A STUDY OF RESIDUALS FOR STRONG GROUND MOTIONS IN ADAPAZARI BASIN, NW TURKEY, BY GROUND MOTION PREDICTION EQUATIONS (GMPEs)

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ABSTRACT

The city of Adapazarı - located in the Marmara Region of northwest Turkey - is situated on a deep sedimentary basin and was the city most heavily damaged by the strong ground motion of the 17 August 1999 Kocaeli earthquake (moment magnitude M_w = 7.4). This study determines site amplifications of the attenuation relationships for shallow earthquakes in the Adapazarı basin by using the previous ground motion prediction equations (GMPEs) and the traditional spectral ratio method. The site amplifications are determined empirically by averaging the residuals between the observed and predicted peak ground acceleration (PGA) and spectral acceleration (SA) values for various periods. Residuals are significantly correlated with the known characteristics of geological units. A new attenuation model has also been developed for 5% damped spectral acceleration to determine the dependence of strong ground motions on frequency.

Site amplification was evaluated at ten stations located in the Adapazarı basin. The PGA site amplification values varied between 1.130 and 3.120 in all stations except two; these exceptions resulted in de-amplifications. Calculated de-amplification values of these stations indicate a consistency for rock medium. The site amplification values of some stations indicate an increase while moving away from the surface rupture and approaching the contact between the alluvial deposits and bedrock. One station, located on the discontinuity between the two different media, has the highest site amplification value (3.12) in the study area. This high value might be a result of the focusing of the seismic waves due to the discontinuities located on both sides of the narrow basin.

The traditional spectral ratio method was also used to determine amplification in the Adapazarı basin. One station on bedrock was chosen as a reference station. When the results of this method are evaluated, the amplifications at high periods are attributed to the thick sedimentary deposits in the basin and the apparent de-amplifications at low periods are partly due to the reference site response.

When the spectral ratios or spectral residuals of the stations located on alluvial deposits or soft soils are considered, it is observed that these stations have high spectral ratio or residual values, especially at high periods. The source of these high period

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amplifications may be the geometry of the basin, the presence of soft-loose soil levels and high period basin-transduced surface waves.

Keywords: site amplification, ground motion prediction equations, spectral acceleration, Kocaeli earthquake, Düzce earthquake

1. INTRODUCTION

The Kocaeli earthquake struck northwestern Turkey on 17 August 1999 with a moment magnitude (M_w) of 7.4. According to official figures, the earthquake caused 17127 deaths and 43953 injuries mainly due to the collapse of buildings. The Düzce earthquake ($M_w = 7.2$) took place just two months later. No previous seismic event in Turkey has caused as much loss of life, structural damage and social consequences as these two earthquakes. Both affected densely populated and built-up areas. Although the construction techniques used in Adapazarı are not different from the other cities in the Marmara region, this city suffered greater damage than neighboring built up areas during the Kocaeli event. A strong ground motion caused severe building damage and killed 3891 people in Adapazarı. The structural damage in the city was concentrated in the central districts over deep alluvial soils that reach depths in excess of 200 m within the city limits (*Bakır et al., 2005*). It is believed that the heavy damage was associated with a site amplification due to the local geological conditions. Soft soils increased the ground shaking, and other factors such as liquefaction, ground failure, and structural deficiencies may also led to heavy damage. The Kocaeli and Düzce earthquakes highlighted a need to characterize the potential effects of local site conditions on the amplification of ground motions. These two earthquakes provided the most extensive strong ground motion data sets ever recorded in Turkey. The first event was recorded by 34 accelerometer stations, associated with a 145 km surface rupture (*Toksöz et al., 1999*). The second event triggered 20 instruments and caused a 40 km surface rupture (*Utkucu et al., 2003*).

In this study we first discuss the characteristics of strong ground motion associated with the Kocaeli and Düzce earthquakes. Available strong ground motion data and previous ground motion prediction equations (GMPEs) are summarized (*Ulutaş and Özer, 2010*; *Ambraseys et al., 2005*). A new attenuation relationship for spectral acceleration of strong ground motion was developed. Then, site amplifications of the study area stations were defined according to the residuals of peak ground accelerations (PGAs) and spectral accelerations (SAs) calculated for 5% damping. Additionally, the traditional spectral ratio method defined for a reference point (rock) was applied to various strong ground motion records to investigate the site amplification of soil deposits in the Adapazarı basin.

GMPEs in terms of magnitude and source to site distance using attenuation relationships have been a major research topic in earthquake hazard assessments and emergency response operations. Such relationships for PGAs and SAs were developed in the past for various regions of the world with a different functional form (*Douglas, 2001*). Most relationships are developed using worldwide acceleration data acquired through strong motion arrays. The general form of regression models has been described by *Campell (1985)*. In some cases, where the data were not sufficient, the empirical relations were developed by using data from other regions (*Campell, 1981*; *Fukushima and Tanaka,*

1990). There were not sufficient acceleration data to develop a regional attenuation function before either of the two 1999 events. Therefore, GMPEs developed for different regions had been generally used. Strong motion recordings resulting from these two earthquakes and that of their aftershocks have increased the near field strong motion data in the Eastern part of the Marmara region. New attenuation relationships have been developed for PGAs and SAs by using the records of two earthquakes (*Gülkan and Kalkan, 2002*; *Özbey et al., 2004*; *Ulusay et al., 2004*; *Ambraseys et al., 2005*; *Gülkan and Kalkan, 2005*; *Altıntaş, 2006*; *Bindi et al., 2007*; *Ulutaş and Özer, 2010*). Therefore, the new derivations of attenuation equations with the records of these two earthquakes can be utilized in a number of national seismic hazard studies. Although these relationships are used in seismic hazard analysis, the damage pattern is not a simple function of these relationships alone. It is highly desirable to map the site amplifications of stations for the areas of potential damage.

This study presents a detailed description of site amplifications in the Adapazarı basin. There are several previous studies that focus on site amplification and its effects within this study area. *Bakır et al. (2002)* studied the local site effects and associated building damage in Adapazarı city based on a field survey and geotechnical data. *Şafak and Erdik (2000)*, *Özel and Sasatani (2004)* and *Özel et al. (2004)* also studied the site effects of the Adapazarı basin. All of these studies documented the fact that unconsolidated sedimentary deposits in the Adapazarı basin amplified the seismic waves and increased the damage during the 17 August 1999 Kocaeli earthquake. Acceleration records available in the afore-mentioned studies were also used here. Results obtained in this study supported site amplification in the Adapazarı basin.

2. GEOLOGICAL SETTING

The geology of the study area and the region consists of two distinct tectonic units brought together by the North Anatolian Fault Zone (NAFZ). The Adapazarı basin located between these two tectonic units developed as a consequence of the NAFZ. The basin contains Quaternary alluvial and fluvial sediments covering the tectonic units within the boundaries of the basin. The tectonic unit in the north is composed of sedimentary rocks varying in age from the Ordovician to the Eocene. Volcanic or volcano-sedimentary rocks exist on the top levels of the north tectonic sedimentary sequence. The south tectonic unit consists of metamorphic and magmatic rocks varying in age from the Cretaceous to the Eocene (*MREI, 2000*) (Fig. 1).

The morphology is closely related to geology. The morphology in the north of the basin characterizes a low rugged peneplained topography, whereas in the south of the basin there is a rugged and very steep morphology causing deposition of colluvial materials on the hillsides. These weakly cemented colluvial materials are called terrestrial Pliocene deposits. The Adapazarı basin is filled with the alluvial materials carried by the Sakarya River and its tributaries. The geometry of the basin has been shaped by the NAFZ. The flow regime of the Sakarya River controls the thickness of the alluvial deposits. Alluvial materials present vertical and horizontal variations based on the flow regime of the Sakarya River. Coarse grained materials are deposited in the main and tributary channels of the Sakarya River, whereas fine grained materials are deposited in

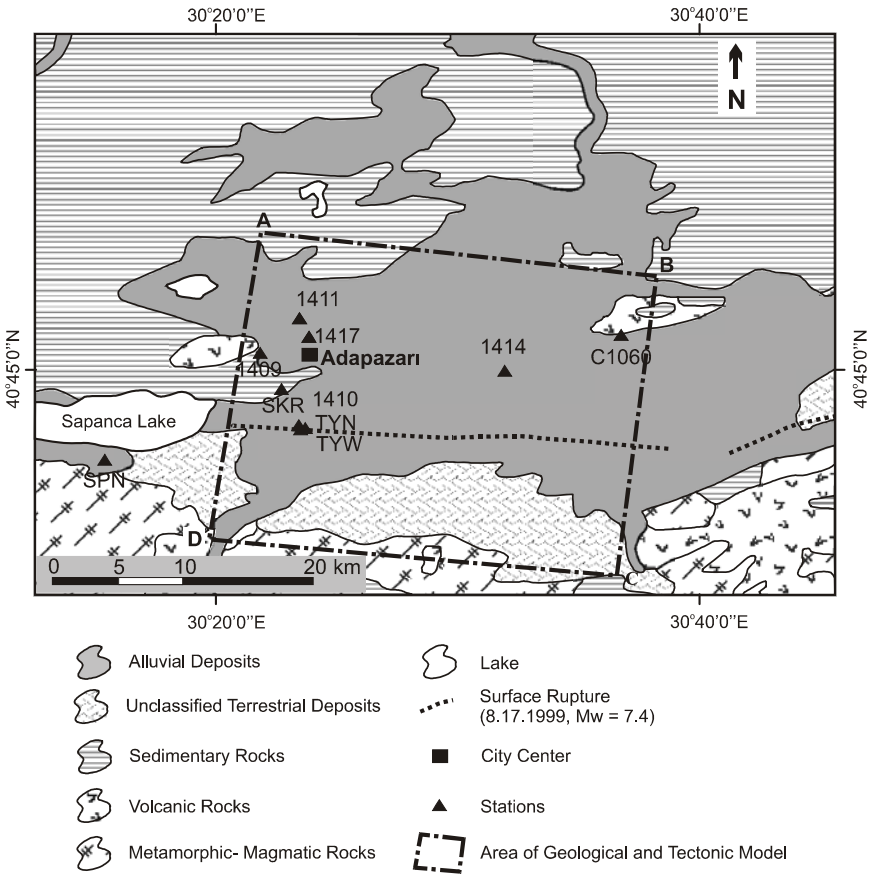


Fig. 1. Simplified surface geology map of the study area. Reproduced from geology map prepared by *MREI (2000)*.

the meander plains and flooding areas. Coarse grained materials are mostly very loose to loose and the consistency of the fine grained levels varies from soft to hard. The thickness of the alluvium in the mid-section of the basin is estimated to be more than 200 m according to the groundwater wells drilled by the State Hydraulic Works (*SHW, 1983*). The basin extends in an east-west direction and the width of the basin in the middle reaches to approximately 30 km. Lake Sapanca is located at the west end of the basin.

The NAF crossing the basin in E-W direction is an active fault and evidence of the earthquake surface rupture may still be observed on the ground surface. Faults located in the south of the basin are also active within the NAFZ (*Emre et al., 1998*). The faults located in the north of the basin have become seismically inactive (*Emre et al., 1998*). The faults that are the contacts between the south sedimentary sequence and the alluvial deposits have the paleo-fault discontinuity planes. Fig. 2 displays the generalized geologic and tectonic model within the study area and its surroundings.

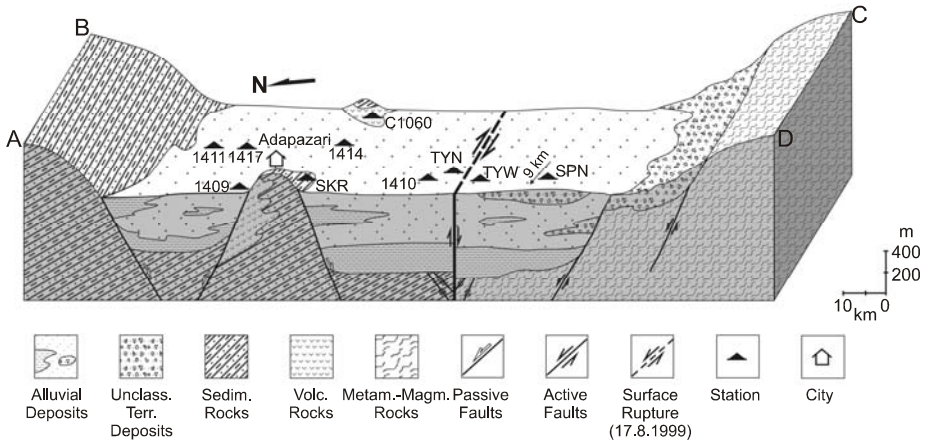


Fig. 2. Generalized geologic and tectonic model within the study area and its surroundings.

3. DATA AND DATA CORRECTION

The data set includes the strong ground motion data of the 1999 Kocaeli earthquake, the 1999 Düzce earthquake and the aftershocks of these earthquakes (Fig. 3). A total of 46 events with shallow depths were used in this study (Table 1). The data sets are restricted to earthquakes with M_w greater than or equal to 4.0. Focal depths of these earthquakes are less than 28 km. The Kocaeli and Düzce earthquakes generated 16 strong ground motion records within 20 km of the fault, contributing to the near field database of ground motions. During the Kocaeli earthquake, the strong ground motion station closest to the fault rupture was SKR (3.0 km), operated by the Earthquake Research Department of the Directorate for Disaster Affairs of the Ministry of Public Works and Settlement (ERD).

The data set for prediction of Spectral Acceleration Attenuation in the NW Marmara region consisted of 46 shallow earthquakes with 359 horizontal strong ground motion components. However, site amplifications were calculated only for the 10 selected stations installed in the Adapazarı basin, using the spectral accelerations recorded by these stations. Each station contains either GSR-12, GSR-16 or SSA-12 type digital recorders. The sampling frequency and resolution of the GSR-12 and SSA-12 recorders are 200 Hz and 12 bits. The SKR station consists of a GSR-16 (16 bits) digital recorder with a sampling frequency of 100 Hz. The instruments were installed either on the foundation or in the basement of a small building and on a free field (*Özel and Sasatani, 2004*).

The strong ground motion stations from which the strong motion data obtained were operated by eight strong motion operators (Table 2). These are; Kandilli Observatory Earthquake Research Institute of Boğaziçi University (KOERI); Earthquake Research Department of the Directorate for Disaster Affairs of the Ministry of Public Works and Settlement (ERD); Istanbul Technical University (ITU); Earthquake Research Institute (ERI); University of Tokyo; Lamont Doherty Earth Observatory of Columbia University

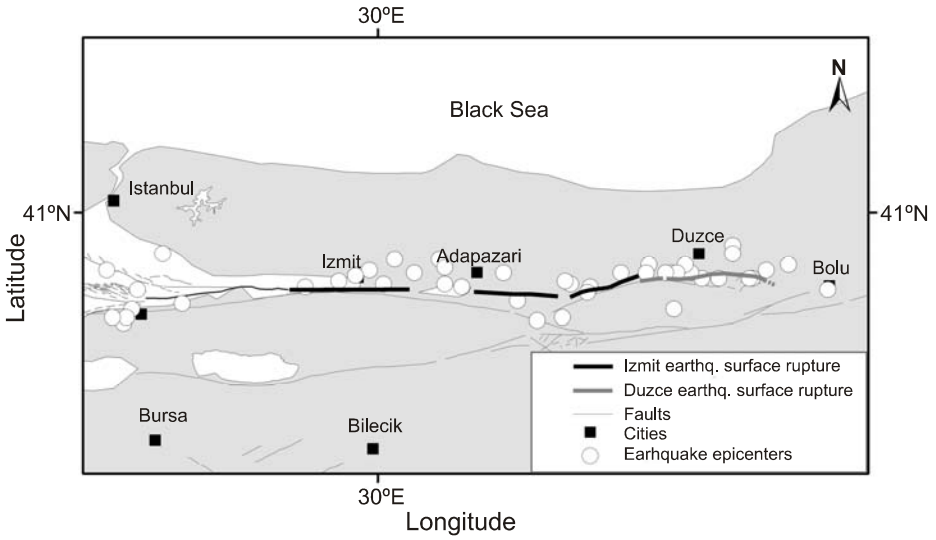


Fig. 3. Epicentral distribution of the 46 events used in this study.

(LDEO); University of Joseph Fourier (IRIGM); Geological Hazards Team (USGS-GOLDEN) and; Earthquake Hazards Team (USGS-MENLO). Strong ground motion data obtained from these operators were recorded by different types of accelerometers located on different ground conditions. All the raw data were obtained from different databases belonging to the following organizations; European Strong-Motion Data (ISESD) (*http://www.isesd.cv.ic.ac.uk/*); the Pacific Earthquake Research Center (PEER) (*http://peer.berkeley.edu/smcat/*); COSMOS (Consortium of Organizations for Strong Motion Observation Systems) (*http://db.cosmos-eq.org/scripts/earthquakes.plx*) and the United States Geological Survey (USGS) (*http://geopubs.wr.usgs.gov/openfile/of01-163*).

The Basic Strong-Motion Accelerogram Processing Software (*Converse and Brady, 1992*) was used to carry out the corrections for all of the time-histories records. This process consists of a high-cut filtering, with a cosine transformation from the roll-off frequency to the cut-off frequency, followed by the low-cut bidirectional Butterworth filtering of the acceleration, after padding the time history with zeros. First, baseline correction was carried out. After assuring the band of selected frequency was the dominant signal band, the Fast Fourier Transform (FFT) was calculated for all of the records. More or less constant amplitude of the FFT spectrum at frequencies lower than f_c (corner frequency) or at frequencies beyond f_{max} (maximum frequency) is generally an indication of large low or high frequency noise, respectively (*Zare and Bard, 2002*). Therefore, these parts may be thought of as noise and the reliable part of the signal limits lie between the two frequencies. The EW component acceleration time history which has the largest peak among the three components and the Fourier spectra of the record obtained in the SKR station during the 17 August 1999 Kocaeli earthquake, ($M_w = 7.4$) are shown in Figs. 4 and 5. In Fig. 4, the parts of the spectra below 0.20 Hz and beyond

Table 1. Earthquake recordings used in this study. Station ground conditions described as 'firm to hard rock' (B), 'dense soil, soft rock' (C), 'special study soils', e.g., liquefiable soils, sensitive clays, organic soils, soft clays > 36 m thick (F) (*Ambraseys et al. 2000*).

Event Index	Date (dd.mm.yyyy)	Time (hr:min:sec)	Lat. [°N]	Long. [°E]	Soil Type (NEHRP)			M_w	Depth [km]
					B	C	F		
1	17.08.1999	00:01:40	40.702	29.987	1			7.4	17
2	19.08.1999	14:15:42	40.610	29.200	1			4.4	10
3	19.08.1999	15:17:45	40.629	29.137	1			4.7	9
4	26.08.1999	17:49:38	40.740	30.020		1		4.3	10
5	31.08.1999	08:10:49	40.756	29.935		1	7	4.7	6
6	31.08.1999	22:28:33	40.620	29.050		1		4.0	8
7	01.09.1999	13:57:35	40.790	29.970		1	2	4.0	11
8	02.09.1999	14:25:19	40.620	30.660		1		4.0	14
9	04.09.1999	10:30:53	40.770	29.920		1	1	4.0	22
10	04.09.1999	18:27:43	40.730	30.300		1	2	4.0	15
11	05.09.1999	19:52:47	40.610	30.570			2	4.0	5
12	06.09.1999	06:33:26	40.730	29.740			1	4.0	10
13	06.09.1999	07:00:00	40.780	31.030			1	4.0	7
14	09.09.1999	01:32:07	40.720	29.140			1	4.0	10
15	13.09.1999	11:55:30	40.761	30.084	2		7	5.8	14
16	17.09.1999	19:50:05	40.780	30.130	1			4.4	12
17	18.09.1999	00:48:25	40.603	29.206	1		2	4.3	8
18	19.09.1999	20:26:36	40.680	30.500	1		2	4.1	8
19	29.09.1999	00:13:06	40.738	29.331	1	1	2	5.0	14
20	20.10.1999	23:08:20	40.831	29.027			2	4.8	5
21	07.11.1999	16:54:41	40.697	30.717	1			5.2	10
22	07.11.1999	17:06:05	40.750	30.670	1			4.2	3
23	11.11.1999	14:55:24	40.780	30.450	1			4.3	10
24	11.11.1999	14:41:23	40.747	30.248	1			6.0	15
25	12.11.1999	17:17:59	40.752	31.084	1			5.6	28

20 Hz are abnormally high. Once the reliable frequency band is determined, the signal window is filtered with the band pass Butterworth filter of order 2. The Fourier spectra of the SKR record after the filtering process are displayed in Fig. 6. The Butterworth filter was chosen because it has a fairly sharp transition from pass band to stop band.

4. SITE CLASSIFICATION OF THE ADAPAZARI BASIN STATIONS

The widely accepted method for classification of station sites is based on the shear wave velocity profiles of their substrata. Unfortunately, the actual shear wave velocity and detailed site description are not available for most stations in Turkey (*Gülkan and Kalkan, 2002*). *Ambraseys et al. (2002)* prepared a CD-ROM collection included European Strong Motion Data and the ground conditions of the stations that recorded the main shock and aftershocks of the 17 August 1999 Kocaeli earthquake. In this study, the site classification for the study area stations was made by an analogy with information for similar geologic

Table 1. Continuation.

Event Index	Date (dd.mm.yyyy)	Time (hr:min:sec)	Lat. [°N]	Long. [°E]	Soil Type (NEHRP)			M_w	Depth [km]
					B	C	F		
26	12.11.1999	20:04:45	40.760	31.220	1			4.4	10
27	12.11.1999	21:24:46	40.650	31.060	1			4.0	8
28	12.11.1999	21:38:32	40.810	31.100	1			4.3	10
29	12.11.1999	22:01:12	40.790	31.390	1			4.0	10
30	12.11.1999	22:38:02	40.760	31.330	1			4.1	13
31	12.11.1999	16:57:20	40.768	31.148	2			7.2	10
32	12.11.1999	22:20:55	40.842	31.356	1			4.3	10
33	13.11.1999	01:03:02	40.810	31.470	1			4.2	7
34	13.11.1999	02:53:07	40.830	30.220	1			4.7	5
35	13.11.1999	08:14:37	40.780	31.050	1			4.0	10
36	13.11.1999	09:59:23	40.780	30.960	1			4.1	10
37	16.11.1999	17:51:17	40.731	31.594	1			5.0	10
38	19.11.1999	10:27:59	40.780	31.070	1			4.0	10
39	19.11.1999	19:59:06	40.831	31.017	1			5.1	6
40	13.12.1999	19:13.37	40.730	30.760	1			4.2	10
41	20.12.1999	03:27:19	40.780	30.870	1			4.0	10
42	05.01.2000	14:10:04	40.850	31.270	1			4.1	8
43	20.01.2000	10:35:58	40.880	31.270	1			4.0	6
44	02.04.2000	18:57:38	40.800	30.240	1			4.2	7
45	07.07.2000	00:15:31	40.800	29.260	1			4.0	9
46	23.08.2000	13:41:28	40.680	30.720	1			5.4	9

materials. The NEHRP (*BSSC, 1994*) site classification was used in categorizing the ground of the study area stations. The NEHRP classification was developed to define different soil conditions. This classification identifies six main categories of soil and rock masses based on the shear wave velocity of the top 30 m of ground. The ground beneath the station is defined according to the NEHRP classification and the geotechnical properties of the soils and rocks (Table 3).

The SKR and C1060 stations are located on rock masses. The ground underneath these stations is categorized as B (firm to hard rock). The SKR station is located on sedimentary rock mass rock, which is the upper level of the north tectonic unit. V_{s-30} was recorded at 1050 m/s for the SKR ground (*Ambraseys et al., 2000)*. The C1060 station is located on a volcano-sedimentary rock mass that belongs to the north tectonic unit. This rock mass also falls into category B (firm to hard rock) due to its geotechnical and physical properties and the recorded shear wave velocity is 800 m/s (*Ambraseys et al., 2000)*. The 1409 station is also located on a sedimentary rock mass that belongs to the north tectonic unit in the northwest of the city of Adapazarı. However, there is a thick weathered zone underneath the station. This weathered ground would behave as a soft rock given its geotechnical properties. Thus the ground of this station was categorized as C (soft rock). Shear wave velocity could range between 360 and 760 m/s based on the site period data for this station.

Table 2. The strong ground motion stations operated by eight strong motion operators. G* represents station ground conditions as 'firm to hard rock' (B), 'dense soil, soft rock' (C), 'special study soils', e.g., liquefiable soils, sensitive clays, organic soils, soft clays > 36 m thick (F) based on *Ambraseys et al. (2000).*

Station Code	Lat. [°N]	Long. [°E]	Operator†	Building Type Instrument Location	G*	Lithology
1409	40.762	30.364	KOERI	Single storey Reinforced concrete bld.	C	Adapazarı Plain Alluvium (Liquefiable)
1410	40.710	30.395	KOERI	Free field Over concrete platform	F	Adapazarı Plain Alluvium (Liquefiable)
1411	40.786	30.391	KOERI	Single storey Masonry bld.	F	Adapazarı Plain Alluvium (Liquefiable)
1414	40.750	30.533	KOERI	Two storey Reinforced concrete bld.	F	Adapazarı Plain Alluvium (Liquefiable)
1417	40.773	30.398	KOERI	Single storey Reinforced concrete bld.	F	Adapazarı Plain Alluvium (Liquefiable)
C1060	40.774	30.612	LDEO	Free field Ground level	B	Volcanic Rocks (Andesite, Spilite, Porphyrite)
SKR	40.737	30.379	ERD	Single storey Prefabricated bld.	B	Limestone, Marl
SPN	40.688	30.257	ERD	Free field Ground level	F	Alluvium - Terrestrial Unclassified Deposits
TYN	40.712	30.390	USGS-GOLDEN	Free field Ground level	F	Alluvium
TYW	40.709	30.392	USGS-GOLDEN	Free field Ground level	F	Alluvium

† Network operator of the stations: KOERI: Kandilli Observatory Earthquake Research Institute of Boğazici University, LDEO: Lamont Doherty Earth Observatory of Columbia University, USGS-GOLDEN: United States Geological Survey Geological Hazards Team, ERD: Earthquake Research Department of the Directorate for Disaster Affairs of the Ministry of Public Works and Settlement.

The 1410, TYN, TYW stations are located very close to the 17 August 1999 main surface rupture. There is also a thick alluvial deposit in this section of the basin. Thus the top 30 m of the alluvial materials consists of soft clay-liquefiable soils categorized as F type ground. This ground with loose and soft geotechnical properties may yield a shear wave velocity that is less than 180 m/s. The 1411, 1414 and 1417 stations are also located on alluvial materials. The lithological properties and geometry of the soil layers are quite different in these sections of the basin due to the presence of the NAF and the morphology of the basin floor. The ground in these locations consists of soft clay and liquefiable soil intercalations. Thus, it was categorized as F with a shear wave velocity less than 180 m/s. The SPN station located in the south is on alluvium that mainly consists of coarse grained sediments derived from the south tectonic unit. Alluvial soils with loose sand-gravel layers are intercalated with soft-stiff clay layers beneath the station. Thus, ground of this station falls into category F with a shear wave velocity less than 180 m/s (Table 3).

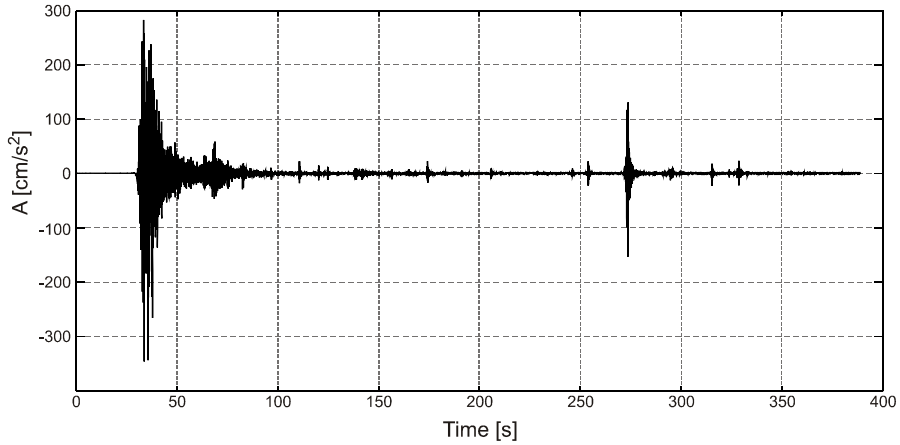


Fig. 4. Horizontal component of the largest peak among the three-component acceleration time history recorded in SKR for the Kocaeli earthquake of 17 August 1999, $M_W = 7.4$ (uncorrected record).

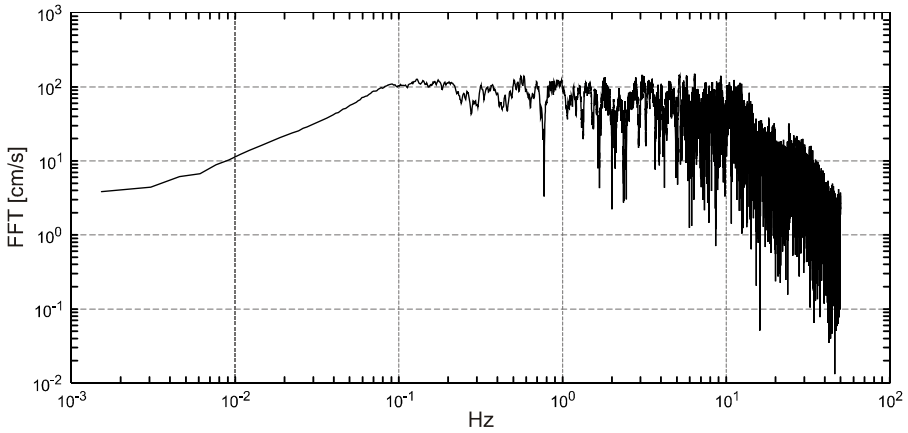


Fig. 5. Fourier spectra of the uncorrected strong ground acceleration recorded at SKR.

5. GROUND MOTION PREDICTION EQUATIONS (GMPEs)

The most common information available immediately following a damaging earthquake is its magnitude and epicentre. However, the damage pattern is not a simple function of these two parameters alone (*Wu et al., 2001*). Thus, more detailed information that enables mapping of PGA and SA distributions using GMPEs is highly desirable. Statistical regression techniques make it possible to bring together the available strong

Table 3. Information about the strong ground motion stations and site amplifications of the stations. Soil conditions are according to the NEHRP (*BSSC, 1994*).

NEHRP Category	Description	Mean Shear Wave Velocity of Top 30 m [m/s]	Stations
A	Hard rock	> 1500	---
B	Firm to hard rock	760–1500	SKR, C1060
C	Dense soil, soft rock	360–760	1409
D	Stiff soil	180–360	---
E	Soft clays	< 180	---
F	Special study soils, e.g., liquefiable soils, sensitive clays, organic soils, soft clays > 36 m thick		1410, TYN, TYW,1411, 1414, 1417, SPN

motion data, recorded under different source, travel path, and local site conditions to define empirical correlations that permit the estimation of ground motion for many earthquake scenarios and seismic hazard analyses (*Reiter, 1990*). Following the 1999 Kocaeli earthquake, the regional GMPEs have been developed (*Gülkan and Kalkan, 2002*; *Özbey et al., 2004*; *Ulusay et al., 2004*; *Ulutaş and Özer, 2010*) as a result of a recent increase in the database of strong motion. *Gülkan and Kalkan (2002)* used the general form of the equation proposed for shallow earthquakes in Western North America by *Boore et al. (1997)*, where the parameters are: moment magnitude, closest horizontal distance between the recording station and a point on the horizontal projection of the rupture zone on the earth's surface, and, shear wave velocity. *Özbey et al. (2004)* used a model with two sources of random variation, which is sometimes referred to as a 'hierarchical model' (*Lindley and Smith, 1972*; *Bryk and Raudenbush, 1992*) or

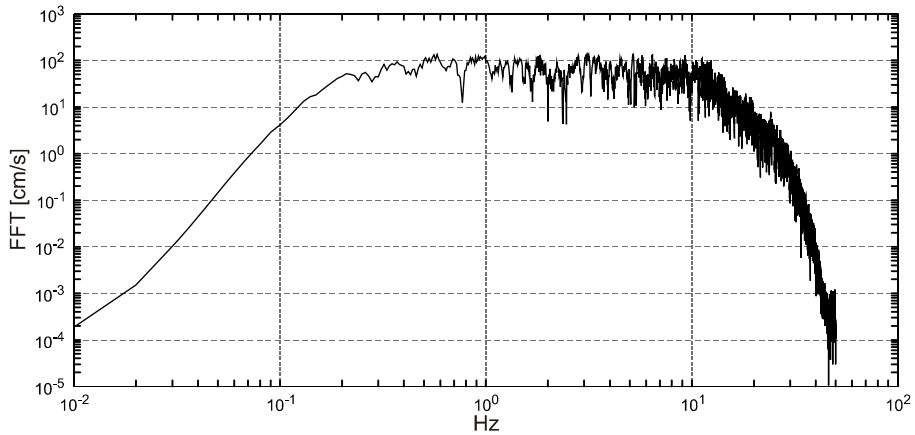


Fig. 6. Fourier spectra of the corrected strong ground acceleration recorded at SKR.

a multilevel model (*Goldstein, 1995*), where the parameters are moment magnitude, closest horizontal distance to the vertical projection of the rupture, and site class coefficient indicators. *Ulusay et al. (2004)* proposed an attenuation relationship model, where the parameters are moment magnitude, distance to epicenter, site class coefficient indicators and largest horizontal PGA. *Ambraseys et al. (2005)* also used a number of records from the NW of Turkey, where the relationship parameters are moment magnitude, distance to the surface projection of the fault, site class coefficient indicators and faulting mechanism indicators. *Ulutaş and Özer (2010)* collected a considerable amount of PGA data and developed an empirical attenuation relationship with the moment magnitude greater than 4.0 and with a surface projection of the rupture area (Fig. 7). This empirical attenuation relationship is formulated in Eq.(1) (*Ulutaş and Özer, 2010*):

$$\log A = -2.7809 + 0.5344M_w - \log\left(r_{rup} + 0.0183\times 10^{0.4537M_w}\right) - 0.0015r_{rup}\,, \qquad (1)$$

where A is acceleration in g and r_{rup} is source to site distance as Joyner and Boore distance (*Joyner and Boore, 1981*) in km. If the surface rupture is not defined for an event, epicentral distance should be used as the source to site distance. The attenuation relationship developed as in Eq.(1) along with the data set of the observed and predicted PGA values for various magnitudes are shown in Fig. 7. No distinction was considered between the records obtained from the stations founded on rock and soil sites in the attenuation relationship developed by *Ulutaş and Özer (2010)*. The standard deviations of the residuals between the observed and the predicted values were 0.39 in terms of natural logarithm. The attenuation relationship developed by *Ulutaş and Özer (2010)* provided a rapid assessment of PGA values within a certain source to site distance.

One of the ground motion estimations is of the spectral attenuation relationship. The PGAs previously mentioned are useful only for analysis of short period ($T \leq 0.3$ s) structures (*Douglas, 2003*). Additionally, PGA is not generally a good measure for earthquake risk assessment of medium and high-rise structures (> 2 storeys) (*Douglas, 2003*). For this purpose, a new attenuation model has been developed for 5% damped spectral accelerations for periods up to 4 s. SA represents the maximum acceleration that a ground motion will cause in a linear oscillator with a specified natural period and damping. In this study, spectral acceleration attenuation relationships were developed by using the same general form of equation proposed by *Wu et al. (2001)*, *Liu (1999)* and *Ulutaş and Özer (2010)*. This equation form was chosen to be identical with the relationships of PGA discussed in the previous section. The basic linear regression model used is given in Eq.(2).

$$LogA = C_1 + C_2M_w - \log\ \left(r_{rup} + h\right) + \log C_3 r_{rup}\,, \qquad (2)$$

where A is PGA, r_{rup} is the source to site distance in terms of the closest distance to the rupture surface, and C_1, C_2, C_3, C_4, and C_5 are the regression coefficients. For some of the smaller events ($M < 5$), rupture surfaces have not been defined clearly; therefore epicentral distances were used instead.

In the regression model, the variable h is the saturation term of the PGA for near source observation (*Liu, 1999*). The square root of rupture area for h as in *Wu et al. (2001)* was used:

$$h_i = C_4 10^{C_5 M_w}, \tag{3}$$

where h_i is i-th earthquake saturation term and C_4 and C_5 are the regression coefficients. For the Kocaeli earthquake, M_w was 7.4, and the fault area was 70×15 km^2 (*Yagi and Kikuchi, 2000*); and for the Düzce earthquake, M_w was 7.2, and the fault area was 40×20 km^2 (*Utkucu et al., 2003*). The fault area can also be obtained by available empirical solutions. For other earthquakes, relations between fault rupture length-magnitude and fault rupture width-magnitude were used as in the following equations (*Wells and Coppersmith, 1994*):

$$M_w = 4.33 + 1.49 \log L \tag{4}$$

and

$$M_w = 3.80 + 2.59 \log W, \tag{5}$$

where L is rupture length and W is rupture width. A total of 46 earthquakes were used in the regression process. Due to the regression process of Eq.(3), h was expressed as

$$h = 0.0183 \times 10^{0.4537 M_w}. \tag{6}$$

This calculated "h" value was used in Eq.(2). The attenuation relationship was developed for SA values by selecting the acceleration values of maximum horizontal components of each recording stations. Following this, a nonlinear regression analysis

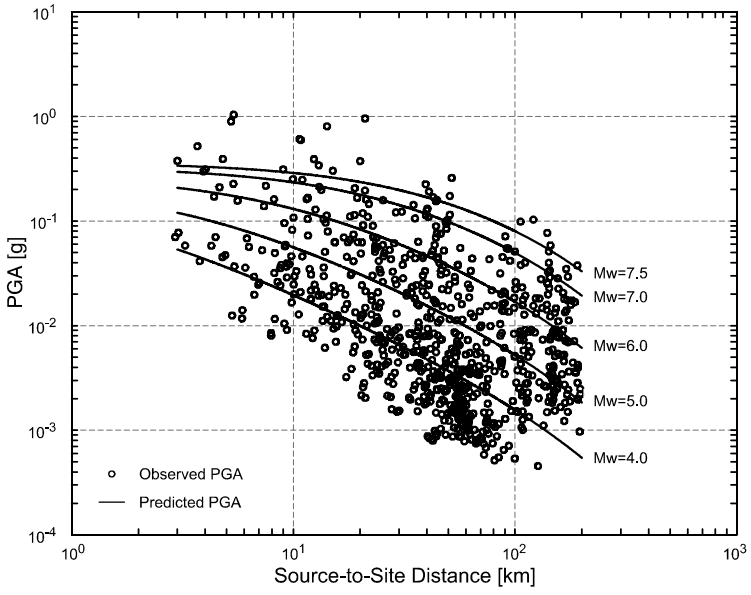


Fig. 7. Observed and predicted of PGAs for various magnitudes (*Ulutaş and Özer, 2010*).

Table 4. Empirical attenuation coefficients C_i and standard deviation values $\sigma_{\log A}$ for the 5% damped spectral accelerations.

Period [s]	C_1	C_2	C_3	C_4	C_5	$\sigma_{\log A}$
0.1	−1.2847	0.4005	−0.0020	0.0183	0.4537	0.44
0.2	−1.2921	0.4157	−0.0014	0.0183	0.4537	0.46
0.3	−1.5093	0.4408	−0.0005	0.0183	0.4537	0.50
0.4	−1.8048	0.4718	0.0001	0.0183	0.4537	0.52
0.5	−2.0588	0.4902	0.0009	0.0183	0.4537	0.54
0.6	−2.4975	0.5505	0.0011	0.0183	0.4537	0.56
0.7	−2.7910	0.5824	0.0015	0.0183	0.4537	0.56
0.8	−3.0392	0.6127	0.0015	0.0183	0.4537	0.57
0.9	−3.2632	0.6391	0.0016	0.0183	0.4537	0.58
1.0	−3.4390	0.6592	0.0016	0.0183	0.4537	0.59
1.1	−3.6213	0.6786	0.0018	0.0183	0.4537	0.61
1.2	−3.7457	0.6917	0.0018	0.0183	0.4537	0.63
1.3	−3.8656	0.7059	0.0015	0.0183	0.4537	0.64
1.4	−4.0054	0.7223	0.0014	0.0183	0.4537	0.64
1.5	−4.1172	0.7333	0.0013	0.0183	0.4537	0.64
1.6	−4.2196	0.7427	0.0013	0.0183	0.4537	0.65
1.7	−4.2660	0.7427	0.0012	0.0183	0.4537	0.66
1.8	−4.2930	0.7398	0.0011	0.0183	0.4537	0.66
1.9	−4.3419	0.7415	0.0010	0.0183	0.4537	0.66
2.0	−4.4080	0.7456	0.0009	0.0183	0.4537	0.67
2.1	−4.4986	0.7542	0.0009	0.0183	0.4537	0.67
2.2	−4.5775	0.7604	0.0009	0.0183	0.4537	0.67
2.3	−4.6185	0.7606	0.0009	0.0183	0.4537	0.67
2.4	−4.6479	0.7596	0.0008	0.0183	0.4537	0.67
2.5	−4.6834	0.7604	0.0007	0.0183	0.4537	0.67
2.6	−4.7484	0.7672	0.0007	0.0183	0.4537	0.67
2.7	−4.8162	0.7746	0.0006	0.0183	0.4537	0.68
2.8	−4.8900	0.7834	0.0006	0.0183	0.4537	0.68
2.9	−4.9666	0.7928	0.0006	0.0183	0.4537	0.68
3.0	−5.0289	0.7996	0.0005	0.0183	0.4537	0.68
3.1	−5.0803	0.8047	0.0005	0.0183	0.4537	0.68
3.2	−5.1282	0.8091	0.0005	0.0183	0.4537	0.70
3.3	−5.1601	0.8107	0.0004	0.0183	0.4537	0.70
3.4	−5.1832	0.8106	0.0004	0.0183	0.4537	0.70
3.5	−5.2088	0.8107	0.0004	0.0183	0.4537	0.69
3.6	−5.2421	0.8124	0.0004	0.0183	0.4537	0.69
3.7	−5.2854	0.8159	0.0004	0.0183	0.4537	0.69
3.8	−5.3215	0.8184	0.0005	0.0183	0.4537	0.69
3.9	−5.3471	0.8193	0.0005	0.0183	0.4537	0.69
4.0	−5.3686	0.8195	0.0005	0.0183	0.4537	0.69

was applied. Based on the model (*Wu et al., 2001*), Table 4 presents the attenuation coefficients C_1, C_2, C_3, C_4, and C_5, and standard deviations of the residuals between the observed and the predicted values for periods up to 4 s. The SA attenuation relationship developed for this study along with the data set of the observed and predicted of SA values for various magnitudes and various periods are shown in Figs. 8a,b,c.

6. COMPARISON WITH OTHER GMPEs

The equations used for PGA (*Ulutaş and Özer, 2010*) and developed for SA in this study were compared with the equations recently developed by *Ambraseys et al. (2005)*. The equations of *Ambraseys et al. (2005)* pertain to soft soil and stiff soil and divide site classes into four groups according to the shear velocities. The attenuation of PGA and SA at 0.2, 0.3, 0.5, 1.0, 1.5 and 2.0 seconds in $M_w = 7.4$ for the sites with soft soil and stiff soil are compared in Figs. 9–11, respectively. The measured database points from the Kocaeli event are also marked on these curves to illustrate how well they fit the estimates. The differences in the curves are judged to be reasonably accurate because the different databases, regression models and analysis methods among the relationships are contained in each model.

7. ESTIMATING THE SITE AMPLIFICATION IN THE ADAPAZARI BASIN

Site amplification is a major concern in earthquake prone regions such as Adapazarı which has been developed on mainly alluvial deposits. Therefore, it is very important to determine the site amplifications of the stations during earthquakes. Ten stations installed in the populated areas of the Adapazarı basin were selected to assess site amplification.

The first method for assessing amplification was the calculation of the residuals. Thus the site amplifications of the stations were determined empirically by averaging the residuals between the observed and predicted PGA and SA values following (*Wu et al., 2001*):

$$S = \exp\left[\frac{1}{n}\sum_{1}^{n}\ln\left(D_i/\bar{D}_i\right)\right], \tag{10}$$

where D_i is the observed PGA or SA value and $\bar{D}_i$ is the predicted PGA or SA value obtained by empirical attenuation relationship. Thus, the site peak ground motion is expressed as

$$\left(Sx\bar{D}_i\right). \tag{11}$$

Table 5 shows the calculated site amplification values of the stations by using the residuals of PGA proposed by *Ulutaş and Özer (2010)* and *Ambraseys et al. (2005)*. The amplification results of these two models are coherent with the soil conditions of the stations.

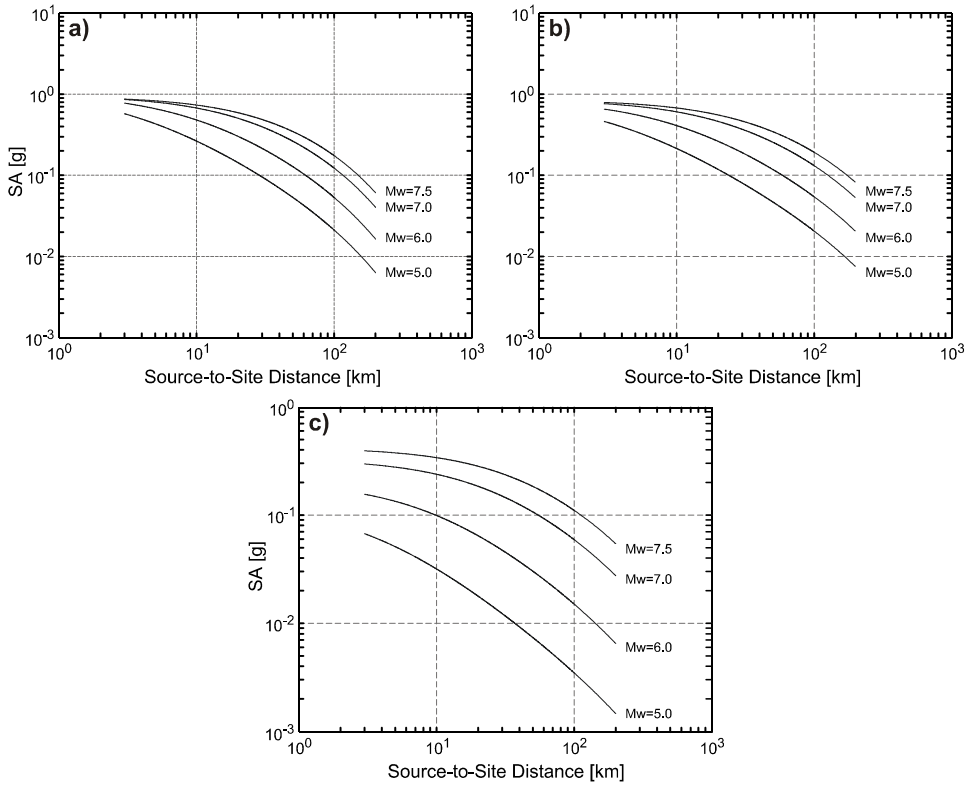


Fig. 8. Curves of spectral accelerations (5% damped) versus distance for magnitudes 7.5, 7.0, 6.0 and 5.0 at natural periods: **a)** $T = 0.2$ s; **b)** $T = 0.3$ s; **c)** $T = 1.0$ s.

The SKR and 1060 stations showed de-amplifications because these stations have the site classification category of B based on the NEHRP. The 1410, TYN, TYW, 1411, 1414, 1417, and SPN stations located on alluvial soils consisting of liquefiable sand-soft clay layers indicated an amplification. Although the site of the 1409 station is soft rock, its amplification value is higher than the expected value. The high amplification values are in short periods for this station. Amplification for this station is 3.2 in 0.1 s. This situation can be explained by the specific location of this station set on the edge of the basin. Also, the reflected waves were intense in these parts of the basin during the earthquake. As mentioned previously, PGAs are useful only for analysis of short periods. Therefore, to define the soil amplifications of the stations on the basin, "a new attenuation model has been developed for 5% damped spectral acceleration" and amplifications of the sites were defined by using the residuals of SA in different periods up to 4 s (Table 6). Fig. 12 shows the SA site amplifications of the Adapazarı basin stations using the methods of calculated residuals of observed and predicted SA acceleration values.

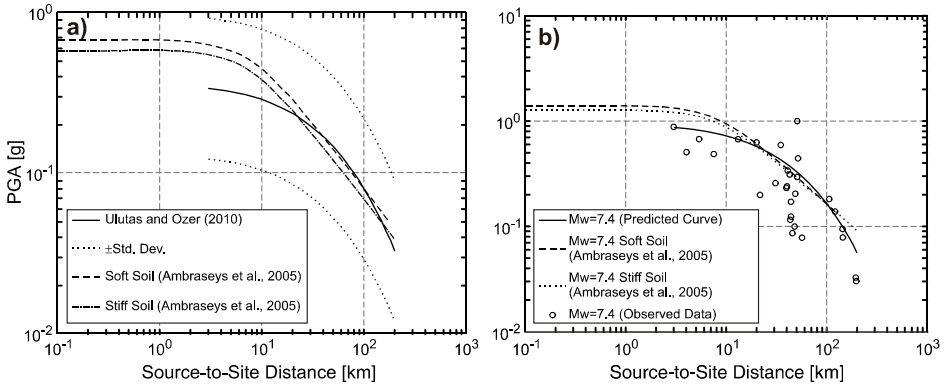


Fig. 9. **a)** Comparison of the attenuation relationships (*Ulutaş and Özer, 2010*; *Ambraseys et al., (2005*). **b)** Comparison of predictions from the proposed attenuation model with a European Model (*Ambraseys et al., 2005*) for spectral acceleration at 0.2 s natural period at soft and stiff soil sites.

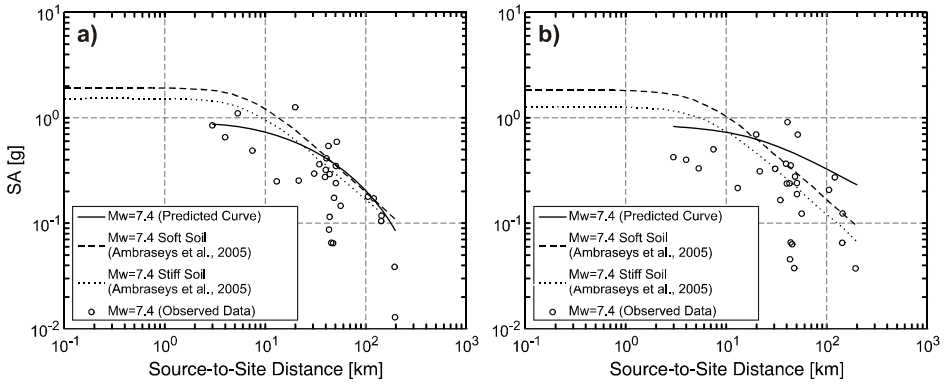


Fig. 10. Comparison of predictions from the proposed attenuation model with a European Model (*Ambraseys et al., 2005*) for spectral accelerations (5% damped) at: **a)** 0.3 s natural period and **b)** 0.5 s natural period at soft and stiff soil sites.

8. SITE AMPLIFICATION BY SPECTRAL RATIO METHOD

There are several methods for estimating site response ground motions. Comparison of ground motions at sites of interest to a nearby rock site is considered a "reference" motion. The critical assumption in these methods is that the surface-rock-site record (reference) is equivalent to the input motion at the base of the soil layers (*Steidl et al., 1996*). The second method to calculate the amplifications in the Adapazarı basin was the traditional spectral ratio method. The SKR station on bedrock was chosen as a reference station. First, the horizontal components that have the peak acceleration values were selected for

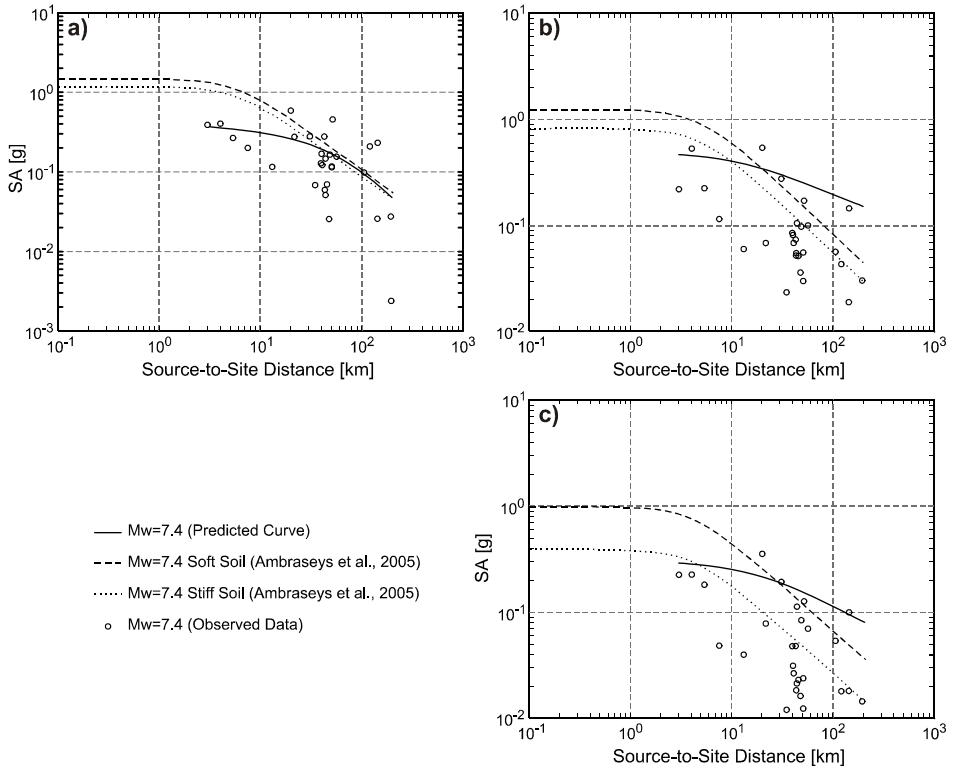


Fig. 11. Comparison of predictions from the proposed attenuation model with a European Model (*Ambraseys et al., 2005*) for spectral accelerations (5% damped) at: **a)** 1.0 s natural period, **b)** 1.5 s natural period, and **c)** 2.0 s natural period at soft and stiff soil sites.

the magnitude of the 5.8 event which was the largest aftershock of the 1999 Kocaeli earthquake. This aftershock was chosen because it was recorded by all of the study area stations set in the Adapazarı basin except the SPN station. Each spectral acceleration value calculated from 0.1 to 4 s periods was divided into the spectral acceleration value of the SKR reference station. Before calculating the traditional spectral ratios, the data corrections were carried out and the corrected waveforms were examined based on their amplitudes and periods. Fig. 13 displays the filtered low pass and high pass waveforms of the 5.8 magnitude aftershock recorded by the study area stations (SKR, C1060, 1409, 1410, 1411, 1414, 1417, TYN, TYW). These records contain horizontal components that have the larger peak accelerations of the two horizontal components. Table 7 presents the filter band of selected frequency by using the Fast Fourier Transform (FFT) for each record. There are some noticeable variations in the periods of waveforms. It is obvious that these variations are due to the ground conditions of each station. The SKR and 1060 stations are in the B category based on the NEHRP site classification and for this reason

Table 5. Site amplifications of Adapazarı basin stations calculated according to the residuals of PGA by using two different attenuation models.

Station Code	Site Amplification for PGA (PGA Relationship Proposed by *Ulutaş and Özer , 2010*)	Site Amplification for PGA (PGA Relationship Proposed by *Ambraseys et al., 2005*)
1409	3.120	2.277
1410	1.130	1.025
1411	2.564	1.948
1414	1.809	1.675
1417	2.339	1.859
C1060	0.430	0.337
SKR	0.757	0.615
SPN	1.217	0.818
TYN	1.375	0.940
TYW	1.241	0.778

they have shorter-period and lower-amplitude waveforms. The 1409 station is in the C category based on the NEHRP site classification. Although the waveform of this station has high amplitude, it contains shorter period ground motions. The reason for this situation may be the location of the station set on the edge of the basin. It is noticeable that the waveforms of the 1411 and 1417 stations located in downtown Adapazarı (where the damages were severe) have high periods and were recorded with long duration. There is a significant delay in the records of the 1411 and 1417 stations in comparison to the SKR and 1409 stations. This delay may be caused by the thick sediments with a low S-wave velocity in the Adapazarı basin (*Özel and Sasatani, 2004*). The peak amplitudes of waveforms of the 1410 station are lower than the 1411 and 1417 stations. Additionally, it has shorter periods than the 1411 and 1417 stations. This situation may be explained by the geotechnical variations of alluvial materials. The peak amplitudes of waveforms of the TYN and TYW stations are lower than the 1411 and 1417 stations. However, the waveforms of the TYN and TYW stations contain longer period ground motions than the waveforms of the SKR and 1060 stations.

The results of spectral ratios in the period range from 0.1 s to 4.0 s. Fig. 14 displays the spectral ratios for each station. It can be seen that the spectral ratios of the stations with the same ground category are different. This is not surprising, because these stations are located on different geological materials with varying distances to the NAF. Also, their epicentral distances range from 26.6 km to 47.0 km.

9. DISCUSSION AND CONCLUSIONS

In this study, site amplifications were studied for the Adapazarı basin. The site amplifications for all sites of strong ground motion stations in the Adapazarı basin were evaluated by the methods of calculated residuals of observed and predicted acceleration values and the traditional spatial ratio method.

Table 6. Site amplifications at basin stations of Adapazarı calculated according to the residuals of SA for periods between 0.1 s and 4 s.

Period [s]	Station Codes									
	1409	1410	1411	1414	1417	C1060	SKR	SPN	TYN	TYW
0.1	2.4234	0.4873	1.2723	0.8032	1.2219	0.2768	0.8096	1.0161	0.6301	0.7817
0.2	1.1532	0.6329	1.7452	1.4746	1.3552	0.3357	0.4868	1.4609	0.786	0.7267
0.3	1.4051	0.5474	0.9035	1.3571	1.4798	0.1745	0.3952	2.2503	0.7794	0.8241
0.4	0.9977	1.2307	0.9847	1.0833	1.3058	0.1484	0.2848	2.2072	1.4297	1.1211
0.5	0.7827	1.1788	1.5528	1.1314	2.2098	0.1392	0.3558	1.8017	1.1739	0.8815
0.6	1.0377	1.4433	1.7138	1.1453	2.9479	0.1244	0.2809	1.6351	0.9499	0.8145
0.7	0.8242	1.7289	1.9245	1.3507	2.5239	0.1417	0.3203	2.0438	1.1579	0.7713
0.8	0.7882	1.6752	2.0446	1.549	2.5538	0.1299	0.3259	1.7515	1.3432	0.7784
0.9	0.9054	1.5066	2.3775	1.4499	3.3199	0.1327	0.3574	2.0907	1.3234	1.0564
1.0	0.8774	1.6378	2.5726	1.5699	3.0107	0.1169	0.3037	2.0602	1.9398	1.3229
1.1	0.9822	1.7589	2.8561	1.3156	3.1554	0.1156	0.3368	2.6744	1.8729	1.285
1.2	1.0412	1.7171	2.7192	1.4402	3.7685	0.1141	0.3401	2.5579	1.6543	1.2833
1.3	1.0506	1.6961	2.9725	1.5388	4.3772	0.119	0.3578	2.2775	1.6365	1.1663
1.4	0.8932	2.0221	3.7135	1.7167	5.2228	0.1316	0.3634	2.4558	1.6063	1.1769
1.5	0.8163	2.0191	4.689	1.5777	5.0657	0.1388	0.3408	2.3473	1.7539	1.1864
1.6	0.7574	2.4072	5.1282	1.2589	4.9925	0.1458	0.3933	2.3358	1.7188	1.2062
1.7	0.856	2.7335	5.2553	1.1746	4.5739	0.1601	0.4495	2.5876	1.7763	1.1689
1.8	0.8701	2.8573	5.4898	1.174	4.007	0.1677	0.4711	2.8263	1.9597	1.1369
1.9	0.824	2.6691	6.2195	1.3634	4.2979	0.169	0.4689	2.8801	2.0252	1.1525
2.0	0.8863	2.6859	6.5293	1.3795	4.2597	0.1728	0.4336	2.5336	2.0057	1.086
2.1	0.9366	2.5706	6.2871	1.3837	4.1349	0.1768	0.3624	2.2674	2.017	1.0272
2.2	0.9767	2.5056	6.8394	1.5228	4.4111	0.1719	0.3249	2.1366	1.9648	1.0009
2.3	1.0008	2.5234	7.3574	1.5324	4.6718	0.1649	0.3195	2.0996	1.9025	0.9868
2.4	0.9492	2.3342	7.3782	1.4895	4.253	0.1586	0.3302	2.1702	1.7652	1.0307
2.5	0.9029	2.2121	7.0541	1.4846	3.5642	0.1573	0.3452	2.6819	1.6748	1.0734
2.6	0.9024	2.0842	6.5464	1.3481	3.2279	0.1518	0.3515	3.2413	1.6089	1.0522
2.7	0.8797	2.0365	6.1558	1.1499	3.0153	0.1492	0.3669	3.4473	1.5568	1.0167
2.8	0.8553	1.9994	5.9452	1.0882	2.7914	0.1475	0.3739	3.5348	1.5516	0.9862
2.9	0.8554	1.9421	5.9695	1.0008	2.5794	0.1462	0.3783	3.4612	1.4965	1.0089
3.0	0.8582	1.8655	5.9519	1.0705	2.5392	0.143	0.384	3.2039	1.4331	1.0309
3.1	0.8685	1.8302	5.8071	1.0211	2.6371	0.1387	0.3782	2.7939	1.3595	1.0243
3.2	0.8678	1.7766	5.5674	0.9453	2.7657	0.1341	0.3735	2.4812	1.3042	1.0049
3.3	0.8538	1.7384	5.2729	0.8713	2.8419	0.1319	0.3769	2.3462	1.2827	0.9862
3.4	0.8477	1.6994	5.0007	0.8252	2.8561	0.1291	0.3786	2.3092	1.2597	0.9535
3.5	0.8352	1.655	4.8092	0.8102	2.8153	0.1249	0.3778	2.195	1.2453	0.9471
3.6	0.8553	1.6128	4.6708	0.7887	2.7293	0.1246	0.3766	2.0736	1.2851	0.9619
3.7	0.8435	1.5634	4.5684	0.7627	2.7085	0.1243	0.3795	2.0456	1.3291	0.9622
3.8	0.8482	1.5293	4.5691	0.7362	2.7387	0.1239	0.3796	2.0407	1.3261	0.9611
3.9	0.85	1.5169	4.6638	0.73	2.7323	0.1256	0.3764	2.0786	1.2853	0.9428
4.0	0.8509	1.5063	4.8053	0.7189	2.662	0.1258	0.3758	2.1288	1.2174	0.9327

Table 7. The filter band of selected low and high frequency of the records. LP, HP - low and high pass limits of the band.

Station	Filters Applied		Epicentral Distance [km]
	LP	HP	
SKR	0.22	20	28.8
C1060	0.15	25	47.0
1409	0.20	18	26.5
1410	0.25	15	31.2
1411	0.20	14	28.3
1414	0.40	25	40.9
1417	0.35	20	29.2
TYN	0.40	20	30.8
TYW	0.22	25	31.0

According to the results of calculated residuals from observed and predicted acceleration values, the site amplification values for the stations (TYN, 1410, TYW and SPN) varied between 1.217 and 1.275. These stations are located around the 17 August 1999 surface rupture and are very close to each other. These amplification results show a consistency for grounds of these stations. The numerical difference among the result values is a function of the distance from the 17 August 1999 surface rupture. The site amplification values for the SKR and C1060 stations located on rock are 0.430 and 0.757 respectively and indicate consistency for a rock medium. The site amplification values of the 1414, 1417, 1411 and 1409 stations are 1.809, 2.339, 2.556 and 3.120 respectively.

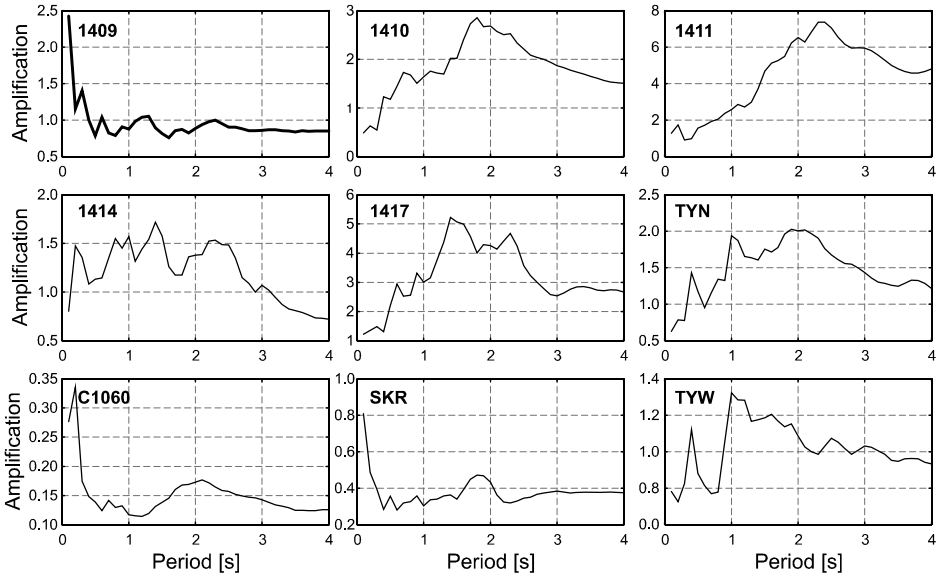


Fig. 12. The SA site amplification factors of the Adapazarı basin stations.

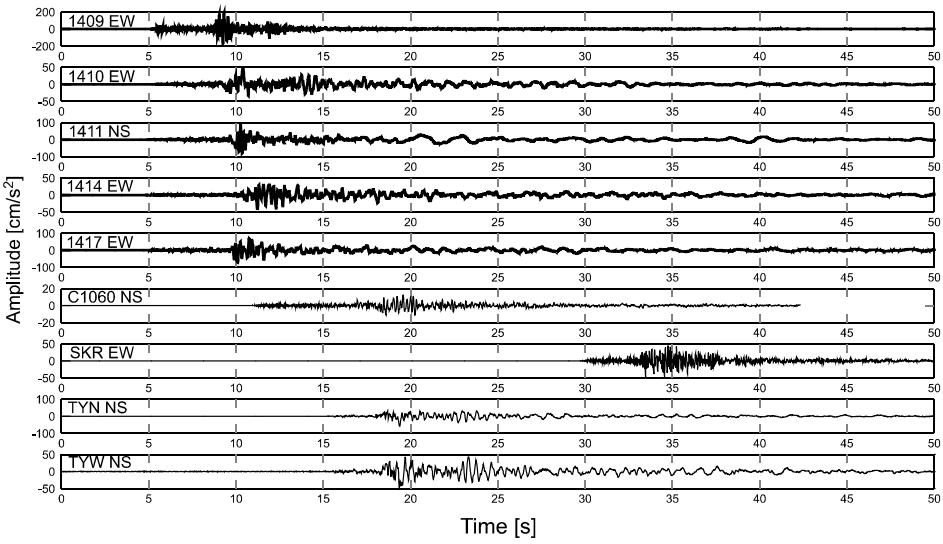


Fig. 13. Peak component acceleration waveforms for the largest aftershocks (M_w = 5.8) observed in the study area.

These values indicate an increase as the stations become more distant from the surface rupture and approach the contact between the alluvial deposits and bedrocks. These stations were located on alluvial deposits that are potentially liquefiable. The 1409 station, located on the discontinuity between the two different media, has the highest site amplification value (3.12) in the study area. This high value must be a result of the reflection and refraction of the seismic waves due to the discontinuities located on both sides of the narrow basin.

A new attenuation model has also been developed for 5% damped spectral acceleration to define the site amplifications of the stations in the basin. The amplifications of the sites were calculated by using the residuals of SAs. The SA attenuation relationship estimated for this study has served as a basis for empirically establishing SA behavior near the west part of the NAFZ. The standard deviations of the residuals between the observed and the predicted values are in the range of 0.44 to 0.70 due to the periods of SAs in terms of natural logarithms. Observed SAs were compared with the proposed SA attenuation relationship of *Ambraseys et al. (2005)* and predicted SA attenuation relationship proposed in the study for 7.4 magnitude at various periods. In some periods, SA values from our database are much smaller or much higher than the empirical prediction curves of *Ambraseys et al. (2005)*. However, the prediction curves pass almost through the middle of the observed values. The parameters used to develop the attenuation curves do not include the site classifications according to local soil conditions as in the attenuation model proposed *by Ambraseys et al. (2005).* Site effects were not included because of the lack of uppermost shear wave velocity values of the stations in the region. Therefore the site amplifications of the station sites were determined by averaging the residuals between the observed and predicted values. The

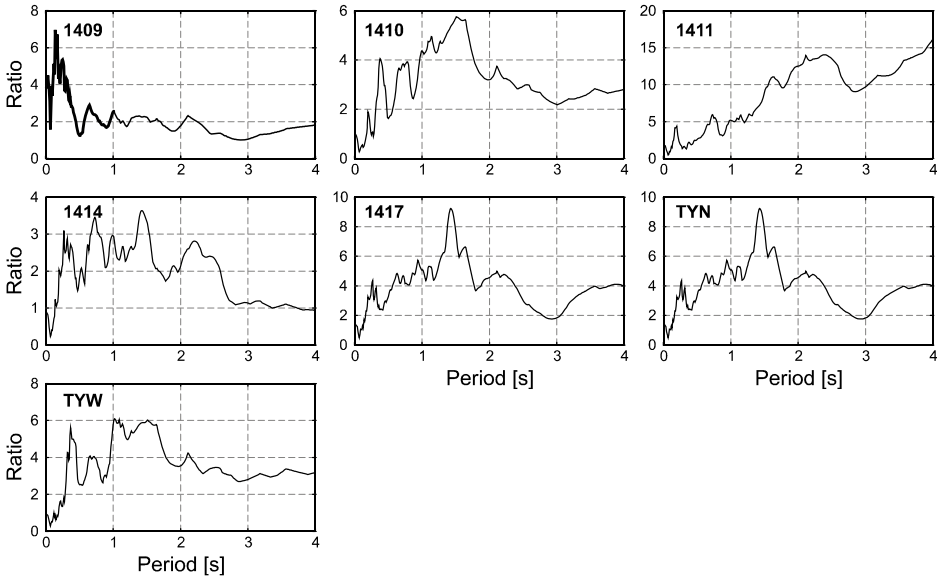


Fig. 14. Spectral acceleration ratios (5% damping) for a magnitude 5.8 event with respect to the reference station SKR

amplification results are coherent with the ground conditions of the stations. The sites of the SKR and C1060 stations are rock. Therefore they showed de-amplifications. The 1410, TYN, TYW, 1411, 1414, 1417, and SPN stations located on alluvial soils consisting of liquefiable sand-soft clay layers indicated an amplification. Although the site of the 1409 station is soft rock, its amplification value is higher than the expected value. The high amplification values are in short periods for this station. Amplification for this station is 3.2 in 0.1 s. However, the ground at this station does not indicate amplification greater than 0.2 s based on the residuals method. This situation can be explained by the specific location of this station which is located on weathered or soft rock on the edge of the basin. The location and the site of the 1409 station should be studied in detail to understand specific site effects of this location.

The traditional spectral ratio method was also used to define the spectral content of amplifications. The SKR station located on rock ground was chosen as the reference station. The spectral ratio value for the 1409 station shows a significant amplification less than 0.3 s. This spectral ratio result is comparable with the result obtained from the residuals method. Spectral ratio values for the 1410 and 1414 stations yielded an average 2.5 amplification value. Amplification values calculated before the 0.2 s period are quite low when compared to the other stations. This situation identifies a soft soil ground with low amplification values at low periods and high amplification values at high periods. Also, de-amplification starts after a 2.5 s period for these two stations. No significant amplification is observed for the C1060 station in both methods. Instead there is a de-amplification at high periods. This situation may be explained by the location of the station set on a rock mass and by its distance from the epicenter of the earthquake. The

TYN station is located on a soft soil and high amplification values resulted at high periods but amplification decreases after 1.4 s. The weathered zones underneath the C1060 and SKR stations are thinner than the weathered zone of the 1409 station. Thus the ground of the 1409 station may behave like a soil at the low periods and then like complete rock. The thickness of the weathered zone underneath the SKR station was reported to be 17 m (*Özel and Sasatani, 2004*). *Özel and Sasatani (2004)* also confirmed that the amplifications at high periods were due to the thick sedimentary layers in the Adapazarı basin and that the apparent de-amplifications at low periods were partly due to the reference site response. It should also be concluded that heavy damage in downtown Adapazarı during the 1999 Kocaeli earthquake was caused not only by strongly amplified PGA values but also by SA values at long periods.

It is concluded that the results are satisfactory for estimating site amplifications for different soil types. The results obtained by these methods agree reasonably well with the surface geology presented in the published maps (*MREI, 2000*). The site amplifications of the stations represent a statistically averaged effect because every event possesses its own characteristics. Thus, this study focused on estimating the site amplifications in the selected area that was highly damaged in the 17 August 1999 Kocaeli earthquake. The site amplification values for strong ground motion stations determined in this study make it possible to calculate the PGA and SA values immediately when a destructive earthquake occurs. The site amplification information for the stations should be updated when more data on strong ground motion are recorded in this region. The method in this study can be regarded as a fast and inexpensive method for damaged areas with strong ground motions, while the outcomes of this study can be used in seismic hazards analysis, land use planning, predicting immediate damage assessments and microzonation studies to reduce earthquake damage. During a disastrous earthquake, the early assessment and timely definition of the PGA and SA for a site could be crucial for an effective rapid response operation. By using the site amplification values obtained from this study, PGA or SA values of strong ground motions can be correctly determined in the Adapazarı basin as soon as the earthquake location is determined and magnitudes are calculated.

APPENDIX A

The attenuation coefficients have been derived from the method proposed by *Wu (2001)*. We have modified the method of *Wu (2001)*. The attenuation model is given by Eq.(2) in text:

$$\log A = C_1 + C_2 M_w \log\left(r_{rup} + h\right) + \log C_3 r_{rup} \,, \tag{A.1}$$

r_{rup} is known for all earthquakes and h was calculated by using Eqs.(3)–(5). The prediction of error, ε, from such an attenuation model can be derived from the Eq.(2) as following:

$$\varepsilon = \sum_{i=1}^{n} \left(C_1 + C_2 M - \log\left(r_{rup} + h\right) + C_3 r_{rup} - \log A_i \right)^2 \,, \tag{A.2}$$

where the added suffix i indicates the i-th record, and n is the total number of records. Then C_1 and C_2 and C_3 can be derived from the following equations:

$$\partial \varepsilon / \partial C_1 = \sum_{i=1}^{n} 2\left(C_1 + C_2 M_i - \log\left(r_i + h\right) + C_3 r_i - \log A_i\right) = 0\,, \tag{A.3}$$

$$\partial \varepsilon / \partial C_2 = \sum_{i=1}^{n} 2\left(C_1 + C_2 M_i - \log\left(r_i + h\right) + C_3 r_i - \log A_i\right) M_i = 0\,, \tag{A.4}$$

$$\partial \varepsilon / \partial C_3 = \sum_{i=1}^{n} 2\left(C_1 + C_2 M_i - \log\left(r_i + h\right) + C_3 r_i - \log A_i\right) r_i = 0\,. \tag{A.5}$$

C_1, C_2 and C_3 coefficients were derived by using the Eqs.(A.3), (A.4) and (A.5):

$$C_1 = \frac{D_1}{D_0}\,,\; C_2 = \frac{D_2}{D_0}\,,\; C_3 = \frac{D_3}{D_0}\,, \tag{A.6}$$

where

$$D_1 = \begin{vmatrix} \sum_{i=1}^{n} \log\left(r_i + h_i\right) + \sum_{i=1}^{n} \log A_i & \sum_{i=1}^{n} M_i & \sum_{i=1}^{n} r_i \\ \sum_{i=1}^{n} \log\left(r_i + h_i\right) M_i + \sum_{i=1}^{n} \log A_i M_i & \sum_{i=1}^{n} M_i^2 & \sum_{i=1}^{n} r_i M_i \\ \sum_{i=1}^{n} \log\left(r_i + h_i\right) r_i + \sum_{i=1}^{n} \log A_i r_i & \sum_{i=1}^{n} r_i M_i & \sum_{i=1}^{n} r_i^2 \end{vmatrix}, \tag{A.7a}$$

$$D_2 = \begin{vmatrix} n & \sum_{i=1}^{n} \log\left(r_i + h_i\right) + \sum_{i=1}^{n} \log A_i & \sum_{i=1}^{n} r_i \\ \sum_{i=1}^{n} M_i & \sum_{i=1}^{n} \log\left(r_i + h_i\right) M_i + \sum_{i=1}^{n} \log A_i M_i & \sum_{i=1}^{n} r_i M_i \\ \sum_{i=1}^{n} r_i & \sum_{i=1}^{n} \log\left(r_i + h_i\right) r_i + \sum_{i=1}^{n} \log A_i r_i & \sum_{i=1}^{n} r_i^2 \end{vmatrix}, \tag{A.7b}$$

$$D_3 = \begin{vmatrix} n & \sum_{i=1}^{n} M_i & \sum_{i=1}^{n} \log\left(r_i + h_i\right) + \sum_{i=1}^{n} \log A_i \\ \sum_{i=1}^{n} M_i & \sum_{i=1}^{n} M_i^2 & \sum_{i=1}^{n} \log\left(r_i + h_i\right) M_i + \sum_{i=1}^{n} \log A_i M_i \\ \sum_{i=1}^{n} r_i & \sum_{i=1}^{n} r_i M_i & \sum_{i=1}^{n} \log\left(r_i + h_i\right) r_i + \sum_{i=1}^{n} \log A_i r_i \end{vmatrix}, \tag{A.7c}$$

$$D_0 = \begin{vmatrix} n & \sum_{i=1}^{n} M_i & \sum_{i=1}^{n} r_i \\ \sum_{i=1}^{n} M_i & \sum_{i=1}^{n} M_i^2 & \sum_{i=1}^{n} r_i M_i \\ \sum_{i=1}^{n} r_i & \sum_{i=1}^{n} r_i M_i & \sum_{i=1}^{n} r_i^2 \end{vmatrix}. \qquad \text{(A7.d)}$$

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