Fifth International Congress on Advances in Civil Engineering, 25-27 September 2002
Istanbul Technical University, Istanbul, Turkey

Attenuation Characteristics of Turkey Based on Recent Strong Motion Data

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Abstract

This paper deals with the derivation of a consistent set of empirical attenuation relationships for predicting free-field horizontal components of peak ground acceleration (PGA) and 5 percent damped pseudo acceleration response spectra (PSA) from 47 strong ground motion records recorded in Turkey. The relationships for Turkey were derived in similar form to those previously developed by Boore et al. (1997) for shallow earthquakes in western North America. The used database was compiled for earthquakes in Turkey with moment magnitudes (M_w) $\geq$ 5 that occurred between 1976-1999, and consisted of horizontal peak ground acceleration and 5 percent damped response spectra of accelerograms recorded on three different site conditions classified as rock, soil and soft soil. The empirical equations for predicting strong ground motion were typically fit to the strong motion data set by applying nonlinear regression analysis according to both random horizontal components and maximum horizontal components. Comparisons of the results shows that ground motion relations for earthquakes in one region cannot be simply modified for use in engineering analyses in another region. Our results, patterned after the Boore et al. expressions and dominated by the Kocaeli and Düzce events in 1999, appear to underestimate predictions based on their curves for up to about 15 km. For larger distances the reverse holds.

Introduction

Estimation of ground motion, either implicitly through the use of special earthquake codes or more specifically from site-specific investigations is essential for the design of engineered structures. The development of design criteria requires, as a minimum, a strong-motion attenuation relationship to estimate earthquake ground motions from specific parameters characterizing the earthquake source, geologic conditions of the site, and the length of the propagation path between the source and the site.

This study describes the best estimates and uncertainties in the ground motion parameters predicted in a functional form that can be used in probabilistic hazard studies and other earthquake engineering applications. These models and the values of the predictor parameters were developed by an extensive analysis of ground motion data and its relevant data. This effort was partly motivated by the occurrence of the 1999 $M_w = 7.4$ Kocaeli and 1999 $M_w = 7.1$ Düzce earthquakes. The Kocaeli earthquake was the largest event that occurred in Turkey within the last 50 years, and it is the first well-studied and widely recorded large NAF (North Anatolian Fault) event.

The data includes records from earthquakes of moment magnitude greater than about 5, and site conditions characterized as soft soil, soil and rock with closest distance less than about 150 km. This presents a unique opportunity to study the indigenous attenuation characteristics of earthquake ground motions. Also, the study of the effects of local site on the attenuation of earthquake ground motions becomes possible since the recording stations are fixed and many stations have several records.

Finally, this paper describes the procedure for estimating ground motion at various soil sites by presenting the tables and equations that describe attenuation functions and associated measures of uncertainty. One of the major purposes of this paper is to make comparisons between the direct uses of attenuation relationships developed elsewhere for Turkey, and to illuminate the reasons for their differences.

Strong Motion Database

After carefully searching the strong motion database of Turkey, a total of 93 records from 47 horizontal components of 19 earthquakes between 1976-1999 were chosen for the analysis. The strong motion database is given in Table 1, and listing of the earthquakes and the number of recordings for each of the strong motion parameters are presented in Table 2. Station names have not been translated so that independent checks may be run. Recordings from small earthquakes were limited to the closer distances than large earthquakes depending on the magnitude and the geology of the recording site to minimize the influence of regional differences in attenuation and to avoid the complex propagation effects coming from longer distances.

In the data set, earthquake size is characterized by moment magnitude M_w, as described by Hanks and Kanamori (1979). When original magnitudes were listed in other scales, conversion was done according to Wells and Coppersmith (1994). The magnitudes are restricted to about $M_w \geq 5.0$ to emphasize those ground motions having greatest engineering interests, and to limit the analysis to the more reliably recorded events. In the regression phase, magnitudes of earthquakes were locked within +/- 0.25 band intervals centered at halves or full numbers in order to eliminate the errors coming from the determination of these magnitude values. Figure 1 shows the distribution of these earthquakes in terms of magnitude, station geology (defined below) and source distance r_{cl}, defined as the closest horizontal distance between the recording station and a point on the horizontal projection of the rupture zone on the earth's surface. However, for some of the smaller events, rupture surfaces have not been defined clearly therefore epicentral distances are used instead. We believe that use of epicentral distance does not introduce significant bias because the dimensions of the rupture area for small earthquakes are usually much smaller than the distance to the recording stations. Examination of the peak ground motion data from the small number of normal-faulting and reverse-faulting earthquakes in the data set showed that they were not significantly different from ground motion characteristics of strike-slip earthquakes. Therefore, normal, reverse or strike-slip earthquakes were combined into a single fault category.

Peak horizontal acceleration (PGA) and pseudo response spectral acceleration (PSA) are represented considering both maximum and random horizontal components. These are explained below.

TABLE 1.
Records Used in the Development of the Attenuation Equations for Peak Horizontal Acceleration and Spectral Accelerations

Date	Earthquake	M_W	r_{cl} (km)	Recording Station	Station Coordinates	Station Site Class	Peak Hor. Acc. (mg) N-S	E-W
19.08.1976	DENİZLİ	5.3	15.20	Denizli: Meteoroloji İstasyonu	37.8140N- 29.1120E	Soil	348.53	290.36
05.10.1977	ÇERKEŞ	5.4	46.00	Çerkeş: Meteoroloji İstasyonu	40.8800N- 32.9100E	Soft Soil	36.03	38.94
16.12.1977	İZMİR	5.5	1.20	İzmir: Meteoroloji İstasyonu	38.4000N- 27.1900E	Soft Soil	391.41	125.40
18.07.1979	DURSUNBEY	5.3	10.30	Dursunbey: Kandilli Gözlem İstasyonu	39.6700N- 28.5300E	Rock	232.29	288.25
05.07.1983	BİGA	6.0	57.70	Edincik: Kandilli Gözlem İstasyonu	40.3600N- 27.8900E	Rock	53.44	46.51
05.07.1983	BİGA	6.1	48.70	Gönen: Meteoroloji İstasyonu	40.0800N- 27.6800E	Soft Soil	50.11	46.77
05.07.1983	BİGA	6.2	75.00	Tekirdağ: Meteoroloji İstasyonu	40.9600N- 27.5300E	Rock	29.89	34.91
30.10.1983	HORASAN-NARMAN	6.5	25.00	Horasan: Meteoroloji İstasyonu	40.0400N- 42.1700E	Soft Soil	150.26	173.30
29.03.1984	BALIKESİR	4.5	2.40	Balıkesir: Meteoroloji İstasyonu	39.6600N- 27.8600E	Soft Soil	223.89	128.97
12.08.1985	KİĞI	4.9	80.77	Kiğı: Meteoroloji İstasyonu	39.3400N- 40.2800E	Soil	163.06	89.09
05.05.1986	MALATYA	6.0	29.63	Gölbaşı: Devlet Hastanesi	37.7810N- 37.6410E	Rock	114.70	76.04
06.06.1986	SÜRGÜ (MALATYA)	6.0	34.70	Gölbaşı: Devlet Hastanesi	37.7810N- 37.6410E	Rock	68.54	34.43
20.04.1988	MURADİYE	5.0	37.30	Muradiye: Meteoroloji İstasyonu	39.0300N- 43.7000E	Rock	49.50	51.18
13.03.1992	ERZİNCAN	6.9	65.00	Refahiye: Kaymakamlık Binası	39.9010N- 38.7690E	Soft Soil	67.21	85.93
13.03.1992	ERZİNCAN	6.9	5.00	Erzincan: Meteoroloji İstasyonu	39.7520N- 39.4870E	Soil	404.97	470.92
06.11.1992	İZMİR	6.1	41.00	Kuşadası: Meteoroloji İstasyonu	37.8610N- 27.2660E	Soft Soil	83.49	71.80
24.05.1994	GİRİT	5.4	20.10	Foça: Gümrük Müdürlüğü	38.6400N- 26.7700E	Rock	36.06	49.80
13.11.1994	KÖYCEĞİZ	5.2	17.41	Köyceğiz: Meteoroloji İstasyonu	36.9700N- 28.6940E	Soft Soil	72.79	96.51
01.10.1995	DİNAR	6.4	3.00	Dinar: Meteoroloji İstasyonu	38.0600N - 30.1500E	Soft Soil	288.30	269.95
01.10.1995	DİNAR	6.4	46.20	Çardak: Sağlık Ocağı	37.8250N- 29.6680E	Soil	65.07	61.30
27.06.1998	ADANA-CEYHAN	6.3	80.10	Mersin: Meteoroloji İstasyonu	36.8300N- 34.6500E	Soft Soil	119.29	132.12
27.06.1998	ADANA-CEYHAN	6.3	28.00	Ceyhan: PTT Müd.	37.0500N 35.8100E	Soft Soil	223.42	273.55
17.08.1999	KOCAELİ	7.4	55.00	Bursa: Sivil Sav. Müd.	40.1830N- 29.1310E	Soft Soil	54.32	45.81
17.08.1999	KOCAELİ	7.4	81.00	Çekmece: Nükleer Santral Bn.	40.9700N- 28.7000E	Soil	118.03	89.61
17.08.1999	KOCAELİ	7.4	11.00	Düzce: Meteoroloji İstasyonu	40.8500N- 31.1700E	Soft Soil	314.88	373.76
17.08.1999	KOCAELİ	7.4	116.00	Ereğli: Kaymakamlık Bn.	40.9800N- 27.7900E	Soil	90.36	101.36
17.08.1999	KOCAELİ	7.4	15.00	Gebze: Tübitak Marmara Araş. Mer.	40.8200N- 29.4400E	Rock	264.82	141.45
17.08.1999	KOCAELİ	7.4	32.00	Göynük: Devlet Hastanesi	40.3850N- 30.7340E	Rock	137.69	117.9
17.08.1999	KOCAELİ	7.4	49.00	İstanbul: Bayındırlık ve İskan Müd.	41.0580N- 29.0130E	Rock	60.67	42.66
17.08.1999	KOCAELİ	7.4	8.00	İzmit: Meteoroloji İstasyonu	40.7900N- 29.9600E	Rock	171.17	224.91
17.08.1999	KOCAELİ	7.4	30.00	İznik: Karayolları Şefliği	40.4370N- 29.6910E	Soft Soil	91.89	123.32
17.08.1999	KOCAELİ	7.4	140.00	Kütahya: Sivil Savunma Müd.	39.4190N- 29.9970E	Soil	50.05	59.66
17.08.1999	KOCAELİ	7.4	3.20	Sakarya: Bayındırlık ve İskan Müd.	40.7370N- 30.3840E	Rock	407.04	-
17.08.1999	KOCAELİ	7.4	150.00	Tekirdağ: Hükümet Konağı	40.9790N- 27.5150E	Rock	129.79	128.33
17.08.1999	KOCAELİ	7.4	17.00	Darıca: Arçelik Arge Bn.	40.82360N- 29.3607E	Soil	211.37	133.68
17.08.1999	KOCAELİ	7.4	82.50	Ambarlı: Termik Santral	40.9809N- 28.6926E	Soft Soil	252.56	186.04
17.08.1999	KOCAELİ	7.4	116.00	M. Ereğlisi: Botaş Gas Terminali	40.9919N- 27.9795E	Soil	98.88	87.10
17.08.1999	KOCAELİ	7.4	72.00	Yeşilköy: Havalimanı	40.9823N- 28.8199E	Soil	90.21	84.47
17.08.1999	KOCAELİ	7.4	63.00	4. Levent: Yapı Kredi Plaza	41.0811N- 20.0111E	Rock	41.08	35.52
17.08.1999	KOCAELİ	7.4	3.28	Yarımca: Petkim Tesisleri	40.7639N-29.7620E	Soil	230.22	322.20
17.08.1999	KOCAELİ	7.4	63.00	Fatih: Fatih Türbesi	41.0196N-28.9500E	Soft Soil	189.39	161.87
17.08.1999	KOCAELİ	7.4	43.00	Heybeliada: Sanatoryum	40.8688N- 29.0875E	Rock	56.15	110.23
17.08.1999	KOCAELİ	7.4	71.00	Bursa: Tofaş Fab.	40.2605N- 29.0680E	Soft Soil	100.89	100.04
17.08.1999	KOCAELİ	7.4	81.00	Çekmece: Nükleer Santral Bn.	40.9700N- 28.7000E	Soil	177.31	132.08
12.11.1999	DÜZCE	7.1	20.41	Bolu: Bayındırlık ve İskan Müd.	40.7450N- 31.6100E	Soft Soil	739.56	805.88
12.11.1999	DÜZCE	7.1	8.23	Düzce : Meteoroloji İstasyonu	40.8500N- 31.1700E	Soft Soil	407.69	513.78
12.11.1999	DÜZCE	7.1	30.90	Mudurnu: Kaymakamlık Binası	40.4630N- 31.1820E	Soft Soil	120.99	58.34

TABLE 2.
Earthquakes Used in the Analysis

Date	Earthquake	Fault Type	M_w	Number of Recordings Soft Soil	Soil	Rock
19.08.1976	DENİZLİ	Normal	5.3		2	
05.10.1977	ÇERKEŞ	Strike-Slip	5.4	2		
16.12.1977	İZMİR	Normal	5.5	2		
18.07.1979	DURSUNBEY	Strike-Slip	5.3			2
05.07.1983	BİGA	Reverse	6.0	2		4
30.10.1983	HORASAN-NARMAN	Strike-Slip	6.5	2		
29.03.1984	BALIKESİR	Strike-Slip	4.5	2		
12.08.1985	KİĞI	Strike-Slip	4.9		2	
05.05.1986	MALATYA	Strike-Slip	6.0			2
06.06.1986	SÜRGÜ (MALATYA)	Strike-Slip	6.0			2
20.04.1988	MURADİYE	Strike-Slip	5.0			2
13.03.1992	ERZİNCAN	Strike-Slip	6.9	2	2	
06.11.1992	İZMİR	Normal	6.1	2		
24.05.1994	GİRİT	Normal	5.4			2
13.11.1994	KÖYCEĞİZ	Normal	5.2	2		
01.10.1995	DİNAR	Normal	6.4	2	2	
27.06.1998	ADANA-CEYHAN	Strike-Slip	6.3	4		
17.08.1999	KOCAELİ	Strike-Slip	7.4	12	16	15
12.11.1999	DÜZCE	Strike-Slip	7.1	6		
			Total	40	24	29

The data used in the analysis constitutes only main shocks of 19 earthquakes. They were recorded mostly in small buildings built as meteorological stations up to three stories tall because the strong motion stations in Turkey are co-located with institutional facilities for ease of access, phone hook-up and security. This causes modified acceleration records. This is one of the unavoidable causes of uncertainties in this study, but there are other attributes that must be mentioned. The first is our omission of aftershock data. Most of these come from the two major 1999 events, and contain free-field data that we did not wish to commingle with the rest of the set. We also omitted the few records for which the peak acceleration caused by the main shock is less than about 0.04 g. Our entire, non-discriminated ensemble is shown in Figure 2.

When we consider the effects of geological conditions on ground motion and response spectra, the widely accepted method of reflecting these effects is to classify the recording stations according to 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. For this reason, we estimated the site classification by analogy with information in similar geologic materials. The type of geologic material underlying each recording site was obtained in a number of ways: consultation with geologists at Earthquake Research Division of Ministry of Public Works and Settlement, various geologic maps, past earthquake reports and geological references prepared for Turkey. In the light of this information we divided soil groups for Turkey into three in ascending order for shear velocity: soft soil, soil, and rock. The average shear-wave velocities assigned for these groups are 200, 400 and 700m/s, respectively. The distribution of the records with respect to magnitude and distance plotted by type of faulting is shown in Figure 3.

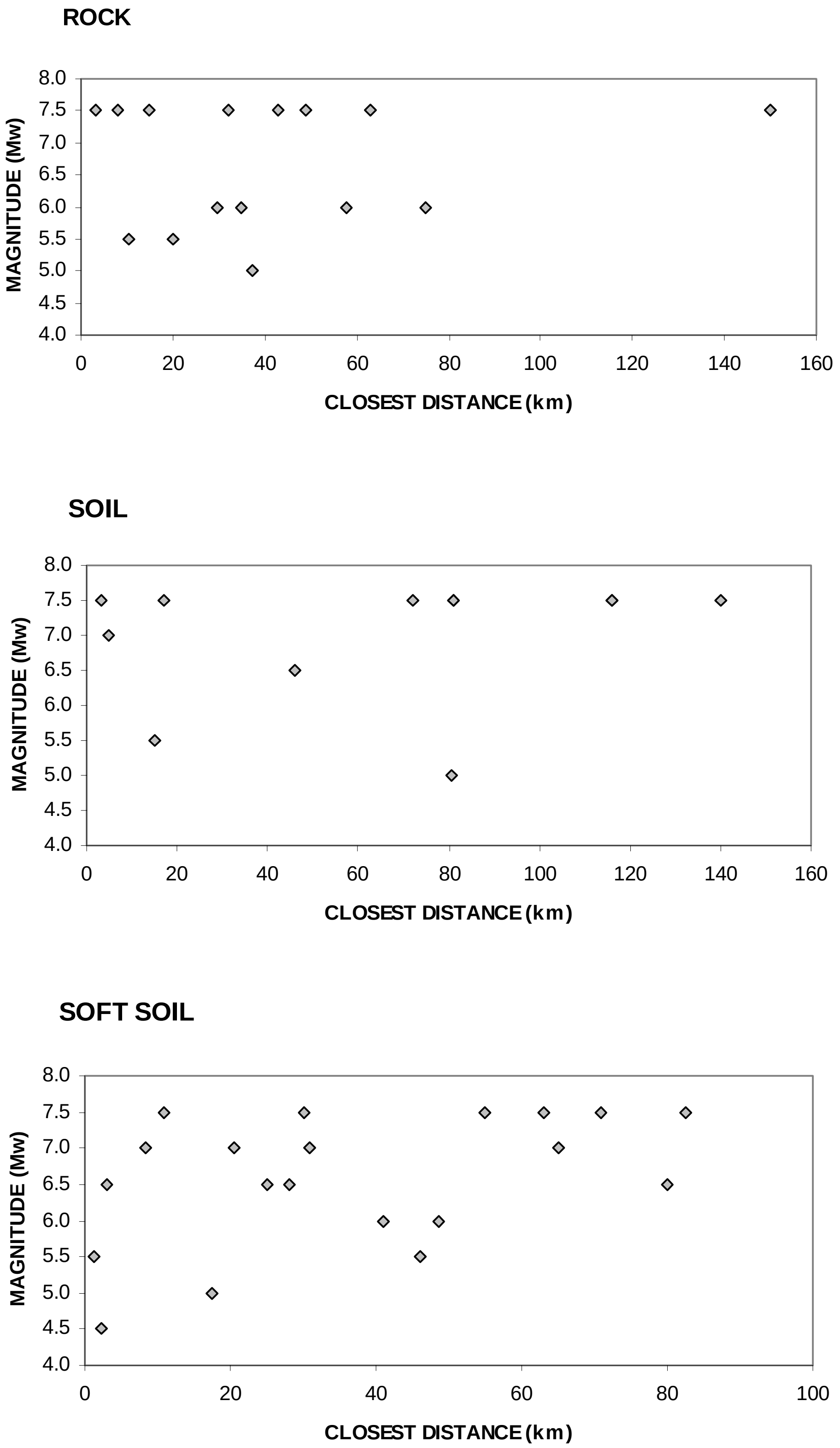


Figure 1. The distribution of records in the database in terms of magnitude, distance and local geological conditions

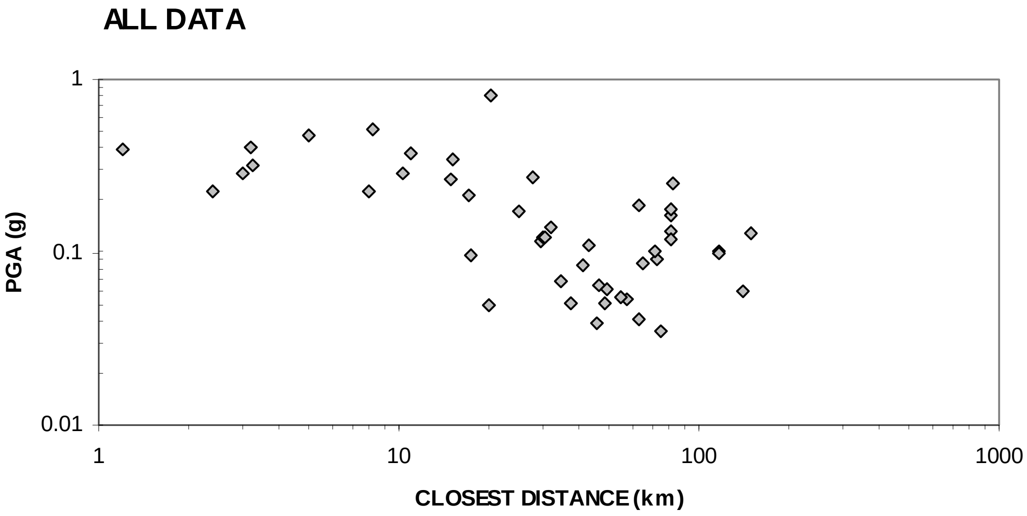


Figure 2. Distribution of the larger maximum horizontal acceleration of either component versus distance

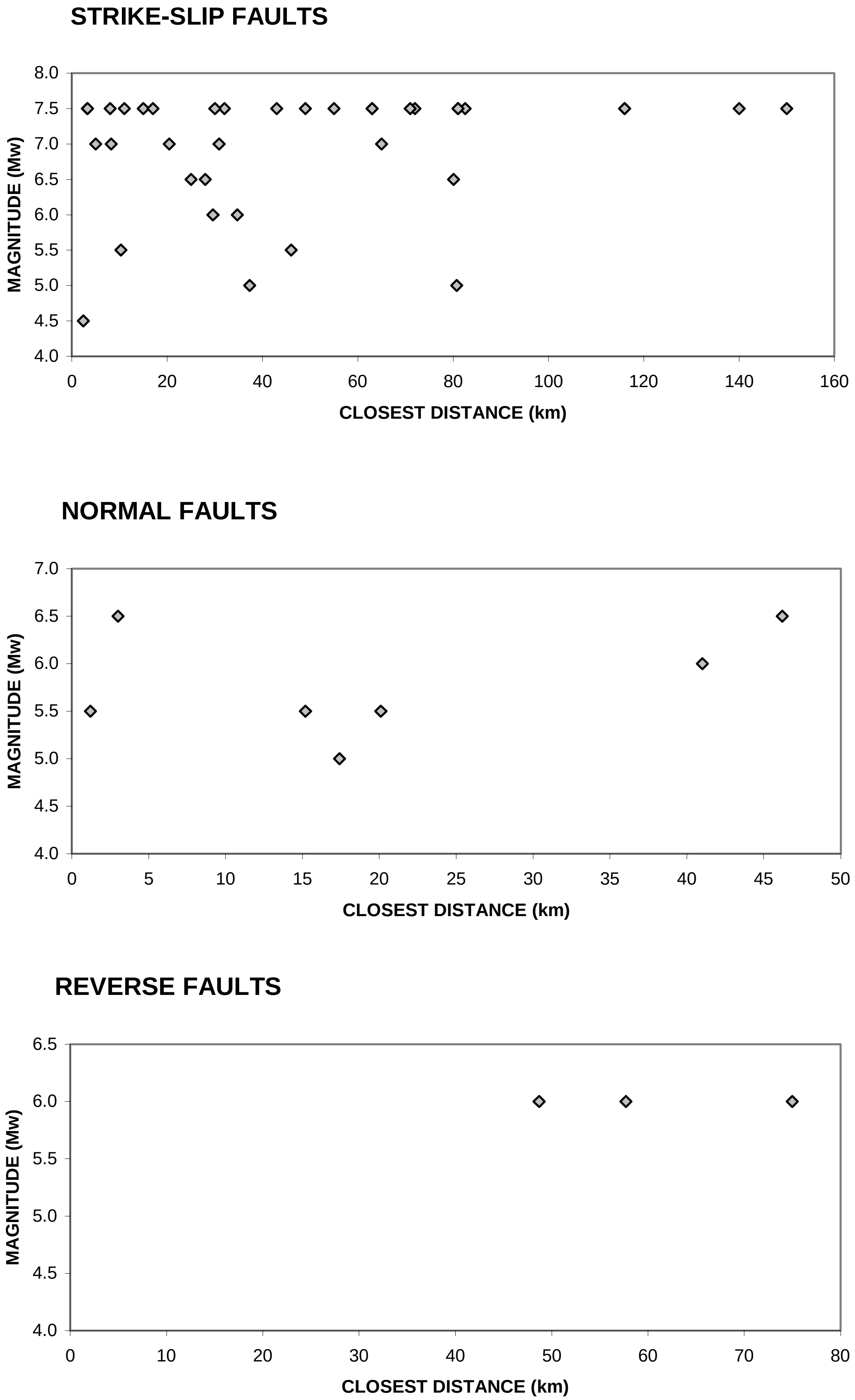


Figure 3. The distribution of records in the database in terms of magnitude, distance and type of faulting

Attenuation Relationship Development

Attenuation relationships were developed by using the same general form of the equation proposed by Boore et al. (1997). The ground motion parameter estimation equation is as follows:

$$\ln Y = b_1 + b_2 (M - 6) + b_3 (M - 6)^2 + b_5 \ln r + b_V \ln (V_S / V_A) \quad (1)$$

$$r = (r_{cl}^2 + h^2)^{1/2} \quad (2)$$

Here Y is the ground motion parameter (peak horizontal acceleration (PGA) or pseudo spectral acceleration (PSA) in g); M is (moment) magnitude; r_{cl} is closest horizontal distance from the station to a site of interest in km; V_S is the shear wave velocity for the station in m/s; b_1, b_2, b_3, b_5, h, b_V, and V_A are the parameters to be determined. Here h is a fictitious depth, and V_A a fictitious velocity that are determined by regression. The coefficients in the equations for predicting ground motion were determined by using nonlinear regression analysis. Nonlinear regression is a method of finding a nonlinear model of the relationship between the dependent variable and a set of independent variables. Unlike traditional linear regression, which is restricted to estimating linear models, nonlinear regression can estimate models with arbitrary relationships between independent and dependent variables. This is accomplished using iterative estimation algorithms. The nonlinear regression procedure on the database was performed using SPSS statistical analysis software program (Ver.9.00, 1998). This exercise was performed separately on PGA and on PSA data at each oscillator period considered (total of 46 periods from 0.1 to 2.0s.).

The procedure that we have used to develop the attenuation curves consists of two stages (Joyner and Boore, 1993). In the first, attenuation relationships were developed for PGA and spectral acceleration values by selecting the acceleration values in the database as maximum horizontal components of each recording station. Then, a nonlinear regression analysis was performed. In the next stage, random horizontal components were selected for the acceleration values in the database and regression analyses were applied. The results were compared for PGA, 0.3 s and 1.0 s PSA cases, and it was concluded that selection of maximum, rather than of random, horizontal components did not yield improved estimates and smaller error terms. This issue is taken up again in the section on comparisons of our results with other relations.

The coefficients for estimating the maximum horizontal-component pseudo-acceleration response by Equation (1) are given in Table 3. The resulting parameters can be used to produce attenuation relationships that predict response spectra over the full range of magnitudes (M_w 5 to 7.5) and distances (r_{cl}) up to 150 km. The results were used to compute errors for PGA and PSA at individual periods. The standard deviation of the residuals, σ, expressing the random variability of ground motions, is an important input parameter in probabilistic hazard analysis. In this study, the observed value of ln σ lies generally within the range of 0.5 to 0.7. The calculated attenuation relationships for PGA for rock, soil and soft soil sites are shown in Figures 4 through 6.

TABLE 3.
Attenuation Relationships of Horizontal PGA and Response Spectral Accelerations (5% damping)

$\ln(Y) = b1 + b2\,(M - 6) + b3\,(M - 6)^2 + b5 \ln r + b_V \ln (V_S / V_A)$ with $r = (r_{cl}^2 + h^2)^{1/2}$

Period	b1	b2	b3	b5	b_V	V_A	h	σ
PGA	-0.682	0.253	0.036	-0.562	-0.297	1381	4.48	0.562
0.10	-0.139	0.200	-0.003	-0.553	-0.167	1063	3.76	0.621
0.11	0.031	0.235	-0.007	-0.573	-0.181	1413	3.89	0.618
0.12	0.123	0.228	-0.031	-0.586	-0.208	1501	4.72	0.615
0.13	0.138	0.216	-0.007	-0.590	-0.237	1591	5.46	0.634
0.14	0.100	0.186	0.014	-0.585	-0.249	1833	4.98	0.635
0.15	0.090	0.210	-0.013	-0.549	-0.196	1810	2.77	0.620
0.16	-0.128	0.214	0.007	-0.519	-0.224	2193	1.32	0.627
0.17	-0.107	0.187	0.037	-0.535	-0.243	2433	1.67	0.621
0.18	0.045	0.168	0.043	-0.556	-0.256	2041	2.44	0.599
0.19	0.053	0.180	0.063	-0.570	-0.288	2086	2.97	0.601
0.20	0.127	0.192	0.065	-0.597	-0.303	2238	3.48	0.611
0.22	-0.081	0.214	0.006	-0.532	-0.319	2198	1.98	0.584
0.24	-0.167	0.265	-0.035	-0.531	-0.382	2198	2.55	0.569
0.26	-0.129	0.345	-0.039	-0.552	-0.395	2160	3.45	0.549
0.28	0.140	0.428	-0.096	-0.616	-0.369	2179	4.95	0.530
0.30	0.296	0.471	-0.140	-0.642	-0.346	2149	6.11	0.540
0.32	0.454	0.476	-0.168	-0.653	-0.290	2144	7.38	0.555
0.34	0.422	0.471	-0.152	-0.651	-0.300	2083	8.30	0.562
0.36	0.554	0.509	-0.114	-0.692	-0.287	2043	9.18	0.563
0.38	0.254	0.499	-0.105	-0.645	-0.341	2009	9.92	0.562
0.40	0.231	0.497	-0.105	-0.647	-0.333	1968	9.92	0.604
0.42	0.120	0.518	-0.135	-0.612	-0.313	1905	9.09	0.634
0.44	0.035	0.544	-0.142	-0.583	-0.286	1899	9.25	0.627
0.46	-0.077	0.580	-0.147	-0.563	-0.285	1863	8.98	0.642
0.48	-0.154	0.611	-0.154	-0.552	-0.293	1801	8.96	0.653
0.50	-0.078	0.638	-0.161	-0.565	-0.259	1768	9.06	0.679
0.55	-0.169	0.707	-0.179	-0.539	-0.216	1724	8.29	0.710
0.60	-0.387	0.698	-0.187	-0.506	-0.259	1629	8.24	0.707
0.65	-0.583	0.689	-0.159	-0.500	-0.304	1607	7.64	0.736
0.70	-0.681	0.698	-0.143	-0.517	-0.360	1530	7.76	0.743
0.75	-0.717	0.730	-0.143	-0.516	-0.331	1492	7.12	0.740
0.80	-0.763	0.757	-0.113	-0.525	-0.302	1491	6.98	0.742
0.85	-0.778	0.810	-0.123	-0.529	-0.283	1438	6.57	0.758
0.90	-0.837	0.856	-0.130	-0.512	-0.252	1446	7.25	0.754
0.95	-0.957	0.870	-0.127	-0.472	-0.163	1384	7.24	0.752
1.00	-1.112	0.904	-0.169	-0.443	-0.200	1391	6.63	0.756
1.10	-1.459	0.898	-0.147	-0.414	-0.252	1380	6.21	0.792
1.20	-1.437	0.962	-0.156	-0.463	-0.267	1415	7.17	0.802
1.30	-1.321	1.000	-0.147	-0.517	-0.219	1429	7.66	0.796
1.40	-1.212	1.000	-0.088	-0.584	-0.178	1454	9.10	0.790
1.50	-1.340	0.997	-0.055	-0.582	-0.165	1490	9.86	0.788
1.60	-1.353	0.999	-0.056	-0.590	-0.135	1513	9.94	0.787
1.70	-1.420	0.996	-0.052	-0.582	-0.097	1569	9.55	0.789
1.80	-1.465	0.995	-0.053	-0.581	-0.058	1653	9.35	0.827
1.90	-1.500	0.999	-0.051	-0.592	-0.047	1707	9.49	0.864
2.00	-1.452	1.020	-0.079	-0.612	-0.019	1787	9.78	0.895

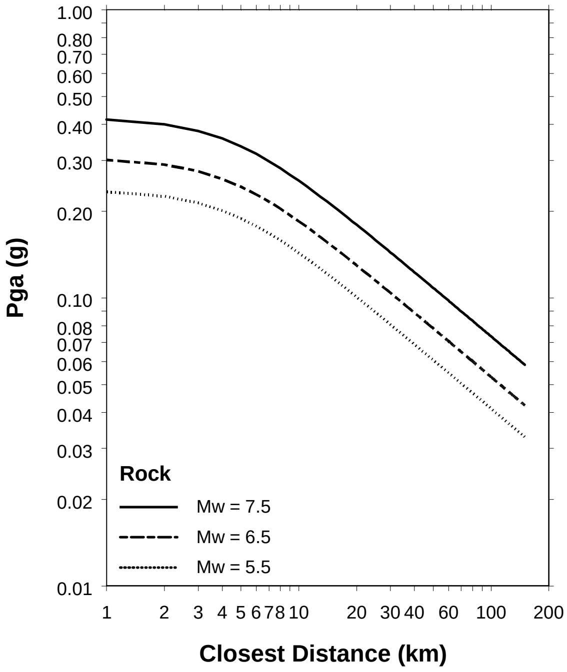


Figure 4. Curves of peak acceleration versus distance for magnitude 5.5, 6.5 and 7.5 earthquakes at rock sites

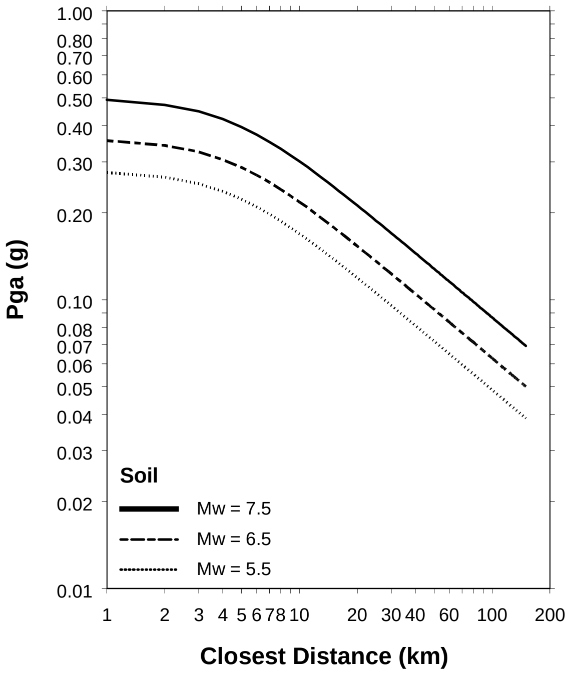


Figure 5. Curves of peak acceleration versus distance for magnitude 5.5, 6.5 and 7.5 earthquakes at soil sites

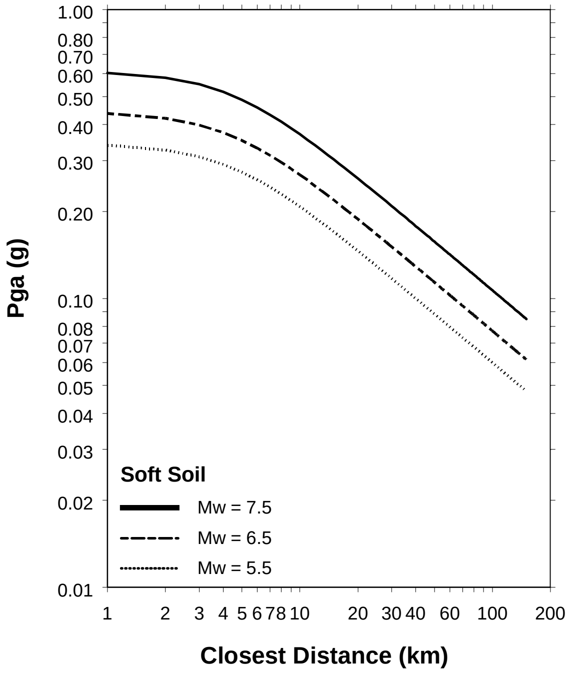


Figure 6. Curves of peak acceleration versus distance for magnitude 5.5, 6.5 and 7.5 earthquakes at soft soil sites

Comparison with Other Recent Ground Motion Relationships

The estimate equations developed in this study were compared to those recently developed by Boore et al. (1997), Campbell (1997), Sadigh et al. (1997), Spudich et al. (1997) and finally Ambraseys et al. (1996). The equations of Boore et al. and Ambraseys et al. divided site classes into four groups according to shear wave velocities. Campbell's equations pertain to alluvium (or firm soil), soft rock and hard rock. Sadigh et al. and Spudich et al. state that their equations are applicable for rock and soil sites.

The attenuation of PGA and PSA at 0.3 and 1.0 s for $M_w = 7.4$ for rock and soil sites are compared in Figures 7-9, 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 reasonable because different databases, regression models and analysis methods, different definitions for source to site distance and magnitude parameters among the relationships are contained in each model.

For some parameters and especially for PGA, there are numerous published attenuation equations for use in any particular engineering application. Atkinson and Boore (1997) showed the differences between attenuation characteristics in western and eastern USA for stable intraplate and interplate regions. Nevertheless, differences among attenuation of strong motions from one region to another have not been definitely proven. Because of this reason it is preferable to use attenuation equations that are based on the records taken from the region in which the estimation equations are to be applied.

Sensors comprising the national or other strong motion networks in Turkey are oriented so that their horizontal axes match the N-S and the E-W directions. Whereas Figure 2 illustrates the larger of these two components as a function of distance, it may not represent the largest horizontal acceleration that occurred before the cessation of the ground motion. The value of the absolute maximum acceleration in whichever direction can be determined by monitoring through a simple book-keeping procedure for the size of the resultant horizontal component, and then resolving all pairs to the direction of that largest component once it is known. At variance with the customary practice, we call this component the "random" horizontal component. In Figure 10, the difference in the predictive power of the regression equations derived from both of these definitions is illustrated for $M_w = 7.4$, and compared against the Kocaeli measurements. We believe that both sets yield essentially the same results. With the differences between the mean or the standard deviation curves substantially less than the value of ln (σ) itself, an improvement in accuracy does not appear to be plausible between the definitions of maximum horizontal acceleration.

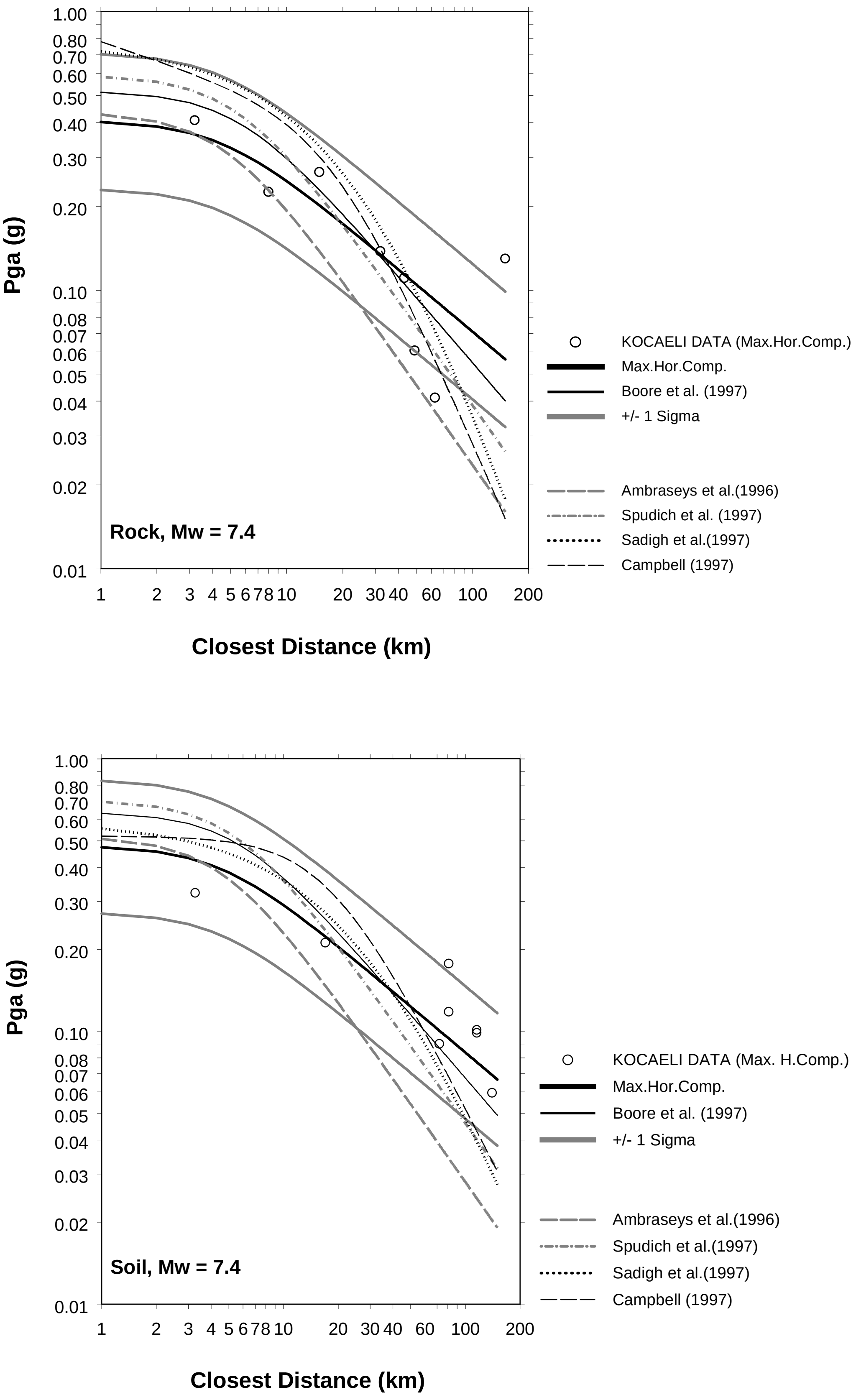


Figure 7. Curves of peak acceleration versus distance for magnitude 7.4 earthquake at rock and soil sites

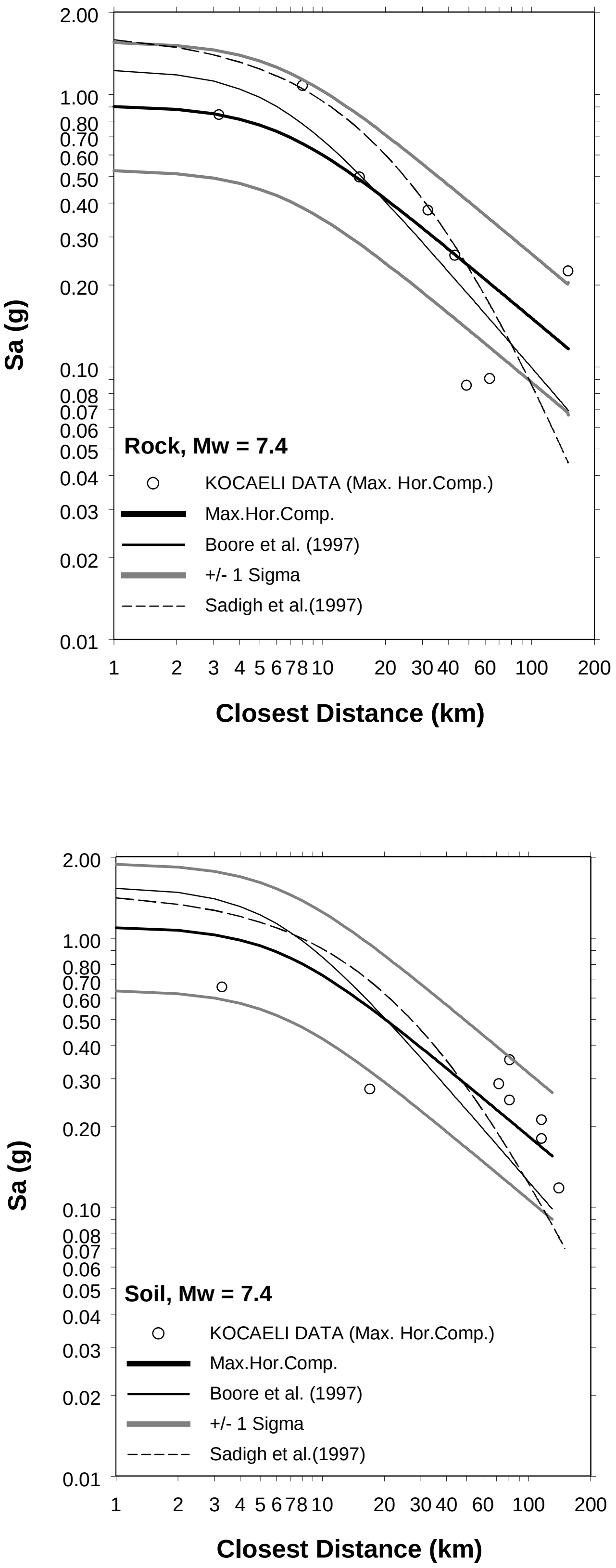
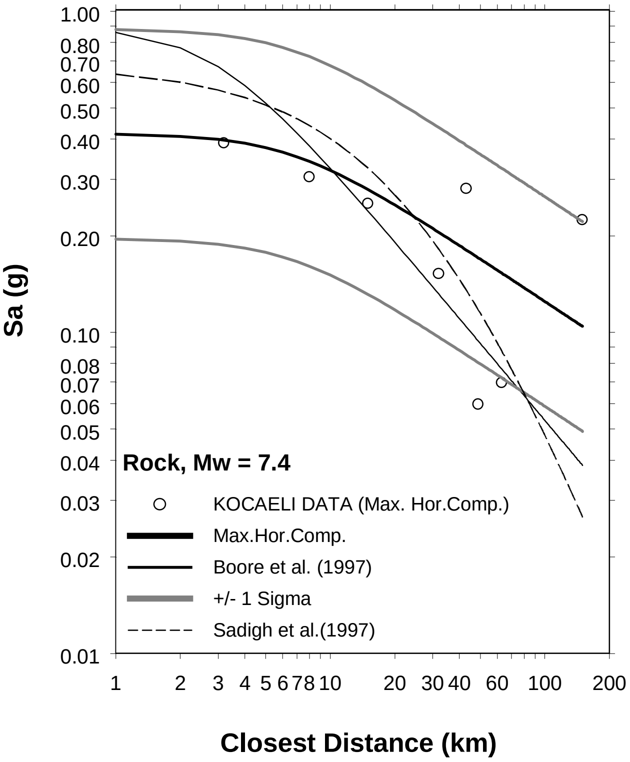


Figure 8. Curves of spectral acceleration at T = 0.3 s versus distance for a magnitude-7.4 earthquake at rock and soil sites



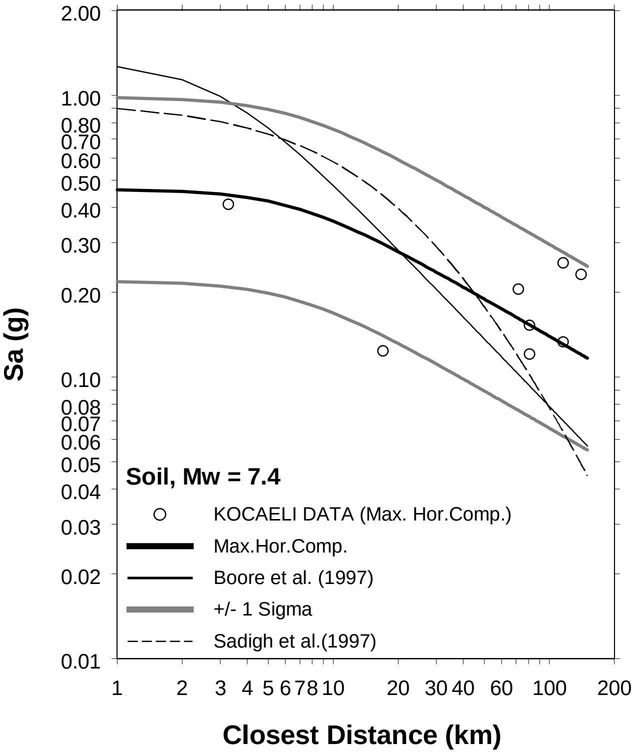


Figure 9. Curves of spectral acceleration at T = 1.0 s versus distance for a magnitude-7.4 earthquake at rock and soil sites

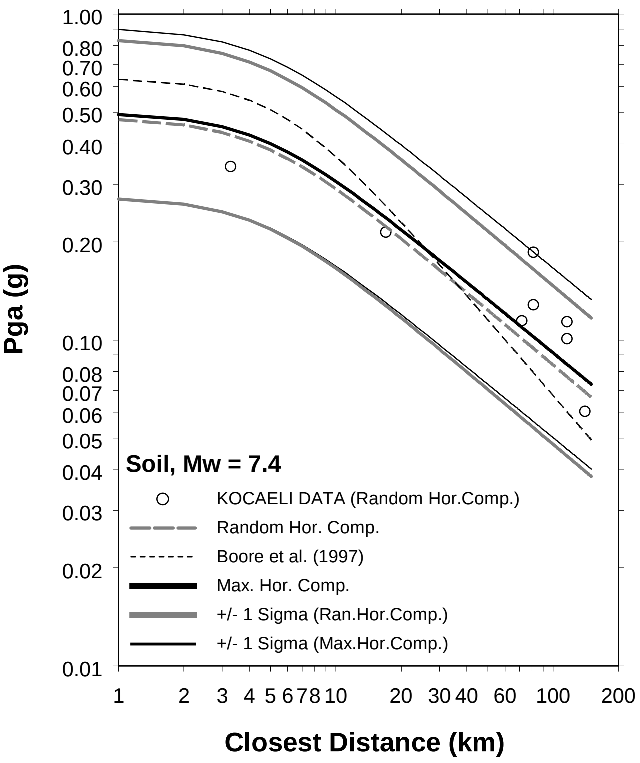


Figure 10. Differences caused by using the larger of the two horizontal components or the component in the direction of the largest resultant

Uncertainty and Reliability

Uncertainty is a condition associated with essentially all aspects of earthquake related science and engineering. The principle sources of uncertainty lie in the characterization of site geology, calculation of closest distances, determination of seismic shaking properties, and in the geotechnical properties of earthquake motion monitoring sites. The regression analysis is based on stochastic analysis method thus the obtained attenuation formula contains unavoidable errors. These uncertainties, for the most part stemming from the lack of and/or the imperfect reliability of the specific supporting data available, affect all analytical methods and procedures applied to the derivation of all aforementioned parameters.

The attenuation relationships presented in this study cannot, and do not, eliminate these uncertainties. However through the use of nonlinear regression analysis, it provides a more sophisticated and direct approach to address the uncertainties than do traditional linear analysis procedures. The results we have presented in tabular and graphical form become meaningful only in the context of the error distributions that are associated with each variable. In general, our results possess larger deviations in comparison with, e.g., Boore et al. (1997). This is plausible because of the smaller number of records from which they have been derived. In view of the limited number of records utilized in this study it may not be appropriate to expect the distributions to conform to the normal distribution. We do this only as a vehicle that permits a direct comparison to be made between our results and those of Boore et al. (1997).

Discussion and Conclusions

The recommended attenuation relationships presented in detail in this paper through Table 3 and illustrated in Figures 4-6 are considered to be appropriate for the estimation of horizontal components of peak ground acceleration, and 5 percent damped pseudo acceleration response spectra for earthquakes with magnitude in the range M_w 5 to 7.5 and r_{cl}<150 km for soft soil, soil and rock site conditions in active tectonic regions of Turkey. The database from which these estimates have been drawn is not pristine. It is handicapped not only because of the sheer dearth of records but also because of their poor distribution, arbitrary location, near-total lack of knowledge of local geology, and possible interference from the response of buildings where the sensors have been stationed. We have excluded aftershock data, and omitted records with peaks of less than about 0.04 g. It is shown in Table 1 that more than half of the records have been recovered from two M 7+ events that occurred in 1999. Inevitably, the regression expressions are heavily imbued with that data proper. A point of generalization is that, in general, the database causes larger margins of error in the estimates. This is more noticeable for spectral accelerations at longer periods.

When we compare our equations with other attenuation relationships not developed specifically from recordings in Turkey, it is concluded that they overestimate the peak and spectral acceleration values for up to about 15-20 km. Trends of our curves are generally above these curves for larger distances because for our expressions the fall-off trend is less strong. We surmise that clipping the minimum peak acceleration at 0.04 g is the cause of this trend. Among the other attenuation relationships we have used for comparison the equations by Ambraseys et al. (1996) for European earthquakes yields the best match with our equations. Whether this is caused by the fact that the Ambraseys study utilized data recorded also in Turkey cannot be answered except on a conjectural basis. But this comparison clearly serves as a reminder that there exists little support for the carefree import of attenuation curves from other environments for use in important engineering applications elsewhere.

It is a truism that, as additional strong motion records, shear wave velocity profiles for recording sites, and better determined distance data become available for Turkey, the attenuation relationships derived in this study can be progressively modified and improved, and their uncertainties reduced.

Acknowledgments

The authors acknowledge with gratefulness the help of Sinan Akkar, Altuğ Erberik and Tolga Yılmaz in the Earthquake Engineering Research Center at Middle East Technical University (METU/EERC). Sincere thanks are extended also to Zahide Çolakoğlu, Tülay Uğraş and Uluğbey Çeken of the General Directorate of Disaster Affairs, Earthquake Research Department for providing references and necessary data.

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