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An empirical attenuation relationship for Northwestern Turkey ground motion using a random effects approach

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Abstract

Using a random effects model that takes into consideration the correlation of data recorded by a single seismic event, a database consisting of 195 recordings from 17 recent events is employed to develop empirical attenuation relationships for the geometric mean of horizontal peak ground acceleration and 5-percent damped spectral acceleration (S_a). The recordings employed are obtained from strong motion stations operating in Northwestern Turkey and resulted from events that include the Kocaeli ($M_w = 7.4$) and the Düzce ($M_w = 7.1$) earthquakes and their aftershocks as well as other events. By studying differences in standard errors, the random effects model is compared with a fixed effects model that does not account for distinctions between intra- and inter-event variability. Effects of local site conditions are included in the empirical relationships developed. The dependence on frequency of the various model parameters is also studied. Frequency-dependent attenuation coefficients for the proposed random effects models developed are summarized in tables to facilitate their use.

Keywords: Attenuation; Northwestern Turkey; Random effects; Ground motion

1. Introduction

On August 17, 1999, the $M_w = 7.4$ Kocaeli earthquake struck a densely populated region in Northwestern Turkey, which is also the industrial heartland of the country. Shortly thereafter, another segment of the North Anatolian fault system ruptured on November 12, 1999 producing the $M_w = 7.2$ Düzce earthquake. Strong motion recordings resulting from these two earthquakes have contributed in a significant way towards augmenting the near-field database of ground motions for large-magnitude ($M_w > 7.0$) strike-slip events. Most of the available attenuation relationships prior to these recent events overpredict peak accelerations in the near-field region because they rely heavily on extrapolation from larger distances and smaller magnitude earthquakes [18]. In the case of the Kocaeli earthquake, low accelerations recorded may also have been due to the smoothness of the rupture and the relatively low stress drop [8,9]. At any rate, as a result of this recent increase in the database on strong motion data and because of the absence of empirical attenuation models, the present study is focused on establishing new region-specific attenuation relationships for Northwestern Turkey. In the following, the development of these models is discussed using motions obtained during the Kocaeli and the Düzce earthquakes and their aftershocks as well as other recent events. The proposed empirical attenuation model that is advocated here is a mixed effects model [16] which is based on a maximum likelihood procedure and accounts for correlation among the data recorded from the same event. Two models, however, are studied here that will be referred to as 'mixed effects' and 'fixed effects' models in the following. The fixed effects model does not distinguish between inter-event and intra-event variability, whereas the mixed effects model accounts for the difference between these two types of variability. The term mixed effects model is used because some of the attenuation model coefficients are modeled as random and others as fixed, based on the Akaike's Information Criterion (AIC) value, a maximum likelihood statistic [7].

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2. Model parameters

Parameters commonly used when establishing empirical attenuation models include earthquake magnitude, distance, site conditions, and style of faulting. Parameters selected for this study are briefly discussed next.

Earthquake magnitude is defined in terms of moment magnitude (M_w) to avoid saturation effects for magnitudes greater than about 6. Local magnitude (M_L) is used for all events with $M \leq 6.0$, under the assumption that M_L is approximately equal to M_w for $M \leq 6.0$ [11].

Various alternative source-to-site distance measures have been used by different researchers in empirical attenuation models. The Joyner–Boore distance, a measure of the closest horizontal distance to the vertical projection of the rupture plane, is employed in this study. Differences between the various definitions of distance used in attenuation models tend to be more significant in the near field, but less so in the far field.

The effect of local site conditions is also included in the attenuation models studied. Parameters in the models are included to represent the different site classes (these site classes are discussed in more detail in the following).

The style of faulting is a parameter that has been included in the development of many empirical attenuation models since it is believed, for example, that reverse and reverse-oblique mechanisms produce larger motions compared to normal and strike-slip mechanisms [5,6]. The fault mechanism for earthquakes that have occurred on the North Anatolian Fault System in Northwestern Turkey is predominantly strike-slip in character as indicated in several studies [2,15]. Orgulu and Aktar [15] analyzed the fault mechanisms of the thirty largest aftershocks of the Kocaeli earthquake and found strike-slip dominance in most of these events and a normal faulting type in some cases. Although it is considered important to distinguish between the various mechanisms—reverse, reverse-oblique, normal, strike-slip, etc.—in the present study, a style-of-faulting parameter is not explicitly modeled. The empirical attenuation models developed here are only for normal and strike-slip earthquakes and should not be used to predict motions from earthquakes associated with reverse and reverse-oblique faulting.

The geometric mean of the two horizontal components of the ground motion parameter (i.e. peak ground acceleration (pga) or spectral acceleration) is chosen as the dependent variable in the attenuation relationships.

3. Strong motion database

The strong motion records used in this study are obtained from stations operated by Boğaziçi University's Kandilli Observatory and Earthquake Research Institute (KOERI), by Istanbul Technical University (ITU), and by the General Directorate of Disaster Affairs' Earthquake Research Department (ERD). The ERD records are obtained from a database maintained at the Pacific Earthquake Engineering Research Center (PEER) website [12]. The overall database available consists of 1188 records from 392 earthquakes recorded at 47 strong motion stations between 1994 and 2001. A subset of this comprising 195 records from 17 earthquakes with $M \geq 5.0$ are used in the regression analyses. The distribution of the records used on the basis

Table 1
Database of strong motion records used in the regression analyses

Event No	Event name	Event date	Origin time	Lat. (deg.)	Long. (deg.)	M	Depth (km)	No of recordings grouped by Site Class			
								A	B	C	D
1	Izmit	17.08.1999	12:01:38 AM	40.76	29.97	7.4	19.6	3	5	7	7
2	Düzce-Bolu	12.11.1999	4:57:21 PM	40.74	31.21	7.2	25.0	1	3	5	18
3	Izmit	13.09.1999	11:55:29 AM	40.77	30.10	5.8	19.6	0	2	5	18
4	Hendek-Akyazi	23.08.2000	1:41:28 PM	40.68	30.71	5.8	15.3	0	1	3	8
5	Sapanca-Adapazari	11.11.1999	2:41:26 PM	40.74	30.27	5.7	22.0	0	1	4	11
6	Izmit	17.08.1999	3:14:01 AM	40.64	30.65	5.5	15.3	0	0	0	3
7	Düzce-Bolu	12.11.1999	5:18:00 PM	40.74	31.05	5.4	10.0	0	1	1	12
8	Izmit	31.08.1999	8:10:51 AM	40.75	29.92	5.2	17.7	0	1	3	13
9	Düzce-Bolu	12.11.1999	5:17:00 PM	40.75	31.10	5.2	10.0	0	2	1	11
10	Marmara Sea	20.09.1999	9:28:00 PM	40.69	27.58	5.0	16.4	0	1	4	10
11	Northeast of Bolu	14.02.2000	6:56:36 AM	40.90	31.75	5.0	15.7	0	0	0	5
12	Cinarcik-Yalova	19.08.1999	3:17:45 PM	40.59	29.08	5.0	11.5	0	0	1	5
13	Kaynasli-Bolu	12.11.1999	6:14:00 PM	40.75	31.36	5.0	10.0	0	0	0	1
14	Hendek-Adapazari	07.11.1999	4:54:42 PM	40.71	30.70	5.0	10.0	0	0	0	4
15	Izmit	19.08.1999	3:17:45 PM	40.36	29.56	5.0	9.8	0	1	1	2
16	Düzce-Bolu	19.11.1999	7:59:08 PM	40.78	30.97	5.0	9.2	0	2	0	3
17	Hendek-Adapazari	22.08.1999	2:30:59 PM	40.74	30.68	5.0	5.4	0	0	0	5
Total number of records:								4	20	35	136

Table 2
Definition of site classes used in the attenuation models

Site Class	Shear wave velocity
A	>750 m/s
B	360–750 m/s
C	180–360 m/s
D	<180 m/s

of site class is summarized in Table 1 while the site class definitions are given in Table 2.

Note that the site classes used in this study are defined according to the average shear wave velocity over the top 30 m. A representation of the distribution of the strong motion data as a function of moment magnitude and distance is shown in Fig. 1 for each of the soil classes (A and B, C, and D) separately. In the case of the ERD data, only records from the Kocaeli and Düzce main shocks that were obtained at sites with distances from the source less than 100 km are used in the analyses. The Bolu record is also excluded because of possible instrument error in the recording.

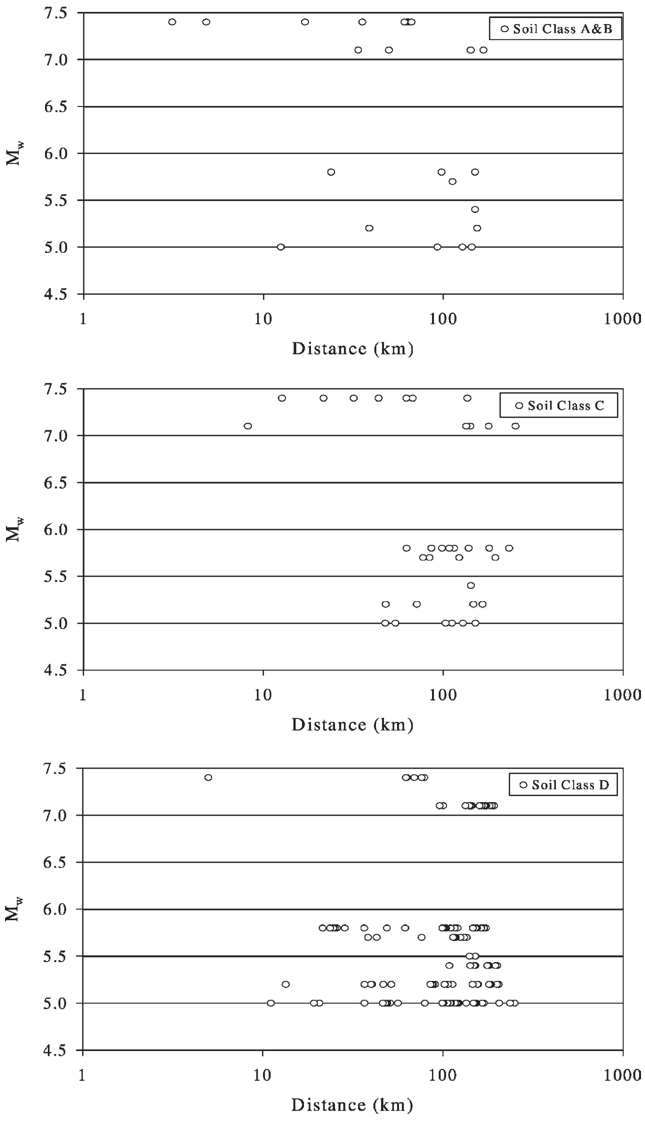

Fig. 1. Data distribution for soil classes A and B, C and D, respectively.

4. Regression method

A nonlinear mixed effects model is defined to account for both inter-event and intra-event variability. Most commonly developed attenuation models do not distinguish between these two types of variability. The mixed effects model that is proposed describes the covariance structure obtained by careful grouping of the data. Such a model describes the relationship between a response variable, the ground motion parameter, and some covariates in the data that are grouped according to one or more classification (e.g. magnitude). Also, such a model with two sources of random variation is sometimes referred to as a 'hierarchical model' [4,14] or a multilevel model [10].

To understand the advantages of a mixed effects model, it is useful to consider first a standard fixed effects model, where the form of the attenuation relation may be written as

$$\log Y_k = f(M_k, r_k, \bar{\theta}) + \varepsilon_k \tag{1}$$

where Y_k, M_k, and r_k are, respectively, the ground motion parameter, the magnitude, and the distance for the kth data point (i.e. the observation associated with a single station's ground acceleration record), while $\bar{\theta}$ is a model coefficient matrix and ε_k is an error term assumed to be normally distributed with mean zero. In such a fixed effects model, one is interested in estimating the model coefficient matrix, $\bar{\theta}$, and the standard deviation of the error term using regression techniques. Importantly, no consideration of the correlation of the data recorded from the same event is included in this fixed effects model.

In direct contrast, in a mixed effects model, the error term in the empirical model development accounts for inter-event and intra-event variability. A mixed effects model is proposed here because such a model accounts from correlation in the data recorded by the same earthquake.

The mixed effects model takes the form

$$\log Y_{ij} = f(M_i, r_{ij}, \bar{\theta}) + \eta_i + \varepsilon_{ij} \tag{2}$$

where Y_{ij} and r_{ij} are the ground motion parameter and distance, respectively, for the jth ground motion recording during the ith event (earthquake). Also, M_i is the magnitude of the ith event, $\bar{\theta}$ is the model coefficient matrix. The error associated with residuals between predicted and observed values of Y_{ij} in this model is comprised of two terms, η_i and ε_{ij}. The inter-event term, η_i, represents between-group variability resulting from differences in the data recorded from different earthquakes, while the intra-event term, ε_{ij}, represents within-group variability resulting from differences in the data recorded among the different stations for the same earthquake. These two error terms, η_i and ε_{ij}, are assumed to be independent and normally distributed with variances, τ^2 and σ^2, respectively. The total standard error for this mixed effects model is then $\sqrt{\sigma^2+\tau^2}$. A maximum likelihood approach is used to estimate the model coefficients, $\bar{\theta}$, and the variances, τ^2 and σ^2.

The mixed effects model outlined above is not expected to yield very different results from the more conventional two-step regression method adopted in Ref. [13] as long as all the events included in the database provide a large number of recordings [1]. The advantage of the proposed mixed effects approach is that the contributions to overall variability may be clearly separated into a portion that results from variability between earthquakes and another that results from variability among recordings in the same earthquake.

Either commercial software [19] or freeware (the R language) may be employed for the estimation of the model coefficients for the mixed effects model as well as for the fixed effects model. Details regarding application of the mixed effects model are described in Ref. [16], and the analysis procedure given in Ref. [7] is used to develop the empirical attenuation models in this study.

5. Regression model

Attenuation relationships are developed for elastic ground motion parameters using the fixed effects and mixed effects models given in Eqs. (1) and (2). The selected functional form, $f(\,)$, for the attenuation relationships there that includes the model coefficient matrix, $\bar{\theta}$, leads to an empirical attenuation model as follows:

$$\log(Y_{ij}) = a + b(M_i - 6) + c(M_i - 6)^2 + d\,\log\sqrt{R_{ij}^2 + h^2} + eG_1 + fG_2 \quad (3)$$

where Y_{ij} is the geometric mean of the two horizontal components of the ground motion parameter (pga or spectral acceleration) in cm/s^2 from the jth recording of the ith event, M_i is the moment magnitude of the ith event, and R_{ij} is the closest horizontal distance to the vertical projection of the rupture from the ith event to the location of the jth recording.

The mixed effects model is our focus in this study. Attenuation model coefficients based on Eq. (3) are developed for this model and presented for various ground motion parameters in the following by tabulating values of a, b, c, d, e, f, and h, as well as including standard error estimates. For the sake of comparison, the standard error estimates from the fixed effects model will also be presented but the model coefficients from that model are not included since it will be shown that the mixed effects model has several advantages and has typically smaller prediction error.

It is important to note that the mixed effects model has two stochastic 'error' terms associated with it—one accounts for inter-event variability, the other for intra-event variability. Together these two terms define the residuals—i.e. the differences between observed values and model predictions—that have zero means but individual standard errors that together (as the square root of the sum of their squares) define the standard error in the model of Eq. (3). In the fixed effects model, no stratification at the event level is made for the data; as a result, only a single overall standard error term is obtained which does not discriminate between inter- and intra-event variability. The coefficients G_1 and G_2 take on values as follows: $G_1 = 0$ and $G_2 = 0$ for site classes A and B; $G_1 = 1$ and $G_2 = 0$ for site class C; and $G_1 = 0$, $G_2 = 1$ for site class D. The coefficients to be estimated are a, b, c, d, e, f, and h. Logarithmic standard deviations are also of interest—smaller values indicate better model fits to data. Note that in Eq. (3) and in our discussion of results, all the logarithms are in base 10.

As linear magnitude dependence is not adequate for attenuation of ground motion at long periods, higher order terms are needed and a quadratic term is used in this model. The coefficient, h, is sometimes referred to as a 'fictitious' depth measure implying that interpretation of h is not clear and its value is estimated as part of the regression. Nevertheless, it is used in this model because Abrahamson and Silva (1997) have reported that it yields a marginally better fit to the data at short distances. The site effects terms are based on an assumption of a linear relationship between soil amplification and the logarithm of the ground motion parameter. The site response coefficients, e and f, are modeled as being independent of magnitude, distance, and level of ground shaking. It may be desirable in future work to study the dependence of site response on the level of ground shaking.

Seventeen earthquakes are considered in the data set as representing a sample from the population of earthquakes to help describe the source of inter-event variability in ground motion attenuation. The model coefficient matrix, $\bar{\theta}$, is made up of the coefficients, a, b, c, d, e, f, and h. In the mixed effects model, these coefficients may be treated as either fixed or random based on physical reasoning. As separate values of the magnitude-dependent terms in Eq. (3) associated with the coefficients, b and c, cannot be estimated with a single M_i value per earthquake, these two coefficients should be treated as fixed. Doing otherwise can lead to computational difficulties (e.g. convergence problems). Similarly, according to Ref. [7], treating the model coefficient, a, as fixed is reasonable. Sixteen different scenarios are considered in estimating the model coefficients, where the coefficients, a, b, and c are always considered as fixed while d, e, f, and h are modeled as either fixed or random. The nlme toolbox available with the S-Plus software [19] is employed for estimation of the model coefficients for the mixed effects model as well as for a fixed effects model. The maximum likelihood method may be used to estimate the model coefficients but it cannot be used to compare different models without some modifications.

Instead, a statistic known as the AIC which is a penalized likelihood criterion is employed when comparing models. The model with the smaller AIC value is selected among the various alternatives (for example, when comparing models, where the different assumptions regarding the coefficients d, e, f, and h are considered). The AIC for a single model is defined as follows:

$$\mathrm{AIC} = -2\log\mathrm{likelihood} + k(\mathrm{npar}) \quad (4)$$

where npar is the number of the random coefficients in the fitted model, and k is 2 for classical AIC.

Table 3 shows a comparison of the logarithmic standard deviations for the fixed effects model with those from the mixed effects model for pga and spectral acceleration at different natural periods. It is clear that the mixed effects model yields the smaller standard errors over the entire range of periods; the difference between the models is greater at short periods. It is believed that the mixed effects model fits the data better on average due in part to the fact that it accounts for inter- and intra-event variability that the fixed effect model ignores. Pinheiro and Bates [16] too, have indicated that the fixed effects model estimates may be similar to mixed effects model estimates but that the standard errors are generally smaller with a mixed effects model.

Table 3
Comparison of logarithmic standard deviation estimates for peak ground acceleration (pga) and spectral acceleration (for various natural periods) from the fixed and mixed effects models

Period (s)	$\sigma_{\log(Y)}$ (fixed)	$\sigma_{\log(Y)}$ (mixed)
pga	0.294	0.260
0.10	0.311	0.274
0.15	0.307	0.266
0.20	0.294	0.243
0.25	0.299	0.250
0.30	0.308	0.262
0.35	0.303	0.267
0.40	0.320	0.281
0.45	0.329	0.289
0.50	0.333	0.293
0.55	0.346	0.306
0.60	0.342	0.302
0.65	0.337	0.303
0.70	0.330	0.300
0.75	0.332	0.305
0.80	0.334	0.307
0.85	0.343	0.315
0.90	0.350	0.324
0.95	0.354	0.328
1.00	0.356	0.331
1.10	0.356	0.334
1.20	0.352	0.330
1.30	0.358	0.339
1.40	0.369	0.349
1.50	0.375	0.357
1.75	0.383	0.364
2.00	0.374	0.353
2.25	0.368	0.347
2.75	0.343	0.323
3.00	0.346	0.324
3.50	0.351	0.329
4.00	0.347	0.324

6. Regression results

Based on the mixed effects model, Table 4 presents attenuation coefficients, a, b, c, d, e, f, and h, and the logarithmic standard deviation for pga and 5%-damped spectral acceleration values for periods up to 4 s. Fig. 2 shows acceleration response spectra based on model predictions for different soil conditions when $M_w = 7.5$ and $R = 10$ km. Although amplification of spectral acceleration is significant for softer soils (site class D) compared to the stiffer soil cases, the period at which spectral acceleration has its peak value is almost the same for all of the soil classes. It is well known that with softer soils over a significant depth, one usually has longer resonant periods than with stiffer soils. The reason that the attenuation model predictions do not capture this effect is

Table 4
Empirical attenuation coefficients and logarithmic standard deviation values for the geometric mean of the horizontal peak ground acceleration, pga, and the 5%-damped spectral acceleration, S_a, based on the mixed effects model

Period (s)	a	b	c	d	h	e	f	$\sigma_{\log(Y)}$
pga	3.287	0.503	−0.079	−1.1177	14.82	0.141	0.331	0.260
0.10	3.755	0.419	−0.052	−1.3361	17.22	0.173	0.255	0.274
0.15	3.922	0.463	−0.085	−1.3422	21.41	0.182	0.268	0.266
0.20	3.518	0.494	−0.094	−1.1162	14.87	0.113	0.285	0.243
0.25	3.270	0.517	−0.099	−0.9781	9.75	0.053	0.288	0.250
0.30	3.040	0.549	−0.095	−0.8762	6.54	0.062	0.320	0.262
0.35	2.951	0.579	−0.121	−0.8402	6.48	0.080	0.352	0.267
0.40	2.825	0.593	−0.112	−0.8089	6.48	0.102	0.394	0.281
0.45	2.690	0.605	−0.111	−0.7572	6.17	0.105	0.408	0.289
0.50	2.685	0.653	−0.171	−0.7302	5.58	0.051	0.385	0.293
0.55	2.581	0.685	−0.177	−0.6928	3.56	0.061	0.393	0.306
0.60	2.423	0.708	−0.177	−0.6291	3.41	0.059	0.399	0.302
0.65	2.325	0.724	−0.177	−0.6032	2.50	0.063	0.411	0.303
0.70	2.276	0.741	−0.174	−0.5932	2.12	0.055	0.407	0.300
0.75	2.247	0.750	−0.170	−0.5946	2.34	0.054	0.396	0.305
0.80	2.247	0.755	−0.166	−0.6075	3.22	0.070	0.392	0.307
0.85	2.243	0.774	−0.161	−0.6353	3.22	0.094	0.407	0.315
0.90	2.272	0.791	−0.172	−0.6630	4.21	0.102	0.416	0.324
0.95	2.246	0.807	−0.182	−0.6570	4.23	0.099	0.414	0.328
1.00	2.237	0.828	−0.207	−0.6543	4.14	0.100	0.413	0.331
1.10	2.227	0.855	−0.248	−0.6616	3.78	0.113	0.415	0.334
1.20	2.267	0.874	−0.267	−0.6910	4.49	0.103	0.397	0.330
1.30	2.353	0.901	−0.284	−0.7516	5.35	0.092	0.394	0.339
1.40	2.376	0.932	−0.296	−0.7752	6.90	0.070	0.375	0.349
1.50	2.445	0.943	−0.314	−0.8117	7.73	0.045	0.328	0.357
1.75	2.466	0.964	−0.331	−0.8671	7.85	0.038	0.298	0.364
2.00	2.490	0.973	−0.331	−0.9397	8.55	0.059	0.301	0.353
2.25	2.581	0.977	−0.326	−1.0345	11.21	0.070	0.299	0.347
2.75	2.559	0.980	−0.282	−1.1235	11.68	0.060	0.286	0.323
3.00	2.564	0.998	−0.282	−1.1473	12.04	0.044	0.273	0.324
3.50	2.549	1.011	−0.278	−1.1950	10.93	0.044	0.261	0.329
4.00	2.366	1.028	−0.244	−1.1710	10.72	0.025	0.253	0.324

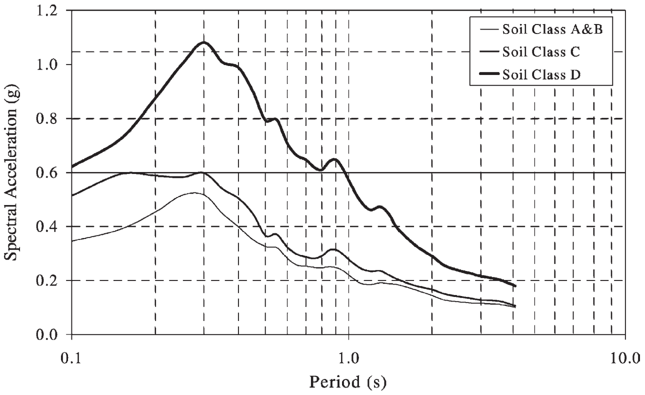

Fig. 2. Effect of soil class for $M_w = 7.5$ and $R = 10$ km on response spectra based on attenuation model predictions.

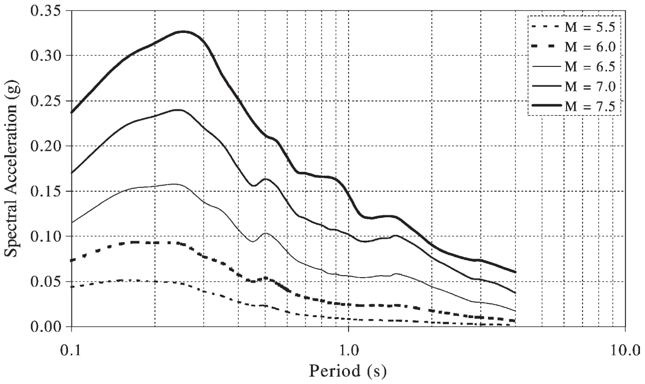

Fig. 3. Effect of magnitude for soil classes A and B and $R = 20$ km on response spectra based on attenuation model predictions.

probably because of the relatively small number of recordings on rock and/or stiff soil sites in the database. The effects of magnitude and distance on predicted response spectra are studied in Figs. 3 and 4, respectively. Expected trends are observed in both figures: a systematic decrease in amplitudes of the response spectra with magnitude at all frequencies; and reduced ground motion attenuation with distance at longer periods.

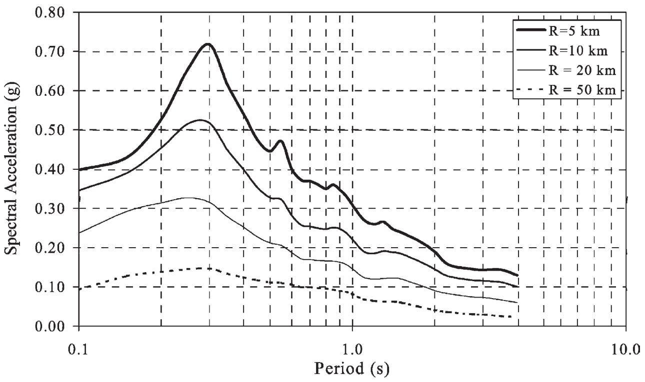

Fig. 4. Effect of distance for soil classes A and B and $M_w = 7.5$ on response spectra based on attenuation model predictions.

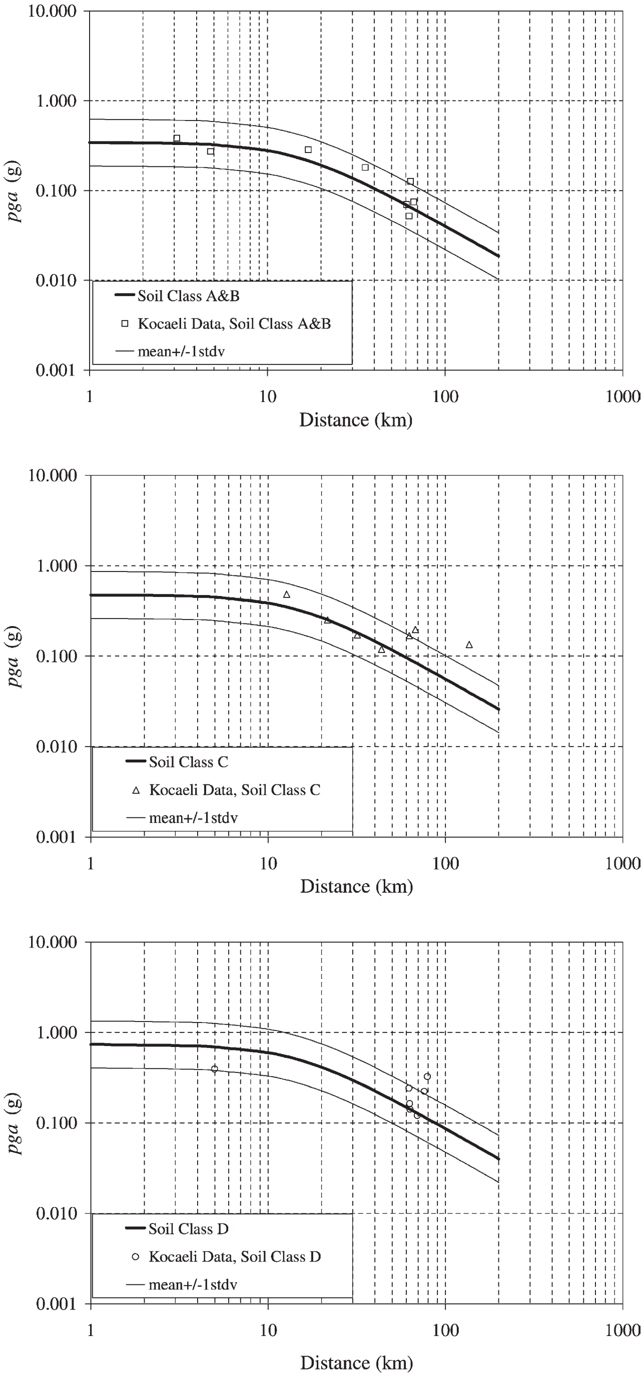

Fig. 5. Comparison of model predictions of pga at mean and mean ± 1 standard deviation levels with observed data from the Kocaeli earthquake for soil classes A and B, C, and D.

In Figs. 5 and 6, model predictions of pga and 1-second spectral acceleration values, respectively, for mean and plus/minus one standard deviation levels are compared with data from the Kocaeli earthquake. To highlight the differences in predicted motions for each soil class, the comparisons for soil classes A and B, C, and D are shown separately. Reasonable fits of the model to the Kocaeli data are seen in Figs. 5 and 6.

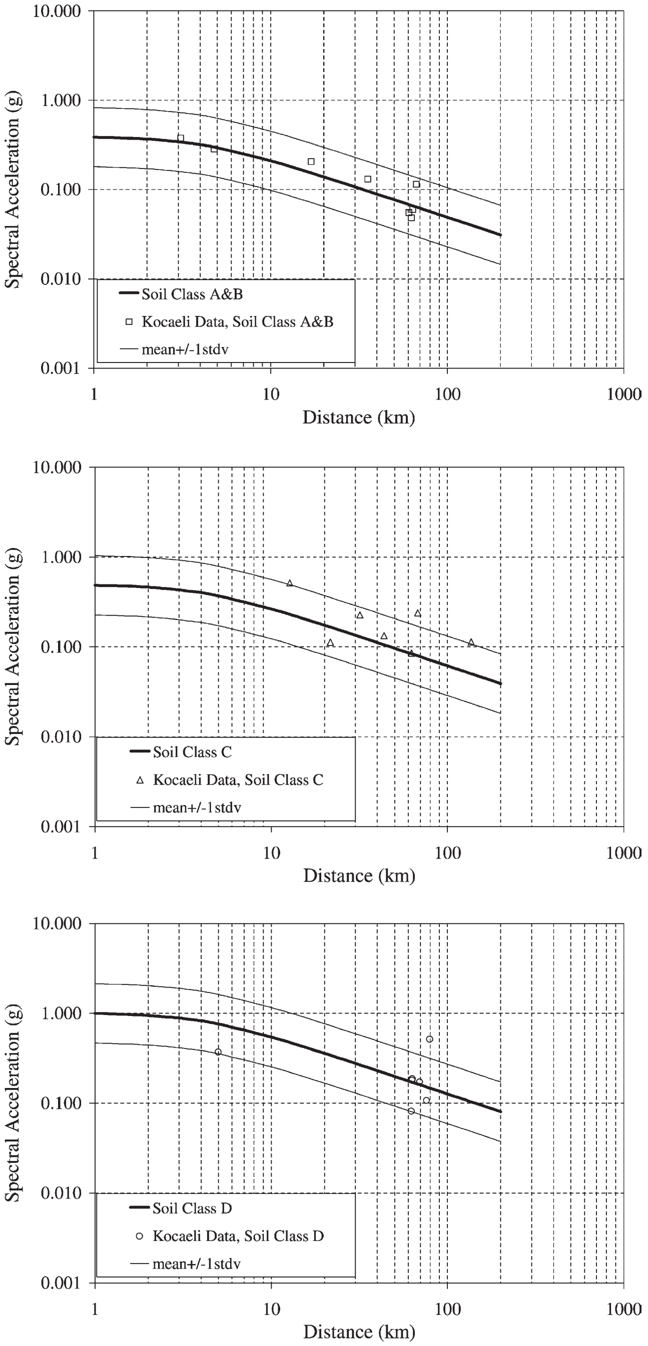

Fig. 6. Comparison of model predictions of 1-second spectral acceleration at mean and mean ± 1 standard deviation levels with observed data from the Kocaeli earthquake for soil classes A and B, C, and D.

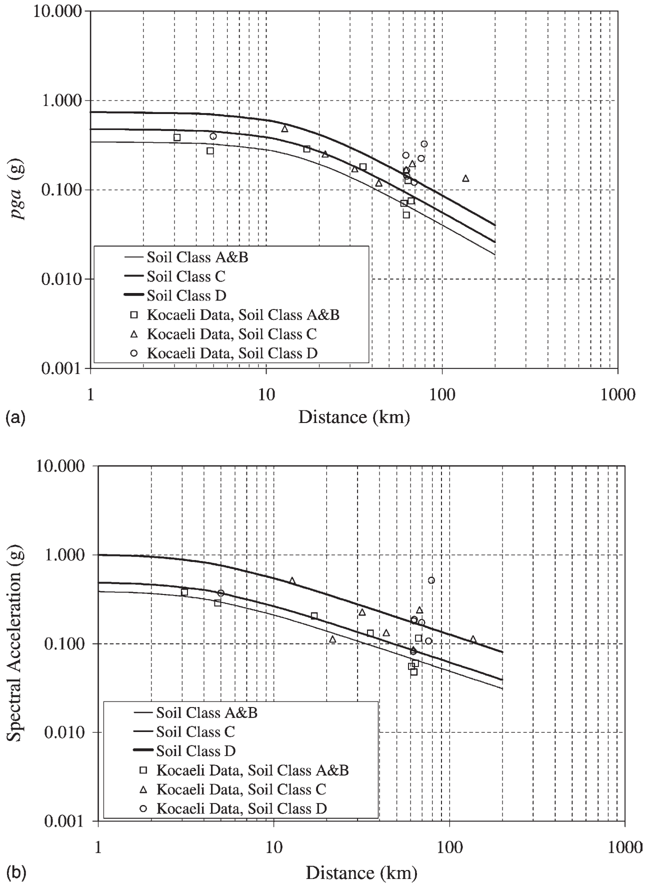

Fig. 7. (a) Comparison of model predictions of mean pga with observed data from the Kocaeli earthquake for all soil classes. (b) Comparison of model predictions of mean 1-second spectral acceleration with observed data from the Kocaeli earthquake for all soil classes.

For the other events as well, similar fits are seen. For example, combining data from all soil classes, predicted mean levels of pga and 1-second spectral acceleration from the attenuation model are compared next with data from the Kocaeli and Düzce main shocks. These comparisons are presented in Figs. 7 and 8. Note that the Kocaeli database consisted largely of records from distances between 60 and 80 km, while the Düzce main shock provided a large number of records at distances greater than 150 km. Thus, even though these two events made available very dissimilar records, reasonable fits of the model to the data of each events were obtained as can be seen in Figs. 7 and 8.

The variation with frequency of the model coefficients, a, b, c, d, e, f, and h as well as of the logarithmic standard deviation (sigma) from the mixed effects model is summarized in Fig. 9. The attenuation model coefficients and the model standard error all appear to be dependent on frequency.

Plots of the inter-event and intra-event residuals (see Eq. (2)) for predicted horizontal pga are presented in Fig. 10. No systematic trends are observed in the variation of these residuals either with distance or with magnitude—this is a desired feature in all regression models. Note that there are a total of 195 intra-event residuals but only 17 inter-event residuals, η_i corresponding to the 17 events in the database (see Table 1). The intra-event residuals are significantly larger than the inter-event residuals as seen in Fig. 10. This observation suggests that any individual event's recordings used in the overall model development follow similar trends with magnitude, distance, etc.

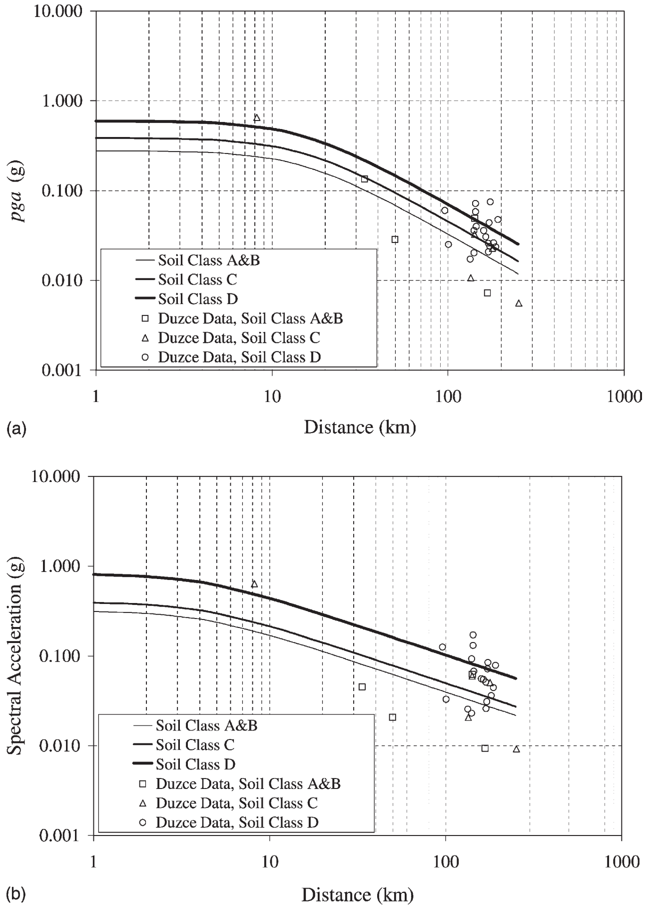

Fig. 8. (a) Comparison of model predictions of mean pga with observed data from the Düzce earthquake for all soil classes. (b) Comparison of model predictions of mean 1-second spectral acceleration with observed data from the Düzce earthquake for all soil classes.

7. Comparison of proposed model with Western US models

A comparison of predictions of ground motion based on the proposed attenuation relationship with that from other empirical models for shallow crustal zones (using a Western US earthquake database) is studied. Figs. 11 and 12 show plots of predictions of pga and 1-second spectral acceleration, respectively, versus distance for a $M_w = 7.4$ event and considering soil classes, A and B. The predictions are based on the proposed attenuation model as well as on two Western US empirical attenuation models proposed in Refs. [3,17]. The model in Ref. [17] as well as the proposed attenuation model uses the geometric mean of the two horizontal components of ground motion parameters while the model in Ref. [3] uses the random horizontal-component of the ground motion parameters.

It is seen from Figs. 11 and 12 that over all distances less than about 100 km, the Western US models predict higher pga and spectral acceleration levels than the proposed attenuation model for Northwestern Turkey. For short distances, both the Western US models predict much higher motions, sometimes greater than one standard deviation above the mean of the proposed attenuation model.

A comparison of response spectra based on the proposed attenuation model and on the two Western US attenuation models is studied next. Both the Western US models are again seen in Fig. 13 to predict significantly higher levels of spectral acceleration than the proposed attenuation model at distances of 20–60 km. The model in Ref. [3] typically predicts motions greater than one standard deviation above the mean of the proposed model. At

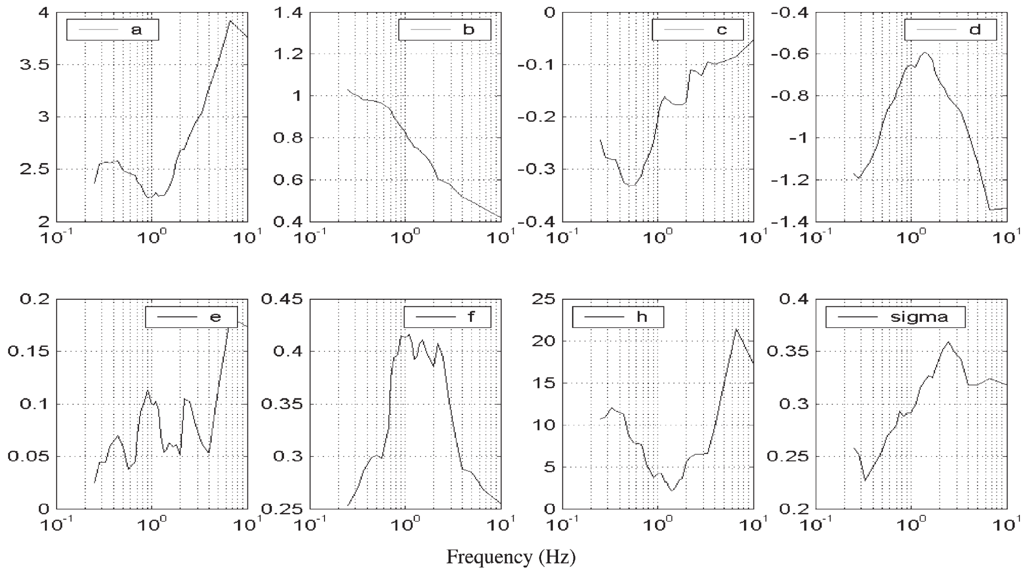

Fig. 9. Variation of empirical attenuation model coefficients and logarithmic standard deviation of spectral acceleration with frequency.

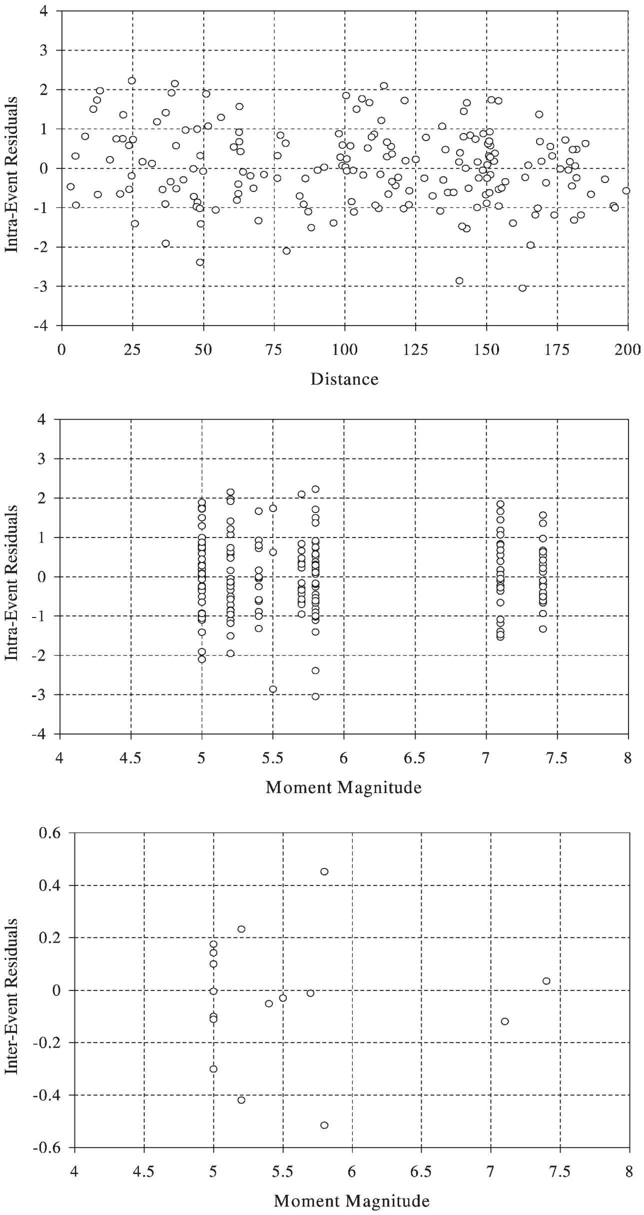

Fig. 10. Variation of residuals for pga with distance and magnitude.

greater distances such as 150 km, the model in Ref. [17] predicts significantly lower ground motions than the proposed model while the model in Ref. [3] still predicts motions that are as much as one standard deviation above that predicted by the proposed model for all natural periods up to 2 s.

The larger differences in ground motion level predictions (indicated by Figs. 11–13) between the proposed model and existing attenuation models for shallow crustal zones in the Western US can significantly change the probabilistic hazard estimates for sites in Turkey that are affected by fault segments on the North Anatolian Fault system (at distances less then 150 km) and magnitudes at a similar level (7.4) to that studied in Figs. 11–13.

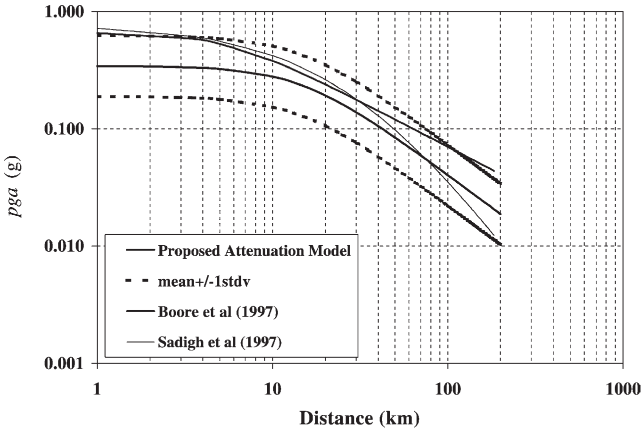

Fig. 11. Comparison of predictions from the proposed attenuation model with those from two Western US models for pga for soil classes A and B and $M_w = 7.4$.

8. Conclusions

An attenuation model has been developed for pga and 5%-damped spectral acceleration for periods up to 4 s. The mixed effects model proposed here accounts for inter- and intra-event variability and leads to smaller standard error than that obtained when a fixed effects model was employed. The model developed is only intended for use with normal and/or strike-slip events; it will likely underestimate motions from reverse and reverse-oblique earthquakes. Source and propagation parameters are region-specific and they could have a great influence on ground motion. This study is region-specific as only recordings from earthquakes that have occurred in Northwestern Turkey have been used in the analyses. The models developed are, therefore, only recommended for prediction of ground motions in Northwestern Turkey.

The attenuation models presented do not account for rupture directivity effects. Ten of the records used in this

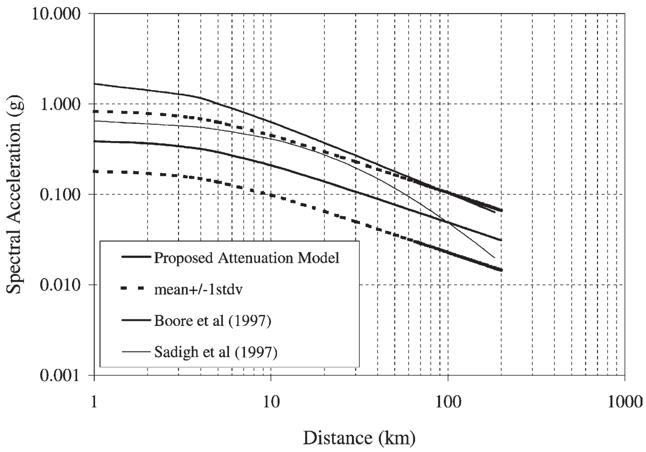

Fig. 12. Comparison of predictions from the proposed attenuation model with those from two Western US models for 1-second spectral acceleration for soil classes A and B and $M_w = 7.4$.

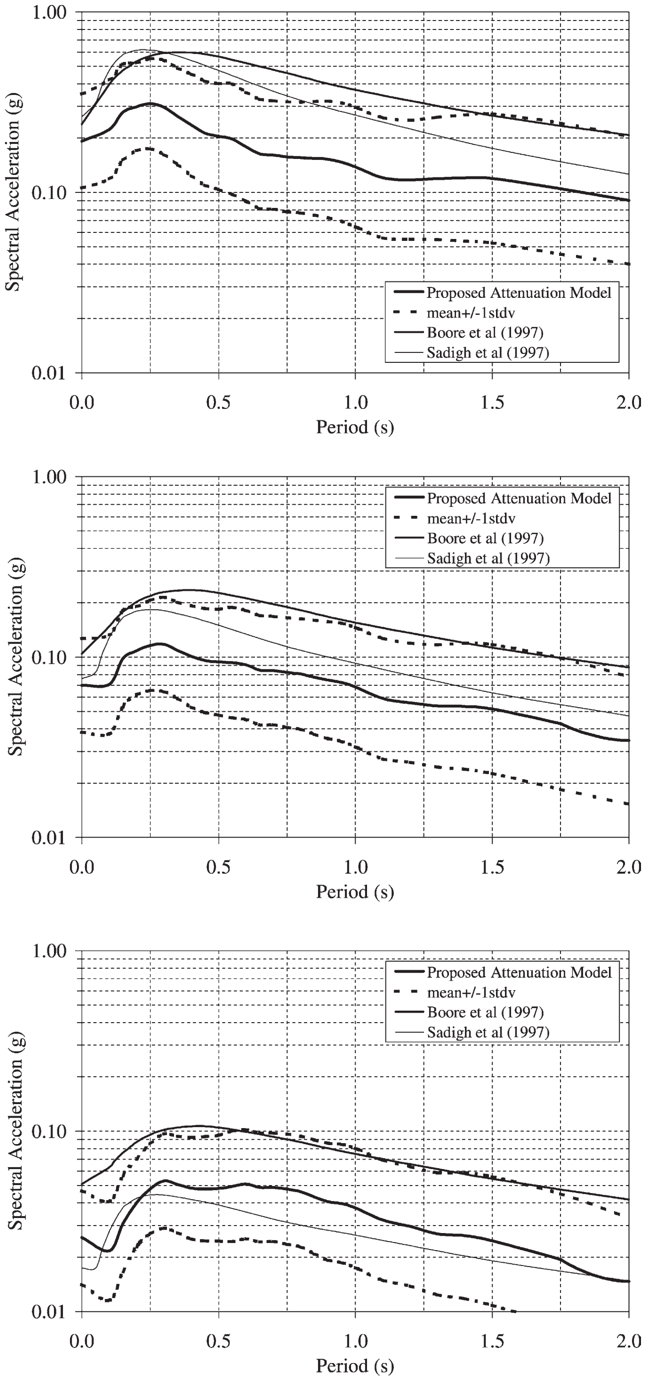

Fig. 13. Comparison of predicted response spectra from the proposed attenuation model with those from two Western US models for different distances (20, 60, and 150 km) for soil classes A and B and $M_w = 7.4$.

study have source-to-site distances less than 20 km, and hence are considered to be recordings in the near-field region. Some of these records exhibit rupture directivity effects. However, no parameter accounting for rupture directivity was included in the model.

This new attenuation model developed here has been proposed to take advantage of the availability of numerous strong motion records from recent earthquakes in Turkey. With additional strong motion instrumentation and improved soil profile data, this model can be improved. The study shows that consideration of intra-event variability in addition to inter-event variability improves the fit of empirical attenuation models to recorded data.

When the proposed model is compared to predictions based on Western US empirical attenuation models for shallow crustal zones, it was found that the Western US models predicted considerably different motions; sometimes these predictions were more than one standard deviation away from that of the proposed model. This was the case for all natural periods of interest. Also, when considering different distances, it was found that the Western US models predicted larger motions at shorter distances while at larger distances, the two Western US models predicted different levels of motion form each other but neither matched the predictions of the proposed model. Differences between the predictions from the proposed model and those from the Western US models suggest that if a seismic hazard analysis study were to be conducted for Turkey, very different findings may result depending on which model is used. Until more data become available and refinements to the proposed attenuation model for Turkey can be made, the epistemic uncertainty associated with alternative model predictions needs to be appropriately included in any seismic hazard studies.

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