displacement time histories and Husid plots for GBZ, DZC, as east-west and south-north components.

ficult to confirm this because its longitudinal component did not function properly during the earthquake. Stations ARC (stiff soil) and GBZ (stiff soil) are located off the western end of the fault and produced only modest rupture directivity features (Fig. 6). These smaller intensity motions can be attributed, in part, to backward rupture directivity.

The SKR was deployed on stiff soil, and the YPT is located on soft soil; both are located north of the fault, and display a static displacement of approximately 2.0 m and 1.5 m, respectively, in the transverse component. The largest static displacement for both records is in the east direction, consistently with the right-lateral displacement along the fault. Significant static offset on the transverse component of the YPT record also indicates some motion to the north. DZC, ARC, and GBZ are located between 10 and 20 km from the fault rupture plane, and represent motions at both the western (ARC and GBZ) and eastern (DZC) ends of the fault rupture. Since these stations are located off the ends of the fault and are further away from the fault, they do not show static offset.

Site response played an important role in the amplification of the ground motion on soft

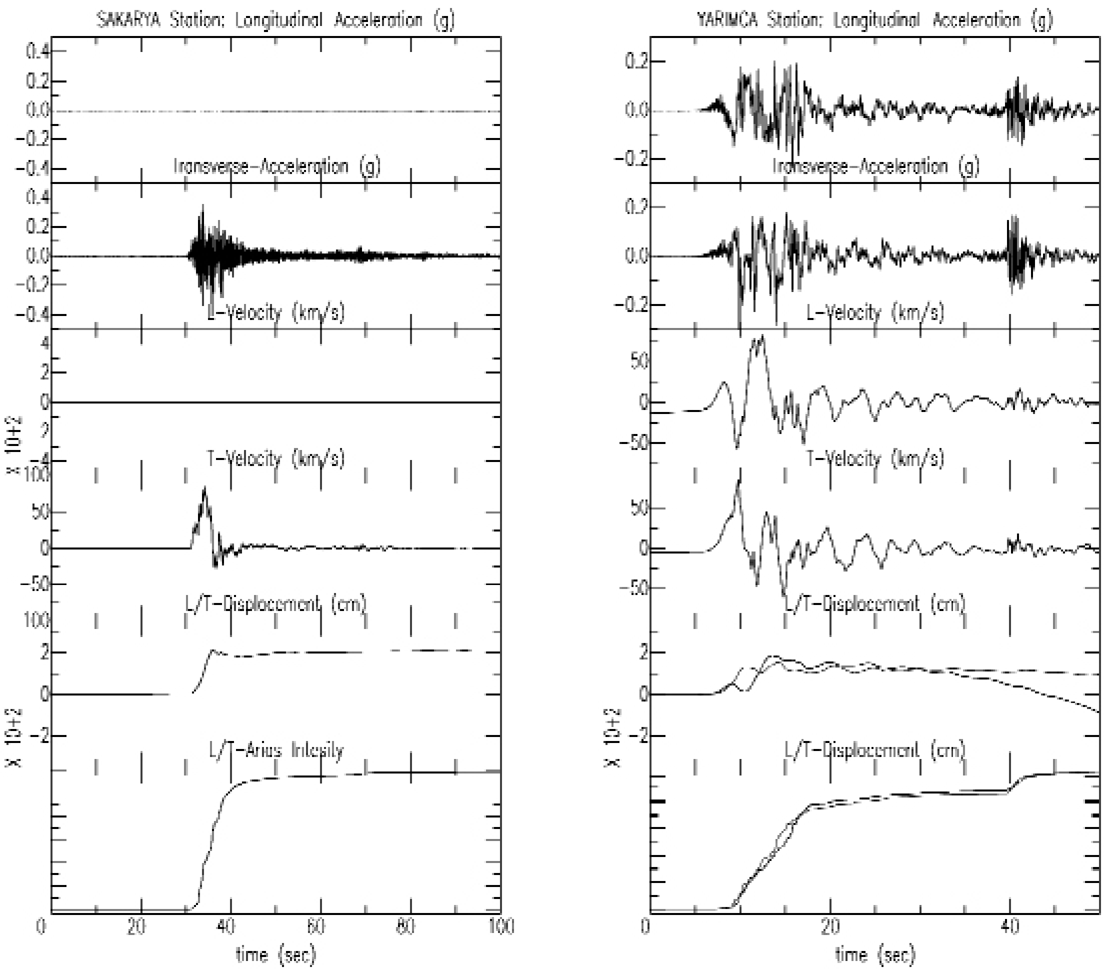

Fig. 5 - Horizontal acceleration, velocity, and displacement time histories and Husid plots for YPT, SKR, as east-west and south-north components.

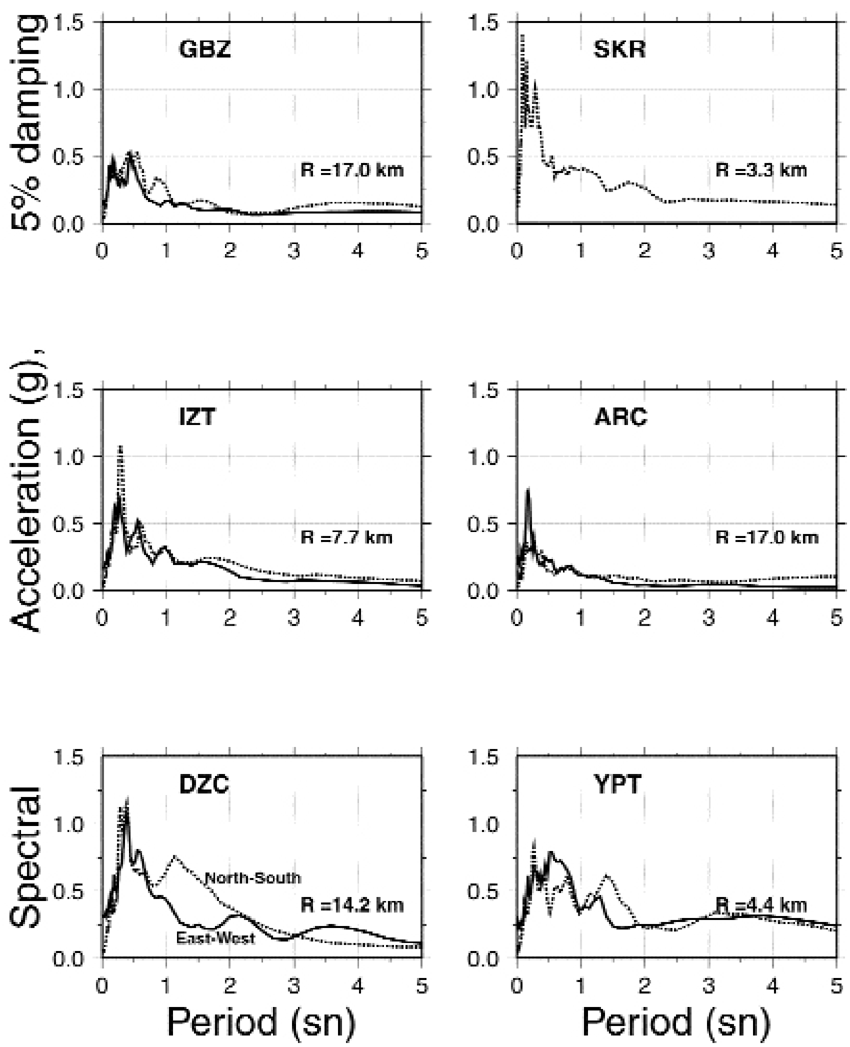

Fig. 6 - Calculated acceleration response spectra, 5% damping, for six stations close to fault rupture (R < 20 km).

soil sites. Fig. 6 shows the spectral acceleration (response spectra, 5% damping) computed on the north-south and the east-west motion observed at 6 stations. The figure refers to the time histories that have been presented in Figs. 3, 4, 5. These stations cover the epicentral area (IZT, 7 km, and YPT, 4 km), as well as locations that were heavily damaged east of the epicentral area (SKR, 3 km, and DZC, 14 km). IZT, YPT and DZC are on alluvial sites whereas SKR, GBZ (17 km), and ARC (17 km) are on stiff soil. As can be seen in Fig. 6, both YPT and DZC have long periods and higher amplitudes due to their site characteristics when compared to the rock motions recorded at IZT and SKR stations. The SKR station is located on a stiff soil site in the undamaged part of Adapazari. As I already stated, if ground motion had been observed in the Adapazarı basin, it would have revealed increasing features, since the effect of liquefaction in the center of the city was also significant. The recorded strong-motion time histories, as well as the observed damage distribution during the Kocaeli earthquake, suggested that the soil amplification effects significantly increased the damage in the region (Anderson et al., 2000).

Fig. 7 plots acceleration response spectra for sites at distances greater than 60 km. The response spectra are grouped according to site classifications: rock and shallow stiff soil, stiff soil and soft soil (Fig. 7). The recordings at rock-shallow stiff soil sites indicate low intensities, with $S_{a,max} < 0.3$ g with almost no long period energy. The stiff soil sites display larger values of $S_{a,max}$ (between 0.3 and 0.6 g). The soft soil sites show the largest values of $S_{a,max}$ (between 0.3 and 1.0 g) and the largest amplitudes at long periods, particularly between 0.5 and 1.5 s. This figure indicates that soft soils can significantly amplify and change the frequency content of the earthquake-induced ground motion. Most of the strong-motion recorded in the intermediate distance range was observed at ATS, which is situated on soft soil. The motion at ATS contains a significant amount of energy between periods of 0.5 and 2.0 s. ATS is located close to the Avcylar section in Istanbul, which experienced significant damage to 5- and 6- story buildings

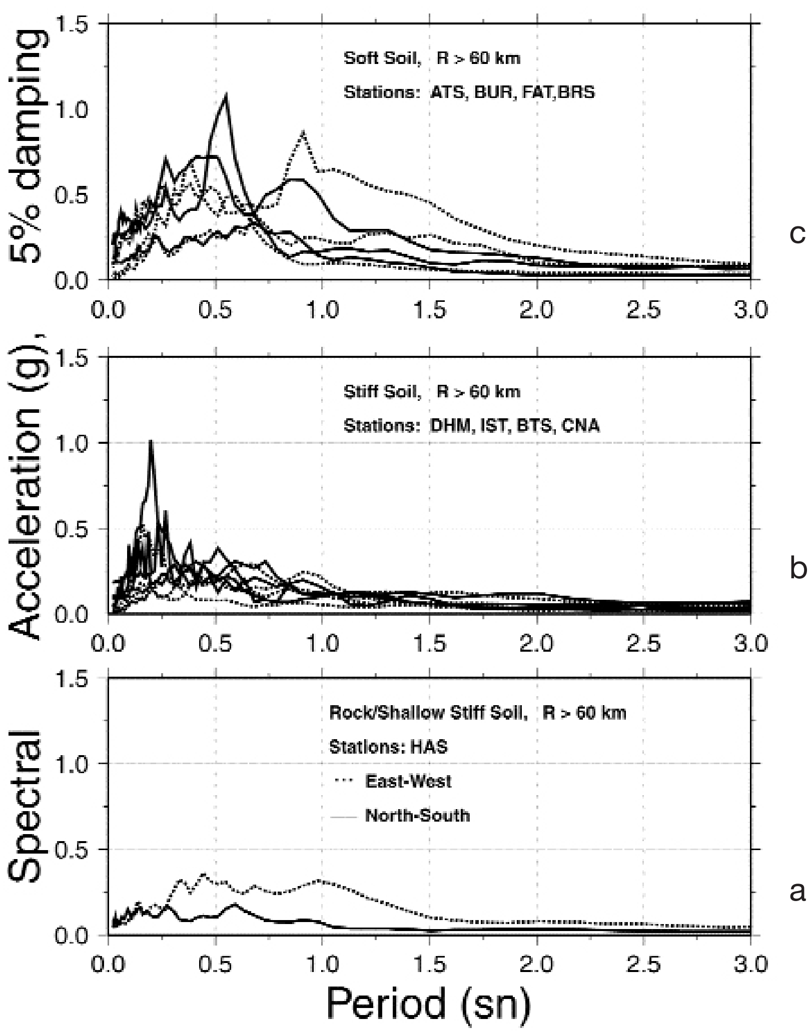

Fig. 7 - Calculated acceleration response spectra, 5% damping, for (a) rock and shallow stiff sites, (b) stiff soil sites, (c) soft soil sites in the intermediate field (R = 60-80 km).

during the earthquake. This damage can be directly attributed to the enhanced amplitudes at long periods produced by the soft soil conditions.

5. Conclusions

1. The forward motion amplitudes in the near field (< 20km) were lower than predicted by current attenuation relationships (Fig. 2). Although peaks of ground acceleration recorded close to the fault rupture of the August 17, 1999 Kocaeli earthquake were below average for an M_w = 7.4 event, peak ground velocities were comparable to the typical value observed in large earthquakes. This is probably an effect of a multiple rupture process.
2. The ground motions recorded at SKR and at YPT displayed a static offset in the displacement time histories since they were very close to the fault rupture (Fig. 3). It is difficult to see forward directivity effects over the station SKR, since one of its components was not functioning during the earthquake. The ground motion recordings at DZC displayed both enhanced short-period and long-period energy, as expected for forward directivity motions. Since this station is located on soft soils, it is also very hard to distinguish between ground amplification due to directivity effect or to site response. Back directivity effects were observed at stations GBZ and ARC, which showed lower amplitudes of the ground motion.
3. Ground motion amplification due to soil conditions was important (Figs. 6 and 7), especially at Avcilar-Istanbul, approximately 80 km west from the end of the fault line. These stations experienced significant amplifications of the ground motion due to the presence of soft soils in the region (ATS). We have certainly to take into account the fragility of the buildings; however, damage and ground motion severity were plausibly affected by the surface geology at the sites.
4. The strong velocity pulse and long duration observed during the earthquake were important factors in the collapse and damage of residences. Recordings of the earthquake at two stations (SKR and YPT) close to the fault indicate that it was characterized by a strong velocity pulse and by a long duration, both being important factors in the damage of buildings in the region (Fig. 5).
5. The most part of the damage due to the Kocaeli, Turkey, earthquake of August 17, 1999 was concentrated in a narrow band along the fault zone. Our understanding of the reasons of the damage, leaving aside the quality of construction, is to be attributed to the near earthquake source effects. However, the following examples are out of this category: the damage in Avcilar, west of Istanbul, the strong contrast of damage at the strong-motion observation site (SKR) and that of downtown Adapazari, and the wide variation in the damage ratio at Gölcük, even in a relatively narrow area. In the Adapazari region, liquefaction failures were significant due to the existence of a shallow ground-water table.
6. Approximately one thousand people were killed due to the collapse of buildings in Istanbul, Turkey, during the 17 August 1999 Izmit (Kocaeli) earthquake, although the epicenter was roughly 90 km east of the city. Most of the fatalities and damage occurred in the suburbs of

Avcilar, which is located 20 km further west of the epicenter, away from the city. Avcilar was heavily damaged in 1894. To investigate this pattern of damage, Cranswick et al. (2000) deployed seven portable seismographs at eight sites in western Istanbul to record aftershocks (M5.2, 4.8, 4.6, 4.1). Their recordings exhibit a large-amplitude phase after the S-wave on the radial components of the ground motion in the heavily damaged area of Avcilar, and this phase does not appear at stations located in less damaged or undamaged areas, located further to the east. In general, ground motion at 0.25 Hz in the damaged area is 2-4 times larger than that observed in less damaged and undamaged areas underlain by similar geology. The damaged area of Avcilar is located on an east- and southward-dipping hillside that rises fairly steeply, relative to the surrounding topography, from the shores of the Sea of Marmara to the south and Kucuk Cekmece to the east. The large amplitude phase may be related to body-wave/surface-wave conversion at these topographic boundaries and/or to surface-wave amplification from the local thickening of low-velocity layers. Poorly constructed 5-10-story apartment buildings are possibly susceptible to shaking in this frequency band only after linearity is exceeded. This may explain why Avcilar, which is even further from the epicenter than Istanbul, suffered more damage during the Izmit earthquake.

7. It is well known that improper design and construction practices played a big role in defining the amount of damage. Therefore, it is important to assess the recorded ground motions, site effects and other earthquake related to hazard issues, which we will need to consider during the rebuilding efforts. Attention must be paid to new developments such as earthquake zoning maps, earthquake hazard maps, liquefaction potentials and susceptibility.
8. The need for seismic hazard studies in the region has become progressively more important for earthquake engineering applications because of the real earthquake threat. A fundamental requirement for these studies is the determination of the ground motion predictive relationships (Kramer, 1996). Attenuation relationships have been developed for many regions of the world (Ambraseys et al., 1996; Boore and Joyner, 1991; Boore, 1983; Toro and McGuire, 1987; Atkinson and Boore, 1995; Atkinson and Silva, 1997; Campell, 1997; Sadigh et al., 1997) mainly by regressing strong-motion data. The sparse distribution of strong-motion stations in Turkey makes the gathering of a substantial set of acceleration recordings from large events and subsequent regression impossible at the present time. Therefore, new monitoring campaigns are needed in Anatolia, along and away from the major transform structures, since seismic hazard is significant throughout Turkey.

Acknowledgments. I would like to thank everybody at KOERI (Kandilli Observatory and Earthquake Research Institute), and at ERD (Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, Earthquake Research Department), for their efforts towards deploying strong-motion stations and for providing acceleration data for earthquake hazard studies. These recordings are the basis of my study. I express my gratitude to Dr. Luca Malagnini, who provided helpful comments on the paper. I also thank Dr. Massimo Cocco and an anonymous reviewer for their critical reviews.

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