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Strong motion attenuation relationship for Turkey—a different perspective

Kamil Kayabali · Turgay Beyaz

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Abstract For Anatolian earthquakes, there are insufficient strong motion data from rock sites to model an attenuation relationship for Turkey. This necessitates the use of records from soil sites, which are significantly affected by amplification. In order to include soil site data in the attenuation analyses, boreholes were drilled at 64 recording stations on soil sites. After removing the effects of soil amplification, rock site and soil site data were combined to establish an attenuation relationship. Various models were tested through regression analyses using moment magnitude, epicentral distance and threshold peak horizontal ground acceleration. A new attenuation relationship is modeled for Turkey.

Keywords Attenuation relationship · Site amplification · Shear wave velocity · Strong ground motion · Downhole seismic

Résumé Pour les séismes d'Anatolie, il y a trop peu de données relatives aux mouvements forts enregistrés au rocher pour établir une loi d'atténuation propre à la Turquie. Ceci nécessite l'usage d'enregistrements issus de sites correspondant à des sols sur substratum, affectés de façon significative par une amplification. Afin d'inclure les données issues de ces sites dans les analyses d'atténuation, des forages ont été réalisés sur 64 de ces sites. Après avoir supprimé les effets d'amplification, les données issues des enregistrements au rocher et des sites correspondant à des sols sur substratum ont été combinées pour établir une loi d'atténuation. Différents modèles ont été testés avec des analyses de régression se référant à la magnitude de moment, la distance épicentrale et l'accélération seuil horizontale de pic. Une nouvelle loi d'atténuation a été établie pour la Turquie.

Mots clés Loi d'atténuation · Amplification de site · Vitesse des ondes de cisaillement · Mouvement fort · Mesure sismique en forage

K. Kayabali (✉)
Geological Engineering Department, Ankara University, Ankara, Turkey
e-mail: kayabali@eng.ankara.edu.tr

T. Beyaz
Geological Engineering Department, Pamukkale University, Denizli, Turkey

Introduction

Peak ground acceleration is one of the most important parameters in designing earthquake resistant structures. In view of the cost of large-scale engineering structures like dams and power plants, it is crucially important to select the best value for peak horizontal ground acceleration. Over-estimating this parameter would inflate the cost of a structure while under-estimating it could result in malfunctions, possibly with catastrophic outcomes. Selecting this input parameter pertinent to earthquake loading is challenging for geotechnical engineers.

The seismic energy released in an earthquake propagates as elastic waves. The amount of energy carried by these waves is commonly measured as some fraction of ground acceleration. The load an earthquake imposes on a structure is referred to as the base shear (UBC 1988). Peak horizontal ground acceleration, which is obtained from the so-called attenuation equation for seismic energy, is one of the two input parameters required to compute base shear.

In the absence of an attenuation relationship designed for a particular region, foreign attenuation relationships are

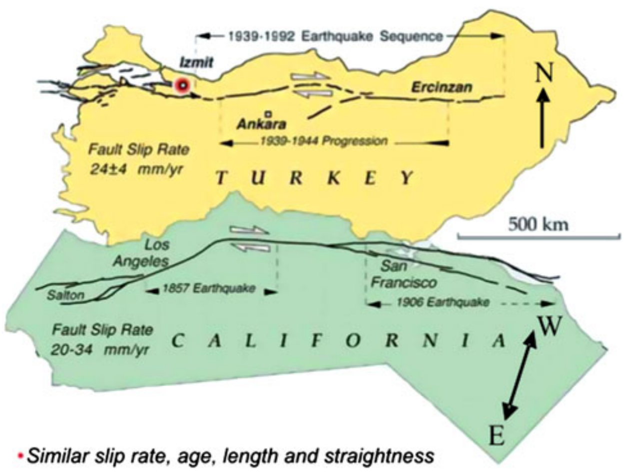

Fig. 1 A comparison between the North Anatolian and San Andreas faults (USGS 2000)

often used (i.e. designed for a different but seismo-tectonically similar region). By the mid-1990s, engineers in Turkey relied upon imported relationships (e.g., Joyner and Boore 1988; Campbell 1988; Sabetta and Pugliese 1987; Fukishima and Tanaka 1990); those developed for the western part of North America were generally used because of the similarity between the seismo-tectonic features of the San Andreas and North Anatolian faults (Fig. 1). However, despite this seismo-tectonic similarity, the slip rates and physiographical features of the two fault systems appear to be somewhat different (Ketin 1976). The authors also suggest that strong motion in western North America attenuates more rapidly than it does in Turkey. In addition, the crustal features of the two regions are probably different, although this may not be true because to date only a small part of the Turkish crustal structure has been studied.

Turkish attenuation relationships date back only to the mid-1990s (e.g., Inan et al. 1996; Aydan et al. 1996; Gulkan and Kalkan 2002; Ulusay et al. 2004; Ozbey et al. 2004). Nearly half of the strong motion recording stations operated by the Earthquake Research Center (working under the General Directorate of Disaster Affairs of Turkey) are located on soil sites in city centers, because of ease of operation and vandalism control.

Kayabali (2002) and Kayabali and Akin (2003) state that the dramatic variations of values predicted with domestic relationships are unequivocally due to the amplification effects of soil sites. Two case histories support this statement. First, the 27 June 1998 Ceyhan earthquake generated a PGA of 24 cm/s^2 (gal) on limestone in the village of Nacarli, 15 km away from the epicenter. A full 30 km away from the epicenter, however, the same earthquake produced a PGA of 122 gal on a soil site in Kilicli village (Gurbuz et al. 2000). Table 1 shows that the recording stations in the towns of Karatas and Iskenderun (36 and 59 km away from the epicenter, respectively) recorded a gradual decrease in PGA, whereas the site in Mersin, 79 km away from the epicenter, recorded a higher PGA (Fig. 2). The second example involves the devastating Golcuk earthquake of 17 August 1999 (Table 2 and Fig. 3). The bold numerals in Table 2 reflect site amplifications in the towns of Gebze, Darica, Goynuk and Fatih, as shown in Fig. 3.

Site amplification can be even greater when the period of the earthquake waves falls within the range of the soil period, which is analytically expressed as four times the height of the soil profile divided by the average shear wave velocity of the soil profile. Some soils underlying the City of Mexico amplified bedrock motion 8–52 times in the 1985 Mexico earthquake (McCall 2000).

Attenuation relationships for Turkey either do not take soil effects into account (e.g., Inan et al. 1996; Aydan et al. 1996) or do so by classifying the sites into general categories, such as rock sites, soil sites and soft soil sites, as was done by Ulusay et al. (2004). However, the authors

Table 1 A comparative example of site amplification: June 27, 1998 Ceyhan earthquake

Station	Date	Time (GMT)	a_{max} (cm/s^2)			Distance from epicenter (km)	Site conditions
			N–S	E–W	Vertical (z)		
Ceyhan	27.06.1998	13:55:53	**223.3**	**273.6**	86.5	**32**	**Soil**
Karatas	27.06.1998	13:55:53	28.5	33.1	19.7	36	Soil
Iskenderun	27.06.1998	13:55:53	14.8	15.5	11.8	59	Rock
Mersin	27.06.1998	13:55:53	**119.3**	**132.1**	22.1	**79**	**Soil**
Hatay	27.06.1998	13:56:11	**27.1**	**25.8**	12.4	**90**	**Soil**
Islahiye	27.06.1998	13:55:53	21.4	18.2	14.1	96	Soil
Kahraman Maras	27.06.1998	13:56:22	8.0	8.5	4.5	146	Soil
Elbistan	27.06.1998	13:56:30	4.7	5.2	2.4	208	Soil
Golbasi	27.06.1998	13:56:54	4.5	3.0	2.5	211	Soil

Bold numerals indicate a significant level of amplification

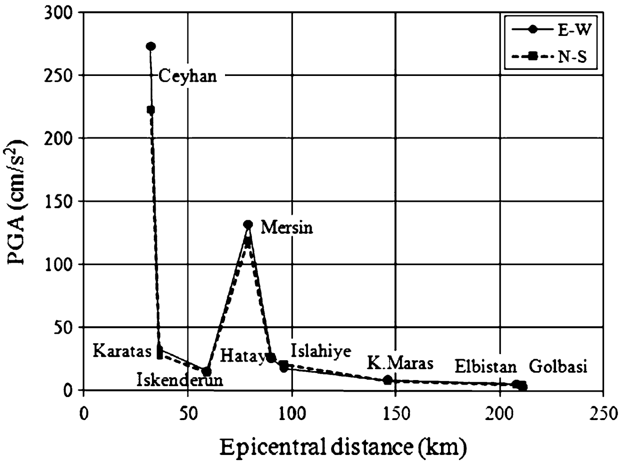

Fig. 2 Site amplification effects for the June 27, 1998 Ceyhan earthquake

feel strongly that because the response of a soil site is directly related to the period characteristics of the individual earthquake and the degree of amplification depends on the proximity of the predominant period of the input motion to the period of the soil site, generalizing a soil site into a single category is misleading. Furthermore, if records from a soil site are used to develop attenuation relationships, those records must be evaluated on an event by event basis.

Developing a reliable attenuation relationship for a region requires substantial data from rock sites. There are not enough strong motion recording stations in Turkey and nearly half of the existing stations are on soil sites. Thus it appears inevitable that records from soil sites must be used to develop an attenuation relationship for Turkey. In this paper, strong motion data collected from soil sites are processed with special techniques so that they can be treated as rock site data. Ultimately, peak horizontal ground acceleration is defined as a function of moment magnitude and distance.

Data acquisition

The data used in this study come from two main sources: strong motion data and field data.

Strong motion data

The strong motion data used in this study were obtained from the following research agencies: General Directorate of Disaster Affairs, Earthquake Research Division (ERD), Bogazici University Kandilli Observatory and Earthquake Research Center (KRDAE) and Istanbul Technical University (ITU). The records cover the period from 1976 to 2004 for earthquake magnitudes (M) greater than or equal to 4.0. All records of individual events were carefully examined and plotted before being included in the analyses. Likely errors arising from sources such as malfunctions of the recording device, testing signals and baseline error were removed using appropriate filters or techniques. Because this investigation focuses on horizontal ground acceleration, vertical components were excluded and only N–S and E–W components were used.

Of some 3,500 records collected by ERD at 140 stations between 1976 and 2005, only 516 files were found to be

Table 2 A comparative example of site amplification: August 17, 1999 Golcuk earthquake

Station	Date	Time (GMT)	a_{max} (cm/s^2)			Distance from epicenter (km)	Site conditions
			N–S	E–W	Vertical (z)		
Adapazari	17.08.1999	00:01:37	–	407	259	9	Rock
Izmit	17.08.1999	00:01:37	171	219	139	10	Rock
Yarimca	17.08.1999	00:01:37	230	322	–	18	Soil (?)
Iznik	17.08.1999	00:01:37	92	123	–	43	Soil
Gebze	17.08.1999	00:01:37	**284**	**141**	–	45	Soil (?)
Darica	17.08.1999	00:01:37	**211**	**134**	–	52	Soil
Heybeliada	17.08.1999	00:01:37	56	110	–	75	?
Goynuk	17.08.1999	00:01:37	**138**	**118**	130	77	?
Istanbul	17.08.1999	00:01:37	61	43	36	82	Rock
Levent	17.08.1999	00:01:37	41	36	–	88	Rock (?)
Fatih	17.08.1999	00:01:37	**189**	**162**	–	90	Soil
Bursa (Tofas)	17.08.1999	00:01:37	**101**	**100**	–	94	Soil
Bursa (Sivil Sav.)	17.08.1999	00:01:37	54	46	26	95.5	?
Yesilkoy	17.08.1999	00:01:37	90	84	–	99	Soil

Bold numerals indicate a significant level of amplification

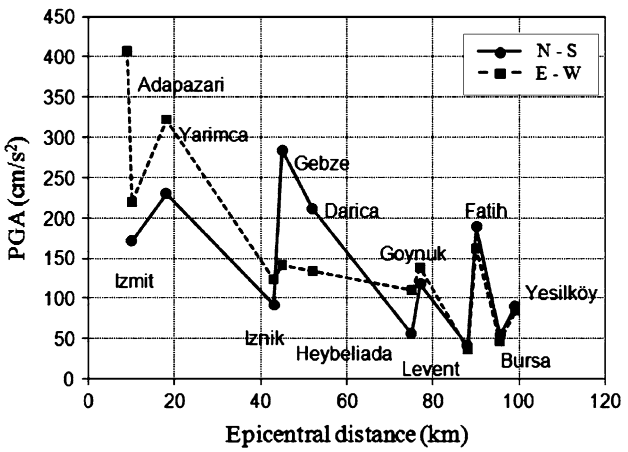

Fig. 3 Site amplification effects for the August 17, 1999 Golcuk earthquake

suitable while only three and one files were acquired from the KRDAE and ITU stations, respectively.

The threshold maximum ground acceleration for the analyses was initially set at 20 cm/s^2 for both rock and soil sites. However, as filtered strong motion data from soil sites sometimes reduced maximum ground acceleration to under 10 cm/s^2 at bedrock, the threshold was dropped to 10 cm/s^2.

Although epicentral distances for individual events were available in the strong motion data files, these numbers were double-checked by independently determining epicentral distances from the arrival times of P and S waves. Events with epicentral distances (R) greater than 200 km were excluded from the study. The relationship to be developed is therefore valid for earthquakes with $M \geq 4.0$, PGA $\geq$ 10 cm/s^2 and $R < 200$ km earthquakes.

Field data

Most soil amplification takes place in the upper 60 m (200 ft) of a soil column (Seed et al. 1999). Because of this, small-diameter investigation boreholes were drilled up to 100 m depth at deep soil sites using rotary drilling techniques. Drilling operations stopped when bedrock was encountered at <100 m. The locations of the 64 boreholes with depths from 25 to 100 m are given in Fig. 4. About 4,500 m of borehole was drilled in total and each hole was logged for stratigraphic horizons (Fig. 5). Immediately after drilling, the borehole was cased with a 2″ PVC pipe for downhole seismic measurements. The pipes were then backfilled with coarse material to ensure good shear wave velocity acquisition.

Of several borehole seismic exploration techniques considered (e.g., Telford et al. 1990; Krinitzsky et al. 1993), the downhole technique was preferred because of its low cost, speed and use of a mechanical energy source (Auld 1977).

Both compressional (P) and shear (S) wave velocities were recorded at each hole with a 3-component probe as a receiver inside the borehole and an energy source on the ground surface (Fig. 6). The energy source had a 100 kg piece of solid iron, which acted as a pendulum-like mechanism. The mass was connected with a 2 m long arm to a bar, allowing the solid mass to move in only one direction. In order to generate strong S waves reaching as deep as 100 m, the solid mass was pulled and released so that it struck the wooden plate underneath the wheels of the drill rig. P waves were collected so that they could be converted into S waves when low velocity levels were encountered.

Downhole seismic recordings were taken at 2 m intervals in the upper 30 m of each hole. Below this,

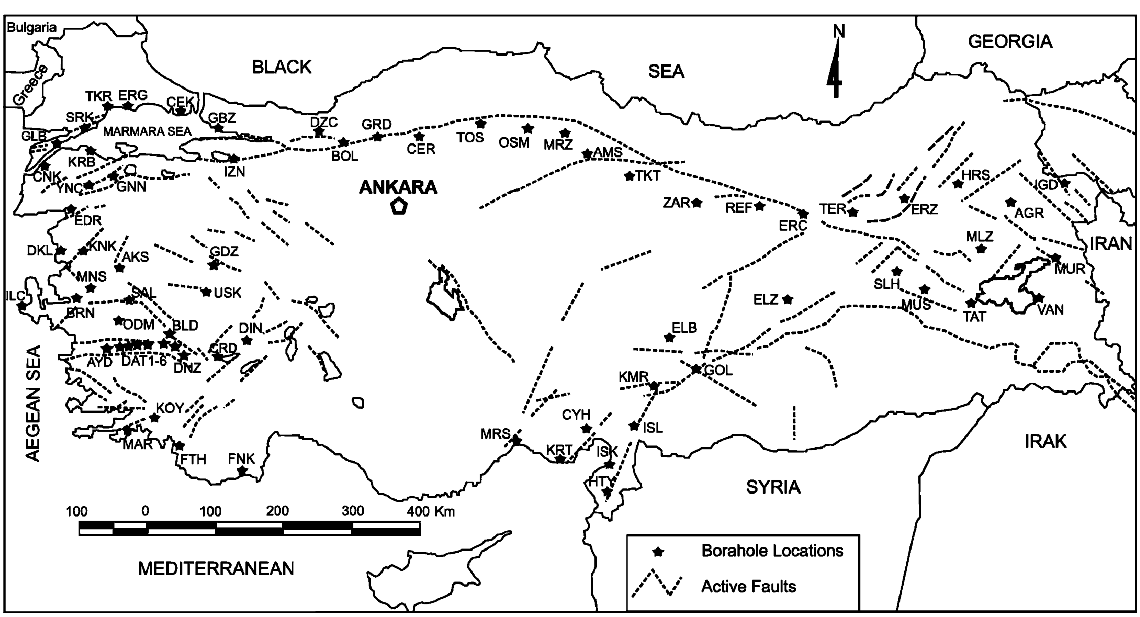

Fig. 4 Location of boreholes drilled at soil sites

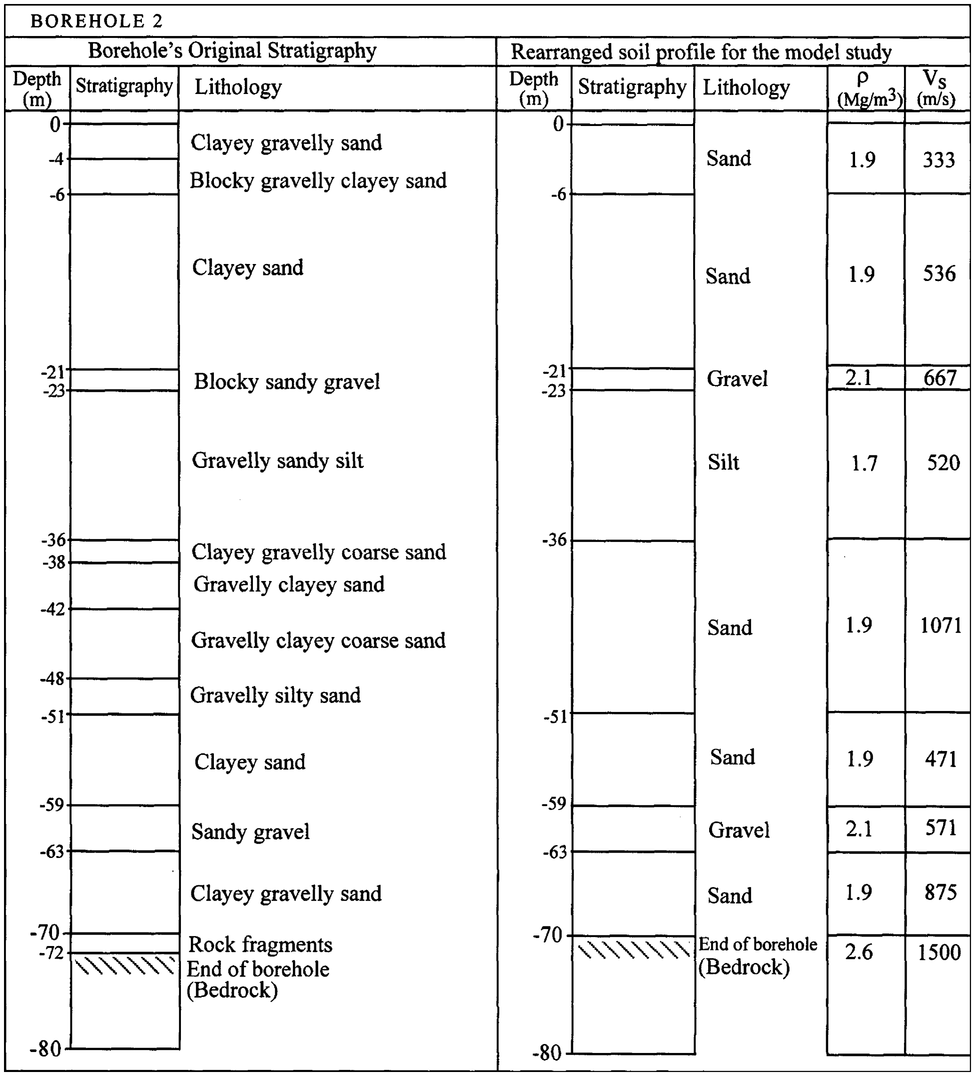

Fig. 5 Well logging obtained in situ and adjusted or site response analysis

measurements were taken at 5 m intervals due to the difficulties of repeating the tests. The raw data obtained were processed by using simple velocity, time and distance relationships; each horizon in a borehole was then assigned an S wave velocity (Fig. 5). Also shown in Fig. 5 are the densities of the soil horizons, which are required for site response analyses. Soil densities were assigned as approximate values depending on the soil types (Table 3).

Methods

Magnitude conversions

Developing an attenuation relationship usually requires one kind of earthquake magnitude. Because Anatolian earthquakes were recorded with different magnitude scales, a series of magnitude conversions were necessary. Magnitude scales other than the moment magnitude (M_w) saturate at certain values (Kanamori 1977; Hanks and Kanamori 1979); because of this, any attenuation relationship developed should use a magnitude scale capable of determining the sizes of large earthquakes. As an example, although both the 1906 San Francisco and the 1960 Chilean earthquakes were recorded as $M_S = 8.3$ events, their moment magnitudes were calculated as 7.9 and 9.5, respectively (Boore 1977; Coduto 1998).

Conversions from surface wave magnitude (M_S), Richter's local magnitude (M_L) and duration magnitude (M_D) into moment magnitude were carried out using Eqs. 1 (Zaré and Bard 2002), 2 (Kalafat 2002), 3 (Yilmazturk and Bayrak 1997):

$$M_w = 0.76M_L + 1.13 \quad (1)$$

$$M_S = (M_D - 1.59)/0.67 \quad (2)$$

$$M_S = 0.554M_w + 3.24 \quad (3)$$

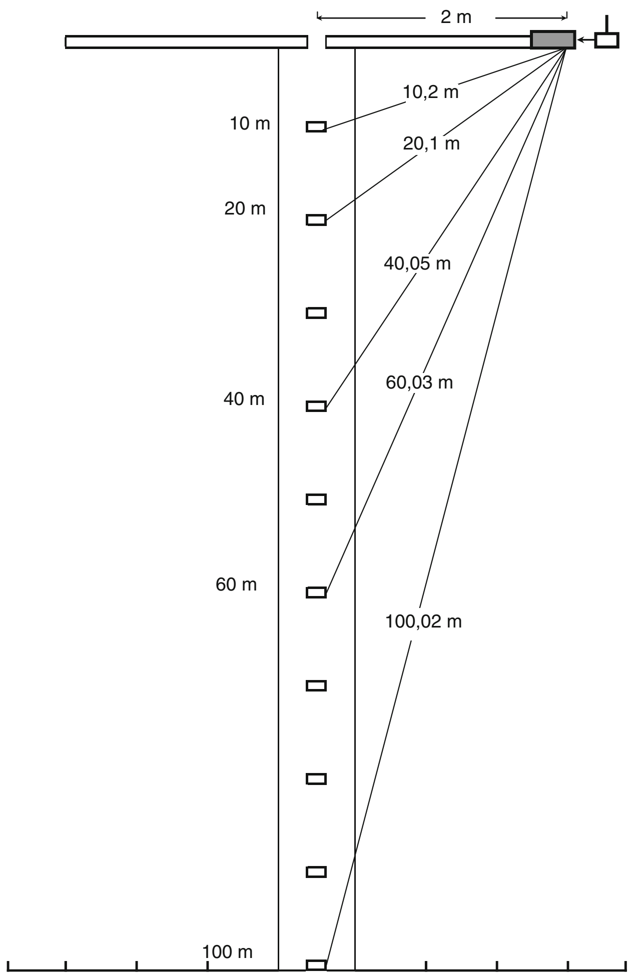

Fig. 6 Schematic illustration of the down-hole technique used for field investigation

Table 3 Approximate densities for different soil types proposed by Tatsuoka et al. (1980)

Soil type reported	Density (mg/m^3)	D_{50} (mm)
Surface soil	1.7	0.02
Gravel	2.1	>0.6
Sand	1.9	0.25
Coarse sand	1.9	0.3
Medium sand	1.9	0.25
Fine sand	1.9	0.20
Silt	1.7	0.02
Silty sand	1.9	0.10
Sandy silt	1.7	0.04

General form of attenuation relationships

In order to quantify the effects of earthquakes at a certain location, ground motion is usually defined with respect to acceleration, velocity and displacement. Because the dynamic forces that affect structures are due to horizontal shaking, peak horizontal ground acceleration has been the major parameter used to develop attenuation relationships (Campbell 1981; Joyner and Boore 1981).

The attenuation of seismic ground motion is a function of absorbance of seismic energy by the earth layers through which elastic waves propagate. As the seismic energy propagates from the focus, the amplitudes of body waves (P and S) reduce with $1/R$ (where R is the epicentral distance). The amplitudes of surface waves, on the other hand, (predominantly Raleigh waves) reduce according to $1/(R)^{0.5}$; thus, distance is considered one of the most important inputs for any attenuation relationship. The second component of such a relationship is earthquake magnitude. The larger the earthquake, the further the effects are felt. With additional parameters, such as site characteristics, attenuation relationships are usually expressed as

$$Y = f(M, R, P_i) \tag{4}$$

where Y is the strong motion parameter (to be defined); M is the magnitude; R is the distance from the source of the earthquake and P_i is a parameter taking into account such effects as earthquake source, propagation path and local site conditions.

Relationships expressed in the form of (4) usually have a log-normal distribution, that is to say, the logarithm of the parameters has a normal distribution, and thus the regression analysis is performed over the logarithm of Y (Chiaruttini and Siro 1981; Sadigh et al. 1993). Some researchers, like Campbell and Bozorgnia (2003), suggest that strong ground motion parameters are better expressed with a ln-normal distribution.

ProShake computer code

Incorporating strong motion data from soil sites into an attenuation relationship requires a transformation procedure to filter soil site effects. This process is too lengthy to perform manually and involves extended mathematical operations. It is therefore necessary to use a computer code like ProShake (Idriss and Sun 1992), which was originally developed by Schnabel et al. (1972) and has since been refined several times. ProShake approximates nonlinear and inelastic soil behavior as equivalent linear behavior, using the frequency domain. This transformation of data requires a vertical soil profile including the type, thickness, density and shear wave velocity for each horizon in the profile, together with a seismic record.

ProShake transforms a seismic record on the top of a soil column and yields a record file for the bottom of the vertical soil profile used in the analysis (Fig. 7). When the bedrock surface is shallow, the bottom of the profile is bedrock. When the bedrock surface is located deeper, the

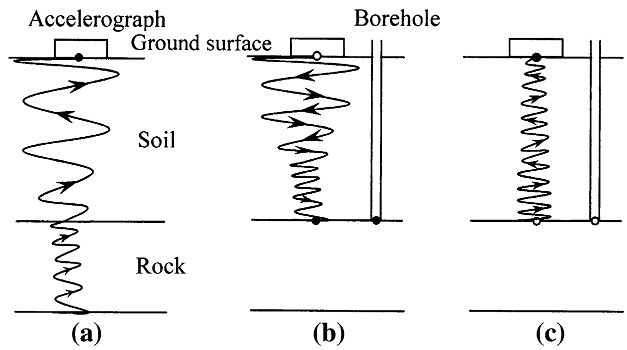

Fig. 7 Schematic illustration of data transformation through Pro-Shake. **a** Accelerograph record at top of a soil column; **b** transformation of seismic record to desired level; **c** carrying back the transformed record to the ground surface as it was recorded on a rock site

depth of the soil profile ranges from about 50 to 100 m, depending on the depth of the borehole at the soil site. The goal of this procedure is to acquire seismic records equivalent to those recorded at rock outcrops, by filtering the effects of soil. This process was applied to about 400 earthquake seismic records from soil sites.

Multiple regression analysis

The interrelationship among the variables affecting an event is investigated through regression analyses (Vardeman 1994), which indicate the variations with dependent variables as well as the best fit with the scatter of the distribution diagrams.

Multiple regression, defined as searching the relationship of multiple independent variables corresponding to a single dependent variable, is expressed in the following general form:

$$Y = a + b_1 * X_1 + b_2 * X_2 + \cdots + b_n * X_n + \varepsilon \quad (5)$$

where Y is the dependent variable; X_i is the independent variables; a and b_i are the correction coefficients and ε is a constant. For regression analyses involving variables with different units (e.g., length-weight or length-acceleration), b_i coefficients are substituted with standard partial regression coefficients (β_i). The regression relationship of events involving only two independent variables is expressed as

$$Y = a + (\beta_1 * X_1) + (\beta_2 * X_2) + \varepsilon \quad (6)$$

where β_i stands for partial regression coefficients. This statement implies that 1 SD with X_1 yields a standard deviation with the dependent variable Y equivalent to β_1, and 1 SD with X_2 yields a standard deviation with the dependent variable Y equivalent to β_2.

Because multiple regression analyses are long and time consuming, they are usually done with computer programs. This research used the program SPSS (SPSS 1998) which computes various coefficients used in regression analyses and applies tests such as F, t and ANOVA. In order to develop an attenuation relationship for seismic energy in Turkey, various models were designed and assessed with SPSS. The correlation coefficients (level of confidence) were computed for all variables. β_i was determined for the model equations that appeared appropriate, and its influence (negative or positive) over the model equations was investigated.

Development of the attenuation relationship

Every seismo-tectonic region has its own inherent characteristics with regard to the absorption of seismic energy, so applying an attenuation relationship developed for other regions to a specific region may lead to major errors (Trifunac and Brady 1975). For this reason, it is best to develop region-specific relationships.

The peak horizontal ground accelerations, both from rock sites and from processed soil sites show log-normal distributions (Fig. 8) and so regression analyses need to be performed over the logarithm of acceleration.

Peak horizontal ground accelerations are positively correlated with magnitude (Fig. 9). Also, the log–log relationship of the same parameters (i.e., PGA and M) is positive (Fig. 10). The relationship between PGA and epicentral distance (R) is negative, but log(PGA) vs. log(R) has a more meaningful distribution (Fig. 11).

In order to obtain the most suitable attenuation relationship, representative of data from rock sites and the processed soil data, a series of models were tested (Table 4). Various combinations of data used in these model trials are defined in Table 5. With the 6 combinations of data groups and 16 model types, model equations were generated for a total of 96 different coefficients. The generated models were tested using least squares, and the following four equations were found to be most suitable for the overall strong motion data:

$$\log A = \beta_0 + (\beta_1 \log M) + (\beta_2 \log R) \quad (7)$$

$$\log A = \beta_0 + (\beta_1 M^2) + (\beta_2 \log(R + 7)) \quad (8)$$

$$\log A = \beta_0 + (\beta_1 M^2) + (\beta_2 \log(R + 1)) \quad (9)$$

$$\log A = \beta_0 + (\beta_1 M) + (\beta_2 (\log(R^2 + 200^2)^{0.5})) + (\beta_3 R) \quad (10)$$

More refinements were carried out over these last four equations and Eq. 9 was found to be the most statistically meaningful with the highest confidence level:

$$\log A = \beta_0 + (\beta_1 M^2) + (\beta_2 \log(R + 1))$$

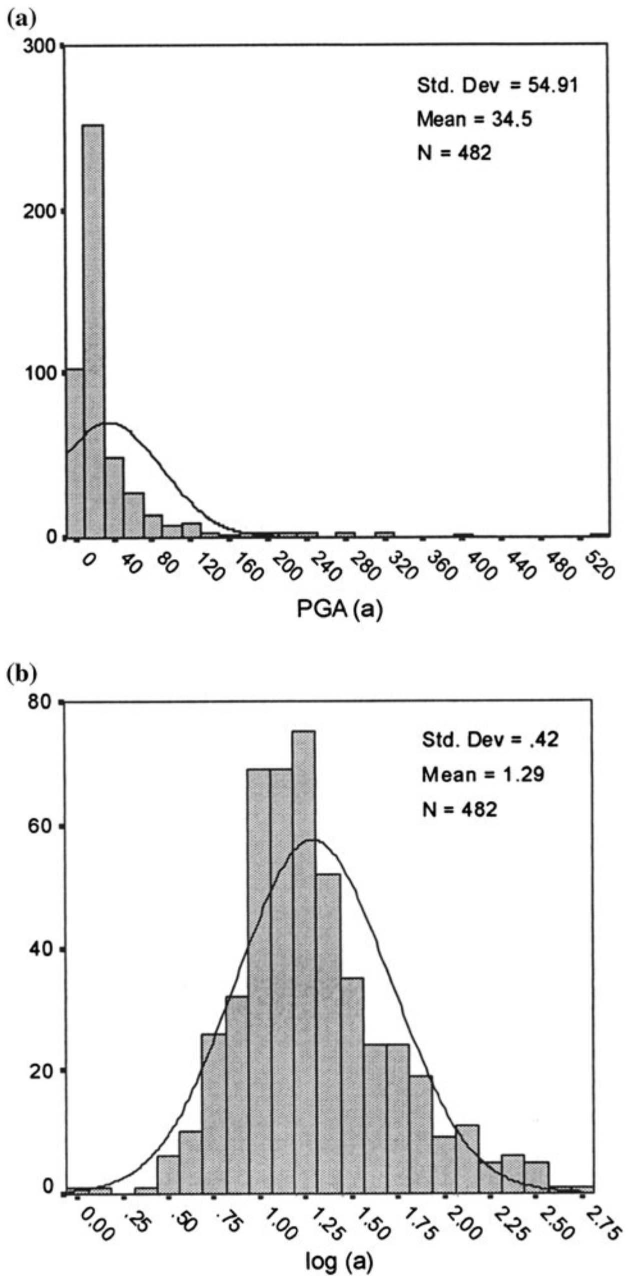

Fig. 8 Histogram of peak horizontal ground accelerations from all sites in Turkey. **a** Inappropriate normal distribution; **b** log-normal distribution (units are cm/s^2)

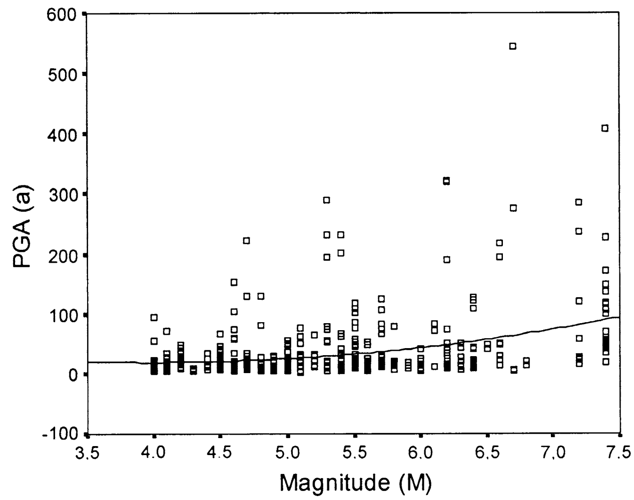

Fig. 9 Peak horizontal ground acceleration versus magnitudes for data from Turkey (magnitudes as recorded)

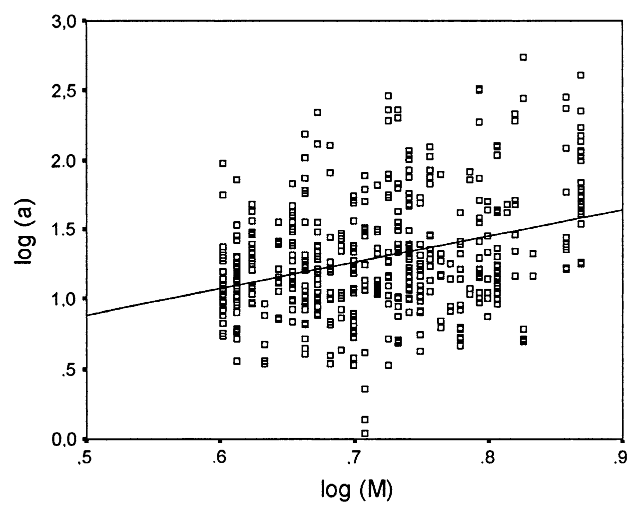

Fig. 10 Logarithmic PGA vs. logarithmic magnitude; all data from Turkey with magnitudes as recorded

where A is the peak horizontal ground acceleration (cm/s^2), M is the moment magnitude (M_w), R is the epicentral distance (km), $\beta_0 = 2.08$, $\beta_1 = 0.0254$ and $\beta_2 = -1.001$. The standard deviation (σ) for this relationship is 0.712.

Assessment of the new relationship compared with others

A list of domestic attenuation relationships using Turkish strong motion data is given in Table 6. For the relationship developed by Aydan et al. (1996), the earthquakes of $3.5 \le M \le 7.3$ from 1969 to 1995 were used. These authors used 18 acceleration records, 4 from rock sites and 14 from soil sites. They also used an additional 32 events without acceleration records, for which acceleration values were estimated using magnitudes and intensity scales. Their relationship does not distinguish between the records from soil and rock sites. For some events, distance, PGA values and the standard deviation are unclear.

The relationship developed by Inan et al. (1996) used Turkish earthquake records from 1976 to 1996. They did not distinguish between rock and soil site data either. Their relationship yields unusually high PGA values, probably attributable to soil site effects. No detail is provided regarding the type of magnitude scale, the number of events or the number or type of strong motion data.

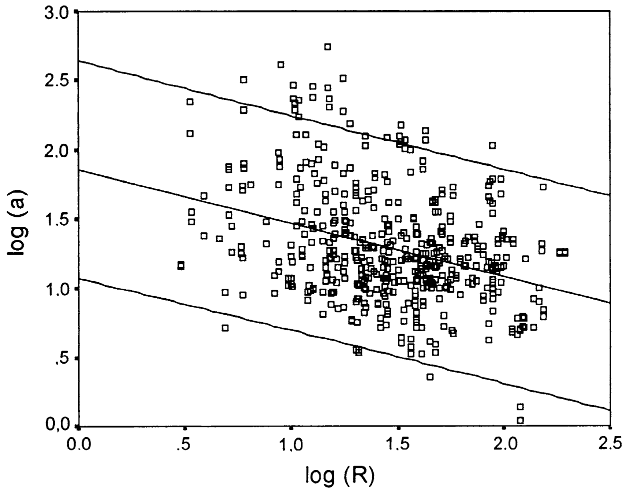

Fig. 11 Log (PGA) vs. log (*R*) for 95% confidence interval. The *middle curve* represents the average; the *upper* and *lower* ones stand for threshold values

Gulkan and Kalkan (2002) used 93 records for 18 earthquakes of $M_w \geq 5.0$ between 1976 and 1999. They included soil site data by using pseudo-spectral acceleration values with 5% damping ratios; they also categorized them into two classes as "soft soils" and "soils". The majority of their data came from a single event; the 1999 Golcuk earthquake. Ulusay et al. (2004) used 221 records from 122 earthquakes of $4.1 \leq M \leq 7.5$ between 1976 and 2003 with epicentral distances from 5 to 100 km. Soil effects significantly affect their relationships, but the soils were categorized as soft or stiff and had certain coefficients assigned to them.

The domestic relationships outlined above are plotted as PGA versus distance for $M = 5$ and $M = 6$ earthquakes in Figs. 12 and 13 for soil and rock sites, respectively. The relationships by Aydan et al. (1996), Inan et al. (1996) and Gulkan and Kalkan (2002) significantly overestimate PGA with respect to true strong motion data from both rock and soil sites. Ulusay et al. (2004) also overestimate PGA, although the discrepancy between predicted values and true records is not as high as in the aforementioned three domestic relationships. The magnitude scale used by Aydan et al. (1996) is M_S and it may be inappropriate to compare it to the M_w scale. In order to eliminate this problem for the curves of Aydan et al. (1996), the equivalent M_w values were used in Figs. 12 and 13. Because Inan et al. (1996) provide no magnitude scale, no specific magnitude conversion was applied for their relationship;

Table 4 Model equations tested for establishing an attenuation relationship

1	$\text{Log } Y = \beta_o + \beta_1 \text{ Log } R + \beta_2 \text{ Log } M + \varepsilon$
2	$\text{Log } Y = \beta_o + \beta_1 \text{ Log } R + \beta_2 M + \varepsilon$
3	$\text{Log } Y = \beta_o + \beta_1 R + \beta_2 \text{ Log } R + \beta_3 M + \varepsilon$
4	$\text{Log } Y = \beta_o + \beta_1 \text{ Log } R + \beta_2 M + \beta_3 \text{ Log } M + \varepsilon$
5	$\text{Log } Y = \beta_o + \beta_1 R + \beta_2 \text{ Log } R + \beta_3 M + \beta_4 \text{ Log } M + \varepsilon$
6	$\text{Log } Y = \beta_o + \beta_1 R + \beta_2 \text{ Log } R + \beta_3 \text{ Log } M + \varepsilon$
7	$\text{Log } Y = \beta_o + \beta_1 M^2 + \beta_2 \text{ Log}(R + 7) + \varepsilon$
8	$\text{Log } Y = \beta_o + \beta_1 M^2 + \beta_2 \text{ Log}((R^2 + 200^2)^{0.5}) + \beta_3 \text{ Log}(R + 2) + \varepsilon$
9	$\text{Log } Y = \beta_o + \beta_1 M^2 + \beta_2 \text{ Log}(R + 1) + \varepsilon$
10	$\text{Log } Y = \beta_o + \beta_1 M + \beta_2 \text{ Log}((R^2 + 200^2)^{0.5}) + \beta_3 R + \varepsilon$
11	$\text{Log } Y = \beta_o + \beta_1 \text{ Log}(R + 7) + \beta_2(10^{M}) + \beta_3 \text{ Log}(e^{M} - M) + \varepsilon$
12	$\text{Log } Y = \beta_o + \beta_1 \text{ Log}(R + 7) + \beta_2 \text{ Log}(e^{M} - M) + \varepsilon$
13	$\text{Log } Y = \beta_o + \beta_1 \text{ Log}(M^2) + \beta_2 \text{ Log}(R + 1) + \varepsilon$
14	$\text{Ln } Y = \beta_o + \beta_1 \text{ Ln}(R + 7) + \beta_2(10^{M}) + \beta_3 \text{Ln}(M + 7) + \varepsilon$
15	$\text{Ln } Y = \beta_o + \beta_1 \text{ Ln}(R + 7) + \beta_2 \text{ Ln}(10^{M}) + \beta_3 \text{ Ln}(M + 7) + \varepsilon$
16	$\text{Ln } Y = \beta_o + \beta_1 \text{ Ln } M + \beta_2(10^{M}) + \beta_3 \text{Ln}(R + 7) + \varepsilon$

Table 5 Properties of earthquake records used for model equations

Magnitude, M_w	Distance, R (km)	Acceleration, a (cm/s^2)	Type of acceleration(s)	Number of data, N
$4.0 \leq M_W \leq 7.4$	$0 < R \leq 200$	$a > 0$	N–S and E–W together	482
$4.0 \leq M_W \leq 7.4$	$0 < R \leq 200$	$a \geq 10$	N–S and E–W together	379
$4.0 \leq M_W \leq 7.4$	$0 < R \leq 200$	$a > 0$	Average of N–S and E–W	260
$4.0 \leq M_W \leq 7.4$	$0 < R \leq 200$	$a > 0$	Greater of N–S and E–W	255
$4.0 \leq M_W \leq 7.4$	$0 < R \leq 150$		N–S and E–W together	475
$4.0 \leq M_W \leq 7.4$	$0 < R \leq 150$	$a \geq 10$	N–S and E–W together	374

Table 6 Attenuation relationships for Turkey developed by other researchers

Attenuation relationship	σ	Reference
$\mathrm{PGA} = 2.8(\mathrm{e}^{(0.9M_\mathrm{S})}\mathrm{e}^{(-0.025R)} - 1)$	*	Aydan et al. (1996)
$\mathrm{PGA} = 10^{((0.65M)\ -\ (0.9\ \log(R))\ -\ 0.44)}$	*	Inan et al. (1996)
$\ln Y = -0.682 + 0.258(M_\mathrm{w} - 6) + 0.036(M_\mathrm{w} - 6)^2 - 0.562\ \ln(r) - 0.297\ \ln(V_\mathrm{S}/V_\mathrm{A})$	0.562	Gulkan and Kalkan (2002)
$r = \sqrt{r_\mathrm{cl}^2 + h^2}, V_\mathrm{A} = 1381$ and $h = 4.48$		
$\mathrm{PGA} = 2.18\mathrm{e}^{(0.0218(33.3M_\mathrm{w} - \mathrm{Re} + 7.8427\mathrm{S_A} + 18.9282\mathrm{S_B})}$	0.63	Ulusay et al. (2004)
$\log(Y_{ij}) = a + b(M_{wi} - 6) + c(M_{wi} - 6)^2 + d\log\left(\sqrt{R_{ij}^2 + h^2}\right) + eG_1 + fG_2$	**	Ozbey et al. (2004)

* Unknown or not given

** σ varies with different period values

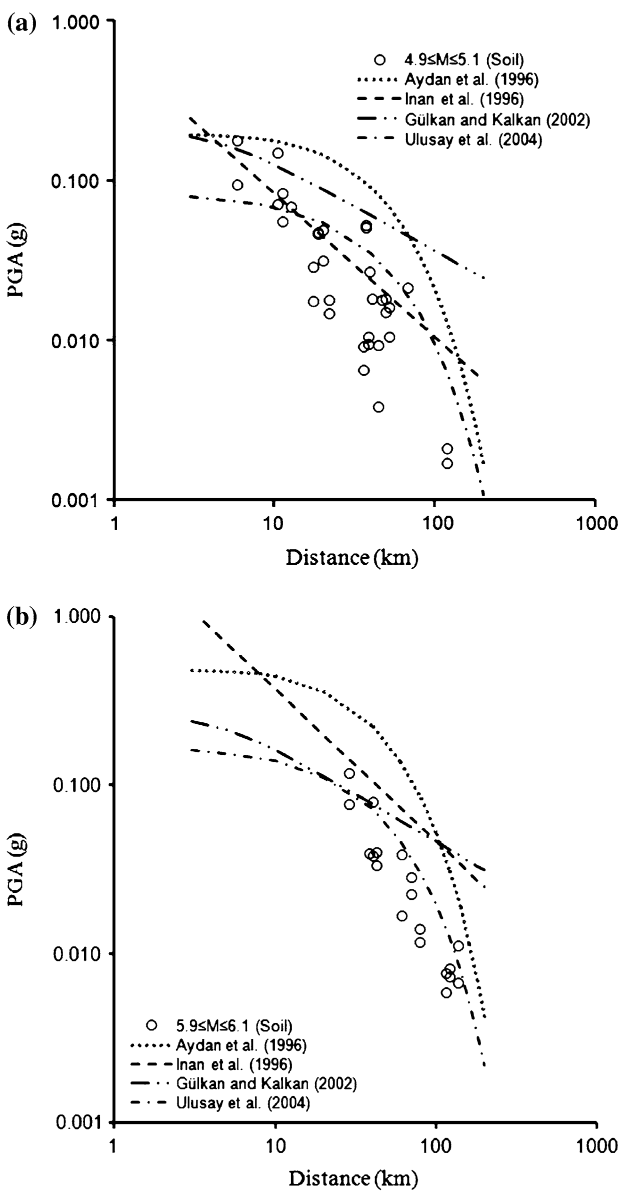

Fig. 12 Comparison between predicted PGA values from domestic attenuation relationships and PGA values of true earthquake records from soil sites: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.1 earthquakes

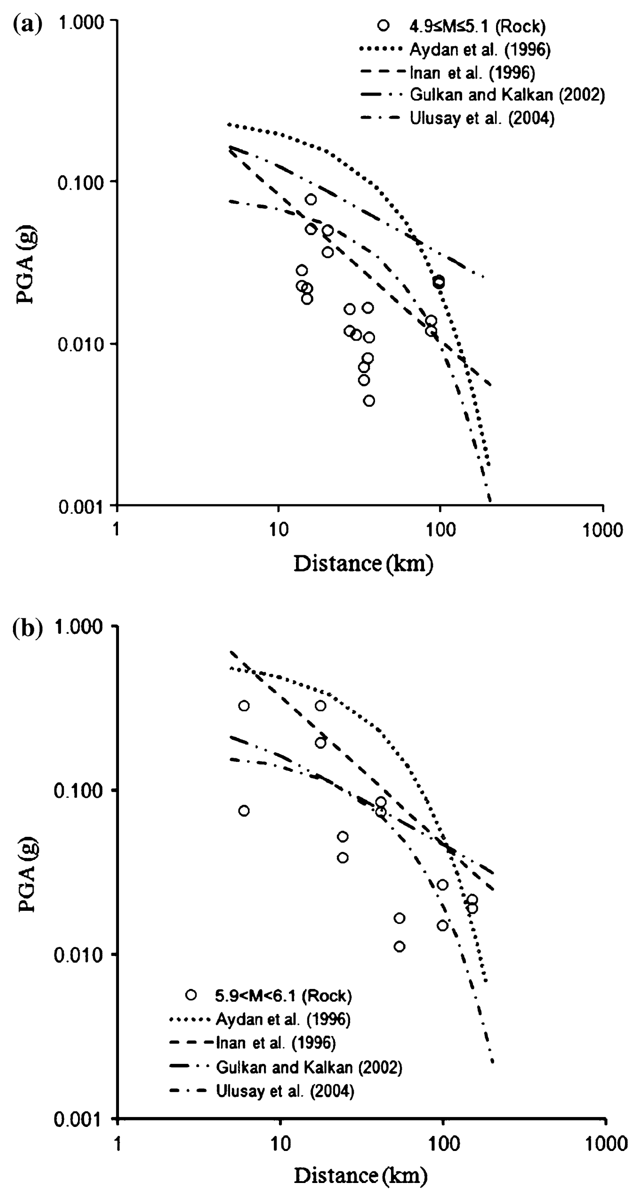

Fig. 13 Comparison between predicted PGA values by domestic attenuation relationships and PGA values of true earthquake records for rock sites: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.2 earthquakes

Table 7 Imported attenuation relationships most frequently used in seismic hazard analyses for Turkey

Attenuation relationship	σ	Reference
$\log A = -1.562 + (0.306 * M) - (\log (R^2 + 33.6)^{0.5})$	0.173	Sabetta and Pugliese (1987)
$\log A = -3.303 + (0.85 * M) - 1.25 * \ln(R + 0.0872 * e^{0.678*M} + 0.0059 * R$	0.30	Campbell (1988)
$\log A = 0.43 + (0.23(M - 6) - \log(R) - 0.0027R$	0.26	Joyner and Boore (1988)
$\log A = (0.41 * M) - \log(R + 0.032 * 10^{0.41*M} - (0.0034 * R) + 1.30$	0.21	Fukishima and Tanaka (1990)

part of the discrepancy between their PGA and true records might be attributed to this fact.

Some of the seismic hazard analyses conducted either for the whole of Turkey or some part of it also used "imported" attenuation relationships (e.g., Kayabali 2002; Kayabali and Akin 2003). The ones most frequently used are listed in Table 7.

Sabetta and Pugliese (1987) used 95 records from 17 earthquakes of $M \geq 4.5$. To account for soil effects, they categorized soils into two classes: shallow soils and deep soft soils. Campbell (1988) used 229 records from 27 earthquakes of $5.0 \leq M \leq 7.7$ from all over the world. Epicentral distance was restricted to 50 km or less. Campbell took into account shallow soil site records by excluding records from very soft soil sites and using the Richter magnitude (M_L if $M \leq 6.0$; M_S otherwise). Joyner and Boore (1988) used 182 records from 23 earthquakes of $5.0 \leq M_w \leq 7.7$ from western North America. Their data include both rock and soil sites, most of them from Campbell (1981). Fukishima and Tanaka (1990) used 300 records of Japanese events along with some data from Campbell (1981). They classified the data into rock sites, stiff soil sites, medium soil sites and soft soil sites with restrictions on focal depth, magnitude and PGA of 30 km, $M_{JMA} > 5.0$ and 10 cm/s^2, respectively.

The imported attenuation relationships outlined above were plotted on diagrams of PGA vs. distance for $M = 5$ and $M = 6$ earthquakes for soil and rock sites, respectively (Figs. 14 and 15). According to those diagrams, the Sabetta and Pugliese (1987) relationship predicts accurate PGA values in the intermediate field but has large discrepancies in the near and far fields. Campbell (1988) significantly underestimates PGA values. Joyner and Boore (1988) and Fukishima and Tanaka (1990) display a nearly 100% discrepancy above recorded values. The magnitude scales used in these comparisons were converted as necessary before being included in analyses.

The final evaluation considered only soil site data after transformation and rock site data (Figs. 16, 17, 18, 19). The results of this study were compared with the results from the other domestic relationships; this revealed that all the domestic attenuation relationships overestimate PGA values (Fig. 16). This conclusion is also valid for the combined data (Fig. 17). None of the imported attenuation relationships can accurately predict PGA for Turkey. There is a large discrepancy between the curves of the imported relationships and the PGA values of true records for Turkey.

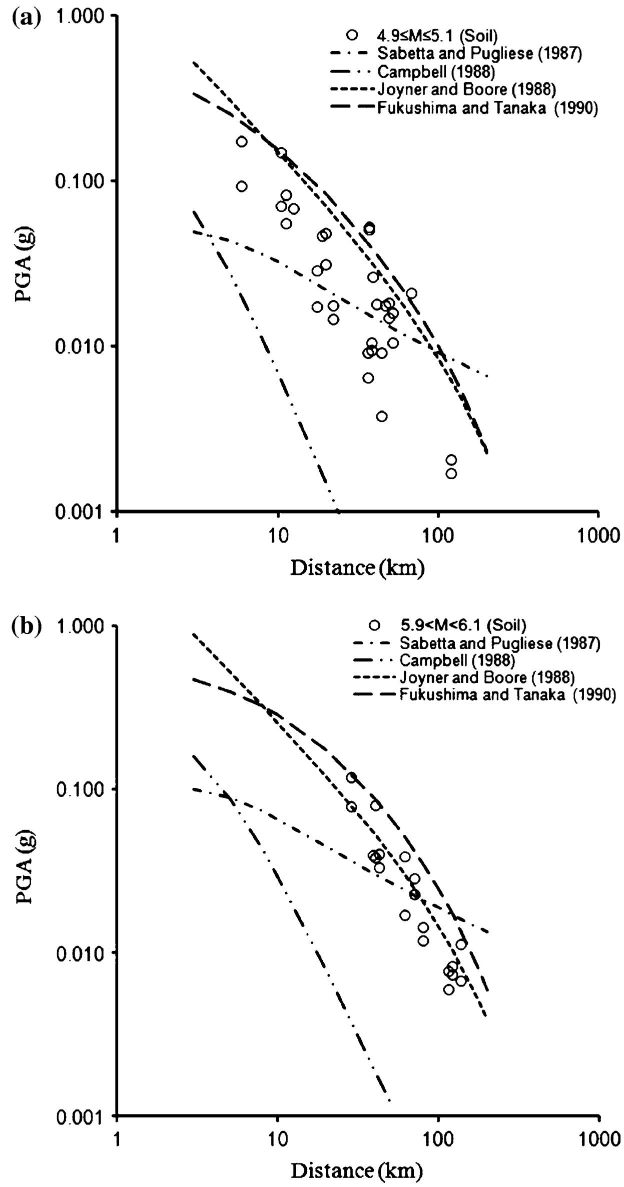

Fig. 14 Comparison between PGA values predicted by imported relationships and true records from Turkish soil sites: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.1 earthquakes

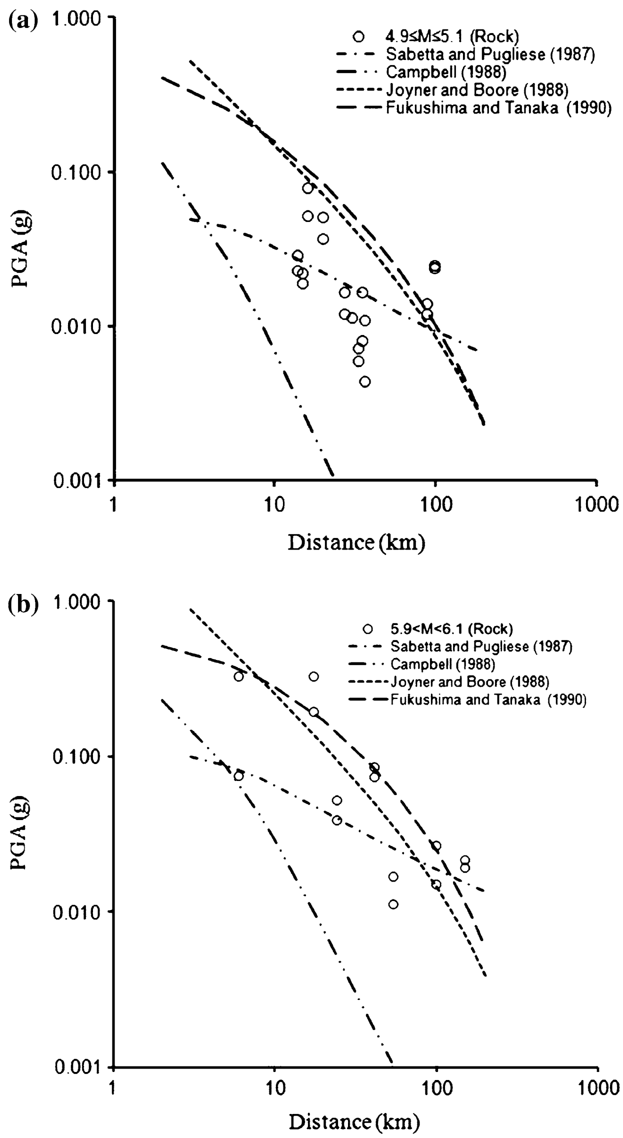

Fig. 15 Comparison between PGA values predicted by imported relationships and true records from Turkish rock sites: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.2 earthquakes

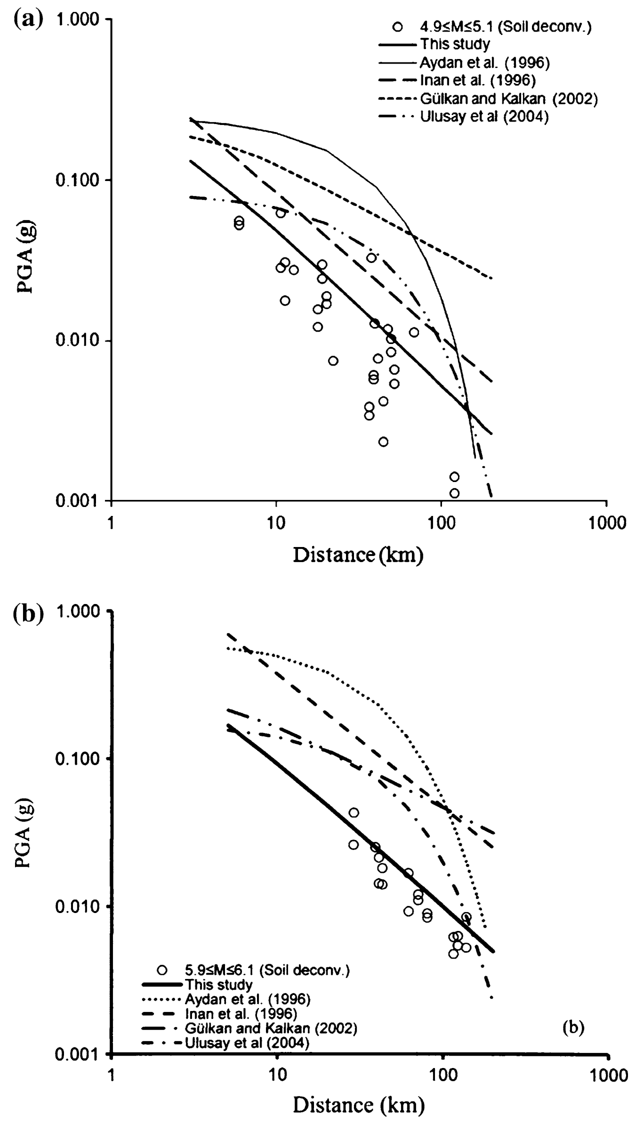

Fig. 16 Comparison between domestic relationships and soil site data (transformed), including the results from this study: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.1 earthquakes

Figures 16, 17, 18, 19 show that the attenuation relationship developed in this study closely fits the true PGA values recorded in Turkey. This is verified by both soil data (transformed) as shown in Figs. 16 and 18 and by rock sites plus transformed soil site data as shown in Figs. 17 and 19.

Discussion and conclusions

Although Turkey is located on a major seismic belt, there are not enough strong motion records on rock sites to establish a reliable attenuation relationship. There are about 3,500 earthquake records from 140 stations for the period 1976–2005. After restricting PGA ($\geq$10 cm/s^2), magnitude ($\geq$4.0) and distance ($\leq$200 km), only 516 records remain, of which nearly 400 come from stations on soil sites. Obviously, data from soil sites must be used in such an analysis. However, because the response of a soil site to an earthquake is not unique owing to the complex interactions between the period characteristics of soils and earthquakes, the response of soil sites must be analyzed event-by-event prior to including the PGA values. In order to accomplish this, 4,500 m of boreholes were drilled at 64 soil sites to collect the data required to perform site response analysis and to convert PGA values recorded at the top of soil columns to their bedrock equivalents. All suitable earthquake records were homogenized (in the form of peak horizontal ground acceleration on bedrock level) and a series of regression models were tested. The

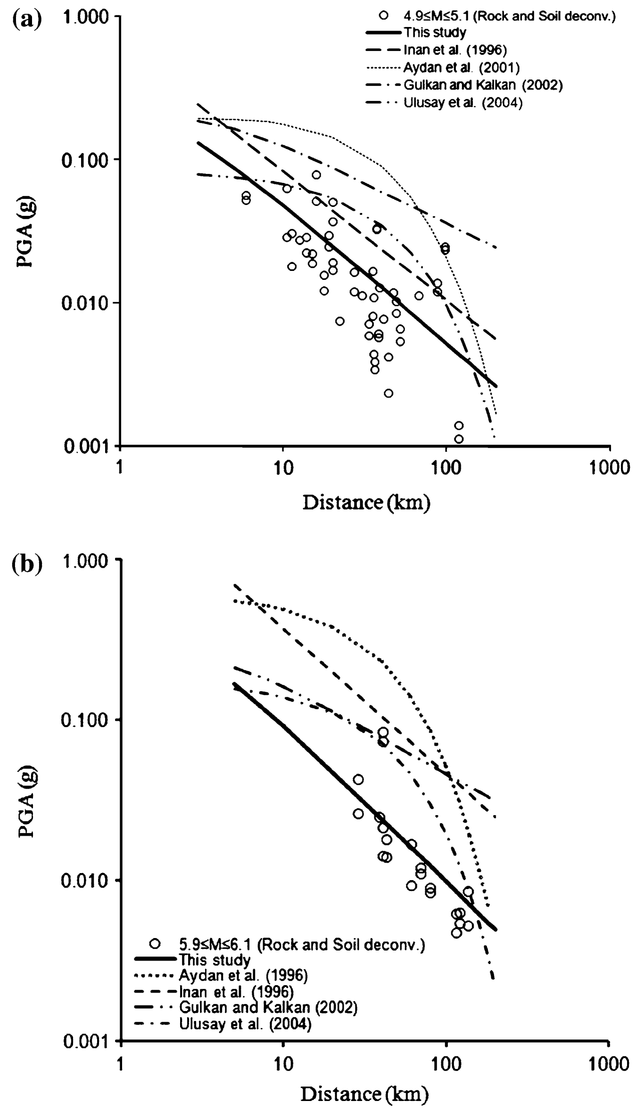

Fig. 17 Comparison between domestic relationships and rock site data plus transformed soil site data including the results from this study: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.1 earthquakes

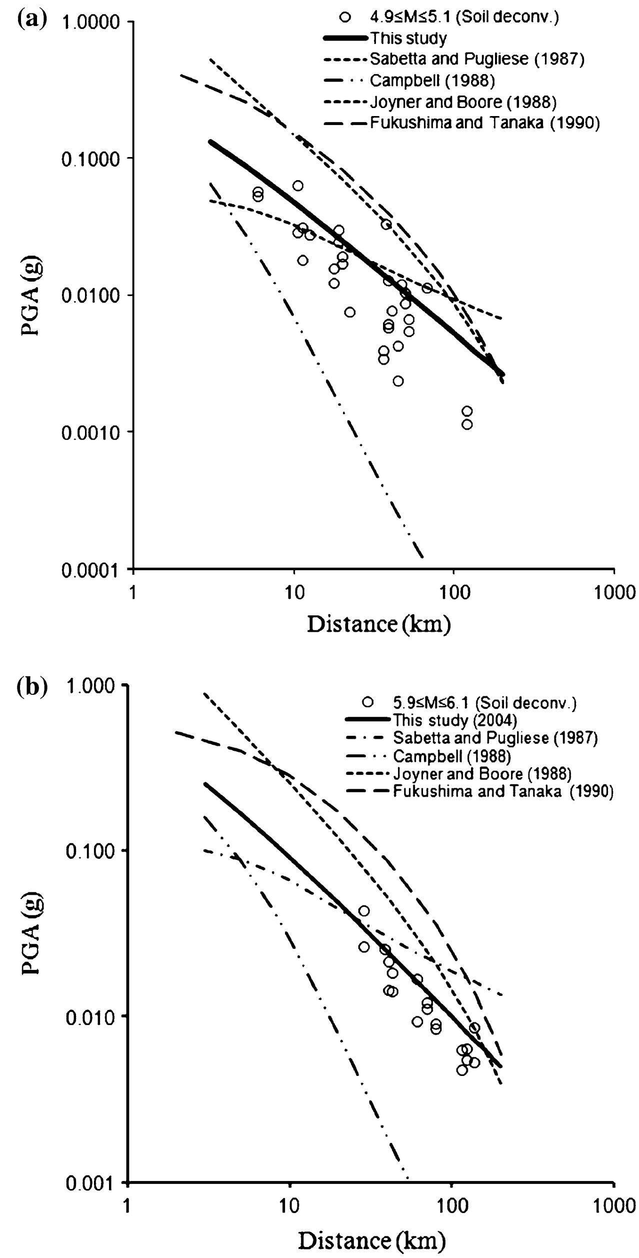

Fig. 18 Comparison between imported relationships and soil site data (transformed), including the results from this study: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.1 earthquakes

following relationship was found to best fit the recorded and corrected strong motion data collected from recording stations in Turkey:

$$\log A = \beta_0 + (\beta_1 M^2) + (\beta_2 \log(R+1))$$

where A is the peak horizontal ground acceleration (cm/s^2), M is the moment magnitude (M_w), R is the epicentral distance (km), $\beta_0 = 2.08$, $\beta_1 = 0.0254$, and $\beta_2 = -1.001$.

Comparisons between previously developed domestic relationships and rock site data plus raw soil data, as well as rock site data plus corrected soil data, reveal that domestic relationships have tended to overestimate PGA for Turkey. This is attributed to amplification effects from soil sites, which dominate Turkish earthquake records. Similarly, imported relationships display great discrepancies with either raw or converted soil data as well as rock site data. This suggests that, even if attenuation relationships are developed for seismo-tectonically similar regions, the imported relationships may not be suitable unless the crustal structures between the two regions are similar.

The seismo-tectonic provinces of Turkey are not homogeneous; hence the proposed relationship may change as the earthquake data grow so that different attenuation relationships could be established for different seismo-tectonic provinces.

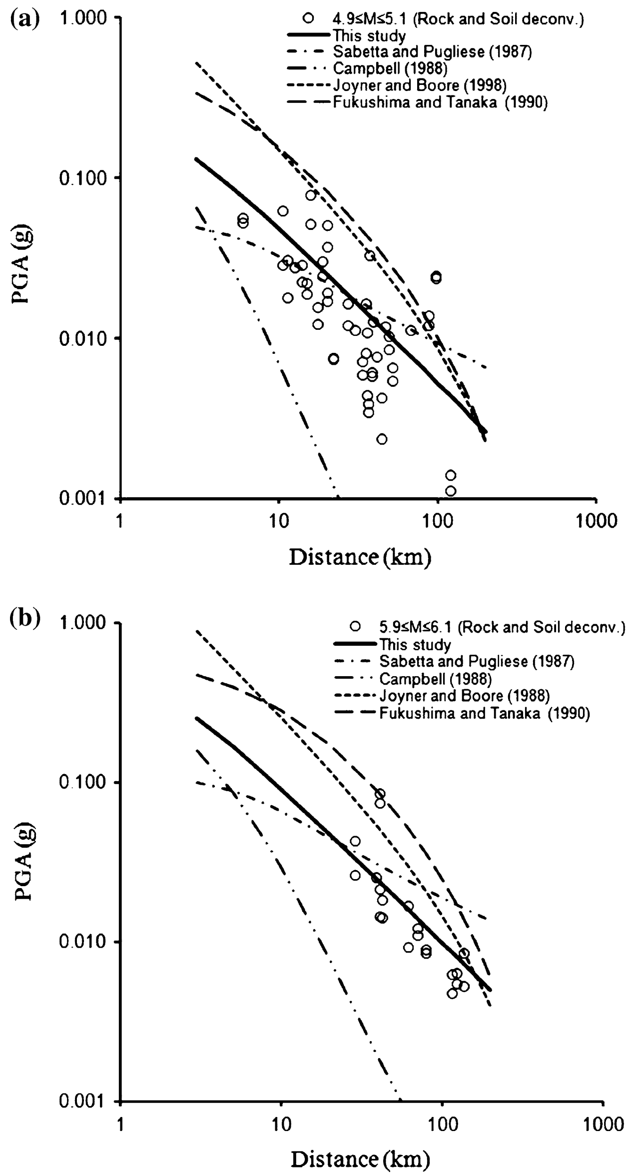

Fig. 19 Comparison between imported relationships and rock site data plus transformed soil site data, including the results from this study: **a** M_w: 5.0 ± 0.1 earthquakes; **b** M_w: 6.0 ± 0.1 earthquakes

It could be argued that comparisons between either domestic or imported relationships and strong motion data for Turkey may not be realistic owing to differing characteristics (such as magnitude scales and distances) inherent to each of the equations. In order to overcome the differences in magnitude scales, all magnitude scales were homogenized by converting them into moment magnitude scales prior to making comparisons. Domestic and imported relationships use different distance parameters (e.g., epicentral distance vs. hypocentral distance) and standardizing distances would not have been easy. However, Kayabali (2005) argues that the error introduced into the calculation of peak ground acceleration by not accounting for hypocentral distance using any attenuation relationship is a marginal issue.

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References

Auld B (1977) Cross-hole and down-hole V_S by mechanical impulse. J Geotech Eng Div ASCE 103(GT12):1381–1398

Aydan O, Sedaki M, Yarar R (1996) The seismic characteristics of Turkish earthquakes. In: Eleventh world conference on earthquake engineering, June 23–28, Acapulco, Mexico

Boore DM (1977) The motion of the ground during earthquakes. Sci Am 237(6):66–78

Campbell KW (1981) Near source attenuation of peak horizontal attenuation. BSSA 71(6):2039–2070

Campbell KW (1988) Predicting strong ground motion in Utah. In: Hays WW, Gori PL (eds) Evaluation of regional and urban earthquake hazard risks in Utah. USGS Professional Paper, L1–L31

Campbell KW, Bozorgnia Y (2003) Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. BSSA 93(1):314–331

Chiaruttini C, Siro L (1981) The correlation of peak ground horizontal acceleration with magnitude, distance, and seismic intensity for Friuli and Ancona, Italy, and the Alpide belt. BSSA 71(6):1993–2009

Coduto DP (1998) Geotechnical engineering principles and practices. Prentice Hall, NJ, 759 pp

Fukishima Y, Tanaka T (1990) A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan. BSSA 80:757–783

Gulkan P, Kalkan E (2002) Attenuation modeling of recent earthquakes in Turkey. J Seismol 6:397–409

Gurbuz M, Kuru T, Apak A (2000) Geological and geophysical investigations at Tosya (Kastamonu), Kargi, Osmancik (Corum), Merzifon (Amasya), Amasya and Tokat recording stations and their interpretations. Earthq Res Bull 83:95–112, Ankara (in Turkish)

Hanks TC, Kanamori H (1979) A moment magnitude scale. J Geophys Res 84(BS):2348–2350

Idriss IM, Sun JI (1992) SHAKE91: a computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits. User's Guide, University of California, Davis, p 13

Inan E, Colakoglu Z, Koc N, Bayulke N, Coruh E (1996). Acceleration records for 1976–1996 earthquakes. General Directorate of Disaster Affairs of Turkey, Earthquake Research Division, 98 p., Ankara (in Turkish)

Joyner WB, Boore DM (1981) Peak horizontal acceleration and velocity from strong motion records, including records from the 1979 Imperial valley, California earthquake. BSSA 71(6): 2011–2038

Joyner WB, Boore DM (1988) Measurement, characterization, and prediction of strong ground motion: earthquake engineering and soil dynamics, 2, recent advances in ground motion evaluation, pp 43–102

Kalafat D (2002) Empirical quantification of earthquake magnitudes in seismic belts: Abstracts of Active Tectonic Research Group of Turkey Workshop (ATAG-6), MTA, Ankara, 105–108 (in Turkish)

Kanamori H (1977) The energy release in great earthquakes. J Geophys Res 82:2981–2987

Kayabali K (2002) Modeling of seismic hazard for Turkey using the recent neotectonic data. Eng Geol 63:221–232

Kayabali K (2005) Comment on "An attenuation relationship based on Turkish strong motion data and iso-acceleration map of Turkey" by Ulusay et al., Eng. Geo 74:265–291 (2004) B Eng Geol 79, 293–295

Kayabali K, Akin M (2003) Seismic hazard map of Turkey using the deterministic approach. Eng Geol 69:127–137

Ketin I (1976) A comparison between San Andreas and North Anatolian faults. TJK Bulteni 19(2):149–154 (in Turkish)

Krinitzsky EL, Gould JP, Edinger PH (1993) Fundamentals of earthquake-resistant construction. Wiley, New York, p 299

McCall J (2000) The great Colchester earthquake of 1884 revisited. Geoscientist 7(10):4–6

Ozbey C, Sari A, Manuel L, Erdik M, Fahjan Y (2004) An empirical attenuation relationship for Northwestern Turkey ground motion using a random effects approach. Soil Dyn Earthq Eng 24:115–125

Sabetta F, Pugliese A (1987) Attenuation of peak horizontal acceleration and velocity from Italian strong ground motion records. BSSA 77:1491–1513

Sadigh K, Chang C-Y, Abrahamson NA, Chiou SJ, Power MS (1993) Specification of long-period ground motions: Updated attenuation relationships for rock site conditions and adjustment factors for near-fault effects. Pages 59–70 of: Proceedings of ATC-17-1 seminar on seismic isolation, passive energy dissipation, and active control

Schnabel PB, Lysmer J, Seed HB (1972) SHAKE: a computer program for earthquake response analysis of horizontally layered sites. Report No. EERC 72-12, Earthquake Engineering Research Center, University of California, Berkeley, California

Seed HB, Chaney RC, Pamukcu S (Prior to 1975) (1999) Earthquake effects on soil-foundation systems. In: Fang H-Y (ed) Foundation Engineering Handbook, Part: I, 594–672

SPSS (1998) Statistical package for social science. SPSS Inc. (www.spssscience.com) USA

Tatsuoka F, Iwasaki T, Tokida K, Yasuda S, Hirose M, Imai T, Konno M (1980) Standard penetration tests and soil liquefaction potential evaluation. Soils Found 20(4):95–111

Telford WM, Geldart LP, Sheriff RE (1990) Applied Geophysics, 2nd edn. Cambridge University Pres, Cambridge, p 770

Trifunac MD, Brady AG (1975) A study of the duration of strong earthquake ground motion. BSSA 65:581–626

UBC (Uniform Building Code) (1988) International conference of building officials, 1988: UBC 1988. Section 2312 Earthquake Regulations. ICBC, Whitter, CA

Ulusay R, Tuncay E, Sonmez H, Gokceoglu C (2004) An attenuation relationship based on Turkish strong motion data and iso-acceleration map of Turkey. Eng Geol 74:265–291

USGS (2000) Implication for earthquake risk reduction in the United States from the Kocaeli, Turkey, Earthquake of August 17, 1999. U.S. Geological Survey Circular 1193, p 64

Vardeman SB (1994) Statistics for engineering problem solving. PWS Publishing Company, Boston, p 712

Yilmazturk A, Bayrak Y (1997) Temporal and spatial distribution of seismic energy released by global earthquakes. Earthq Res Bull 75:17–53 (in Turkish)

Zaré M, Bard P-Y (2002) Strong motion data set of Turkey: data processing and site classification. Soil Dyn Earthq Eng 22:703–718