ENGINEERING GROUND MOTION PARAMETERS ATTENUATION RELATIONSHIPS FOR GREECE

Laurentiu Danciu and G-Akis Tselentis[1]

SUMMARY

Engineering ground motion parameters can be used to describe the damage potential of an earthquake. Some of them correlate well with several commonly used demand measures of structural performance, liquefaction, and seismic slope stability. The importance of these parameters comes from the necessity of an alternative measure to the earthquake intensity. In the proposed new attenuation relationship we consider peak values of strong motion, spectral acceleration, elastic input energy at selected frequencies, root mean square acceleration, Arias intensity, characteristic intensity, Fajfar index, cumulative absolute velocity, CAV_5 and spectrum intensity energy. This paper describes the steps involved in the development of new attenuation relationships for all the above parameters, using all existing, up to date Greek strong-motion data. The functional form of the empirical equation is selected based on a theoretical model, and the coefficients of the independent variables are determined by employing mixed effects regression analysis methodologies.

INTRODUCTION

Prediction of the ground motions at a site is one of the most important issues of engineering seismology since this can provide a first order quick indication of the expected damage potential of future earthquakes. Generally speaking the earthquake damage potential depends upon the time duration of motion, energy absorption capacity of structure or equipment, number of train cycles, and the energy content of the earthquake. Therefore, for engineering purposes, parameters that incorporate in their definition the above mentioned characteristics are more reliable predictors of the earthquake's damage potential. These parameters are: peak ground velocity (*PGV*), Arias intensity (I_a), a_{rms}, characteristic intensity (I_c), Fajfar's index (I_f), Housner spectrum intensity *(SI)*, acceleration response spectrum (S_a), elastic input energy (E_i), cumulative absolute velocity (*CAV*) and cumulative absolute velocity integrated with a 5 cm/sec^2 lower threshold (CAV_5). These ground motion parameters are described in great detail in [Kramer, 1996].

The objective of this study is to propose new empirical ground motion prediction equations (so-called attenuation relationships) for the engineering ground motion parameters mentioned above instead of the traditionally used, for seismic hazard analysis in Greece such as maximum or spectral acceleration [Theodulidis 1991, Theodulidis and Papazachos, 1992, Margaris et al. 2002, Skarlatoudis et al. 2003]. Ground motion prediction equations along with motion-to-motion variability, are derived for each of the selected ground motion parameters using mixed effects regression analyses and based on a dataset of strong motion recordings from Greek earthquake events.

DATABASE AND METHODOLOGY

The strong motion records used for the study of the attenuation relationships of engineering ground motion have been provided by European Strong Motion Database [Ambraseys *et al.*, 2004]. In Greece a large number of strong-motion instruments are located in the ground floor or basement of relatively large buildings. In other regions these records are excluded from analysis in order to minimize the possible bias

---

[1] University of Patras, Department of Geology, Laboratory of Seismology, laurentin.danciu@upatras.gr, tselentis@upatras.gr

associated with the effects of such buildings in the measured ground motion. Since in Greece there is a limitation on the available good quality data it was decided to consider the records from free-field stations and from stations located on the basements of less than two storey buildings. The final dataset consists of 335 records from 151 Greek earthquakes. No correction has been applied to the selected records because these records were available in an already corrected form.

A brief description of the dependent and independent variables used to develop the regression analysis is given below. The independent variables consist of those parameters which describe the source, travel path and site conditions which determine the character and the strength of the ground motion.

The magnitude scale, which we will refer to as *M* in this article, corresponds to the moment magnitude [Hanks & Kanamori, 1979]. For the selected dataset based on data from Greece, *M* is ranging between 4.5 and 6.9. The regression analysis was performed using epicentral distance which we will refer to as *R* in this article. Since most of the events are offshore and for those onshore the surface geology does not show often any evident faulting, it is impossible to use a fault distance definition like the closest distance to the fault rupture or to the surface projection of the rupture [Paciello *et al.*, 2000]. Hypocentral depths of the selected earthquakes are in the interval 0 to 30 km with a mean of 10.66 km. The local site classification of each recording station was based on the average shear-wave velocity (V_s), over up to 30m in depth from the ground surface [Borcherdt, 1994] and presented in Table 1. In this study, 197 recording stations were classified as category C, 63 as category D and 75 as category B.

Site Categories		***Shear Wave Velocity***
B	*Rock*	*Vs > 800 m/sec*
C	*Stiff Soil*	*Vs=360-665 m/sec*
D	*Soft Soil*	*Vs=200-360 m/sec*

Table 1: Definition of site categories used in the attenuation models

The distribution of the selected dataset with respect to magnitude, distance and hypocentral depth is illustrated in the Figure 1. Judging from this figure we note that, large magnitude events are recorded at intermediate and long distances; small magnitudes events are observed over small epicentral distances. An exponential trend can be observed and the correlation coefficient between magnitude and distance is 0.64. Based on data distribution, we recommend that the presented attenuation relationships should not be used to predict motions at magnitudes less than 4.5 or greater than 6.9 or epicentral distances greater than 136 km.

The style-of-faulting parameter is used in this study to distinguish between different source types and is classified into three categories. These categories include: thrust, strike slip and normal fault mechanism. For the selected dataset, the records without information regarding style-of-faulting were completed with available information provided by the study of [Skarlatoudis *et al.*, 2003]. Their study empirically demonstrates that the effect of thrust and strike slip faulting in Greece are similar. [Campbell, 1981] empirically demonstrated that thrust faulting causes higher ground motion than strike-slip or normal faulting. In the past, it has been common practice to put strike-slip and normal-faulting events into a single category. However, a recent study by [Spudich *et al.*, 1999] suggests that normal-faulting events, or strike-slip events in an extensional stress regime, may have lower ground motions than other types of shallow crustal earthquakes.

In addition to the selected engineering ground motion parameters, *PGA* was introduced in this study in order to demonstrate the validity of the model, having in mind that for Greece there are no definitive engineering ground motion parameters empirical attenuation models available. Using the recorded strong motion data for these earthquakes, for each horizontal component we computed the above mentioned ground motion parameters. The arithmetic average between the two horizontal components of these dependent variables was used to evaluate the attenuation relationships through the regression analysis.

REGRESSION ANALYSIS AND RESULTS

Repeated or hierarchical measurements are data where individuals have multiple measurements over time or space. Analyzing these data requires recognizing and estimating variability both between and within individuals. Further, it is not uncommon for the relationship between an explanatory variable (e.g. magnitude) and a response variable (e.g. *PGA*) to be nonlinear in the parameters. Nonlinear mixed effects models provide a tool for analyzing repeated measurements data, by taking into consideration these two types of variability as well as, the nonlinear relationships between the explanatory and the response variable. Earthquakes data used to develop empirical attenuation relationships can be viewed as repeated measurements, where the unit of repeated measurement is the earthquake and the epicentral distance plays the role of time.

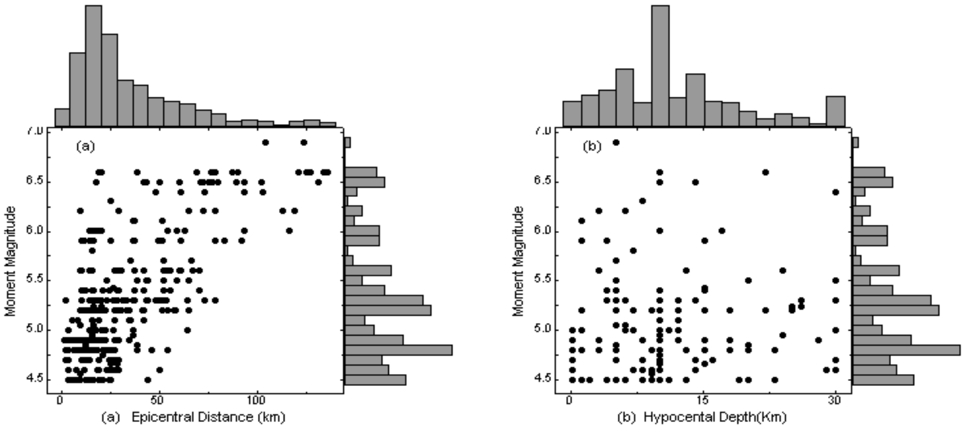

Figure 1: Distribution of the selected dataset in (a) magnitude and epicentral distance, (b) magnitude and focal depth

In the attenuation relationship situation, the mixed effects model can be set to reduce the bias introduced if the data are not distributed evenly among the parameters, for example, if magnitude and distance are statistically correlated, or if the data are dominated by many recordings from few earthquakes or recording sites. One approach of the problem is to seek to enhance the estimation of the coefficients of one earthquake from the data available for others. One such way is to introduce a random effects model.

[Brillinger & Preisler, 1984; Brillinger & Preisler, 1985] have proposed a random effects model to separate the uncertainties associated with between-earthquake (earthquake-to earthquake) and within-earthquake (record-to-record) variations. [Abrahamson & Youngs, 1992] introduced an alternative algorithm, which they considered more stable though less efficient. The methods are based on maximum likelihood approach.

The predictive equation adopted in the present investigation to represent the attenuation of the ground motion has the following form:

$$\log_{10}(Y_{ij}) = a + bM_i - c\log_{10}\sqrt{R_{ij}^2 + h^2} + eS + fF + \varepsilon_{ij} \qquad (1)$$

where Y_{ij} is the response variable (the arithmetic average of the two horizontal components) from the j^{th} record of the i^{th} event, M_i is the moment magnitude of the i^{th} event, R_{ij} is the epicentral distance from the i^{th} event to the location, and h is the "*fictitious*" focal depth obtained from the regression analysis.

The error term in Equation (1) is normally distributed with zero mean and standard deviation σ^2. The dummy variables S and F refer to the site classification and fault mechanism, respectively. Prior to selection of the attenuation model presented in Equation (1) we examined the same model with separate terms for soil category C and D and for separate terms for thrust and strike slip fault mechanism. Based on the coefficient values, the results suggest that the coefficient values for soil category D is twice than coefficient values for soil category C. The regression showed that the two coefficients for normal and strike slip fault mechanism were almost identical. Therefore, the results indicated that, for the present database, the S can be assumed to take the values: 0 for rock soil (B), 1 for stiff soil (C) and 2 for soft soil (D) and F takes the values: 0 for normal, 1 for thrust and strike slip fault mechanism. These later statements are in the agreement with those presented by[Skarlatoudis *et al.*, 2003].

Coefficient, "*h*", is referred to as a "*fictitious*" depth measure and its values are estimated as a part of the regression. It has been observed by [Abrahamson & Silva, 1997] and [Ozbey *et al.*, 2004], that this "*fictitious*" depth coefficient provides a better fit to the data at short distances. The soil condition coefficients, "*e*" and "*f*", are considered independent of magnitude, distance and level of ground shaking.

A nonlinear mixed effects model [Pinheiro & Bates, 2000] and the procedure given by [Davidian & Giltinan, 1995], were used to determine the regression coefficients for the empirical models of dependent variables. The model was fitted using the conditional linearization method of [Lindstrom & Bates, 1990], as implemented in the NLME software [Pinheiro & Bates, 2000]. The coefficients of the attenuation model and the variance components, together with their standard errors estimated from the regression analysis are presented in Table 2. Standard error terms presented in Table 2 show that the aleatory variability in the predictability of I_a and CAV_5 is large. This is not a disadvantage because it has been accepted that I_a has the largest aleatory variability in its prediction compared to the other intensity measures, [Travasarou et al. 2003]. The smallest value of standard deviation is provided by CAV.

The analysis of the residuals resulting from the regression did not show systematic trends as a function of the independent variables used in the model. Moreover, the correlation analysis has confirmed that the residuals were uncorrelated with magnitude, distance and predicted engineering ground motion parameters at greater than 99 per cent level of confidence. These observations are similar and valid for all ground motion parameters considered in the regression model.

The empirical attenuation relationships for engineering ground motion parameters for the three soil classification and a fixed magnitude shown that the soft soil exhibit larger amplitudes than stiff soil and rock. Moreover, for rock local soil condition, the amplitudes for thrust and strike slip mechanisms are higher than for normal fault mechanism. Also the increased amplitudes in integral parameters like a_{rms}, I_a, CAV, CAV_5 can be partially attributed to the longer duration of earthquake motion associated with soft soil sites relative to nearby rock sites [Kayen & Mitchell, 1997]. Herein these effects are reported only for the spectral parameters S_a and V_{ei} and presented in Figure 2a-d. The amplification effects of soft soil with respect to stiff and rock are somewhat more important at the short period for the specific values of magnitude (M=6.5) and distance (R=10km) used in the evaluation of S_a and V_{ei}.

Figure 2a-d also shows that thrust faults exhibit higher amplitudes for both cases, noting that, for S_a, this effect becomes negligible at periods greater than about 2 sec. This tendency is consistent with the expectation that thrust and strike slip fault mechanisms, might have on average higher dynamic stress drops than normal fault mechanism. Another trend observed was that, at fixed magnitude and fixed soil condition for spectral parameters, the shape and amplitudes decrease with increasing distances. This trend is valid for all ground motion parameters analyzed here and more details can be found in [Danciu & Tselentis, 2007].

COMPARISON OF PROPOSED MODEL WITH OTHER

For Greece, there are no engineering ground motion parameters empirical attenuation models available today that may be used for comparison. Considering this lack of models, the validity of the model is demonstrated by comparison for PGA predictive equations proposed for the area of Greece. Previously proposed predictive equations of [Theodulidis & Papazachos, 1992, 1994], [Margaris *et al.*, 2002], [Skarlatoudis *et al.*, 2003] and [Ambraseys *et al.*, 2005] were selected for comparison purpose and plotted in the Figure 3a. All the comparisons presented in this section were computed for epicentral distances ranging from 1km to 150km and for a fixed moment magnitude (M=6.5) at rock sites. The proposed relationship is in good agreement with the previous proposed attenuation relationships. The shape of the present equation follows the similar trend with the proposed equations and exhibits lower PGA values for short distances.

The difference observed in the near-field can be attributed to the fact that we have used the average of the two horizontal components instead of the larger of the two, (as other authors), and thus we have introduced some sort of smoothing of data, eventually lowering high values. Also, this discrepancy on the near-field can be attributed to the difference in the “fictitious” depth coefficient. The fact that the “fictitious” depth coefficient obtained thought the regression analysis provides a better fit to the data at short distances was observed by [Abrahamson & Silva, 1997] and [Ozbey *et al.*, 2004].

The previous mentioned predictive relationships derived from Greek data have been considered in the comparison study for PGV attenuation relationship. The comparison is presented in the Figure 3b. The similar trend related to the PGV proposed relations is present and different PGV values for all range of distances from 0 to 150 km are observed. Again, the discrepancies in the near-field can be assigned to the differences in the “fictitious” depth coefficient. The equations of [Theodulidis & Papazachos, 1992] predict consistently higher PGA and PGV values and are probably due to the regression method and much smaller data used.

Among engineering ground motion parameters, I_a is the parameter with the greatest number of proposed attenuation relationships. For comparison purposes, in addition to the results of [Paciello *et al.*, 2000] the equations of [Sabetta & Pugliese, 1996], [Kayen & Mitchell, 1997] [Travasarou *et al.*, 2003] and [Bragato & Slejko, 2005], are also depicted in Figure 3c. Judging from this figure we can see that the predicted Arias intensity is lower than previous proposed relationships. This can be explained by the different amount of data that these relationships have been based on, different distance definitions, soil category and fault type definitions. This study used epicentral distance; the same distance is used by [Paciello *et al.*, 2000] and [Sabetta & Pugliese, 1996]. [Travasarou *et al.*, 2003] and [Bragato & Slejko, 2005] used rupture distance and [Kayen & Mitchell, 1997] the closest distance to the surface projection of the rupture plane. Alternative definitions of Arias intensity, largest of the two horizontal peaks [Paciello et al. 2000], arithmetic average [Travasarou et al. 2003] or their geometric mean [Bragato and Slejko 2005] can explain the observed discrepancies.

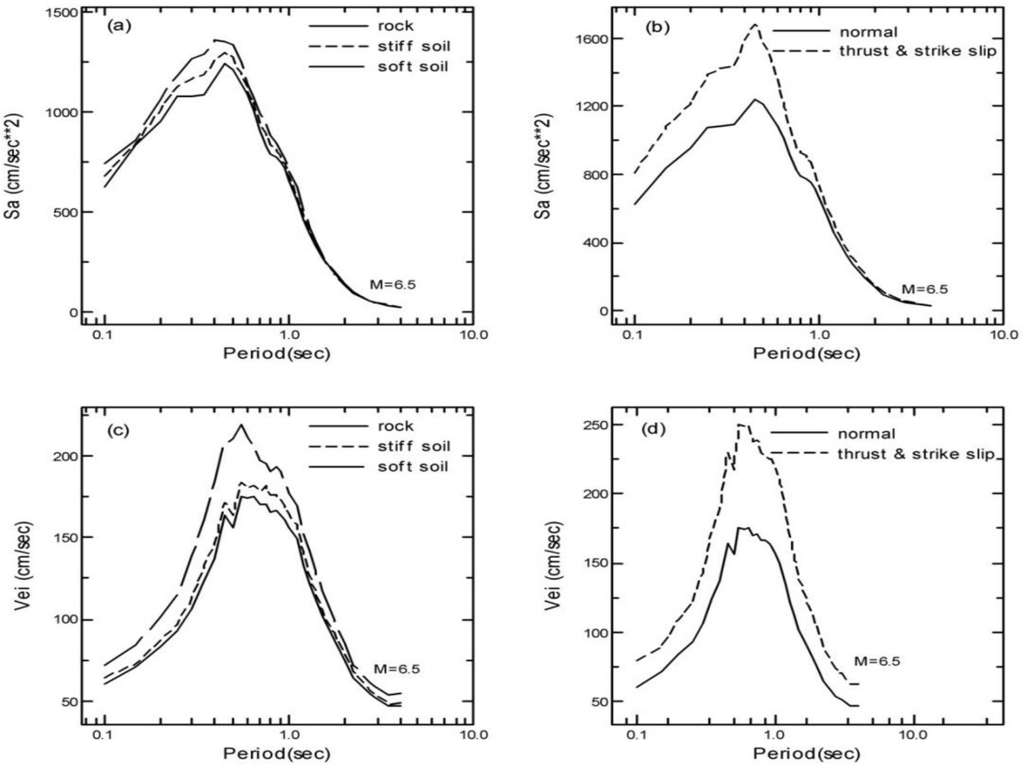

Figure 2: Predicted values of engineering ground motion parameters for various periods for a fixed moment magnitude M=6.5 and for a fixed epicentral distance R=10km: (a) S_a for different soils and normal fault mechanism, (b) S_a for different fault mechanisms and rock soil category, (c) V_{ei} for different soils and normal fault mechanism (d) V_{ei} for different fault mechanisms and rock soil category.

In Figure 3d, we compare the proposed attenuation relationship with that proposed by [Kramer & Mitchell, 2006]. It can be observed that the two attenuation relationships give different results both at short and long distances. At short distances the present CAV_5 curve is slightly higher; while for long distances the opposite situation occurs. To explain these differences in the results, we should point out that different data was used. The 50% of data used by [Kramer & Mitchell, 2006] are from events with moment magnitude greater or equal than 6. Also, different distance definition (closest distance to the rupture) and the data distribution related to this distance can explain these differences.

The new estimated ground motion relations for S_a and E_i were compared with ground motion relations proposed in the studies of [Theodulidis & Papazachos, 1994] because it is the only single attenuation relationship available for Greece. The attenuation relationship for S_a is characterized by lack of data. No data for $R < 30$ km and for $M > 6.5$ suggest that a lot of caution is required for using these equations in that range. Thus, comparison between the attenuation relationship for S_a were calculated at fixed epicentral distance (R=30km) for magnitude 6.5 at rock sites. Additional, widely used relations to estimate S_a proposed by [Ambraseys *et al.*, 2005] and [Sadigh *et al.*, 1997] were considered.

Figure 3e compares the predicted S_a from the three selected ground motion relations with the proposed ground motion relation. The observed deviation between the present results and those proposed by [Theodulidis & Papazachos, 1992] can be attributed to the lack of near-field data used by these authors.

Furthermore, significant discrepancies are observed between our model and that proposed by [Theodulidis & Papazachos, 1992] for periods greater than 0.5sec due mainly to different digitizing and processing procedures. S_a attenuations obtained using Equation (1) are similar to those predicted by the equations of [Ambraseys *et al.*, 2005] and [Sadigh *et al.*, 1997], except for short periods where our model predicts lower values. This difference could be due to the different definition of distance used here compared to that used by [Ambraseys *et al.*, 2005]and Sadigh [Sadigh *et al.*, 1997].

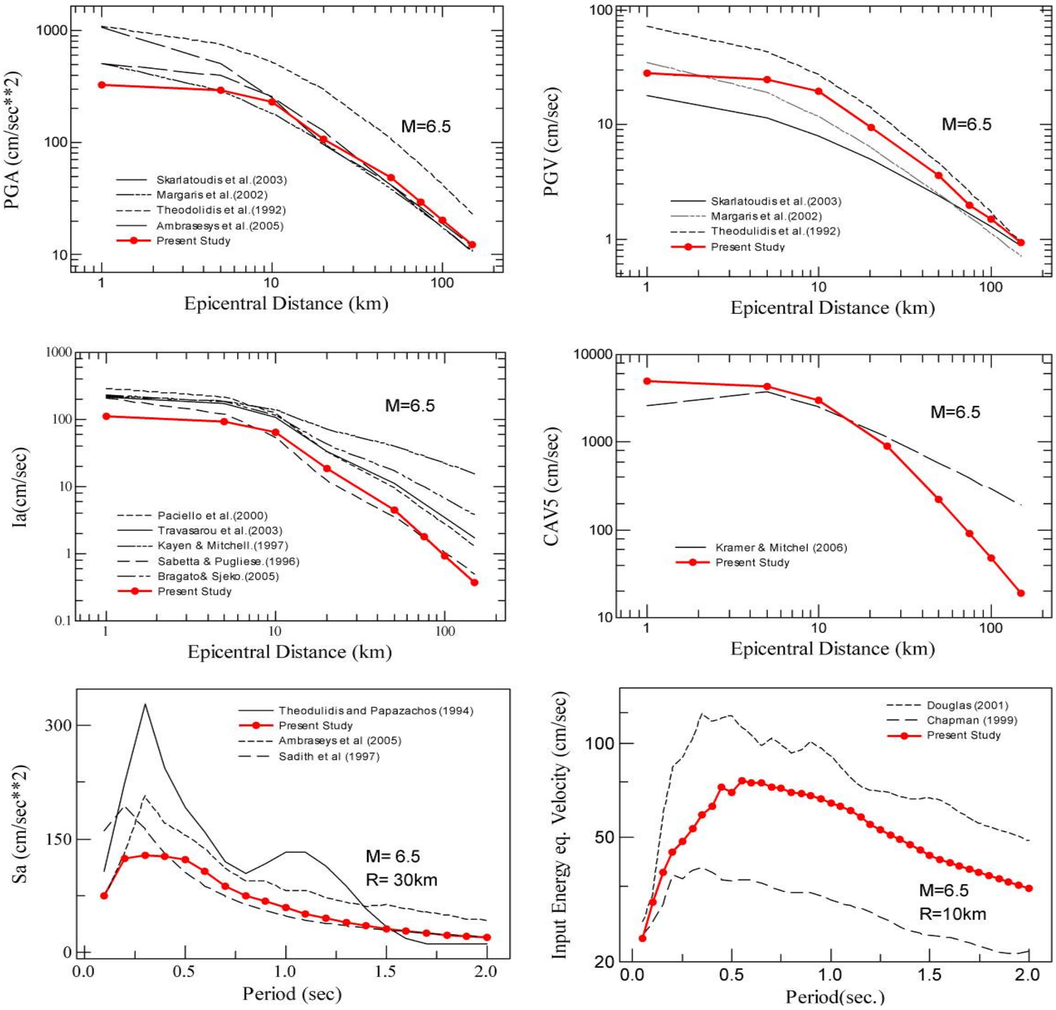

Figure 3: Comparison of the derived PGA (a), *PGV (b),* I_a *(c),* CAV_5 *(d),* S_a *(e),* V_{ei} *(f)* attenuation relationships with other proposed in the literature.

Comparison of the predicted by our model values for V_{ei} , (Figure 3f), with those predicted by the only two attenuation relations for horizontal energy available in the literature [Chapman, 1999; Douglas, 2001], shows similar trend. The peak values of V_{ei} appear at periods in the neighbourhood of 0.5 sec for all three relations. V_{ei} predicted by Equation (1), show lower values than those of [Douglas, 2001] and higher values than those by [Chapman, 1999].

CONCLUSIONS

An attenuation model has been developed for engineering ground motion parameters for the area of Greece. The engineering parameters have been incorporated for a first time in the empirical attenuation relations for Greece. The engineering ground motion parameters capture the effects of amplitude, frequency content, duration and energy of a ground motion record, thus the earthquake damage potential. Therefore, the proposed attenuation relationships could provide an improvement criterion to select and/or describe the seismic hazard scenarios.

Table 2: Coefficients and Standard Deviations of Attenuation Model for Engineering Ground-Motion Parameters

	a	***b***	***c***	***h***	***e***	***f***	τ	σ	ε_{total}
PGA	0.883	0.458	-1.278	11.515	0.038	0.116	0.109	0.27	0.291
PGV	-1.436	0.625	-1.152	10.586	0.026	0.086	0.124	0.283	0.309
PGD	-2.365	0.512	-0.799	10.33	0.009	0.061	0.201	0.257	0.326
Ic	-0.929	0.883	-1.954	10.638	0.03	0.137	0.208	0.426	0.474
If	-1.272	0.650	-1.171	11.403	0.023	0.101	0.119	0.281	0.306
Ia	-2.663	1.125	-2.332	13.092	0.028	0.200	0.205	0.482	0.524
arms	-0.156	0.512	-1.177	10.134	0.026	0.082	0.133	0.264	0.295
CAV	0.015	0.654	-1.163	14.876	0.009	0.103	0.106	0.251	0.272
CAV5	-1.665	1.138	-2.304	13.47	0.063	0.234	0.183	0.566	0.595
Sa(T)	***a***	***b***	***c***	***H***	***e***	***f***	τ	σ	ε_{total}
0.10	1.544	0.41	-1.364	11.708	0.039	0.112	0.139	0.264	0.299
0.15	1.810	0.429	-1.492	15.721	0.008	0.113	0.107	0.285	0.304
0.20	1.339	0.477	-1.368	14.302	0.024	0.103	0.103	0.287	0.304
0.25	1.126	0.537	-1.443	16.446	0.020	0.109	0.104	0.304	0.321
0.30	0.688	0.582	-1.374	15.117	0.034	0.121	0.107	0.323	0.341
0.35	0.311	0.623	-1.31	14.474	0.037	0.121	0.124	0.323	0.346
0.40	-0.109	0.669	-1.247	12.733	0.033	0.136	0.151	0.322	0.355
0.45	-0.361	0.702	-1.227	11.834	0.019	0.132	0.154	0.322	0.357
0.50	-0.619	0.726	-1.174	10.945	0.021	0.117	0.163	0.318	0.357
0.60	-0.938	0.742	-1.087	8.732	0.011	0.098	0.167	0.321	0.362
0.70	-1.177	0.756	-1.051	7.597	0.020	0.072	0.151	0.329	0.362
0.80	-1.315	0.77	-1.067	7.986	0.024	0.069	0.14	0.331	0.359
0.90	-1.429	0.791	-1.101	8.566	0.016	0.063	0.145	0.325	0.356
1.00	-1.517	0.799	-1.113	9.128	0.016	0.05	0.156	0.314	0.351
1.10	-1.650	0.806	-1.098	9.340	0.025	0.046	0.148	0.307	0.341
1.20	-1.661	0.799	-1.099	10.185	0.023	0.053	0.142	0.303	0.335
1.30	-1.663	0.79	-1.093	10.89	0.015	0.054	0.149	0.299	0.334
1.40	-1.745	0.779	-1.029	10.359	0.013	0.051	0.147	0.296	0.330
1.50	-1.786	0.764	-0.980	9.889	0.011	0.058	0.151	0.291	0.327
2.00	-1.764	0.687	-0.825	9.191	0.009	0.061	0.172	0.267	0.318
V_{ei}(T)	***a***	***b***	***c***	***h***	***e***	***f***	τ	σ	ε_{total}
0.10	-0.923	0.566	-1.107	9.56	0.032	0.079	0.125	0.242	0.272
0.15	-0.321	0.527	-1.239	13.542	0.009	0.075	0.099	0.257	0.275
0.20	-0.483	0.541	-1.149	12.459	0.017	0.082	0.116	0.248	0.273
0.25	-0.498	0.563	-1.178	14.649	0.017	0.090	0.114	0.268	0.291
0.30	-0.804	0.600	-1.127	13.098	0.026	0.114	0.127	0.281	0.309
0.35	-1.099	0.643	-1.087	12.42	0.032	0.115	0.143	0.286	0.320
0.40	-1.275	0.672	-1.079	12.238	0.029	0.130	0.14	0.293	0.325
0.45	-1.552	0.712	-1.037	11.139	0.019	0.104	0.146	0.292	0.326
0.50	-1.433	0.700	-1.072	11.609	0.021	0.130	0.143	0.295	0.328
0.60	-1.807	0.734	-0.973	8.658	0.017	0.086	0.155	0.300	0.338
0.70	-1.893	0.744	-0.972	8.284	0.021	0.066	0.146	0.308	0.341
0.80	-1.944	0.755	-0.998	8.646	0.025	0.061	0.142	0.307	0.338
0.90	-2.01	0.765	-1.006	8.661	0.024	0.064	0.138	0.304	0.334
1.00	-2.019	0.769	-1.024	9.543	0.022	0.055	0.148	0.297	0.332
1.10	-2.081	0.776	-1.025	9.778	0.025	0.056	0.142	0.294	0.326
1.20	-2.093	0.769	-1.007	10.198	0.025	0.063	0.137	0.290	0.320
1.30	-2.046	0.755	-0.996	10.311	0.017	0.067	0.138	0.284	0.316
1.40	-2.058	0.744	-0.959	9.900	0.018	0.062	0.133	0.284	0.314
1.50	-2.04	0.730	-0.932	9.401	0.018	0.064	0.131	0.282	0.311
2.00	-1.913	0.676	-0.847	8.594	0.021	0.054	0.143	0.267	0.303

REFERENCES

Abrahamson N.A. & Silva W.J., (1997), Empirical Response Spectral attenuation Relations for Shallow Crustal Earthquakes, *Seismological Research Letters***,** 94–127.

Abrahamson N.A. & Youngs R.R., (1992), A stable algorithm for regression analysis using the ransom effects model, *Bulletin Seismological Society of America,* **82,** 505-510

Ambraseys N., Douglas J., Sarma S.K. & Smit P.M., (2005), Equations for the estimation of strong ground motion from shallow crustal earthquakes using data from Europe and the Middle-Est: horizontal peak ground acceleration and spectral acceleration, *Bulletin of Earthquake Engineering,* **3,** 1-53

Ambraseys N., Smit P., Douglas J., Margaris B., Sigbjornsson R., Olafsson S., Suhadolc P. & Costa G., (2004), Internet-Site for European Strong-Motion Data, *Bollettino di Geofisica Teorica ed Applicata,* **45,** 113-129.

Borcherdt R.D., (1994), Estimates of site-dependent response spectra for design (methodology and justification), *Earthquake Spectra,* **10,** 617–653

Bragato P.L. & Slejko D., (2005), Empirical Ground-Motion Attenuation Relations for the Eastern Alps in the Magnitude Range 2.5–6.3, *Bulletin of the Seismological Society of America,* **95,** 252–276

Brillinger D.R. & Preisler H.K., (1984), An exploratory data analysis of the Joyner-Boore attenuation data. , *Bulletin Seismological Society of America,* **74,** 1441-1450

Brillinger D.R. & Preisler H.K., (1985), Further analysis of the Joyner-Boore attenuation data, *Bulletin Seismological Society of America,* **75,** 611-614

Campbell K.W., (1981), Near-Source Attenuation of Peak Horizontal Acceleration, *Bulletin of the Seismological Society of America,* **71,** 2039–2070

Chapman M.C., (1999), On the use of elastic input energy for seismic hazard analysis. , *Earthquake Spectra,* **15,** 607-635

Danciu L. & Tselentis G.A., (2007), Engineering Ground-Motion Parameters Attenuation Relationships for Greece, *Bulletin of the Seismological Society of America,* **97,** 162-183

Davidian M. & Giltinan D.M., (1995), *Nonlinear models for repeated measurement data.* New York: Chapman and Hall/CRC,

Douglas J., (2001), A critical reappraisal of some problems in engineering seismology, In *Department of Civil and Environmental Engineering* PhD Thesis, Imperial College, London,

Hanks T.C. & Kanamori T.C., (1979), A moment magnitude scale, *Journal of Geophysical Research,* **84,** 2348-2350

Kayen R.E. & Mitchell J.K., (1997), Assessment of liquefaction potential during earthquakes by Arias Intensity, *Journal of Geotechnical and Geoenvironmental Engineering (ASCE),* **123,** 1162-1174

Kramer S.L., (1996), *Geotechnical Earthquake Engineering.* Prentice Hall,

Kramer S.L. & Mitchell R., (2006), Ground Motion Intensity Measures for Liquefaction Hazard Evaluation, *Earthquake Spectra,* **22,** 413-438

Lindstrom M.J. & Bates D.M., (1990), Nonlinear mixed effects models for repeated measures data, *Biometrics,* **46,** 673-687

Margaris B., Papazachos C., Papaioannou C., Theodulidis N., Kalogeras I.S. & Skarlatoudis A.A., (2002), Ground motion attenuation relations for shallow earthquakes in Greece, *Proc of Twelfth European Conference on Earthquake Engineering,* **paper ref. 385.,**

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 Dynamics and Earthquake Engineering,* **24,** 115-125

Paciello A., Rinaldis D. & Romeo R., (2000), Incorporating ground motion parameters related to earthquake damage into seismic hazard analysis, In *Proc 6th Int Conf on Seismic Zonation: Managing Earthquake Risk in the 21st Century*, ed. Inst. E. E. R., pp. 321-326, Oakland, CA,

Pinheiro J.C. & Bates D.M., (2000), *Mixed-effects models in S and S-Plus*. New York:Springer

Sabetta F. & Pugliese A., (1996), Estimation of response spectra and simulation of nonstationary earthquake ground motions., *Bulletin of the Seismological Society of America,* **86,** 337–352

Sadigh K., Chang C.-Y., Egan J.A., Makdisi F. & Youngs R.R., (1997), Attenuation relationships for shallow crustal earthquakes based on California strong motion data., *Seismological Research Letters,* **68,** 180–189

Skarlatoudis A.A., Papazachos B.C., Margaris B.N., Theodulidis N., Papaioannou C., Kalogeras I., Scordilis E.M. & Karakostas V., (2003), Empirical Peak Ground – Motion Predictive Relations for Shallow Earthquakes in Greece, *Bulletin of the Seismological Society of America,* **93,** 2591-2603

Spudich P., Joyner W.B., Lindh A.G., Boore D.M., Margaris B.M. & Fletcher J.B., (1999), SEA99: A Revised Ground Motion Prediction Relation for Use in Extensional Tectonic Regimes, *Bulletin of the Seismological Society of America,* **89,** 1156–1170

Theodulidis N.P. & Papazachos B.C., (1992), Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, peak horizontal acceleration, velocity and displacement, *Soil Dynamics and Earthquake Engineering,* **11,** 387–402

Theodulidis N.P. & Papazachos B.C., (1994), Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: II, Horizontal Pseudo-velocity, *Soil Dynamics and Earthquake Engineering,* **13,** 317–343

Travasarou T., Bray J.B. & Abrahamson A., (2003), Empirical attenuation relationship for Arias Intensity, *Earthquake Engineering and Structural Dynamics,* **32,** 1133-1155