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Empirical Peak Ground-Motion Predictive Relations for Shallow Earthquakes in Greece

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Abstract In the present article new predictive relations are proposed for the peak values of the horizontal components of ground acceleration, velocity, and displacement, using 619 strong motion recordings from shallow earthquakes in the broader Aegean area, which are processed using the same procedure in order to obtain a homogeneous strong motion database. The data set is derived from 225 earthquakes, mainly of normal and strike-slip focal mechanisms with magnitudes $4.5 \leq \mathbf{M} \leq 7.0$ and epicentral distances in the range $1 \text{ km} \leq R \leq 160$ km that have been relocated using an appropriate technique. About 1000 values of peak ground acceleration (PGA), velocity (PGV), and displacement (PGD) from horizontal components were used to derive the empirical predictive relations proposed in this study. A term accounting for the effect of faulting mechanisms in the predictive relations is introduced, and the UBC (1997) site classification is adopted for the quantification of the site effects. The new relations are compared to previous ones proposed for Greece or other regions with comparable seismotectonic environments. The regression analysis showed a noticeable (up to ~30%) variance reduction of the proposed relations for predicting PGA, PGV, and PGD values compared to previous ones for the Aegean area, suggesting a significant improvement of predictive relations due to the use of a homogeneous strong motion database and improved earthquake parameter information.

Introduction

Empirical predictive attenuation relations are a fundamental tool for seismic hazard assessment. Such relations are based on the recorded peak ground motions using appropriate instruments (e.g., accelerographs) and are expressed as mathematical functions relating the observed quantity to earthquake source parameters, the propagation path, and the local site conditions. So far, much effort has been made in this field, and a large number of predictive relations for peak ground motion have already been published. These relations usually refer to large regions such as the northwest United States, Canada (Milne and Davenport, 1969; Campbell, 1985; Boore *et al.*, 1993), or Europe (Ambraseys and Bommer, 1991; Ambraseys, 1995; Ambraseys *et al.*, 1996; Rinaldis *et al.*, 1998), but also to smaller regions with high levels of seismicity, such as Greece or Italy (Chiaruttini and Siro, 1981; Papaioannou, 1986).

Two major efforts for estimating empirical predictive relations were previously made in Greece, the first one by Theodulidis (1991) and Theodulidis and Papazachos (1992) and the latest by Margaris *et al.* (2002). The occurrence of recent strong disastrous earthquakes close to urban areas, the continuous increase of the number of strong motion recordings in Greece, the new more accurate automatic methods for digitization of analog recordings, and the new relocation techniques resulting in more accurate hypocenter determination raised the need for new improved predictive relations. Therefore, our aim is to propose new predictive relations for Greece by incorporating the most recent information available.

The study area (Fig. 1a) is seismically one of the most active regions in western Eurasia. The most dominant feature of the area is the Hellenic trench, where subduction of the eastern Mediterranean lithosphere takes place under the Aegean microplate. Shallow as well as intermediate-depth earthquakes with magnitudes up to about 8.0 have occurred in this area (e.g., Papazachos and Papazachou, 2002). To the north of the trench, the sedimentary part of the Hellenic arc (Dinarides–Hellenides mountains–Crete–Rhodes) represents the accretionary prism. Moving further north we can identify other typical elements of a subduction system, namely the south Aegean basin (Sea of Crete) and the volcanic arc. In the north Aegean the North Aegean trough, which is the continuation of the North Anatolia fault system into the Aegean, controls the regional tectonics and exhibits large

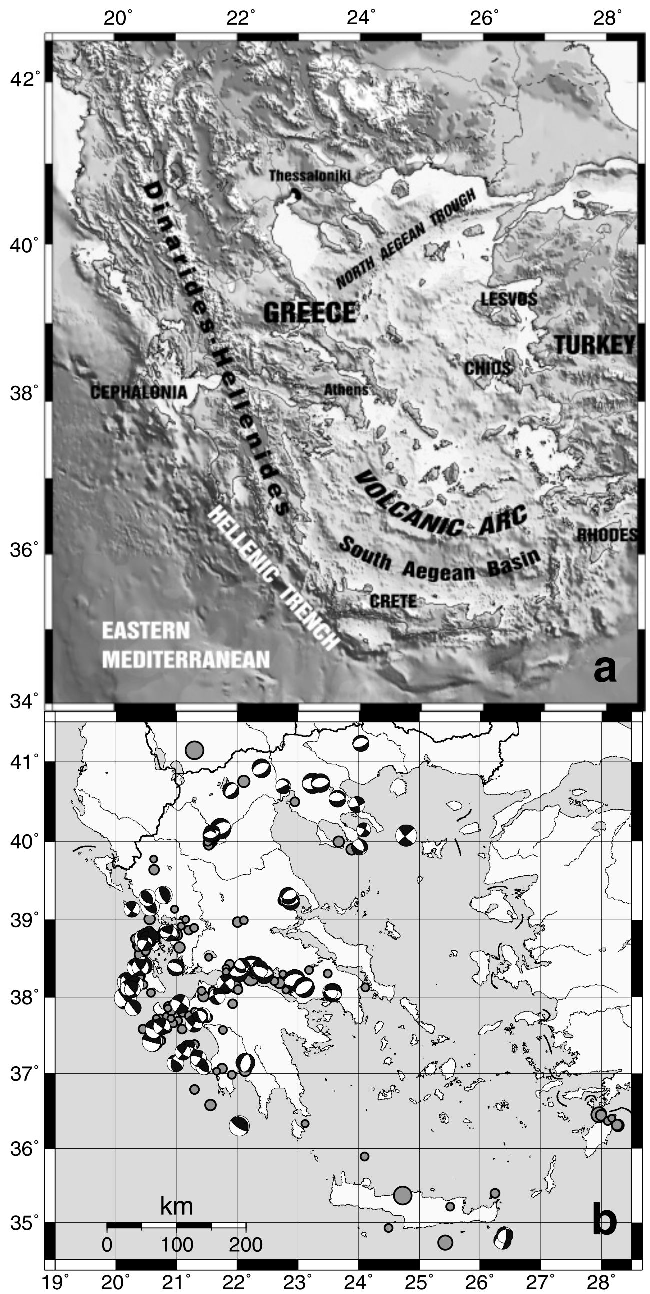

Figure 1. (a) Map of the study area where the main morphotectonic features are also noted. (b) Map of the available focal mechanisms and epicenters of the earthquakes used in this study.

strike-slip faults, whereas the remaining back-arc area is dominated by approximately north–south extension (e.g., Papazachos *et al.*, 1998, 1999).

Data Used

The data used in this article consist of 1000 peak ground-motion values, corresponding to 225 mainly normal and strike-slip faulting, shallow earthquakes in Greece. This data set was selected from the entire database of the available accelerograms in Greece (Institute of Engineering Seismology and Earthquake Engineering [ITSAK], www.itsak.gr, and National Observatory of Athens [NOA], www.gein.noa.gr) that spans the period 1973–1999. The selected records satisfy at least one of the following criteria: (a) the earthquake that triggered the instrument should have a moment magnitude of $\mathbf{M} \geq 4.5$; (b) the strong motion record should have PGA $\geq 0.05g$, independent of the earthquake magnitude; or (c) the record has PGA $< 0.05g$, but another record with PGA $\geq 0.05g$ should be available for the same earthquake.

The need for higher accuracy in the earthquake location routines used in Greece has led to the development of a relocation method that incorporates not only recent developments of the earthquake location software but also new time delays for P_n and S_n waves for the broader Aegean area, estimated using data from local experiments (Skarlatoudis, 2002; Skarlatoudis *et al.*, 2003). This approach involves correction of the seismic-wave travel times at regional stations based on a calibration with well-located local earthquakes. From the comparison of the expected and the observed travel times of seismic waves, we calculated "absolute" residuals for each one of the regional stations located within the area of interest. These absolute residuals were processed through an inversion technique, which resulted in the estimation of time corrections for each one of the $1° \times 1°$ square windows into which the examined area had been divided. The data processing and relocation procedure was described in detail in Skarlatoudis (2002) and Skarlatoudis *et al.* (2003). Using this relocation method a new catalog with accurate earthquake hypocenter parameters (especially for focal depths) was compiled. The errors of this catalog were reduced to 9.8 $\pm$ 9.1 km for the horizontal error 3.0 $\pm$ 6.5 km for focal depths, and a root mean square (rms) error of 1.0 $\pm$ 0.2 sec. The importance of this relocated catalog for the results obtained in the regression analysis is examined in the present study. In Table 1 the earthquakes that produced the strong motion data set used in this article are listed.

The continuously increasing number of analog strong motion records from different institutions in Greece during recent years imposed the need of a database with homogenously processed strong motion data. In order to create this database, all the strong motion records were automatically digitized at 600 dots per inch scanning resolution. From the comparison of the Fourier amplitude spectra (FAS) of the components with the FAS of the fixed traces of the accelerogram the characteristic frequencies of a digital bandpass filter were computed. This filter was applied to the accelerograms in order to remove the noise introduced during the digitization and the processing of the records (Skarlatoudis *et al.*, 2002). This filtering procedure succeeded in removing noise, especially in the low-frequency range that mostly affects velocities and displacements (due to the integration that is used for their computation from acceleration). Depending on the individual signal-to-noise spectral ratio, a different frequency range is available for each strong motion record-

Table 1
Hypocentral Parameters of the Earthquakes used in the Present Study

Year	Origin Time	Lat. (°N)	Lon. (°E)	Dep. (km)	**M**	F
1973	1104155213.35	38.755	20.454	20.2	5.8	2
1973	1104161136.44	38.753	20.333	21.1	5.0	1
1977	1229165257.52	38.449	22.322	8.9	5.0	0
1978	0620200323.59	40.732	23.242	13.0	6.5	0
1978	0523233411.72	40.737	23.373	4.9	5.8	0
1978	0427083327.70	38.971	22.008	1.1	5.0	0
1978	0518001846.67	38.374	21.817	0.0	4.5	1
1980	0811091559.91	39.309	22.837	10.7	5.3	0
1980	0412113211.31	38.553	20.402	6.4	5.3	1
1980	0716000657.06	39.252	22.758	0.0	5.0	0
1980	0926041919.00	39.241	22.771	9.7	4.8	0
1981	0224205336.88	38.221	22.945	0.0	6.7	0
1981	0225023551.98	38.126	23.103	0.0	6.4	0
1981	0310151617.66	39.315	20.787	3.9	5.6	2
1981	0527181201.73	38.809	20.968	11.3	5.2	2
1981	0527152551.83	38.806	20.989	7.4	5.2	2
1981	0527150359.51	38.805	21.004	5.3	5.2	2
1981	0525230358.77	38.807	20.983	9.4	4.6	2
1981	0410083331.19	38.917	21.077	6.3	4.5	2
1983	0117124129.75	37.985	20.155	11.7	7.0	1
1983	0806154353.02	40.076	24.783	12.3	6.8	1
1983	0323235104.56	38.193	20.188	0.0	6.2	1
1983	0119000214.10	38.188	20.229	9.5	5.8	1
1983	0324041730.67	38.107	20.238	10.1	5.4	1
1983	0131152659.52	38.159	20.315	4.3	5.4	1
1983	0117165328.18	38.113	20.217	10.2	5.3	1
1983	0117155353.95	38.100	20.272	11.5	5.2	1
1983	0323190359.67	38.830	20.880	4.6	5.2	1
1983	0826125210.02	40.466	23.975	8.8	5.1	1
1983	0220054511.16	37.687	21.269	11.9	4.9	1
1984	0211080249.24	38.373	22.076	3.3	5.6	0
1984	1025143827.88	40.087	21.617	2.4	5.5	0
1984	0709185712.19	40.642	21.895	13.2	5.2	0
1984	1004101509.63	37.584	20.775	7.6	5.0	2
1984	1025094917.65	37.062	21.751	0.0	5.0	0
1984	1002110243.79	37.657	20.943	0.0	4.7	2
1984	0817212256.60	38.210	22.610	2.8	4.6	0
1984	1009021221.39	37.025	21.661	0.0	4.5	0
1985	0430181412.23	39.239	22.883	6.5	5.6	0
1985	0907102049.09	37.325	21.194	4.7	5.4	0
1985	0831060345.05	39.009	20.554	7.4	5.2	2
1985	1109233042.86	41.231	24.036	4.3	5.2	0
1985	0131163935.09	38.894	21.291	1.5	4.6	2
1985	0322203737.92	39.003	21.147	5.0	4.5	2
1986	0913172433.83	37.140	22.134	0.6	6.0	0
1986	0915114130.10	37.040	22.130	8.0	5.3	0
1986	0218143403.50	40.756	22.108	5.3	5.3	0
1986	0218053442.63	40.686	23.193	3.3	4.8	0
1987	0227233452.75	38.387	20.329	8.2	5.7	1
1987	0610145010.63	37.145	21.369	12.5	5.3	0
1987	1005092701.82	36.308	28.275	9.0	5.3	1
1987	1210225111.09	36.579	21.556	0.0	5.2	2
1987	1025130200.27	36.315	28.254	13.1	5.1	1
1987	0209122824.59	35.397	26.246	0.0	4.9	0
1987	0201053534.78	37.915	21.922	0.0	4.8	1
1988	1016123403.72	37.910	21.061	13.0	6.0	1
1988	0522034414.37	38.378	20.433	12.8	5.4	1
1988	0922120538.27	37.937	21.076	14.5	5.3	1
1988	0518051741.33	38.385	20.404	10.1	5.3	1
1988	0122061853.70	38.645	21.049	18.7	5.1	2

(*continued*)

Table 1
(*Continued*)

Year	Origin Time	Lat. (°N)	Lon. (°E)	Dep. (km)	**M**	F
1988	0308113855.37	38.870	21.203	10.1	4.9	2
1988	0705203450.98	38.115	22.837	0.8	4.9	0
1988	1222095647.32	38.424	21.875	0.0	4.9	0
1988	1213110034.75	37.757	21.206	16.6	4.8	1
1988	1020140059.31	40.501	22.948	14.3	4.8	0
1988	0424101032.97	38.854	20.551	9.7	4.8	1
1988	0602103525.65	38.332	20.415	7.1	4.8	1
1988	1031025948.68	37.880	20.975	6.3	4.8	2
1988	1223074518.47	35.893	24.097	21.3	4.7	0
1988	0930130257.39	37.712	21.303	10.3	4.7	1
1988	0402215759.66	38.124	24.112	0.0	4.6	0
1988	0930110358.06	37.815	21.299	16.9	4.5	1
1988	0403033507.59	38.140	22.883	10.5	4.5	0
1988	1022145814.64	37.957	21.028	0.0	4.5	1
1988	1127163843.78	37.915	20.941	0.0	4.5	1
1989	0607194552.71	38.008	21.672	6.6	5.2	1
1989	0831212930.70	38.107	21.831	21.8	4.8	1
1989	0412100542.51	38.100	22.014	0.4	4.8	1
1989	0515092239.59	38.328	21.839	0.0	4.8	1
1990	1221065744.41	40.920	22.398	10.2	6.0	0
1990	0616021619.31	39.169	20.564	3.7	6.0	2
1990	0909190039.38	39.926	24.015	5.9	5.0	0
1990	0517084403.20	38.370	22.277	10.3	4.9	0
1990	0524195907.13	37.880	20.866	10.8	4.8	2
1990	0808003507.68	37.178	22.104	0.0	4.8	0
1990	0524171837.17	37.743	20.833	0.0	4.7	2
1990	0903053549.97	39.925	23.988	8.1	4.6	0
1990	0520055725.41	37.857	20.854	16.7	4.5	2
1990	0824125440.45	38.271	20.415	10.1	4.5	1
1990	0410031915.87	38.255	20.406	8.3	4.5	1
1990	0524185148.66	37.723	20.908	1.9	4.5	1
1991	0319120925.61	34.754	26.367	0.0	5.5	0
1991	0626114333.24	38.384	20.986	12.4	5.3	0
1991	0319212928.97	34.834	26.407	0.0	5.2	0
1991	0601054201.15	36.982	21.907	1.1	4.7	0
1991	0617002627.06	34.931	24.488	0.0	4.6	2
1992	1118211041.49	38.296	22.444	4.7	5.9	0
1992	0123042416.23	38.413	20.480	4.0	5.6	2
1992	0530185539.27	38.011	21.440	17.4	5.2	1
1992	1110221459.33	38.768	20.656	22.0	4.8	1
1992	1111194509.08	38.079	21.414	12.5	4.7	1
1992	0201090517.50	38.332	20.355	6.9	4.5	1
1992	0125122319.10	38.316	20.357	6.4	4.5	1
1993	0714123148.80	38.180	21.810	2.1	5.6	1
1993	0326115819.29	37.653	21.286	30.1	5.4	1
1993	0613232640.38	39.285	20.524	8.9	5.3	2
1993	1104051835.88	38.401	22.044	0.0	5.3	0
1993	0305065506.28	37.084	21.448	0.0	5.2	0
1993	0204022255.17	38.186	22.689	0.0	5.1	0
1993	0926075325.38	37.714	20.735	14.3	4.9	1
1993	0326115614.28	37.763	21.438	9.1	4.9	2
1993	0326114516.26	37.709	21.393	9.1	4.9	1
1993	0604032427.03	38.693	20.505	8.4	4.8	1
1993	0429075430.43	37.733	21.513	0.0	4.8	1
1993	0326124916.29	37.788	21.367	13.8	4.7	1
1993	0710202605.81	37.871	21.109	13.4	4.7	1
1993	0910133318.99	38.590	20.493	8.3	4.6	1
1993	0330190856.98	37.752	21.411	2.8	4.6	1
1993	0714123910.99	38.079	21.594	0.0	4.6	1
1993	0214101745.77	37.762	21.385	14.2	4.5	0
1993	0216004308.46	38.520	21.530	11.7	4.5	0

(*continued*)

Table 1
(*Continued*)

Year	Origin Time	Lat. (°N)	Lon. (°E)	Dep. (km)	**M**	F
1993	1222194012.72	38.331	21.817	8.9	4.5	0
1993	0326122632.93	37.782	21.408	7.2	4.5	1
1993	0325054409.48	37.697	21.399	4.3	4.5	1
1994	0901161241.45	41.146	21.299	6.5	6.1	0
1994	0225023049.54	38.772	20.544	10.2	5.4	1
1994	1201071735.24	38.727	20.561	6.1	5.3	1
1994	0410194620.89	39.997	23.675	12.1	5.1	0
1994	1129143027.72	38.752	20.527	7.4	5.1	1
1994	0114060750.36	37.661	20.783	27.2	4.9	1
1994	0718154417.12	38.636	20.502	12.4	4.9	2
1994	0227223454.00	38.771	20.552	10.2	4.8	1
1994	1027070230.39	37.689	21.024	14.3	4.7	1
1994	1017090217.35	37.810	20.913	24.3	4.6	1
1994	1201073257.23	38.739	20.460	10.3	4.6	1
1994	0414230134.34	39.138	20.968	17.0	4.5	2
1994	0315224103.52	38.648	20.434	7.9	4.5	1
1995	0513084713.83	40.162	21.724	3.1	6.6	0
1995	0615001550.20	38.401	22.235	17.6	6.4	0
1995	0615003051.66	38.313	22.028	14.0	5.6	0
1995	0517041424.81	40.046	21.580	9.9	5.3	0
1995	0504003410.65	40.540	23.652	7.4	5.3	0
1995	0517041425.94	40.074	21.626	5.4	5.3	0
1995	0717231815.41	40.108	21.584	5.3	5.2	0
1995	0503214327.26	40.562	23.656	9.0	5.1	0
1995	0515041356.49	40.083	21.591	8.7	5.1	0
1995	0519064849.47	40.009	21.577	7.5	5.1	0
1995	0519064850.62	40.054	21.580	6.8	5.1	0
1995	0517094507.92	40.014	21.549	8.2	5.0	0
1995	0503213654.09	40.547	23.646	7.2	5.0	0
1995	0517094506.83	39.975	21.523	5.8	5.0	0
1995	0513114330.97	40.129	21.631	12.1	4.9	0
1995	0516235728.48	40.095	21.619	3.3	4.9	0
1995	0513180600.57	40.129	21.621	13.3	4.8	0
1995	1005082130.37	38.160	20.292	9.9	4.8	1
1995	0611185146.80	39.950	21.532	9.2	4.8	0
1995	0519073649.13	40.041	21.586	8.8	4.8	0
1995	0213131635.99	40.695	22.758	7.3	4.8	1
1995	0606043559.45	40.128	21.601	6.5	4.8	0
1995	0611185147.85	39.967	21.559	4.5	4.8	0
1995	0316062509.86	38.665	20.347	13.6	4.7	1
1995	0705182439.22	38.454	22.279	11.9	4.7	0
1995	0718074254.35	40.117	21.628	5.8	4.7	0
1995	0503153955.89	40.569	23.699	5.3	4.7	0
1995	0316062510.21	38.646	20.368	2.4	4.7	1
1995	0516230041.93	40.031	21.572	0.3	4.7	0
1995	0510224600.25	38.056	20.576	17.9	4.6	1
1995	0608021348.18	39.995	21.516	13.6	4.6	0
1995	1217082226.05	38.163	20.458	13.3	4.6	1
1995	0404171009.99	40.563	23.668	7.5	4.6	0
1995	0528195640.36	38.388	22.026	4.9	4.6	0
1995	0518062255.28	40.019	21.550	3.9	4.6	0
1995	0615045119.81	38.287	22.281	11.2	4.5	0
1995	0514144657.66	40.123	21.666	9.0	4.5	0
1995	0813051729.41	38.091	22.802	6.8	4.5	0
1995	0515081700.54	40.111	21.525	3.9	4.5	0
1996	0606162535.90	37.580	21.092	8.9	4.9	1
1996	1009094629.37	36.784	21.294	0.0	4.9	2
1996	0811114345.35	37.671	21.345	12.9	4.7	1
1996	0526214418.87	38.183	20.240	10.2	4.7	1
1996	0704215718.53	38.189	20.262	8.3	4.6	1
1996	0629010903.28	36.332	23.116	6.3	4.5	0

(*continued*)

Table 1
(*Continued*)

Year	Origin Time	Lat. (°N)	Lon. (°E)	Dep. (km)	**M**	F
1997	1118130739.88	37.421	20.603	14.1	6.6	2
1997	1013133937.10	36.303	22.038	2.3	6.4	2
1997	1118131350.76	37.584	20.636	29.8	6.0	1
1997	1105211028.10	38.364	22.361	8.4	5.6	0
1997	1118152331.75	37.279	21.105	11.3	5.1	1
1997	0426221834.08	37.194	21.364	10.4	5.1	1
1997	1112162656.61	39.137	20.265	7.9	5.0	1
1997	0216110317.32	37.582	20.445	13.8	4.9	1
1997	1119003306.77	37.524	20.691	11.4	4.8	1
1997	1118134406.02	37.593	20.840	6.5	4.8	1
1997	1021175746.20	38.995	22.111	14.1	4.7	0
1997	0718014522.84	36.368	28.107	12.6	4.6	0
1997	1105102753.14	38.307	23.486	0.0	4.6	0
1997	0717132101.73	36.403	28.167	8.7	4.5	0
1997	1214092653.72	38.345	22.372	5.9	4.5	1
1997	0822031747.00	40.150	21.623	3.1	4.5	0
1997	0429235217.02	37.436	20.703	2.4	4.5	2
1998	1006122741.93	37.130	20.982	0.1	5.4	2
1998	0501040014.57	37.618	20.755	10.0	5.3	1
1998	1008035018.30	37.862	20.281	13.6	5.2	0
1998	0411092913.51	39.903	23.884	7.0	5.2	0
1998	0224151143.77	36.442	27.993	2.4	5.1	0
1998	0716172915.59	38.695	20.478	8.9	4.8	1
1998	1122215252.04	38.143	20.315	11.7	4.7	1
1998	0423120332.50	38.288	20.397	9.9	4.5	1
1999	0907115651.40	38.059	23.571	14.5	5.9	0
1999	1124033854.23	39.639	20.628	5.2	5.0	2
1999	0907204455.65	38.069	23.535	4.6	4.9	0
1999	0908125501.66	38.070	23.542	14.1	4.7	0
1999	0308051015.43	37.570	21.762	1.1	4.7	1
1999	0314152117.10	37.438	20.749	12.1	4.6	2
1999	1021084548.08	38.217	21.775	11.8	4.6	0
1999	0903052933.33	38.354	23.179	11.3	4.6	0
1999	0605061918.75	38.322	22.383	10.1	4.6	0
1999	0629150959.18	38.411	22.076	1.0	4.6	0
1999	1226200537.01	37.723	20.664	18.0	4.5	1
1999	1102034248.98	39.774	20.622	15.0	4.5	2
1999	0625074214.76	38.298	22.754	11.4	4.5	0
1999	0908165409.03	38.088	23.541	11.3	4.5	0
1999	1009103112.92	38.342	22.228	10.3	4.5	1
1999	1212192558.24	40.554	23.646	10.0	4.5	0
1999	1219095749.50	38.120	20.230	5.0	4.5	1
1999	0406123231.11	37.427	20.753	4.5	4.5	2

Normal, strike-slip, and thrust faulting mechanisms are denoted in the last column (F) with 0, 1, and 2, respectively.

ing. However, comparison of the PGA values from the uncorrected and the processed (filtered) accelerograms showed practically identical values for almost all records, hence the filtering procedure was able to remove noise without significantly affecting peak value characteristics (Skarlatoudis *et al.*, 2002). Therefore, using the previous routine all the accelerograms of the Greek strong motion database were homogeneously processed and corrected in order to obtain and use the peak values of the corresponding records in the present study.

The magnitudes of the earthquakes in our database come from the catalog of the geophysical laboratory of Aristotle University of Thessaloniki (Papazachos *et al.*, 2000). The size of the earthquakes in this catalog is expressed in a scale equal or equivalent to the moment magnitude, **M** (Hanks and Kanamori, 1979). For earthquakes lacking original moment magnitude estimates, the equivalent moment magnitude was used, as it is calculated from the equation (Papazachos *et al.*, 1997)

$$M_W^* = 0.97M_{LGR} + 0.58, \quad (1)$$

where M_{LGR} is the local magnitude calculated from the trace amplitudes of the Wood–Anderson and short-period instruments of the Institute of Geodynamics of the National Observatory of Athens and the geophysical laboratory of Aristotle University of Thessaloniki. Moment magnitude was confirmed to be a suitable independent variable in defining predictive relations for the Aegean area (Papazachos *et al.*, 2001a), in agreement with similar observations worldwide (Joyner and Boore, 1981). Furthermore, the linearity of equation (1) has been shown (Papazachos *et al.*, 1997; Margaris and Papazachos, 1999) to be valid for the examined M_{LGR} range ($4.0 \le M_{LGR} \le 6.5$). This is important issue in order to avoid introducing nonlinear effects in the predictive relations from magnitude-conversion relations (e.g., Fukushima, 1996; Papazachos *et al.*, 2001a).

The effect of source mechanism in predictive attenuation relations was recognized and pointed out many times by many researchers. McGarr (1984), Campbell (1984, 1997), Sadigh *et al.* (1993), Boore *et al.* (1997), and Anooshehpoor and Brune (2002) showed that thrust faults exhibit higher PGAs than those from other source mechanisms. Accordingly all the available information on the focal mechanisms of the earthquakes of our data set was collected from Papazachos and Papazachou (2002), from Papazachos *et al.* (2001c), as well as from the online catalog of the institutes Istituto Nazionale di Geofisica (I.N.G.), Eidgenössische Technische Hochschule (E.T.H.), and Harvard. For 67 earthquakes fault-plane solutions were available from the previous catalog. An effort to quantify the previous results and include them in the relations proposed by this article has been made. Earthquakes were classified in three categories of normal, strike-slip, and thrust faulting using the plunges of the *P* and *T* axes according to Zoback (1992). Beach-ball symbols in Figure 1b denote the fault-plane solutions, while gray circles denote the epicenters of the remaining earthquakes of our data set. These earthquakes were also categorized in the three categories, using current knowledge about the geotectonic environment for the regions where they occurred (Papazachos *et al.*, 1998, 1999, 2001b).

Figure 2 shows the distribution of epicentral distance, *R*, against moment magnitude, **M**, of the earthquakes used in the study for normal, strike-slip, and thrust faulting. It is observed that a correlation exists between these two parameters, introducing some difficulties in defining predictive attenuation relations. In fact, for small magnitudes, $4.5 \le \mathbf{M} \le 5.0$, the existing recordings are mainly distributed over small epicentral distances ($R \le 40$ km). On the contrary, large-magnitude events are mostly recorded at intermediate and long distances. Furthermore, for earthquakes with $\mathbf{M} > 6.0$ there is a lack of observations in the near field ($R < 20$ km). Figure 3 shows the distribution of PGA values as a function of epicentral distance (Fig. 3a) and magnitude **M** (Fig. 3b), respectively. A dense coverage for distances up to 40 km is observed for PGA values less than 100 cm/sec^2. Similar remarks can be made for $\mathbf{M} < 6.0$.

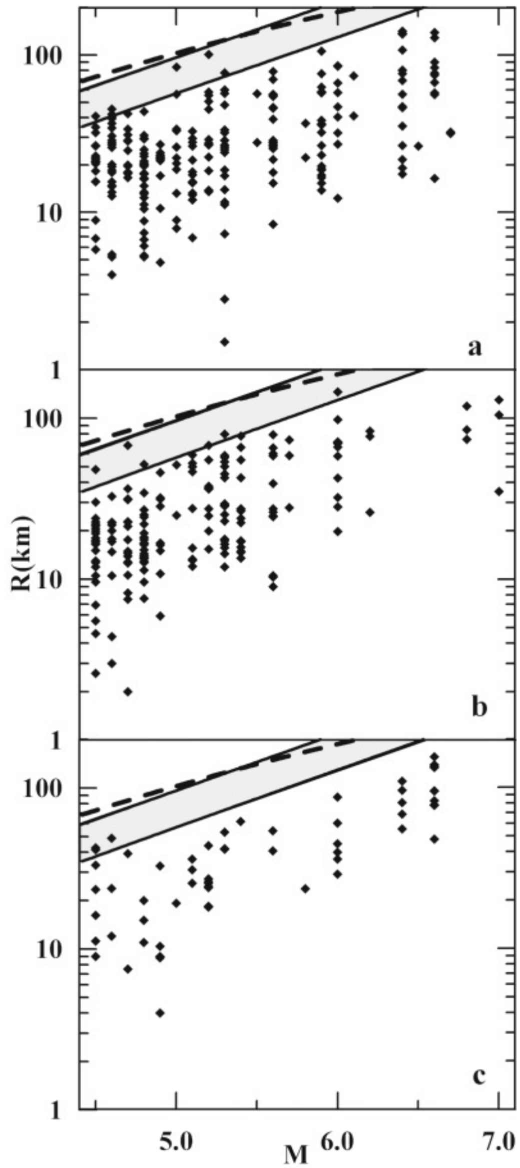

Figure 2. Distribution of the data in terms of moment magnitude, **M**, and epicentral distance, *R*, for (a) normal, (b) strike-slip, and (c) thrust faulting. The trigger level plus one standard deviation cut-off distance limit proposed by Fukushima and Tanaka (1990) and the corresponding trigger level (upper curve)/trigger level plus one standard deviation (lower curve) limits derived from the present study attenuation curves are also shown by dashed line and gray-shaded area, respectively (see text for explanation).

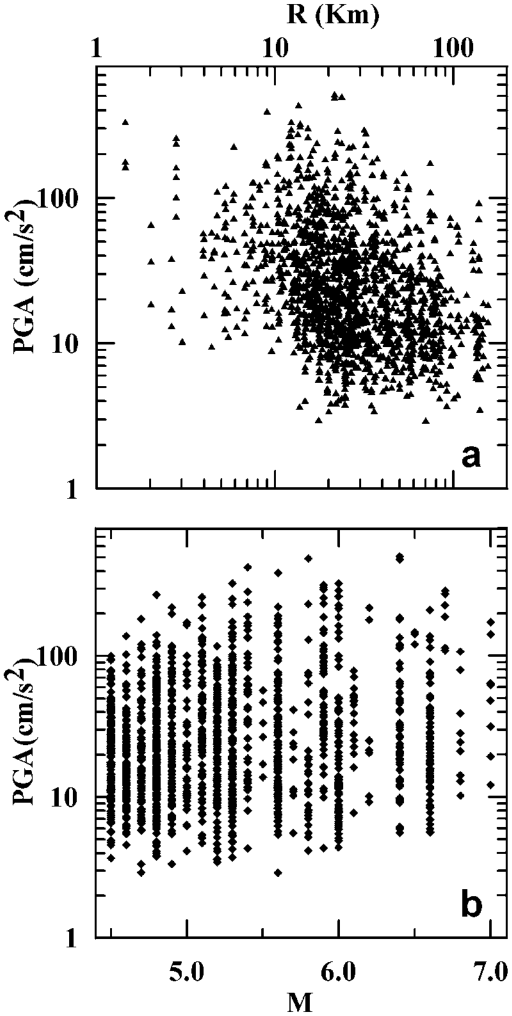

Figure 3. Distribution of the peak ground acceleration, PGA, as a function of (a) the epicentral distance, R, and (b) moment magnitude, **M**, for the strong motion records used in the present work.

An important point to be considered in the determination of predictive relations is the effect of record truncation at large distances. This problem is imposed by the trigger threshold of accelerographs (typically ~3–5 cm/sec^2), which excludes lower-level acceleration data from the analysis (as they are not recorded) and may lead to the introduction of bias at large distances in cases of unusually high accelerations due to, for example, the presence of high-Q zones (e.g., Fukushima, 1997). It must be noted that such high accelerations at large distances are usually observed from intermediate-depth or deep subduction events, which were specifically excluded from this analysis. However, in order to avoid such bias, Joyner and Boore (1981) and Fukushima and Tanaka (1990) have suggested rejecting data at distances further from the trigger level or the trigger level plus one standard deviation, respectively. Such a procedure involves adoption of an attenuation relation in order to define the trigger-level distance threshold for each examined magnitude. In Figure 2 the dashed line corresponds to the limits proposed by Fukushima and Tanaka (1990), while the gray-shaded area corresponds to the trigger level (5 cm/sec^2, upper curve) and trigger level plus one standard deviation (~10 cm/sec^2, lower curve) for the mean predictive relation defined later in the present work. It is evident that all the data lie within the acceptable magnitude–distance area, while only 14 points (2% of our data set) are within one standard deviation from the theoretically estimated trigger threshold limit. After tests we found that excluding these data did not change the result presented later in the regression analysis; hence we can safely conclude that record truncation at large distances does not affect the analysis of the present data set.

In order to classify the local site conditions of the recording stations, we adopted the classification proposed by NEHRP (1994) and UBC (1997), classifying them in the five Universal Building Code categories, namely, A, B, C, D, and E. The classification was performed by using geotechnical information for the sites where such information was available (Klimis *et al.*, 1999). For the remaining stations, information from the geological map of the specific area was used. In our case, the vast majority of recording stations that were finally adopted in this study corresponded to categories B, C, and D. Specifically, 19 recording stations were classified in category B, 68 in C, and 25 in D. Very few sites (six) having geotechnical/geological characteristics between A and B were also included in category B. In Table 2 the classification of site conditions of the recording stations used is presented.

Data Regression and Results

The equations examined in the regression analysis (e.g., Campbell, 1985) were

$$\log Y = c_0 + c_1\mathbf{M} + c_2 \log(R^2 + h^2)^{1/2} + c_3F + c_5S \quad (2a)$$

$$\log Y = c_0 + c_1\mathbf{M} + c_2 \log(R + c_4) + c_3F + c_5S, \quad (2b)$$

where Y is the strong motion parameter to be predicted, usually in centimeters per second squared, in centimeters per second, and centimeters if Y stands for PGA, PGV, and PGD, respectively, **M** is the moment magnitude, R is the epicentral distance, h is the focal depth of each earthquake, S is the variable accounting for the local site conditions, and F is the variable referring to the effect of the faulting mechanism of the earthquakes in the predicting relations. In equations (2a) and (2b) a base-10 logarithm is used and units for R and h are in kilometers. Scaling coefficients c_0, c_1, c_2, c_3, and c_5 are to be determined from regression analysis. Coefficient c_4 in equation (2b) accounts for saturation in the near field and is difficult to determine directly by regression analysis on the available data, given its strong correlation with scal-

Table 2
Site Classification Proposed by NEHRP (1994) for the Recording Stations Used in This Study

Name	Lat. (°N)	Lon. (°E)	Class
ABS1	40.650	23.100	B
AGR1	38.621	21.406	D
AGRA	38.630	21.420	D
AIG1	38.250	22.067	C
ALM1[†]	39.181	22.761	C
AMAA	37.800	21.350	D
AMIA	38.530	22.380	C
AML1	38.858	21.160	B
ANS1	36.472	23.101	B
ARCA	36.200	28.130	C
ARG1[†]	38.167	20.483	C
ARGA	38.170	20.470	C
ART1	39.158	20.984	B
ARTA	39.159	20.985	C
ATH1	38.018	23.789	C
ATH2	38.018	23.789	C
ATH3	37.972	23.706	C
ATH4	37.996	23.743	C
ATHA	38.000	23.770	C
ATHB	37.937	23.700	C
ATHC	37.980	23.730	C
ATLA	38.650	23.000	B
CHN1	35.518	24.019	D
CHNA	35.510	24.020	C
CHR1	40.133	21.733	C
DEKA	38.100	23.780	A/B
DMKA	37.990	23.820	B
DRA1	41.139	24.142	C
EDE1	40.805	22.051	C
EGIA	38.250	22.080	C
FLO1	40.787	21.404	B
GRE1	40.086	21.425	C
GRE2	40.085	21.426	C
GTH1	36.754	22.567	A/B
HER1	35.318	25.102	C
HERA	35.350	25.130	C
IER1	40.391	23.873	C
IGM1	39.503	20.268	A/B
ISTA	38.950	23.150	D
JAN1	39.659	20.851	C
KAL1[†]	37.033	22.100	C
KAL2[†]	37.033	22.100	C
KALA	37.030	22.120	C
KAR1	39.366	21.920	C
KAS1[†]	40.518	21.259	B
KAT1	40.267	22.500	C
KAV1	40.935	24.403	B
KEN1	40.017	21.617	B
KIL1	40.990	22.869	C
KNI1	40.083	21.583	C
KOR1	37.939	22.933	D
KORA	37.930	22.930	D
KOZ1	40.302	21.784	B
KOZ2	40.300	21.790	C
KRN1	36.802	21.961	C
KRP1	38.917	21.800	A/B
KRR1	39.950	21.617	C
KYL1	37.933	21.133	C
KYP1[†]	37.250	21.667	B
KYPA	37.250	21.670	B
LAM1	38.902	22.425	B
LAR1	39.637	22.417	D
LEF1[†]	38.826	20.702	D
LEFA	38.830	20.710	D
LEVA	38.430	22.880	C
LXRA	38.200	20.440	C
MES1	37.050	22.000	C
MRNA	38.530	22.120	C
MSLA	38.370	21.430	D
NAUA	38.400	21.830	B
OUR1	40.326	23.974	B
PAL1	39.935	23.673	C
PAT1[†]	38.250	21.733	C
PAT2	38.238	21.738	C
PAT3[†]	38.254	21.738	D
PATA	38.250	21.730	C
PATB	38.236	21.718	D
PEL1	37.050	21.850	C
POL1	40.374	23.438	B
PRE1	38.956	20.755	C
PREA	38.950	20.750	C
PYR1[†]	37.670	21.438	D
PYR2	37.670	21.438	D
PYR3	37.670	21.438	D
PYR4	37.670	21.438	D
PYRA	37.670	21.430	D
RFNA	38.060	23.980	C
ROD1	36.433	28.233	C
ROD2	36.433	28.233	B
ROD3	36.433	28.233	C
ROD4	36.433	28.233	C
RODA	36.430	28.220	C
RTHA	35.370	24.470	D
SAR1	40.091	23.974	C
SER1	41.085	23.541	C
SGMA	37.980	23.740	C
SIT1	35.216	26.104	C
SPAA	37.080	22.430	C
THE1[†]	40.620	22.970	C
THE2	40.617	22.967	B
THE3[†]	40.633	22.933	C
THE4[†]	40.517	23.017	D
THE5[†]	40.633	22.933	C
THE6[†]	40.633	22.933	C
THE7[†]	40.633	22.933	C
THEA	40.630	22.960	D
THV1[†]	38.317	23.317	C
THVC	38.320	23.318	C
TMN1[†]	40.667	22.900	C
TMU1[†]	40.617	22.967	C
VAR1	37.850	21.200	D
VAS1	38.626	20.605	C
VER1	40.526	22.203	A/B
VLSA	38.170	20.600	A/B
VOL1	39.366	22.951	C
XLCA	38.080	22.630	D
ZAK1	37.785	20.900	D
ZAKA	37.780	20.900	D

[†]Stations where geotechnical information was available.

ing coefficient c_2, as was shown using appropriate Monte Carlo simulations (Papazachos and Papaioannou, 1997, 1998). For this reason, the value of $c_4 = 6$ km was adopted from Margaris *et al.* (2002), roughly corresponding to the average focal depth of the events used in the present study.

Joyner and Boore (1981) and Fukushima and Tanaka (1990), among others, have proposed various regression methods based on two-step regression procedures for predicting strong ground motion. Those methods aimed to overcome the problem of distance–magnitude correlation that was observed in all strong motion data sets used by previous researchers. More recent studies (Joyner and Boore, 1993) have shown that the stagewise regression methods give similar results with maximum likelihood analysis in one step. Since stagewise regression methods always give results with less precision than maximum likelihood analysis in one step (Draper and Smith, 1981), an optimization procedure based on the least-squares method in one step using the singular value decomposition method (Lanczos, 1961) was used in this article. Such an analysis allows controlling the stability of the optimization and accurate determination and analysis of the errors in the final solution (e.g., Golub and Reinsch, 1970; Press *et al.*, 1992). Furthermore, through this analysis we also expect to overcome and quantify the problems arising from the observed correlation between magnitude and epicentral distance in our data set.

The term for describing site conditions in the predicting equations (2a) and (2b) is expressed as a linear transformation of the classification proposed by NEHRP (1994) and UBC (1997). However, we have also examined the possibility of including separate terms in the predicting equations for site conditions. Therefore, we considered that equations (2) without the site-effect term correspond to soil category B and included two additional terms, one for describing soil category C (S_C) and one for the effect for soil category D (S_D). Using all the available data, the values obtained for the two coefficients from the regression of equations (2a) and (2b) were $S_C = 0.058$ and $S_D = 0.125$. From these results it is clear that the S_D value (site effect of D category) is essentially twice the value of S_C. This result verifies the applicability of the usual assumption for the linearity between the finally adopted variable S in equations (2a) and (2b) and the classification proposed by NEHRP (1994) and UBC (1997). Therefore, the results obtained suggest that the variable S in equations (2a) and (2b) can be assumed to take the values of 0, 1, and 2 for soil categories B, C, and D, respectively.

A similar approach was adopted for the independent variable that describes the effects of focal mechanisms. Initially two different variables, F_S and F_T, were used in equations (2a) and (2b) for strike-slip and thrust faults, respectively, in order to estimate the different contributions for F_S and F_T, considering that strike-slip and thrust faults possibly exhibit higher PGA values than normal faults. The regression showed that the two coefficients were almost equal, revealing that the effects in the predicting equations (2a) and (2b) from both strike-slip and thrust faults in Greece are similar using the data set of the present study. Therefore, only one variable was used in the regression, in order to describe the higher PGA values from strike-slip and thrust faults, merging F_S and F_T into a common variable, F.

In order to incorporate nonlinear effects of large earthquakes in the proposed equations for strong motion prediction, a second-order magnitude term was also added in predicting equations (2a) and (2b) (e.g., Boore *et al.*, 1993). Unfortunately the small number of large earthquakes in our data set resulted in inadmissible values of magnitude coefficients (positive coefficient for the second-order magnitude term) in the regression analysis; hence such effect could not be resolved from the present strong motion data set in Greece.

Following the previously described procedure, empirical predictive relations were defined for PGA, PGV, and PGD. The results are summarized in the following equations:

$$\log \mathrm{PGA} = 0.86 + 0.45\mathbf{M} - 1.27 \log(R^2 + h^2)^{1/2} + 0.10F + 0.06S \pm 0.286 \quad (3a)$$

$$\log \mathrm{PGA} = 1.07 + 0.45\mathbf{M} - 1.35 \log(R + 6) + 0.09F + 0.06S \pm 0.286 \quad (3b)$$

$$\log \mathrm{PGV} = -1.47 + 0.52\mathbf{M} - 0.93 \log(R^2 + h^2)^{1/2} + 0.07F + 0.11S \pm 0.303 \quad (4a)$$

$$\log \mathrm{PGV} = -1.31 + 0.52\mathbf{M} - 0.97 \log(R + 6) + 0.06F + 0.11S \pm 0.305 \quad (4b)$$

$$\log \mathrm{PGD} = -4.08 + 0.88\mathbf{M} - 1.27 \log(R^2 + h^2)^{1/2} - 0.02F + 0.25S \pm 0.424 \quad (5a)$$

$$\log \mathrm{PGD} = -3.87 + 0.87\mathbf{M} - 1.31 \log(R + 6) - 0.04F + 0.24S \pm 0.428. \quad (5b)$$

The last term in equations (3) to (5) expresses the standard deviation of the predicted value for each equation.

In Figure 4a we present a comparison of the observed values and our relation for PGA versus PGD reduced to a magnitude **M** 6.5, plotted together with the ± 1 standard deviation curves. In Figures 4b and 4c the same plots for PGV and PGD, respectively, are shown. All the proposed relations were plotted in the previous figures for "rock" soil conditions (UBC category B), that is, $S = 0$, for normal faulting mechanisms, that is, $F = 0$, and for focal depth equal to the "effective" depth of shallow events, that is, the average depth where seismic energy is released. For Greece the value that corresponds to the average focal depth being $h_0 = 7$ km, as this value was estimated using mainly macroseismic data for the area of Greece (Papazachos and Papaioannou, 1997, 1998). It is clear that Figure 4 is slightly misleading, as the reduction of all data to a common magnitude (**M** 6.5) neglects the magnitude–distance correlation

(Fig. 2). However, examination of Figure 4 allows a rough visual inspection of the data fit of proposed relations, reduced to a typical magnitude of a strong earthquake. Therefore the true validity and quality of the fit of the proposed relations are to be evaluated from the rms error of each relation and from the additional statistical analysis presented later in the text.

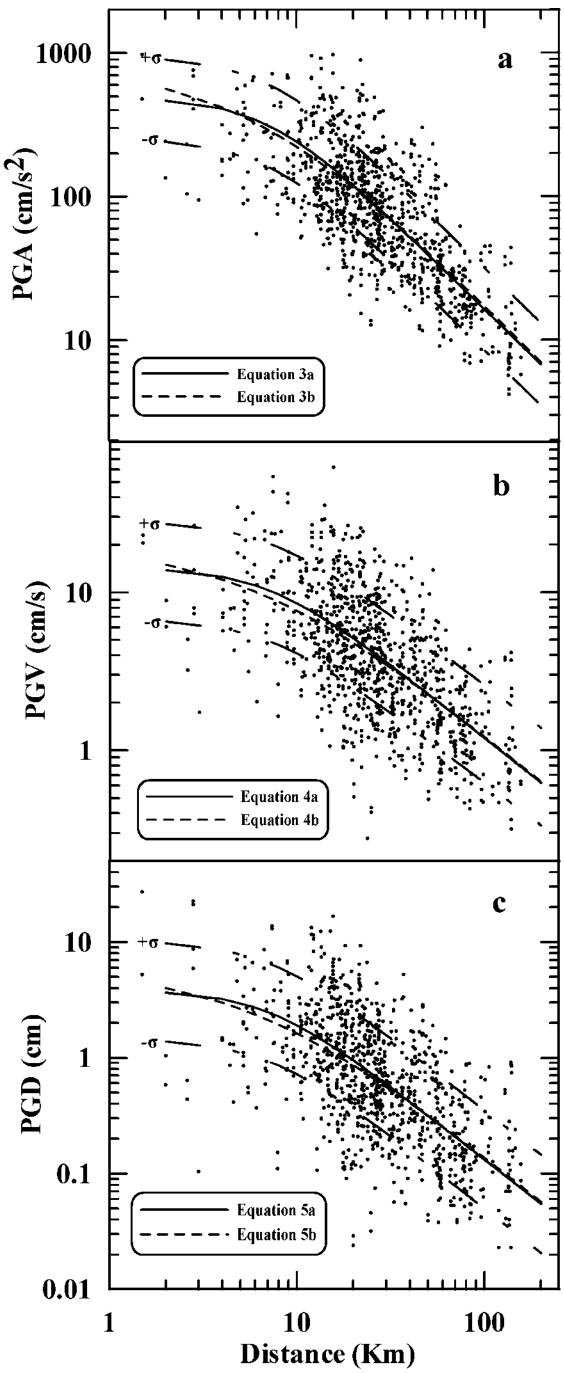

Figure 4. Comparison of the horizontal (a) PGA empirical relation, (b) PGV empirical relations, and (c) PGD empirical relations, plotted together with the $\pm 1\sigma$ curves with the observed values scaled to **M** 6.5.

The examination of the residuals resulting from the regression analysis for each of the variables used in the regression model did not show any systematic variations as a function of the remaining variables. As an example, the distribution of the resulting residuals for each proposed relation is plotted against distance in Figure 5. It is obvious that no apparent trend can be identified in the residuals.

Comparison with Similar Predictive Relations

Comparison of the proposed horizontal PGA predictive relations with those previously proposed for the area of Greece (Theodulidis, 1991; Margaris *et al.*, 2002), for UBC soil category B, $S = 0$, are shown in Figure 6a. The higher levels of PGA values predicted by Theodulidis (1991) are probably due to the multiple-step least-squares method followed in his regression analysis, which resulted in a strong correlation between coefficient c_1 and predicted values, the more rough and empirical soil categorization, and the much smaller data set used. Significant differences are observed mainly at smaller distances and for large magnitudes, with the relation proposed in this study resulting in higher values in the near field than the one proposed by Margaris *et al.* (2002). This is probably due to the much larger number of records in near-field distances used in the present work, amplifying the completeness of our data set in this distance range (Figs. 2 and 3).

In Figures 6b and 6c the same comparison of the proposed horizontal PGV and PGD relations is shown. We can

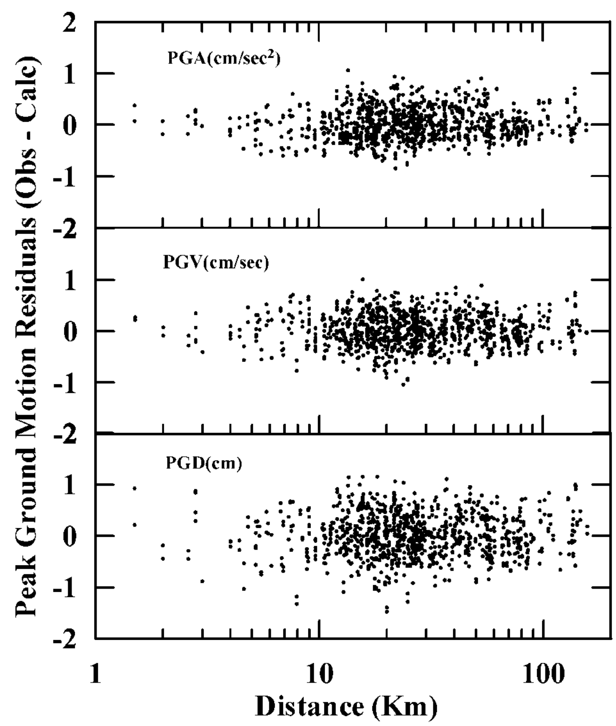

Figure 5. Distribution of the residuals of PGA, PGV, and PGD in terms of distance.

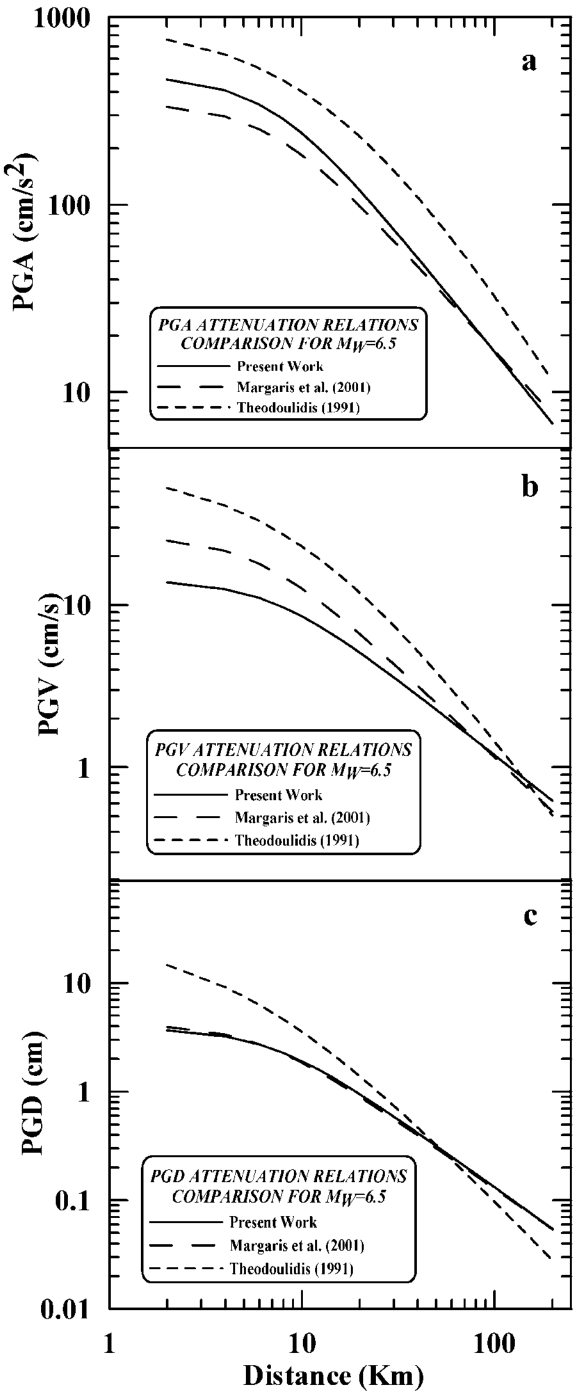

Figure 6. Comparison of the PGA, PGV, and PGD empirical relations (continuous line) with those proposed by Theodulidis (1991) (black dash-dotted line) and Margaris *et al.* (2002) (dashed line) for Greek data: (a) comparison for PGA empirical relations, (b) comparison for PGV relations, and (c) comparison for PGD empirical relations, for **M** 6.5 and rock soil conditions (UBC class B, $S = 0$).

observe some differences in the comparison of horizontal PGV relations, resulting from both the enriched data set used, as described earlier, and better classification of the recording stations with respect to local site conditions. A noticeable agreement between the relations defined in this work and the relations proposed by Margaris *et al.* (2002) for PGD for earthquakes with **M** 6.5 is observed.

In Table 3 a comparison between the standard deviations of each proposed relation for Greece and the corresponding variance reduction are shown. It is obvious that incorporating the relocated catalog for the earthquakes that produced the Greek strong motion data set (Skarlatoudis *et al.*, 2003), as well as the homogeneous analog recording processing (Skarlatoudis, 2002; Skarlatoudis *et al.*, 2002), resulted in improved and more accurate predictive relations, mainly for PGD and PGV and to a lesser extent for PGA. The previous arguments and the comparison of the proposed relations with the ones of Margaris *et al.* (2002), which were calculated with similar regression method and with the use of a slightly smaller catalog, demonstrate the validity of the proposed relations of this study.

In Figure 7 a comparison of the horizontal PGA relations with those proposed by Ambraseys *et al.* (1996), Sabetta and Pugliese (1987), and Spudich *et al.* (1999) for rock ($S = 0$) soil conditions (UBC B class) is shown. The comparison is made for **M** 6.5 in order to overcome the problem related to the different magnitude scales used by Ambraseys *et al.* (1996) and Sabetta and Pugliese (1987), as pointed out by Papazachos *et al.* (1997) for $M_S < 6.0$. The comparison with the Ambraseys relation shows good agreement for a range of distances from 10 to 30 km. For distances greater than 30 km, Ambraseys's relation shows a deviation and gives higher PGA values. Considering the fact that for the derivation of this relation different data sets have been used, which come from various seismotectonic environments with different stress fields (northern Europe, Mediterranean region, etc.), different distance measures, and different regression models in the regression analysis, such a deviation can be expected. In fact, the smaller attenuation rate observed in the Ambraseys *et al.* (1996) relation, which included data from less active tectonic environments, is in agreement with similar observations from macroseismic data (Papazachos and Papaioannou, 1997, 1998).

Table 3
Standard Deviation and Variance Reduction of the Regression Analysis for Predictive Relations Proposed by Three Different Studies for Greece

	PGA		PGV		PGD	
	σ_{PGA}	V_r^{PGA}	σ_{PGV}	V_r^{PGV}	σ_{PGD}	V_r^{PGD}
Present study	0.286	–	0.303	–	0.424	–
Margaris *et al.* (2002)	0.304	11%	0.347	24%	0.469	18%
Theodulidis (1991)	0.286	0%	0.317	9%	0.516	32%

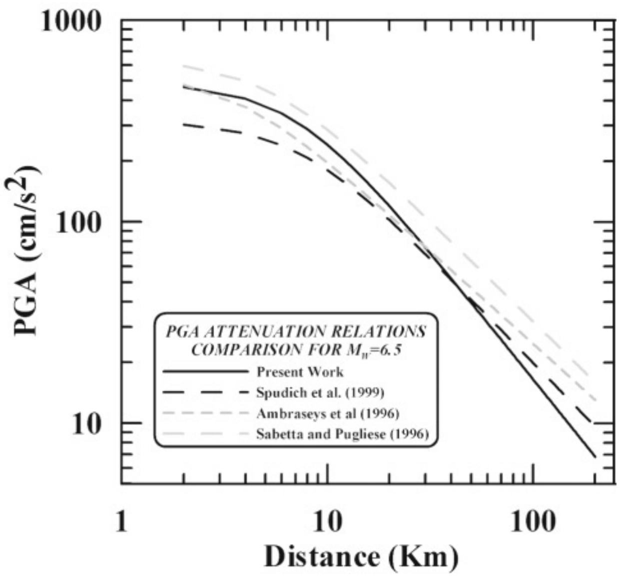

Figure 7. Comparison of the PGA empirical relations (black continuous line) with those proposed by Ambraseys *et al.* (1996) (dark gray dashed line), Sabetta and Pugliese (1996) (light gray continuous line), and Spudich *et al.* (1999) (black dashed line) for **M** 6.5 and rock soil conditions (UBC class B, $S = 0$).

Relations proposed by Sabetta and Pugliese (1987) show higher predicted values for all epicentral distances. The use of a high percentage (50%) of thrust faulting earthquakes in their data set probably produces part of this divergence. Spudich *et al.* (1999) proposed empirical predicting relations of PGA based on records from earthquakes that occurred in mainly normal faulting (extensional regime) regions. In general, the Spudich *et al.* (1999) relation is in good agreement with the one proposed in this work, exhibiting comparable values for far-field distances, although the predicted values in the near-field range are considerably lower.

Discussion and Conclusions

Abrahamson and Silva (1997), Boore *et al.* (1997), and Campbell (1997) proposed various empirical relations (in the framework of the National Seismic Hazard Mapping Project in the United States) taking into account the type of earthquake faulting. The incorporation of such a term that accounts for the effects of focal mechanisms in the attenuation of seismic waves has been applied for the first time in empirical prediction relations for Greece. In our proposed relations a decrease in the values of coefficient c_3 is observed, as we move from PGA to PGV and PGD relations. This decrease shows that the high-frequency portion of the source spectra is affected mostly from the faulting mechanism since ground acceleration records are "richer" in high frequencies than ground velocity records, and the same applies also for ground velocity and ground displacement records. The high-frequency part of the source spectra is physically related with the estimated Brune stress drop, $\Delta\sigma$, through the corner frequency of the spectra (Boore, 1983). Many researchers showed that thrust and strike-slip faulting earthquakes exhibit higher values for Brune stress (McGarr, 1984; Cocco and Rovelli, 1989; Rovelli *et al.*, 1991; Margaris and Hatzidimitriou, 2002) or apparent stress (McGarr and Fletcher, 2002) than normal faulting earthquakes for different regions. We should point out that the stress drop notion used here refers to its traditional use as a scaling parameter of the high-frequency acceleration spectrum, similar to the M-drop, ΔM, quantity proposed by Atkinson and Beresnev (1997). This dynamic stress drop derived using Brune's or other equivalent point-source model may be very different and bear a rather complex relation to the static stress-drop (fault slip as a fraction of fault dimension). Hence, the higher stress drop proposed for thrust and strike-slip events in the Aegean area does not necessarily reflect differences in source geometry (slip, dimensions) but a rather systematic higher acceleration level of the Fourier spectrum at high frequencies for such events.

However, the enhancement in high frequencies of the source spectra may be also attributed to other factors except from the high dynamic stress drop. A very critical factor that affects the frequency content of the source spectra is the dimension of the fault rupture (Thatcher and Hanks, 1973) and asperity (Kanamori, 1981). Also, high rupture velocities or local high-Q values can result in more rich high-frequency components in the spectra (Mori, 1983). In our case the data set used comes from earthquakes with equivalent moment magnitudes from **M** 4.5 to 7.0, that is, faults with very different dimensions; thus the coefficient c_3 was calculated independently of the fault dimension. Moreover, there are no observations of systematically higher rupture velocities for thrust and strike-slip faults (compared to normal faults) in the Aegean area, where all the examined earthquakes have occurred. In addition, the areas where most of the recorded thrust or strike-slip fault earthquakes occur (western Greece–Ionian Islands) have relatively low Q-values due to thick layers of sediments of the recording sites (usually category D). The previous observations may provide evidence that the decrease in c_3 from PGA to PGV and PGD should be attributed to the fact that thrust and strike-slip faults are simply more rich in the higher frequency part of the source spectra compared to normal faults. It should be noted that the similar values of amplification found for thrust and strike-slip faults in Greece are probably due to the fact that the examined strike-slip faults (mainly from the Ionian Islands) usually have a significant thrust component, suggesting that the tectonic setting is closer to compressional than extensional.

The coefficient c_5 in equations (3) to (5) shows a relatively large value for the PGV relation (compared to PGA) and a much larger value for the PGD proposed relation. Hence, sites for soil category D show an increase of 30%

for expected PGA values at the same distance and magnitude in comparison to soil category A/B or B. However, this amplification increases to approximately 70% and 300% when considering PGV and PGD values, respectively. This strong amplification increase is the expected evidence of the strong dependence of ground velocity and displacement on the local soil conditions. It is known that surficial layers of soft sediments are strongly affected by the low-frequency content of seismic waves, because of their relatively low resonance frequency (small elastic modulus, deposits which usually have significant thickness). This correlates with the fact that ground velocity and displacement records have enhanced low-frequency content, unlike with PGA ones, as has been mentioned before. As a result, the local site effect for sedimentary deposits is expected to be stronger for PGV and even more pronounced for PGD values, which is reflected in the increase of coefficient c_5 from PGA to PGV and PGD. Unfortunately, a similar tendency is seen for the standard deviation of the proposed relations for PGV and PGD. This increase is mainly due to the limitations of the processing and filtering during the correction of strong motion records, which attempts to reduce spectral noise mostly in low frequencies (Skarlatoudis *et al.*, 2002) that affects velocities and displacements more than acceleration, as previously explained.

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Erratum to

Empirical Peak Ground-Motion Predictive Relations for Shallow Earthquakes in Greece

by A. A. Skarlatoudis, C. B. Papazachos, B. N. Margaris, N. Theodulidis, Ch. Papaioannou, I. Kalogeras, E. M. Scordilis, and V. Karakostas

In a previously published article related to peak ground-motion attenuation in Greece (Skarlatoudis *et al.*, 2003) equations (3a) and (3b) described the empirical peak ground velocity (PGV) predicting relation for shallow earthquakes in Greece. Since their publication these relations were used in some applications for the broader Aegean area and were also compared with independent results produced by other researchers. After significant differences recognized in these comparisons, the input data and all regression stages were checked again. This check resulted in the recognition of misprints in the PGV data set, which led to underestimating the predicted PGV levels, mostly at near source distances by a factor of 2–3.

After correcting the misprints and applying the same regression technique, as in Skarlatoudis *et al.* (2003), equations (3a) and (3b) became

$$\log \mathrm{PGV} = -1.66 + 0.65M_{\mathrm{w}} - 1.224\log(R^2 + h^2)^{1/2} + 0.03F + 0.15S \pm 0.321, \quad (3a)$$

$$\log \mathrm{PGV} = -1.46 + 0.64M_{\mathrm{w}} - 1.29\log(R + 6) + 0.02F + 0.14S \pm 0.32, \quad (3b)$$

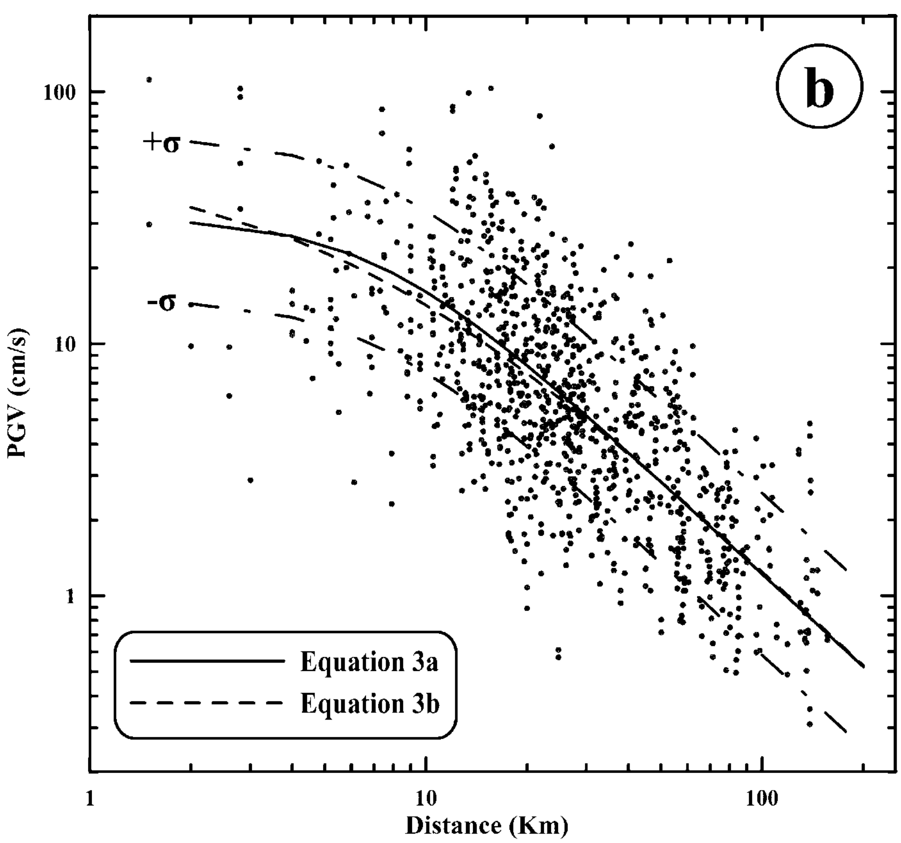

Figure 4. Comparison of the horizontal PGV empirical relations plotted together with the $\pm 1\sigma$ curves with the observed values, scaled to M_{w} 6.5. This is the corrected version of figure 4b in the original paper.

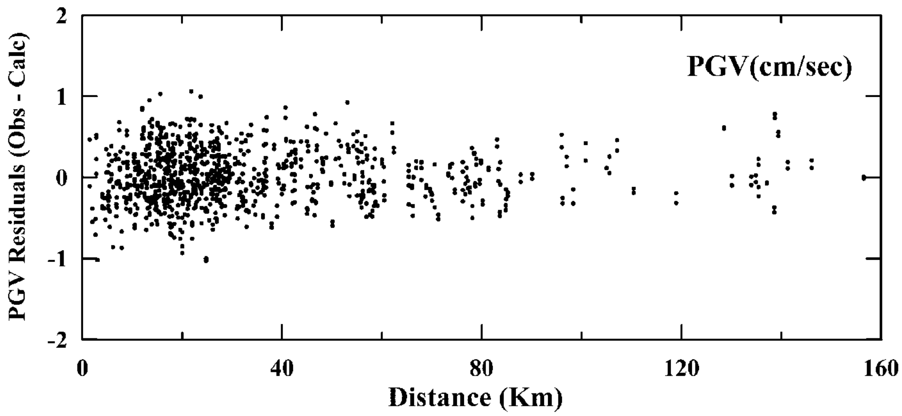

Figure 5. Distribution of the residuals of peak velocity (PGV) in terms of distance. This is the corrected version of figure 5b in the original paper.

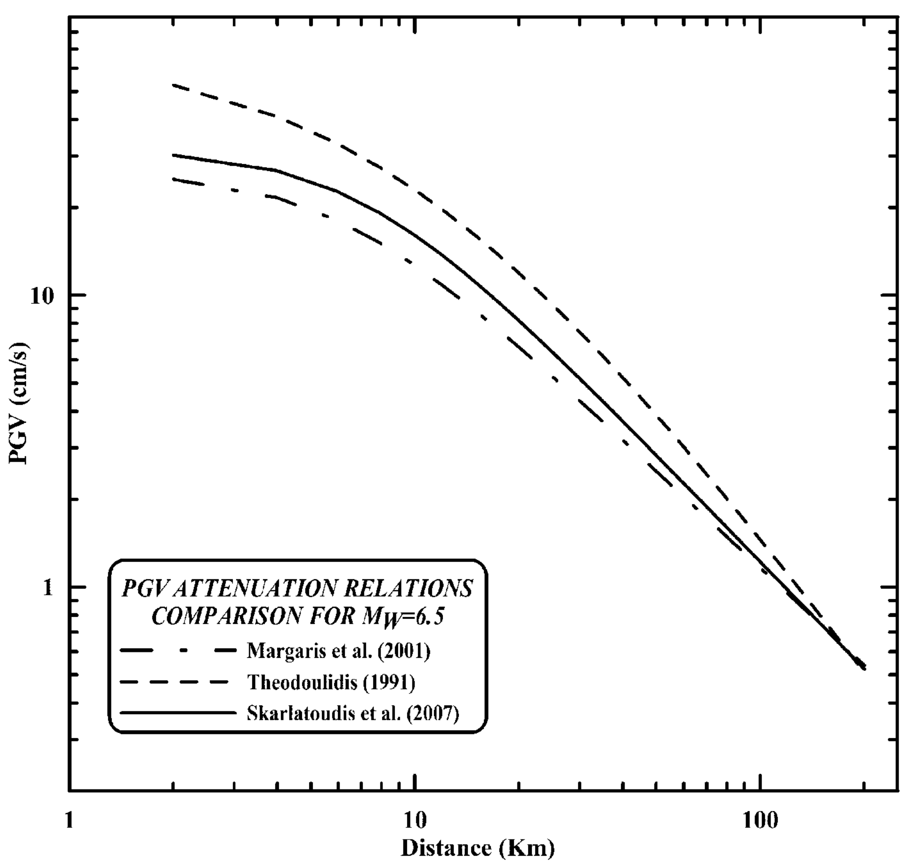

Figure 6. Comparison of the PGV empirical relations, (black continuous line) with those proposed by Theodulidis (1991) (black dashed-dotted line) and Margaris *et al.* (2002) (black dashed line) for Greek data, for M_w 6.5 and rock soil conditions (UBC class B, $S = 0$). This is the corrected version of figure 6b in the original paper.

where PGV is in cm/ sec, M_w is the moment magnitude, R is the epicentral distance, h is the focal depth of each earthquake, S is the variable accounting for the local site conditions, and F is the variable referring to the effect of the faulting mechanism of the earthquakes in the predicting relations. Consequently the corresponding figures, Figures 4b, 5b, and 6b have been revised and are shown here.

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