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EMPIRICAL STRONG GROUND MOTION ATTENUATION RELATIONS FOR NORTHWESTERN TURKEY

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ABSTRACT

Using a random effects model that takes into consideration the correlation of data recorded by a single event, we employ a database consisting of 195 recordings from recent seismic events to develop empirical attenuation relationships for the geometric mean of horizontal peak ground acceleration (*pga*) and 5-percent damped spectral acceleration (S_a). The recordings employed were obtained from strong motion stations operating in Northwestern Turkey and resulted from events that included the Kocaeli (M_w 7.4) and the Düzce (M_w 7.1) earthquakes and their aftershocks as well as other events. Predictions based on the random effects model are compared with those from 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.

Keywords: Attenuation relationship, spectral acceleration, random effects, Northwestern Turkey.

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 over-predicted peak accelerations in the near-field region because they relied heavily on extrapolation from larger distances and smaller magnitude earthquakes. In the case of the Kocaeli earthquake, these low accelerations may also have been due to the smoothness of the rupture and the relatively low stress drop (Erdik, 2000; Durukal, 2002). 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 focused on establishing new region-specific attenuation relationships for Northwestern Turkey. In the following, we discuss the development of these models using motions obtained during the Kocaeli and the Düzce earthquakes and their aftershocks as well as other recent events. The procedure for developing these attenuation models is based on a random effects model which is based on a maximum likelihood procedure and which accounts for correlation among the data recorded from the same event. We will refer to a "mixed effects" and a "fixed effects" model 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. Rather than call the model that we prefer simply a "random effects" model, we refer to it as a mixed effects model because some of the attenuation model coefficients are modeled as random and others as fixed, based on the AIC (Akaike's Information Criterion) value, a maximum likelihood statistic (see Davidian and Giltinan, 1995).

STRONG MOTION DATABASE

The strong motion records used in this study were 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 overall database consists of 1188 records from 392 earthquakes recorded at 47 strong motion stations between 1994 and 2001. The ERD records were obtained from a database maintained at the Pacific Earthquake Engineering Research Center (PEER) website (http://peer.berkeley.edu/smcat/). A total of 195 records from 17 earthquakes with $M \geq 5.0$ were used in the regression analyses (see Table 1). A representation of the distribution of the strong motion data as a function of moment magnitude and distance is shown in Figure 1 for each of the soil classes (A&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 that were less than 100 km were used in the analyses. The Bolu record was also excluded because of possible instrument error in the recording.

MODEL PARAMETERS

In this study, earthquake magnitude was defined in terms of moment magnitude (M_w) to avoid saturation effects for magnitudes greater than about 6. Local magnitude (M_L) was used for all events with M ≤ 6.0, under the assumption that M_L is approximately equal to M_w for M ≤ 6.0 (Heaton et al., 1986). For distance measures, the closest horizontal distance to the vertical projection of the rupture plane was employed. The effect of local site conditions was included in attenuation model parameters that were adjusted to represent the different site classes. The site classes used in this study were defined according to the average shear wave velocity over the top 30 meters as presented in Table 2. The geometric mean of the two horizontal components of the ground motion parameter (i.e., peak ground acceleration or spectral acceleration) was chosen as the dependent variable in the attenuation relationships.

Style of faulting

The style of faulting is a parameter that has been included in many empirical attenuation models since it is believed that reverse and reverse-oblique mechanisms produce larger motions compared to normal and strike-slip mechanisms (Campbell, 1983, 1984). 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 (Barka and Kadinsky-Cade, 1988; Orgulu and Aktar, 2001). Orgulu and Aktar (2001) analyzed the fault mechanisms of the thirty largest aftershocks of the Kocaeli earthquake and found a strike-slip dominancy in the mechanism of these events as well as a normal faulting type in some cases. Although it is considered important to distinguish between reverse and reverse-oblique earthquakes and normal and strike-slip earthquakes in attenuation models, this style of faulting parameter was not included in the present study. 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.

REGRESSION MODEL

A nonlinear mixed effects model was defined to account for both inter-event (fixed effects) and intra-event (random effects) variability. In representing both fixed and random effects, this mixed effects model describes the covariance structure obtained by careful grouping of the data. Such a model with two sources of random variation is sometimes called a hierarchical model (Lindley and Smith, 1972; Bryk and Raudenbush, 1992) or a multilevel model (Goldstein, 1995). Random effects are associated with the particular experimental units – earthquakes in our case –that are selected at random from the population of interest. A random effects model is expected to not yield different results from the more conventional two-step regression method adopted by Joyner and Boore (1981) as long as all the events included provide a large number of recordings (Abrahamson and Youngs, 1992). The S-Plus software (S-PLUS, 2000) was employed for the determination of the model coefficients for a mixed effects model as well as for a fixed effects model (where intra-event variability is not considered). Details regarding the mixed effects model are described by Pinherio and Bates (2000) and an analysis procedure as given by Davidian and Giltinan (1995) was used to develop the empirical attenuation model.

The functional form for the attenuation relationship that we employed with the mixed effects model is given as follows:

$$\log(Y_{ij}) = a + b(M_i - 6) + c(M_i - 6)^2 + d\log\sqrt{R_{ij}^2 + h^2} + eG_1 + fG_2 \qquad (1)$$

where Y_{ij} is the geometric mean of the ground motion parameter (peak ground acceleration or spectral acceleration) in cm/sec^2 from the j^{th} recording of the i^{th} event, M_i is the moment magnitude of the i^{th} event, and R_{ij} is the closest horizontal distance to the vertical projection of the rupture for the j^{th} recording from the i^{th} event. Such a 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. They each are assumed to be normally distributed with zero means but with individual standard errors that together (as the square root of the sum of their squares) define the standard error in the model of Eq. 1. 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. 1 and in our discussion of results, all the logarithms are in base 10.

Table 3 shows a comparison of the logarithmic standard deviations for the fixed effects model with those from the mixed effects model as a function of period. From this table, it is clear that the mixed effects model yields the smaller logarithmic standard deviations over the entire range of periods; the differences are larger for short periods. From this, we believe that the mixed effects model with smaller standard error is expected to fit 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.

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 error for *pga* (shown as 0.00 sec.) and 5%-damped spectral acceleration values for periods up to 4 seconds. Figure 2 shows the variation in the acceleration response spectra with different soil conditions when $M = 7.5$ and $R = 10$ km based on model predictions. Although amplification of spectral acceleration is significant for softer soils (site class D) compared to the stiffer soil and rock cases, the period at which spectral acceleration is at its peak value is almost the same for all of the soil classes. It is well known that softer soils have longer resonant periods than stiffer soils; the reason that this effect was not captured by the attenuation model is 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 Figures 3 and 4, respectively.

The attenuation model predictions are compared with data from the Kocaeli main shock data for peak ground acceleration and for 1-second spectral accelerations. These comparisons for all soil classes are presented in Figures 5 and 6. Reasonable fits of the model to the data are obtained.

The variation with frequency of the model parameters/coefficients, *a*, *b*, *c*, *d*, *e*, *f*, and *h* as well as of the logarithmic standard error from the mixed effects model is summarized in Figure 7. The attenuation model coefficients and the model standard error all appear to be dependent on frequency.

Plots of the residuals for predicted horizontal peak ground acceleration are presented in Figure 8. No systematic trends were observed in the variation of these residuals either with distance or with magnitude.

CONCLUSIONS

An attenuation model has been developed for *pga* and 5%-damped spectral acceleration for periods up to 4 seconds. The mixed effects model employed accounts for inter- and intra-event variability and leads to smaller standard error than when a fixed effects model is 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 have a great influence on ground motion. This study is region-specific as only recordings from earthquakes that have occurred in Northwestern Turkey were 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 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.

The attenuation model developed here has been proposed due to 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.

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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*	*H (km)*	*No. of Recordings* 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.

Site Class	**Vs_{30}**
A	> 750 m/s
B	360 m/s to 750 m/s
C	180 m/s to 360 m/s
D	< 180 m/s

Table 3. Comparison of the logarithmic standard deviations from the fixed and mixed effects models.

Period (s)	$\sigma_{log(Y)}$ (fixed)	$\sigma_{log(Y)}$ (mixed)	Period (s)	$\sigma_{log(Y)}$ (fixed)	$\sigma_{log(Y)}$ (mixed)
0.00	0.294	0.246	0.85	0.343	0.308
0.10	0.311	0.258	0.9	0.350	0.316
0.15	0.307	0.252	0.95	0.354	0.320
0.20	0.294	0.227	1.00	0.356	0.323
0.25	0.299	0.234	1.10	0.356	0.327
0.30	0.308	0.247	1.20	0.352	0.325
0.35	0.303	0.256	1.30	0.358	0.334
0.40	0.320	0.270	1.40	0.369	0.344
0.45	0.329	0.277	1.50	0.375	0.353
0.50	0.333	0.281	1.75	0.383	0.359
0.55	0.346	0.293	2.00	0.374	0.349
0.60	0.342	0.288	2.25	0.368	0.342
0.65	0.337	0.291	2.75	0.343	0.318
0.70	0.330	0.291	3.00	0.346	0.318
0.75	0.332	0.296	3.50	0.351	0.324
0.80	0.334	0.298	4.00	0.347	0.319

Table 4. Empirical attenuation coefficients and logarithmic standard deviation 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***	$\sigma_{log(Y)}$
0.00	3.287	0.503	-0.079	-1.1177	14.82	0.141	0.331	0.245
0.10	3.755	0.419	-0.052	-1.3361	17.22	0.173	0.255	0.258
0.15	3.922	0.463	-0.085	-1.3422	21.41	0.182	0.268	0.252
0.20	3.518	0.494	-0.094	-1.1162	14.87	0.113	0.285	0.227
0.25	3.270	0.517	-0.099	-0.9781	9.75	0.053	0.288	0.234
0.30	3.040	0.549	-0.095	-0.8762	6.54	0.062	0.320	0.247
0.35	2.951	0.579	-0.121	-0.8402	6.48	0.080	0.352	0.256
0.40	2.825	0.593	-0.112	-0.8089	6.48	0.102	0.394	0.270
0.45	2.690	0.605	-0.111	-0.7572	6.17	0.105	0.408	0.277
0.50	2.685	0.653	-0.171	-0.7302	5.58	0.051	0.385	0.281
0.55	2.581	0.685	-0.177	-0.6928	3.56	0.061	0.393	0.293
0.60	2.423	0.708	-0.177	-0.6291	3.41	0.059	0.399	0.288
0.65	2.325	0.724	-0.177	-0.6032	2.50	0.063	0.411	0.291
0.70	2.276	0.741	-0.174	-0.5932	2.12	0.055	0.407	0.291
0.75	2.247	0.750	-0.170	-0.5946	2.34	0.054	0.396	0.296
0.80	2.247	0.755	-0.166	-0.6075	3.22	0.070	0.392	0.298
0.85	2.243	0.774	-0.161	-0.6353	3.22	0.094	0.407	0.308
0.90	2.272	0.791	-0.172	-0.6630	4.21	0.102	0.416	0.316
0.95	2.246	0.807	-0.182	-0.6570	4.23	0.099	0.414	0.320
1.00	2.237	0.828	-0.207	-0.6543	4.14	0.100	0.413	0.323
1.10	2.227	0.855	-0.248	-0.6616	3.78	0.113	0.415	0.327
1.20	2.267	0.874	-0.267	-0.6910	4.49	0.103	0.397	0.325
1.30	2.353	0.901	-0.284	-0.7516	5.35	0.092	0.394	0.334
1.40	2.376	0.932	-0.296	-0.7752	6.90	0.070	0.375	0.344
1.50	2.445	0.943	-0.314	-0.8117	7.73	0.045	0.328	0.353
1.75	2.466	0.964	-0.331	-0.8671	7.85	0.038	0.298	0.359
2.00	2.490	0.973	-0.331	-0.9397	8.55	0.059	0.301	0.349
2.25	2.581	0.977	-0.326	-1.0345	11.21	0.070	0.299	0.342
2.75	2.559	0.980	-0.282	-1.1235	11.68	0.060	0.286	0.318
3.00	2.564	0.998	-0.282	-1.1473	12.04	0.044	0.273	0.318
3.50	2.549	1.011	-0.278	-1.1950	10.93	0.044	0.261	0.324
4.00	2.366	1.028	-0.244	-1.1710	10.72	0.025	0.253	0.318

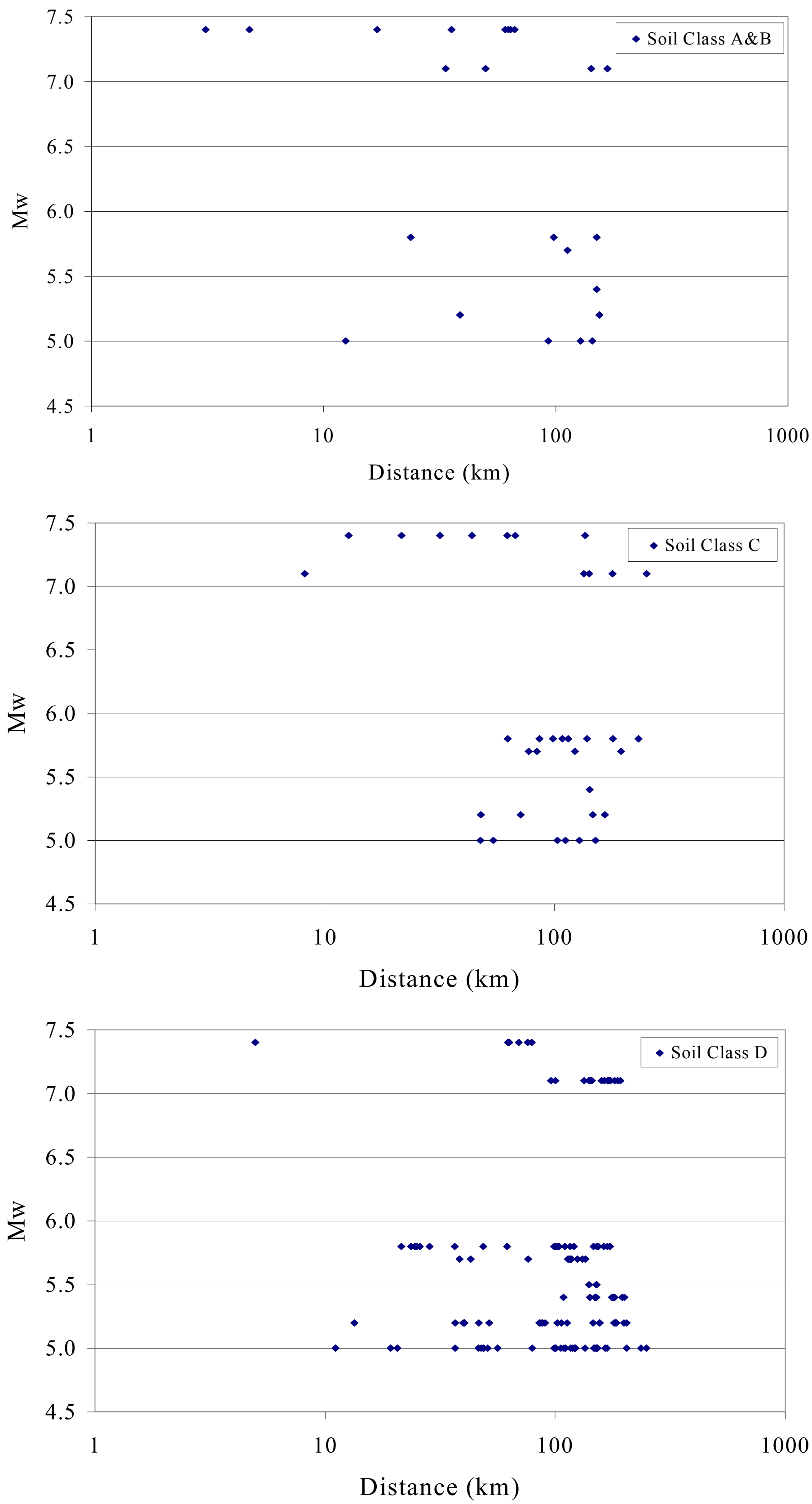

Figure 1. Distribution of the records as a function of magnitude and distance for soil classes A & B, C, and D, respectively.

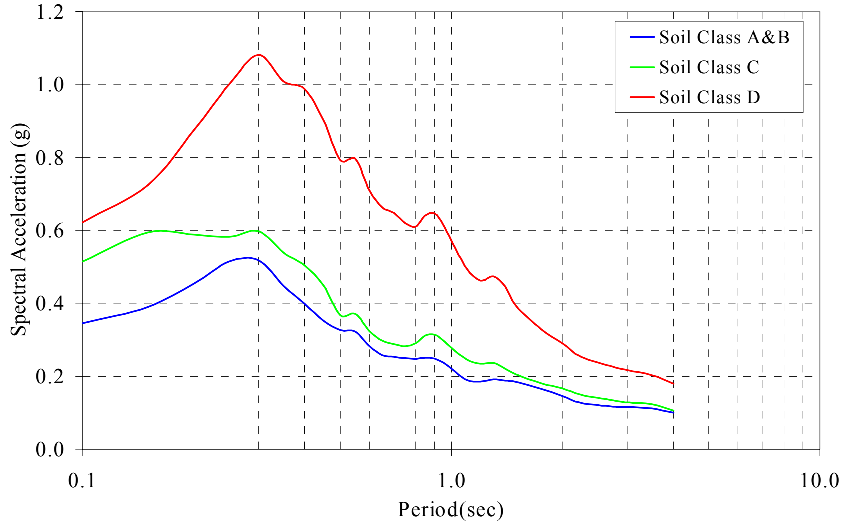

Figure 2. Effect of soil class – $M_w = 7.5$ and R = 10 km.

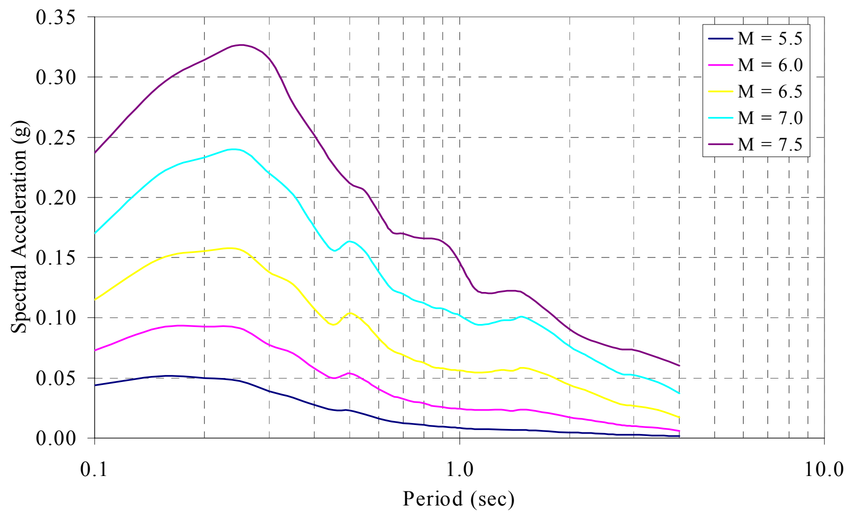

Figure 3. Effect of magnitude – soil classes A&B, R = 20 km.

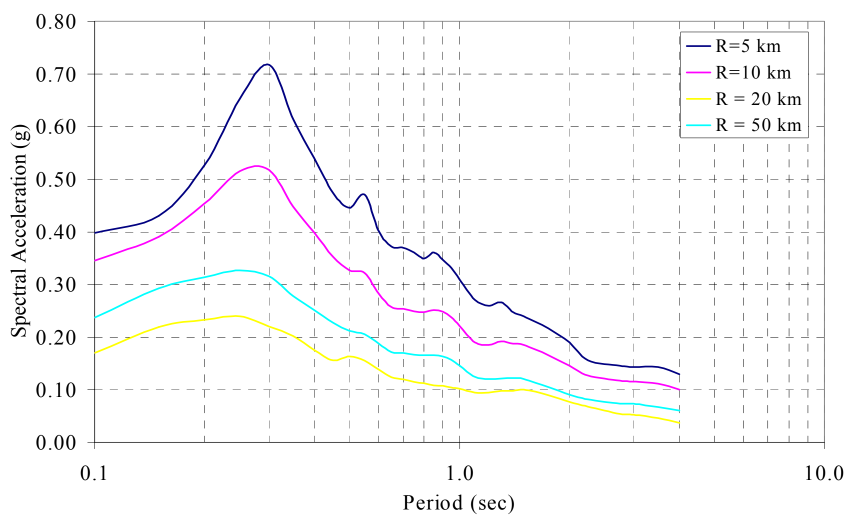

Figure 4. Effect of distance – soil classes A&B, $M_w = 7.5$.

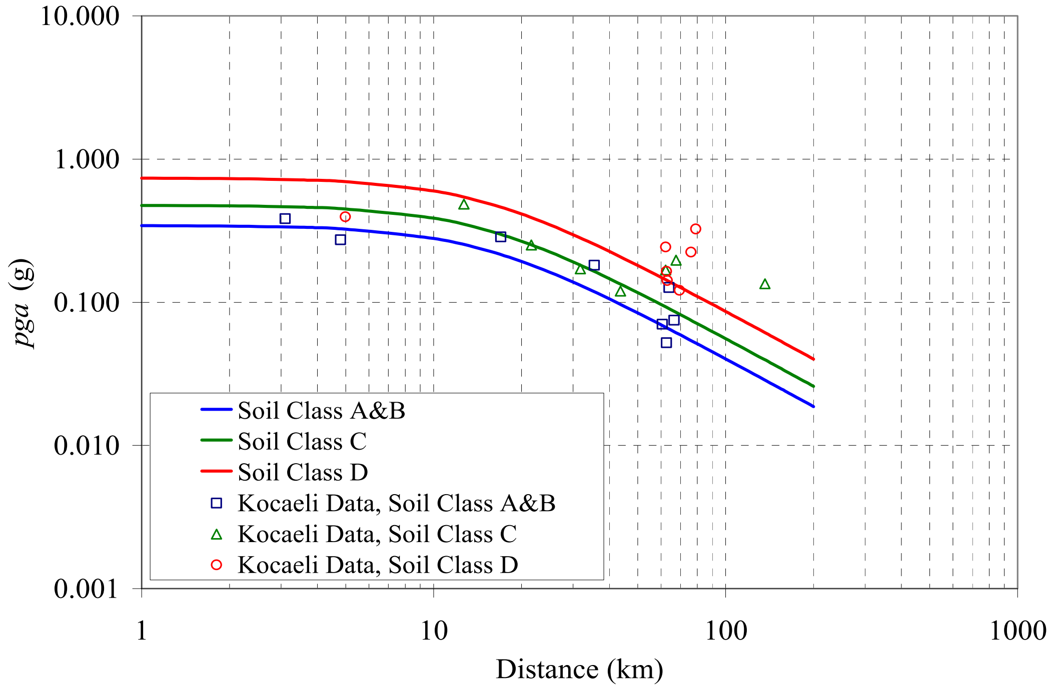

Figure 5. Comparison of attenuation model predictions with Kocaeli data for peak ground acceleration.

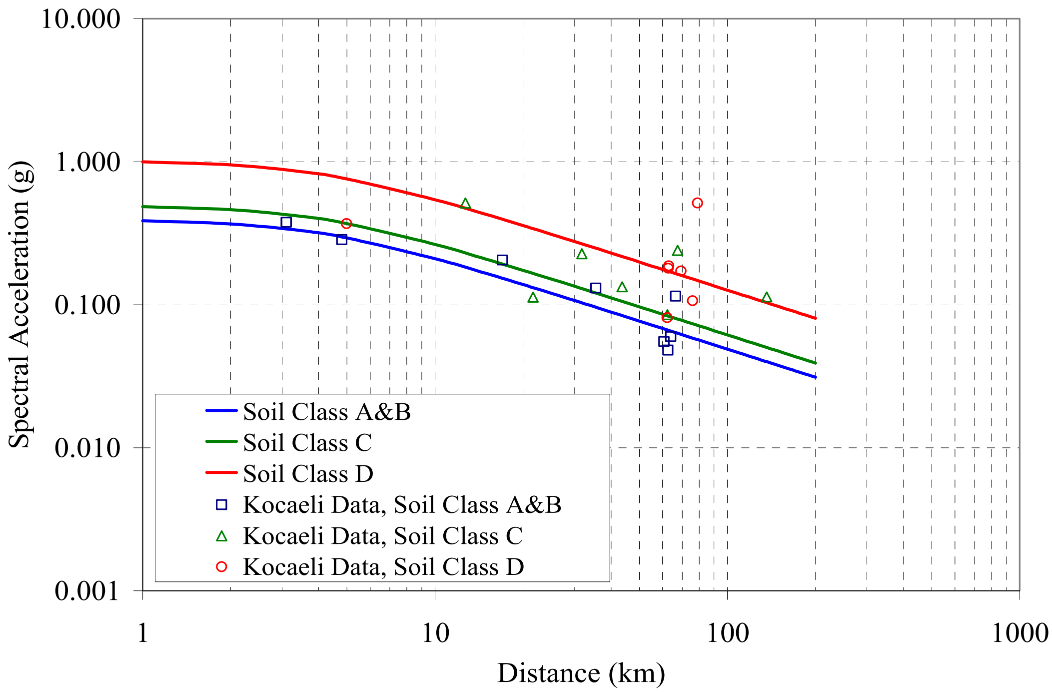

Figure 6. Comparison of attenuation model predictions with Kocaeli Data for 5%-damped 1.0-second spectral acceleration.

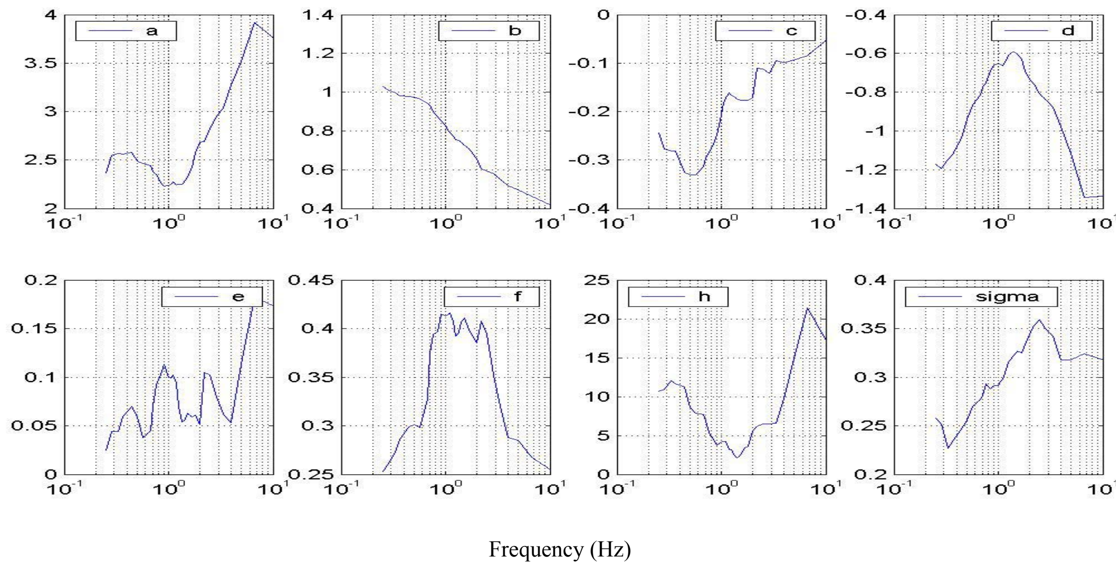

Figure 7. Variation of empirical attenuation model coefficients and logarithmic standard deviation with frequency.

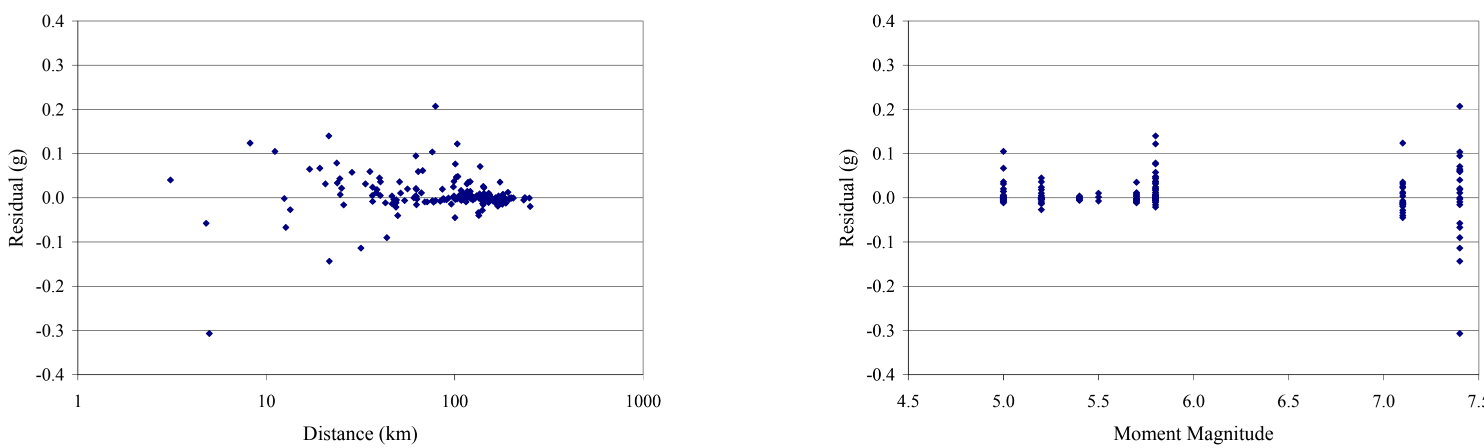

Figure 8. Variation of residuals for peak ground acceleration with distance and magnitude, respectively.