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The available Greek strong ground motion records to date are used in order to study the duration of strong-motion in Greece, covering magnitudes between 4.5 and 6.9 and distances from 1 km to 128 km. An attenuation relation of strong-motion duration is calculated and compared to earlier existing similar relations proposed for Greece and Japan. Furthermore, the seismic hazard for the area of Greece is assessed, using the strong-motion parameters of duration and peak ground acceleration. The results are presented in the form of a map according to which Greece is classified in four different categories of equal seismic hazard.

Keywords: Strong ground motion duration; attenuation relations; probabilistic hazard assessment.

1. Introduction

The assessment of seismic hazard in Greece has become the subject of a growing number of studies in the last 25 years. These studies are mainly concerned with the evaluation of seismic hazard of macroseismic intensities [e.g. Papazachos *et al.*, 1985; Papaioannou, 1986; Papoulia and Slejko, 1997; Papaioannou and Papazachos, 2000], as well as with the estimation of peak ground accelerations, velocities and strong-motion durations [for example, Algermissen *et al.*, 1976; Drakopoulos and Makropoulos, 1983; Papazachos *et al.*, 1990, 1992, 1993; Theodoulidis and Papazachos, 1992]. Based on the results of these publications, a map was compiled according to which Greece is divided into four zones of equal seismic hazard [Papazachos *et al.*, 1993]. This map was proposed jointly, by four

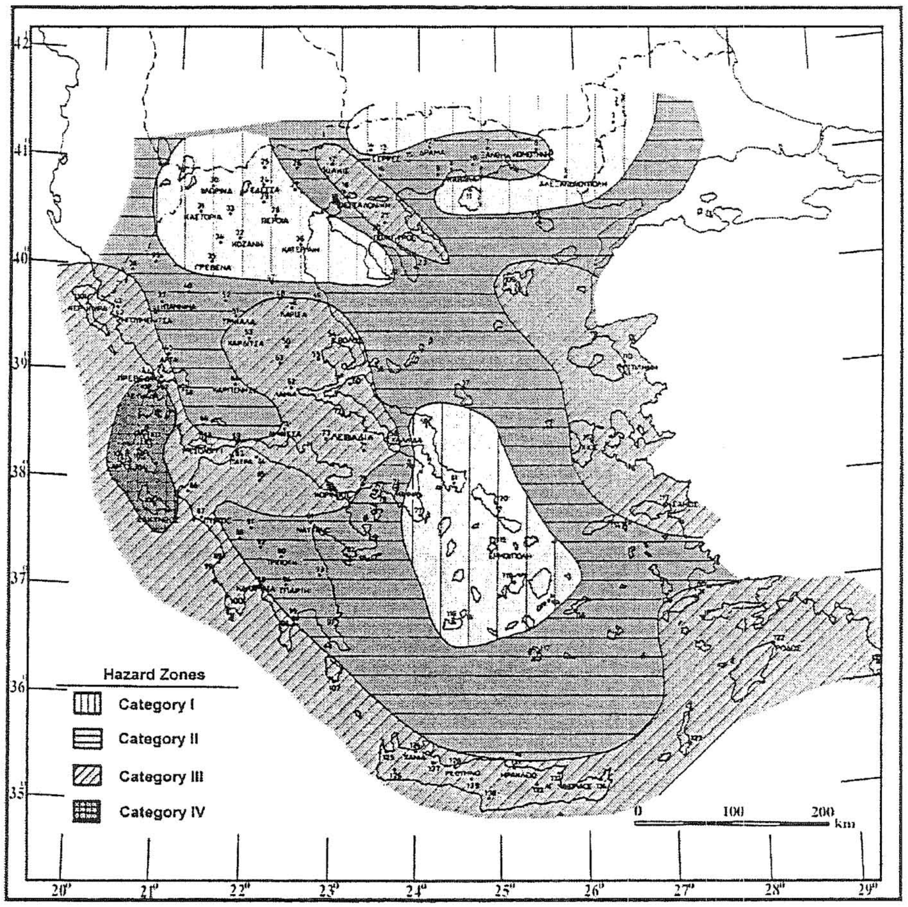

Fig. 1. The division of Greece into zones of equal seismic hazard according to the Greek Seismic Code.

different seismological research institutions and constitutes part of the Seismic Code of Greece since 1995 (Fig. 1).

Several studies have also been made concerning duration and energy characteristics of strong ground motion in Greece, due to the interest of this issue to both seismologists and engineers. Theofanopoulos and Drakopoulos [1986] accomplished the first of these studies, and a new measure of strong-motion duration was introduced and was subsequently used to study a number of major earthquakes that occurred in Greece. Margaris *et al.* [1990] attempted to utilise the strong-motion database available at that time to study the duration of strong ground-motion in Greece. More specifically, the bracketed and significant duration of strong-motion were computed and their relation to rupture duration was studied. Furthermore, relations were defined to associate bracketed duration with macroseismic intensity and peak ground acceleration. Finally, an attempt was made to calculate attenuation relations for these two different measures of strong-motion duration. Papazachos *et al.* [1992] studied the bracketed duration if strong-motion and proposed a corresponding attenuation relation. Koliopoulos *et al.* [1998] studied various measures of strong-motion duration along with energy characteristics of Greek strong-motion records. Koutrakis *et al.* [1999] and Koutrakis [2000] proposed a new attenuation relation for the bracketed duration in Greece and made an effort to use this duration measure for the assessment of seismic hazard.

The fact that duration is an important parameter that affects both inelastic deformation and energy dissipation demand, is well established [Bommer and Martinez-Perreira, 1999]. However, there is no generally accepted procedure for duration to be taken into account in design codes. One attempt to account duration, is via the construction of 3-D response spectra [Safak, 1998; Koliopoulos and Margaris, 2001]. Yet, another attempt is to compute energy demand spectra, which incorporate the effect of duration [Chapman, 1999]. Nevertheless, the implementation of the resulting (3-D or energy) spectra into the design process is yet to be established. A third line of approach, adopted herein, is to firstly perform a duration-based seismic hazard assessment that will modify the PGA seismic hazard results. This methodology will in fact, introduce penalty factors in the PGA values of seismic zones with long duration seismic events. The resulting seismic hazard assessment has the advantage to be expressed in terms of modified PGA values and conventional design spectra, and therefore does not introduce any significant deviation from standard design process.

Firstly, in order to assess seismic hazard in Greece based on strong-motion duration, the evaluation of an accurate attenuation relation for strong-motion duration using all strong-motion data available for Greece was performed. Secondly, the assessment of seismic hazard has also been made for the parameter of peak ground acceleration, using earlier published attenuation relations. Finally, the composite result of these calculations is presented in a form of a map where Greece is divided into four equal seismic hazard categories.

2. Strong-motion Data Used

The dataset used in the present study, summarised in Table 1, consists of strong-motion records provided by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK), the Geophysical Laboratory of the Aristotle University of Thessaloniki and the Geodynamic Institute of the National Observatory of Athens. These records span a time range of 20 years, from 1978 to 1997. They consist of 141 sets of two horizontal components of strong-motion acceleration, representing 93 different seismic events. The majority of these recordings correspond to surface events, with the exception of one earthquake (two records in total), which is of intermediate depth. Due to the fact that focal depths of Greek seismic events are only qualitatively known (http://geohazards.cr.usgs.gov/iaspei/europe/greece/the), this information is not included in Table 1. In the seismic hazard analysis, shallow and

Table 1. Parameters of the earthquakes used in the present study.

EQ.	DATE	OR. TIME	LAT.	LONG.	M_w	REC. CODE	NC	REF.
1	780620	20:03:21	40.80	23.20	6.4	THE78-1	1, 2	1
2	800716	00:23:30	39,25	22,75	5.3	ALM80-2U	3, 4	2
3	800811	09:15:59	39,31	22,86	5.6	ALM80-4U	5, 6	2
4	800926	04:19:18	39,26	22,75	5.2	ALM80-5U	7, 8	2
5	810224	20:53:38	38.22	22.93	6.6	KOR81-1	9, 10	1
6	830117	12:41:29	38.09	20.19	6.9	AGR83-1	11, 12	3
						LEF83-1	13, 14	3
						ARG83-1	15, 16	3
7	830117	16:53:30	38.11	20.37	5.1	ARG83-3	17, 18	3
8	830119	00:02:14	38.17	20.23	5.8	ARG83-4	19, 20	3
9	830131	15:27:00	38.11	20.30	5.4	ARG83-6	21, 22	3
						ZAK83-1	23, 24	3
10	830220	14:42:29	37.76	21.11	5.2	ZAK83-2	25, 26	3
11	830316	21:19:39	38.80	20.88	4.9	LEF83-2	27, 28	3
12	830323	19:04:00	38.78	20.83	5.3	LEF83-3	29, 30	3
13	830323	23:51:06	38.33	20.22	6.2	ZAK83-3	31, 32	3
						LEF83-4	33, 34	3
						ARG83-7	35, 36	3
14	830324	04:17:32	38.10	20.49	5.4	ARG83-8	37, 38	3
15	830806	15:43:53	40.18	24.73	6.6	POL83-1	39, 40	3
						IER83-2	41, 42	3
16	830826	12:52:10	40.51	23.92	5.1	POL83-2	43, 44	3
						IER83-3	45, 46	3
17	840219	03:47:22	40.61	23.40	4.9	POL84-1	47, 48	3
18	840709	18:57:10	40.69	21.82	5.2	EDE84-1	49, 50	3
						VER84-1	51, 52	3
19	841004	10:15:12	37.64	20.85	5.2	ZAK84-1	53, 54	3
20	841025	09:49:16	36.83	21.71	5.3	KYP84-2	55, **	3
						PEL84-1	56, 57	3
21	850322	20:37:39	38.98	21.11	4.8	AMF85-3	58, 59	3
22	850322	20:38:54	38.91	21.06	4.5	AMF85-4	60, 61	3
23	850831	06:03:46	38.99	20.59	5.5	LEF85-1	62, 63	3
						PRE85-1	64, 65	3
24	851109	23:30:42	41.24	23.93	5.2	DRA85-1	66, 67	3
						KAV85-1	68, 69	3
25	860218	14:34:03	40.77	22.11	5.2	EDE86-1	70, 71	3
26	860913	17:24:34	37.03	22.20	5.9	KAL86-1	72, 73	3
27	860915	11:41:30	37.04	22.13	5.5	KAL86-8	74, 75	3
						KAL286-2	76, 77	3
						MES186-1	78, 79	3
29	870610	14:50:11	37.17	21.39	5.5	KYP87-1	80, 81	3
32	880303	11:38:58	38.87	21.23	5.0	AMF88-2	82, 83	3
34	880424	10:10:33	38.83	20.54	4.9	LEF88-2	84, 85	3

Table 1. (*Continued*)

EQ.	DATE	OR. TIME	LAT.	LONG.	M_w	REC. CODE	NC	REF.
35	880518	05:17:42	38.36	20.42	5.7	ARG88-2	86, 87	3
36	880705	20:34:51	38.11	22.85	4.6	KOR88-2	88, 89	3
37	881016	12:34:06	37.95	20.90	5.8	ZAK88-4	90, 91	3
						AML88-6	92, 93	3
40	890831	21:29:30	38.08	21.81	4.7	PAT189-3	94, 95	3
41	901221	06:57:44	40.98	22.34	6.1	EDE90-1	96, 97	3
						KIL90-1	98, 99	3
42	910319	12:09:26	34.67	26.35	5.7	SIT91-1	100, 101	3
43	910319	21:29:26	34.74	26.37	5.0	SIT91-2	102, 103	3
44	920123	04:24:00	38.40	20.57	5.4	ARG92-1	104, 105	3
46	920530	18:55:38	37.93	21.44	5.0	PAT92-1	106, 107	3
47	921110	22:14:59	38.78	20.66	4.8	LEF92-1	108, 109	3
49	930326	11:45:16	37.66	21.39	5.3	PYR93-6	110, 111	3
50	930326	11:56:13	37.69	21.43	5.1	PYR93-7	112, 113	3
51	930326	11:58:15	37.49	21.49	5.4	PYR93-8	114, 115	3
52	930326	12:26:32	37.55	21.27	5.2	PYR93-10	116, 117	3
53	930326	12:49:17	37.77	21.33	4.9	PYR93-11	118, 119	3
54	930429	07:54:29	37.40	21.58	5.8	PYR93-17	120, 121	3
55	930604	03:24:27	38.70	20.45	4.8	VAS93-2	122, 123	3
57	930714	12:31:49	38.24	21.78	5.6	PAT193-2	124, 125	3
						PAT393-2	126, 127	3
58	940225	02:30:49	38.76	20.55	5.5	LEF94-1	128, 129	3
						VAS94-1	130, 131	3
60	940523	06:46:12	35.16	24.59	5.7	HAN94-1	132, 133	3
						HRA94-1	134, 135	3
61	941126	14:30:30	38.87	20.48	5.1	LEF94-6	136, 137	3
62	950504	00:34:11	40.54	23.63	5.4	POL95-6	138, 139	3
						IER95-5	140, 141	3
						PRO16-14	142, 143	3
						SAR95-1	144, 145	3
						STC16-18	146, 147	3
						STE12-18	148, 149	3
						TST16-12	150, 151	3
63	950513	08:47:15	40.16	21.67	6.5	KOZ195-1	152, 153	3
						KAR195-1	154, 155	3
						KRP195-1	156, 157	3
						KAS195-1	158, 159	3
						VER195-1	160, 161	3
						FLO195-1	162, 163	3
64	950514	14:46:57	40.13	21.66	4.9	CHR195-5	164, 165	3
65	950515	04:13:57	40.07	21.67	5.2	CHR195-13	166, 167	3
						KOZ295-4	168, 169	3

Table 1. (*Continued*)

EQ.	DATE	OR. TIME	LAT.	LONG.	M_w	REC. CODE	NC	REF.
						KOZ195-7	170, 171	3
						GRE195-1	172, 173	3
66	950515	08:17:00	40.11	21.50	4.6	GRE195-3	174, 175	3
67	950516	23:00:42	40.02	21.56	4.7	CHR195-29	176, 177	3
68	950516	23:57:28	40.09	21.62	5.1	CHR195-30	178, 179	3
						KOZ295-6	180, 181	3
69	950517	04:14:26	40.07	21.61	5.2	KOZ295-7	182, 183	3
						KOZ195-8	184, 185	3
						GRE195-9	186, 187	3
						CHR195-32	188, 189	3
70	950517	09:45:07	40.01	21.56	4.8	GRE195-11	190, 191	3
						CHR195-34	192, 193	3
71	950518	06:22:55	40.03	21.56	4.5	CHR195-35	194, 195	3
72	950519	06:48:50	40.03	21.62	5.0	KOZ295-13	196, 197	3
						KPE195-1	198, 199	3
						GRE295-1	200, 201	3
						GRE195-12	202, 203	3
74	950520	21:06:25	40.00	21.58	4.5	KPE195-3	204, 205	3
						KND195-1	206, 207	3
75	950606	04:36:00	40.14	21.61	4.7	KPE195-7	208, 209	3
						KND195-4	210, 211	3
						KEN195-55	212, 213	3
						CHR195-49	214, 215	3
						KOZ295-22	216, 217	3
78	950717	23:18:15	40.10	21.58	5.0	GRE195-20	218, 219	3
79	950718	07:42:55	40.12	21.61	4.5	GRE195-22	220, 221	3
80	960804	08:03:21	40.04	20.70	4.7	KONL-028	222, 223	3
						KONU-105	224, **	3
81	960804	10:08:47	40.04	20.70	4.8	KONL-029	225, 226	3
						KONU-106	227, **	3
82	960805	22:46:42	40.06	20.66	6.3	KONL-032	228, 229	3
						KONU-107	230, 231	3
83	960805	23:58:46	40.03	20.72	4.5	KONL-039	232, 233	3
						KONU-108	234, **	3
84	960806	05:13:51	40.03	20.69	4.5	KONU-109	235, **	3
85	960811	07:57:15	40.08	20.73	5.4	AETP-005	236, 237	3
						KONL-070	238, 239	3
						KONU-123	240, **	3
86	960811	08:30:27	40.04	20.74	4.5	KONL-074	241, 242	3
						KONU-127	243, **	3
87	960820	01:26:46	40.04	20.70	5.4	AETP-010	244, 245	3
88	960821	07:10:34	40.02	20.78	4.7	KONL-101	246, 247	3

Table 1. (*Continued*)

EQ.	DATE	OR. TIME	LAT.	LONG.	M_w	REC. CODE	NC	REF.
89	960901	07:41:45	40.07	20.72	4.7	KONL-112	248, 249	3
						KONU-132	250, **	3
90	960901	21:15:00	40.01	20.74	5.0	AETP-013	251, 252	3
						KONL-117	253, 254	3
						KONU-134	255, 256	3
91	960926	12:31:49	40.05	20.75	5.4	AETP-016	257, 258	3
						KONL-132	259, 260	3
						KONU-137	261, 262	3
92	971013	13:39:46	36.10	22.04	6.4	KRN197-2	263, 264	3
						KYP197-2	265, 266	3
						KAL197-1	267, 268	3
						GTH197-1	269, 270	3
						ANS197-1	271, 272	3
93	971118	13:07:53	37.33	20.84	6.6	ZAK197-3	273, 274	3
						KYP197-3	275, 276	3
						KRN197-3	277, 278	3
						PYR197-1	279, 280	3
						KAL197-2	281, 282	3

1. Geodynamic Institute, Athens National Observatory.
2. Geophysical Laboratory, Aristotle University of Thessaloniki.
3. Institute of Engineering Seismology and Earthquake Engineering.
**The recording instrument was not functioning.

intermediate depth earthquakes are considered through the seismotectonic model [Papaioannou and Papazachos, 2000] assuming shallow and intermediate depth seismic sources. For the shallow seismic sources a mean depth of approximately 10 km and for intermediate depth seismic sources mean depths of 80 and 140 km are taken into consideration. The magnitudes used are taken from Papazachos *et al.* [1997] and range between 4.5 and 6.5. In the above study, an effort was made to produce a statistically homogeneous catalogue of historical and recent earthquakes of the Aegean area expressing the size of these earthquakes in the moment-magnitude scale. It was shown that the proposed magnitude M is equivalent to moment magnitude, M_w, for a wide range of earthquake sizes ($5 \leq M \leq 8$) and to the surface-wave magnitude, M_s, for large earthquake sizes ($6 \leq M \leq 8$). Concerning seismic events with magnitude lower than 5, moment-magnitude relations [Margaris and Papazachos, 1999] based on strong-motion records are used.

The distance considered herein, is the epicentral distance. Although other relevant studies use the closest distance to the fault rupture or to the surface projection of the rupture, these distances could not be calculated in the majority of the cases considered in the present study since the fault rupture was not adequately determined. In addition, due to the uncertainty of the focal depth determination, the application of the hypocentral distance was avoided. Thus, the epicentral distance was adopted, varying from 1 to 128 km. The distribution of the records in terms of epicentral distance and earthquake magnitude are shown in Fig. 2. In order to facilitate the comparison of the data sets used in study by Papazachos *et al.* [1992] and the present study, two sets of plots are shown in Fig. 2. In particular, the former study includes 37 seismic events and 54 accelerograms while the latter study compromises 93 seismic events and 141 accelerograms. It is obvious from the first graph of Fig. 2 that there is a lack of strong-motion records from large earthquakes in the near field. This lack is partly due to the limited number of strong-motion installations developed throughout Greece, along with the fact that most large earthquakes occur offshore.

The strong-motion data have been recorded from ITSAK (Institute of Engineering Seismology and Earthquake Engineering) and NOA-GI (National Observatory of Athens-Geodynamic Institute) accelerographic networks (www.itsak.gr, www.gein.noa.gr). The recording instruments are mainly consisted of SMA-1 type and few digital installations constituting aftershock arrays. The available records have been processed and corrected by the standard procedure applied in ITSAK. Processing included interpolation to 600 samples/s, low pass filter at 25–50 Hz depending on instrument type, high-pass filter based on the signal to noise ratio per each record, and decimation to 200 samples/s.

The available dataset, stems from national network located mainly at basements of low-rise governmental buildings (up to 3 storey). Numerous studies have shown [Kavazanjian *et al.*, 1985] that the effect of soil-structure interaction on duration is negligible for low-rise buildings. This was further supported from the fact that duration measures of Greek records are rather short, in accordance with the Greek seismotectonic environment.

Rupture directivity [Boore and Joyner, 1978; Boatwright and Boore, 1982], can cause significant variations in ground motion amplitudes and duration around the faults. Deviations from the mean duration from earthquake to earthquake are observed and this is often due to the multiplicity of the earthquake source. Those deviations become significant at a period of 0.6 s and generally grow in size with increasing period [Somerville *et al.*, 1997]. Analytical studies taking into account the wave propagation and directivity effects have been made after strong seismic events recorded by a significant number of accelerographs adequately covering the epicentral area [Boatwright and Boore, 1982; Somerville *et al.*, 1997]. Unfortunately, a lack of such strong-motion data exist in Greece and therefore, dependence of duration in terms of rupture directivity and wave propagation it is not possible to accomplish. Nevertheless, application of an anisotropic radiation of seismic waves for estimation of the strong-motion attenuation in Greece [Papazachos, 1992] is adopted in seismic hazard assessment through the input model [Margaris and Papazachos, 1994].

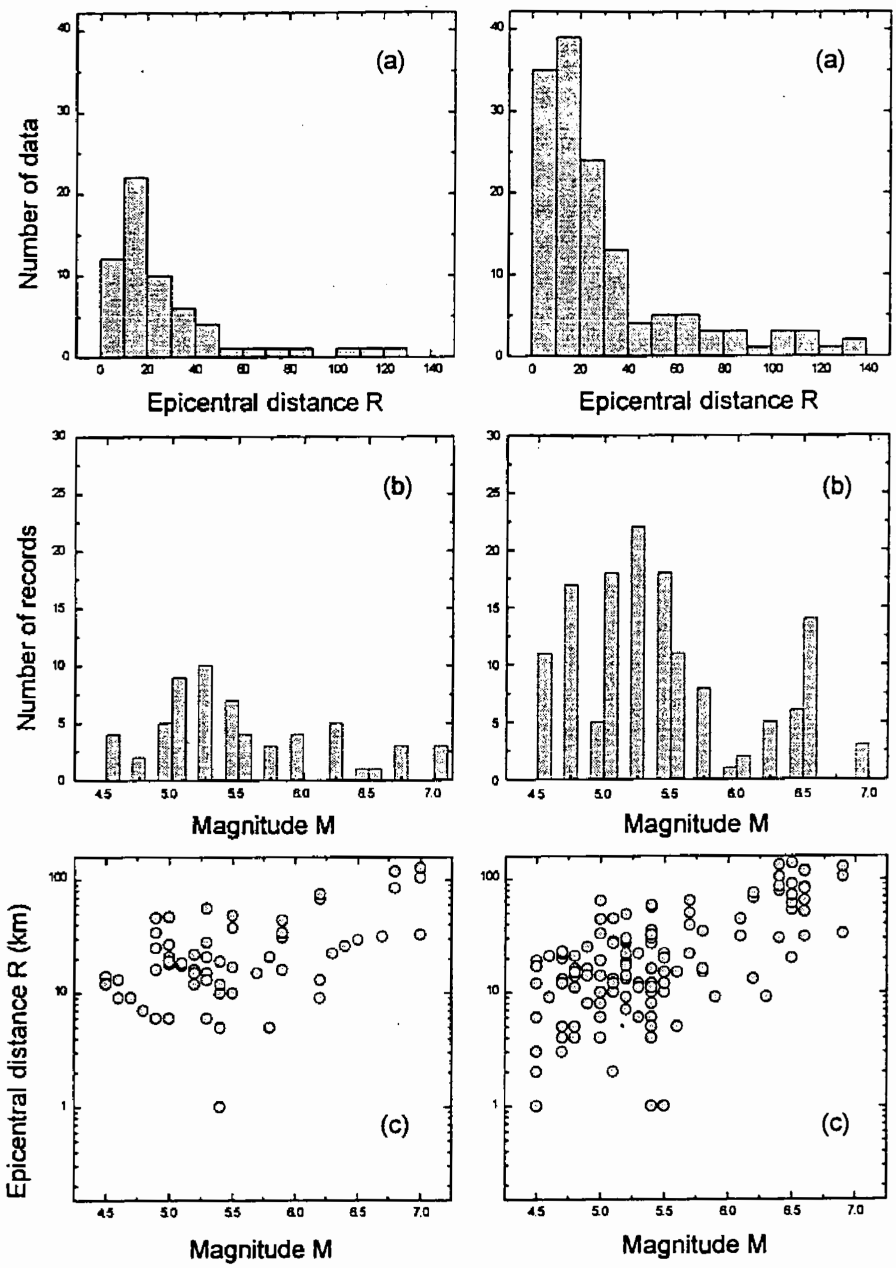

Fig. 2. (a) Distribution of data in terms of epicentral distance. (b) Distribution of data in terms of earthquake magnitude. (c) Distribution of epicentral distance vs. earthquake magnitude. The left column includes data from previous work [Papazachos *et al.*, 1992], in the right column are the data from the present study.

3. Attenuation of the Bracketed Duration of Strong Motion

No universally accepted measure of the duration of strong ground-motion exists. In a recent publication concerning the study of strong-motion duration [Bommer and Martínez-Pereira, 1999], approximately 30 different definitions of strong-motion duration are referred. Thus, the first problem encountered was the selection of an appropriate definition of strong-motion duration. After some consideration, the definition adopted is the one proposed by Bolt [1973], known as bracketed duration. For a given strong-motion record, it is defined as the time interval between the first and last excursion of the peak ground acceleration beyond a certain predefined level of it, usually 5%g. The rationale behind the choice of bracketed duration, rather than any other duration definition [Bommer and Martinez-Perreira, 1999], lies on the fact that bracketed duration correlates well with rupture duration [Margaris *et al.*, 1990; Papazachos *et al.*, 1992], significant duration (for specific level of bracketed duration) and macroseismic intensity I_{MM} [Koliopoulos *et al.*, 1998]. In fact Kawashima and Aizawa [1989] also used the same definition of duration and applied multiple regression analyses using the bulk of the available Japanese strong-motion data.

The available records were inspected in order to remove any possible secondary events following the main shock, which may lead to an overestimation of the calculated strong-motion duration. The bracketed durations where calculated for a series of different acceleration levels equally spanning the interval between 1 and 20%g. It was decided to keep only the bracketed durations corresponding to levels between 2 and 10%g, specifically 2, 2.5, 3, 3.5, 4, 5, 6.5, 8 and 10%g. Lower acceleration levels were not considered, to avoid an overestimation of corresponding durations, in case the signal/noise ratio of the record is low. The reason for the removal of the measured durations for levels above 10%g, lies in the fact that the resulting number of data is very small and the calculated durations are extremely short and exhibit a large statistical scatter. This often led to a behaviour entirely different than expected (for example, the calculated duration decreases with the increase of earthquake magnitude). The finally accepted values of strong-motion duration are given in Table 2, while the distribution of these values for the level of 5%g is shown in Fig. 3. It can be seen that scatter of the bracketed duration is considerable, however as a general trend bracketed duration increases as earthquake magnitude increases and epicentral distance decreases [Kawashima and Aizawa, 1989]. Notably the dependence of duration on the epicentral distance is not very strong. Earlier studies [Papazachos *et al.*, 1992] revealed that taking into account the epicentral distance in the same functional form decreases the standard deviation by 40%. Although it has been reported [Bommer and Martinez-Pereira, 1999] that bracketed duration can be rather unstable for low threshold of accelerations (0.02, 0.03g) in our case no significant instabilities have been observed. Furthermore previous studies using Greek data [Koliopoulos *et al.*, 1998], shows that 0.03g bracketed correlates well with significant duration, which is generally considered as stable.

Table 2. Calculated values of bracketed duration for the earthquakes of Table 1.

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
1	6.4	30	0	8.82	8.23	8.21	8.20	8.19	5.94	5.89	1.34	1.06
2	6.4	30	0	13.19	8.99	7.70	7.68	7.46	5.73	5.56	5.05	0.91
3	5.3	6	1	4.31	3.47	2.79	2.77	2.03	2.02	1.18	0.05	0.04
4	5.3 6	1	4.47	2.93	2.92	1.92	1.43	1.18	1.05	0.16	0.02	
5	5.6	15	1	5.74	4.71	4.70	4.68	0.82	0.81			
6	5.6	15	1	5.85	4.86	3.49	3.48	2.66	1.40	0.01		
7	5.2	7	1	4.08	2.58	2.12	2.11	2.10	0.32			
8	5.2	7	1	2.25	2.23	1.73	1.49	0.46	0.38			
9	6.6	31	0	28.27	18.99	18.46	18.43	17.18	17.14	8.47	8.43	5.88
10	6.6	31	0	22.41	20.28	17.61	17.47	14.68	13.14	11.18	7.65	6.18
11	6.9	128	0	5.13	3.77	0.01						
12	6.9	128	0	4.90	4.61	2.79	1.25	0.52	0.02			
13	6.9	105	0	15.90	9.28	9.24	9.17	6.58	4.90	0.01		
14	6.9	105	0	13.82	12.94	11.30	10.33	8.11	2.66			
15	6.9	33	1	17.94	17.61	16.24	11.86	11.85	10.50	6.38	4.50	3.29
16	6.9	33	1	17.22	15.21	13.64	11.35	8.69	8.28	8.26	3.94	1.66
17	5.1	13	1	3.20	1.23	0.28	0.22	0.21	0.08	0.02		
18	5.1	13	1	1.48	0.43							
19	5.8	15	1	6.04	6.03	3.75	3.63	3.43	3.07	0.51		
20	5.8	15	1	7.12	3.88	3.11	3.10	2.97	2.52	0.25		
21	5.4	6	1	3.60	2.30	1.80	1.36	0.94	0.49			
22	5.4	6	1	3.43	1.74	1.57	1.51	1.47	0.87	0.02		
23	5.4	56	0									
24	5.4	56	0									
25	5.2	19	0	7.29	6.65	6.63						
26	5.2	19	0	2.80	1.25							
27	4.9	16	0	0.15	0.02							
28	4.9	16	0									
29	5.3	12	0	7.98	2.64	0.50	0.48	0.34	0.18			
30	5.3	12	0	2.99	2.26	0.02						
31	6.2	68	0	0.02								
32	6.2	68	0	2.43	0.01							
33	6.2	75	0	5.06								
34	6.2	75	0	4.01	1.28							
35	6.2	13	1	16.23	13.08	13.07	10.65	10.65	10.63	6.11	6.09	2.27
36	6.2	13	1	14.82	14.79	10.30	10.29	8.83	7.98	7.77	5.54	5.26
37	5.4	10	1	7.03	5.69	3.59	1.61	1.57	1.50	1.47	1.23	0.55
38	5.4	10	1	4.77	4.37	4.32	3.78	1.88	1.53	1.23	1.21	0.53
39	6.6	119	2	0.01								
40	6.6	119	2	0.01								
41	6.6	85	0	3.67	3.27							
42	6.6	85	0	1.99	1.97							
43	5.1	45	2	2.17	1.95	1.85	1.45	1.39	0.25	0.15	0.07	

Table 2. (*Continued*)

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
44	5.1	45	2	1.21	1.13	1.05	0.62	0.61	0.01			
45	5.1	10	0	4.13	3.37	3.37	2.91	2.15	1.45	1.26	0.20	0.19
46	5.1	10	0	5.27	3.06	3.06	2.86	2.86	2.85	1.33	0.77	0.51
47	4.9	25	2									
48	4.9	25	2									
49	5.2	21	1	6.44	4.56	0.23						
50	5.2	21	1	4.29	3.19	2.56	1.51	1.29				
51	5.2	28	2									
52	5.2	28	2									
53	5.2	18	0	4.27	2.77	2.09						
54	5.2	18	0	1.28	0.83	0.67	0.65	0.35	0.20	0.18		
55	5.3	22	2	0.02								
56	5.3	11	2	8.82	8.80	5.55	5.19	5.18	4.28	3.22	2.66	2.07
57	5.3	11	2	10.45	7.68	7.60	6.45	4.98	3.94	3.02	2.01	1.98
58	4.8	14	2	1.00	0.63	0.52	0.40	0.34	0.02			
59	4.8	14	2	2.25	2.14	1.99	0.28	0.07	0.05	0.01		
60	4.5	12	2	0.17	0.10	0.08	0.07					
61	4.5	12	2	2.14	1.62	0.86	0.50					
62	5.5	22	0	7.76	5.31	5.29	2.66	0.33	0.20	0.04		
63	5.5	22	0	8.32	6.20	6.16	6.02	0.20	0.17			
64	5.5	15	1	5.87	3.27	2.91	2.90	0.03				
65	5.5	15	1	3.10	3.07	2.45	2.44	0.74	0.63			
66	5.2	17	1	3.50	2.98	2.36						
67	5.2	17	1	4.41	1.03	0.93	0.91	0.88	0.37	0.33	0.02	
68	5.2	49	2	6.49	5.94	0.60	0.33	0.04	0.01			
69	5.2	49	2	5.43	1.96	0.75						
70	5.2	13	1	6.17	5.20	4.30	2.98	2.96	2.05	0.09	0.04	
71	5.2	13	1	6.18	5.22	4.96	3.46	0.86				
72	5.9	9	1	11.84	11.51	6.42	6.40	5.71	5.69	5.62	4.08	2.61
73	5.9	9	1	17.19	11.33	10.73	10.69	8.14	8.02	3.88	3.51	2.46
74	5.5	1	1	6.14	4.37	4.35	4.18	3.42	3.19	1.12	0.99	0.98
75	5.5	1	1	4.78	4.37	1.80	1.79	1.78	1.13	0.88	0.65	0.25
76	5.5	1	1	3.73	3.10	2.80	2.78	2.75	1.11	1.00	0.45	0.23
77	5.5	1	1	4.56	3.93	3.91	2.84	2.28	1.45	1.44	1.15	1.01
78	5.5	10	0	10.19	1.33	0.01						
79	5.5	10	0	5.04	2.84	0.68	0.03	0.02				
80	5.5	20	2	2.45	2.37	1.93	1.91	1.29	0.40	0.38	0.11	0.04
81	5.5	20	2	2.82	2.80	2.53	2.52	2.51	1.52	0.10	0.10	0.09
82	5.0	6	2	0.91	0.81	0.72	0.50	0.42	0.32			
83	5.0	6	2	0.94	0.85	0.83	0.01					
84	4.9	14	0	4.37	0.58	0.57	0.54	0.37	0.29	0.08		
85	4.9	14	0	0.05								
86	5.7	22	1	2.99	2.90	2.21	1.46	1.46	0.02			

Table 2. (*Continued*)

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
87	5.7	22	1	3.51	3.50	1.58	1.57	1.27				
88	4.6	21	0	1.46	0.55	0.54	0.52	0.48	0.38	0.02		
89	4.6	21	0	2.85	2.23	0.94	0.93	0.66	0.01			
90	5.8	16	0	18.34	16.84	16.62	16.37	11.40	6.81	6.24	2.63	1.41
91	5.8	16	0	20.00	17.33	17.02	16.07	11.28	10.96	7.14	6.31	6.27
92	5.8	34	0	11.34	9.82	9.52	9.51	7.80	4.11	0.56	0.01	
93	5.8	34	0	13.92	7.69	7.66	7.63	7.35	1.76	1.09	1.07	0.34
94	4.7	20	0	4.03	4.02	0.19	0.19	0.18	0.04			
95	4.7	20	0	4.21	4.17	3.91	3.75	0.09	0.07	0.06	0.04	
96	6.1	31	1	11.61	11.27	7.31	6.69	5.85	5.61	3.46	1.55	0.01
97	6.1	31	1	12.04	6.36	6.34	6.31	6.06	4.08	0.41	0.34	
98	6.1	44	1	5.01	4.98	3.43	1.46	0.109				
99	6.1	44	1	3.96	2.62	0.35	0.34	0.01				
100	5.7	39	0	1.80	1.32	1.16	0.95	0.53	0.03			
101	5.7	39	0	1.93	1.02	0.70	0.06	0.04				
102	5.0	65	0	0.68	0.67	0.66	0.64	0.27				
103	5.0	65	0	0.87	0.02							
104	5.4	16	1	6.06	5.23	5.22	3.76	3.75	3.74	3.72	3.49	0.25
105	5.4	16	1	6.91	5.28	4.89	4.17	3.93	3.92	3.58	1.06	0.61
106	5.0	44	0	1.29	0.18	0.12	0.11	0.11	0.09	0.06		
107	5.0	44	0	1.56	1.42	0.78	0.76	0.76	0.01			
108	4.8	11	0	1.32	0.29	0.27	0.16	0.14				
109	4.8	11	0	0.62	0.61	0.59	0.49	0.47	0.41	0.40	0.38	0.34
110	5.3	6	0	2.47	2.14	1.65	1.47	1.46	1.08	1.03	1.01	
111	5.3	6	0	5.63	5.62	5.61	3.46	1.77	1.76	1.21	0.95	0.94
112	5.1	2	0	5.65	1.84	1.81	1.24	1.23	0.64	0.56	0.33	
113	5.1	2	0	5.03	4.49	2.52	2.51	2.50	1.39	0.28	0.19	0.02
114	5.4	12	0	7.31	7.23	4.55	4.53	4.52	4.50	2.48	0.65	0.41
115	5.4	12	0	8.10	7.35	5.12	4.93	4.91	4.88	2.11	1.61	1.57
116	5.2	21	0	0.03								
117	5.2	21	0	0.10	0.09	0.07	0.05	0.02				
118	4.9	14	0	0.03								
119	4.9	14	0	0.51	0.31							
120	5.8	34	0	0.41	0.38	0.06						
121	5.8	34	0	1.30	0.94	0.41	0.39	0.03				
122	4.8	16	0	4.03	2.76	0.91	0.90	0.21				
123	4.8	16	0	5.10	4.24	0.77	0.66	0.65	0.03			
124	5.6	5	0	12.30	9.39	9.38	9.37	6.59	6.58	6.44	2.71	2.24
125	5.6	5	0	13.14	7.81	7.81	6.35	5.10	4.61	4.23	4.22	2.45
126	5.6	5	1	12.67	9.85	9.24	7.22	7.22	6.31	4.59	2.53	1.66
127	5.6	5	1	11.92	10.03	10.01	6.91	6.76	6.75	5.89	5.88	1.60
128	5.5	15	0	14.69	10.70	8.63	8.61	8.58	7.56	3.59	0.60	0.55
129	5.5	15	0	16.52	9.10	9.07	4.19	3.89	3.31	3.28	3.22	0.37

Table 2. (*Continued*)

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
130	5.5	12	0	8.18	4.92	4.38	4.37	4.34	1.88			
131	5.5	12	0	8.16	6.26	6.24	3.85	3.84	3.81			
132	5.7	65	0	3.10	1.56	1.53	1.51	1.49	0.03			
133	5.7	65	0	3.93	2.10	1.68	0.36	0.07				
134	5.7	50	0	22.22	17.49	13.05	8.57	2.46	2.44			
135	5.7	50	0	19.84	17.51	17.28	12.37	12.33				
136	5.1	28	0	6.69	5.93	5.91	5.78	4.02				
137	5.1	28	0	10.04	7.52	4.67	4.64	1.56	0.80	0.05		
138	5.4	27	2	1.81	1.73	1.67	1.48	1.47	1.39	0.94	0.46	0.17
139	5.4	27	2	2.00	1.72	1.65	1.63	1.21	1.20	0.70	0.03	
140	5.4	27	0	0.70	0.02							
141	5.4	27	0	1.65	0.49	0.01						
142	5.4	35	1									
143	5.4	35	1	0.79	0.08	0.01						
144	5.4	59	1									
145	5.4	59	1									
146	5.4	31	1	0.63	0.28	0.03						
147	5.4	31	1	0.43	0.01							
148	5.4	30	2	0.80	0.61	0.48						
149	5.4	30	2	1.75	1.67	1.14	0.50	0.48				
150	5.4	32	0	2.20	0.03	0.02						
151	5.4	32	0	0.02								
152	6.5	20	2	14.10	8.62	7.35	7.04	5.67	4.96	4.45	4.44	2.83
153	6.5	20	2	14.22	11.62	11.61	9.92	9.91	6.83	3.89	3.41	2.94
154	6.5	90	0	1.49								
155	6.5	90	0	6.37								
156	6.5	138	2									
157	6.5	138	2									
158	6.5	53	2									
159	6.5	53	2									
160	6.5	61	2	5.90	1.10							
161	6.5	61	2	0.10								
162	6.5	72	2	2.34								
163	6.5	72	2	0.06								
164	4.9	8	1	2.75	1.75	1.69	0.58	0.23	0.01			
165	4.9	8	1	2.78	0.95	0.94	0.93	0.42	0.39	0.11	0.03	
166	5.2	9	1	5.49	3.94	3.89	3.88	3.88	2.24	2.23	2.04	1.13
167	5.2	9	1	5.43	4.58	4.48	4.40	4.39	2.10	1.83	0.46	0.08
168	5.2	27	1	1.23	0.01							
169	5.2	27	1	1.48	0.16	0.09	0.02					
170	5.2	28	2									
171	5.2	28	2									
172	5.2	22	1	2.91	0.81	0.30	0.03	0.03				

Table 2. (*Continued*)

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
173	5.2	22	1	2.14	0.19							
174	4.6	9	1	0.36	0.02							
175	4.6	9	1	0.81	0.58	0.35	0.34	0.18				
176	4.7	20	1									
177	4.7	20	1									
178	5.1	12	1	3.16	2.87	2.85	2.55	2.53	1.93	1.58	0.16	
179	5.1	12	1	3.27	2.23	2.22	2.22	2.20	1.07	0.09		
180	5.1	27	1									
181	5.1	27	1									
182	5.2	29	1	1.30	0.18							
183	5.2	29	1	0.92								
184	5.2	30	2									
185	5.2	30	2									
186	5.2	22	1									
187	5.2	22	1	0.73	0.72							
188	5.2	14	1	7.21	4.26	4.24	3.19	2.87	1.60	1.49	1.17	0.31
189	5.2	14	1	6.36	4.57	4.55	4.47	2.16	2.14	1.58	0.92	0.04
190	4.8	15	1	0.46	0.29	0.01						
191	4.8	15	1	3.18								
192	4.8	21	1									
193	4.8	21	1									
194	4.5	19	1									
195	4.5	19	1									
196	5.0	33	1									
197	5.0	33	1									
198	5.0	8	1	11.17	10.68	9.68	9.66	6.93	5.65	3.61	2.50	2.37
199	5.0	8	1	11.18	10.02	9.25	8.46	6.67	5.96	4.74	4.37	4.35
200	5.0	19	1	1.19								
201	5.0	19	1	0.18								
202	5.0	19	1	1.15	1.13	0.01						
203	5.0	19	1	1.20								
204	4.5	6	1	3.10	1.34	0.69	0.04	0.03	0.01			
205	4.5	6	1	2.54	2.52	1.88	1.87	0.71				
206	4.5	12	1	0.31								
207	4.5	12	1									
208	4.7	22	1									
209	4.7	22	1									
210	4.7	5	1	3.34	3.27	2.37	2.09	1.21	0.88			
211	4.7	5	1	4.37	4.04	3.65	2.56	1.21	0.89	0.56	0.01	
212	4.7	13	2	0.01								
213	4.7	13	2	1.55								
214	4.7	12	1	2.61	1.57	1.47	1.46	0.25	0.14	0.12		
215	4.7	12	1	1.90	1.56	1.54	0.68					

Table 2. (*Continued*)

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
216	4.7	23	1									
217	4.7	23	1									
218	5.0	14	1	1.70	0.01							
219	5.0	14	1	1.02	1.00	0.38	0.36					
220	4.5	17	1									
221	4.5	17	1	0.01								
222	4.7	5	0	0.46	0.13	0.03	0.02					
223	4.7	5	0	0.29	0.22	0.06						
224	4.7	5	2									
225	4.8	4	0	0.71	0.11	0.01						
226	4.8	4	0									
227	4.8	5	2	0.21	0.05							
228	6.3	9	0	5.09	5.08	5.06	4.92	3.00	2.99	2.89	1.35	1.14
229	6.3	9	0	6.26	6.18	4.37	4.36	4.19	3.72	3.13	2.90	2.74
230	6.3	9	2	4.64	4.48	4.30	4.09	2.42	2.34	2.22	2.11	1.98
231	6.3	9	2	4.27	2.44	2.42	2.29	2.26	1.95	0.86	0.82	0.74
232	4.5	3	0									
233	4.5	3	0	0.04	0.03	0.02						
234	4.5	4	2									
235	4.5	6	2									
236	5.4	8	0									
237	5.4	8	0									
238	5.4	4	0	3.68	3.39	3.24	2.79	2.79	2.77	2.15	1.52	1.51
239	5.4	4	0	3.44	3.02	3.00	2.60	2.59	2.20	2.13	1.97	1.95
240	5.4	4	2	3.25	3.23	2.72	2.58	1.68	1.38			
241	4.5	1	0	0.01								
242	4.5	1	0	0.54	0.04	0.03	0.03	0.01				
243	4.5	2	2									
244	5.4	5	0	3.48	2.70	2.68	1.77	1.22	1.20	0.14	0.13	0.03
245	5.4	5	0	2.32	1.91	1.90	1.15	1.14	1.13	0.02		
246	4.7	4	0	0.38								
247	4.7	4	0	0.90	0.26	0.19	0.18					
248	4.7	3	0	0.88	0.53	0.35						
249	4.7	3	0	1.19	0.64	0.51	0.41					
250	4.7	4	2									
251	5.0	10	0									
252	5.0	10	0									
253	5.0	4	0	1.49	1.47	0.99	0.80	0.45	0.43	0.01		
254	5.0	4	0	1.64	1.49	1.44	1.21	0.85	0.09	0.03	0.02	
255	5.0	4	2	0.37	0.23	0.12	0.11	0.11	0.03			
256	5.0	4	2	0.54	0.19	0.18	0.01					
257	5.4	11	0									
258	5.4	11	0									

Table 2. (*Continued*)

NC	M_w	R	SC	BD02	BD025	BD03	BD035	BD04	BD05	BD065	BD08	BD10
259	5.4	1	0	2.66	2.04	1.64	1.28	1.12	1.11	0.58	0.48	0.46
260	5.4	1	0	2.68	2.59	2.43	2.42	2.08	1.60	0.79	0.78	0.38
261	5.4	1	2	2.85	2.12	1.34	1.33	1.32	0.22	0.20	0.05	0.02
262	5.4	1	2	2.95	1.81	1.48	1.47	1.38	0.92	0.03		
263	6.4	78	2	21.07	19.78	16.28	11.39	10.12	8.90	7.69	7.62	6.64
264	6.4 7	8	2	26.82	19.83	13.97	10.09	8.73	5.14	3.46	0.54	0.36
265	6.4	132	2									
266	6.4	132	2									
267	6.4	104	1	7.47	3.33	3.30						
268	6.4	104	1	6.38	1.09							
269	6.4	86	2	0.01								
270	6.4	86	2									
271	6.4	105	2	0.04								
272	6.4	105	2	0.06								
273	6.6	51	0	30.45	25.17	20.01	17.17	17.14	16.35	0.72	0.60	0.50
274	6.6	51	0	30.89	30.84	28.50	21.83	20.54	20.51	4.80	0.94	0.89
275	6.6	116	2	9.34	6.49	6.41	5.01	4.30	4.04	0.05		
276	6.6	116	2	11.79	7.92	7.41	5.99	4.34	3.37	0.02		
277	6.6	82	2	15.30	14.61	14.58	9.92	6.66	5.25	1.89	1.40	
278	6.6	82	2	12.62	11.92	9.71	9.59	5.60	4.94	2.48		
279	6.6	65	0	12.78	11.86	7.23	6.44	3.23	1.16			
280	6.6	65	0	13.30	9.31	7.65	7.64	3.70				
281	6.6	117	1	10.47	5.90	4.15	2.79					
282	6.6	117	1	7.01	4.53	0.02						

The independent variables, which were selected to describe the attenuation relation of the dependent variable of bracketed duration, are the earthquake magnitude, the epicentral distance, a variable representing the soil conditions at the recording site and a variable representing the level of ground acceleration for which the bracketed duration was estimated. Typically, studies aiming to develop empirical ground motion models select a single, preferred mathematical relationship to describe the attenuation of strong-motion parameters. Models are selected on the basis of fundamental physical arguments that lead to the basic functional dependence of ground motion on the independent variables, usually magnitude and distance. The dependence of the strong-motion duration, in terms of magnitude distance and soil conditions, has been examined by many authors [Esteva and Rosenblueth, 1964; Trifunac and Brady, 1975; McGuire and Barnhard, 1979]. The same mathematical models of the empirical prediction of the duration as a function of magnitude, distance and soil conditions have been proposed for Greece and other regions [Xie and Zhang, 1988; Kawashima and Aizawa, 1989; Margaris *et al.*, 1990; Papazachos

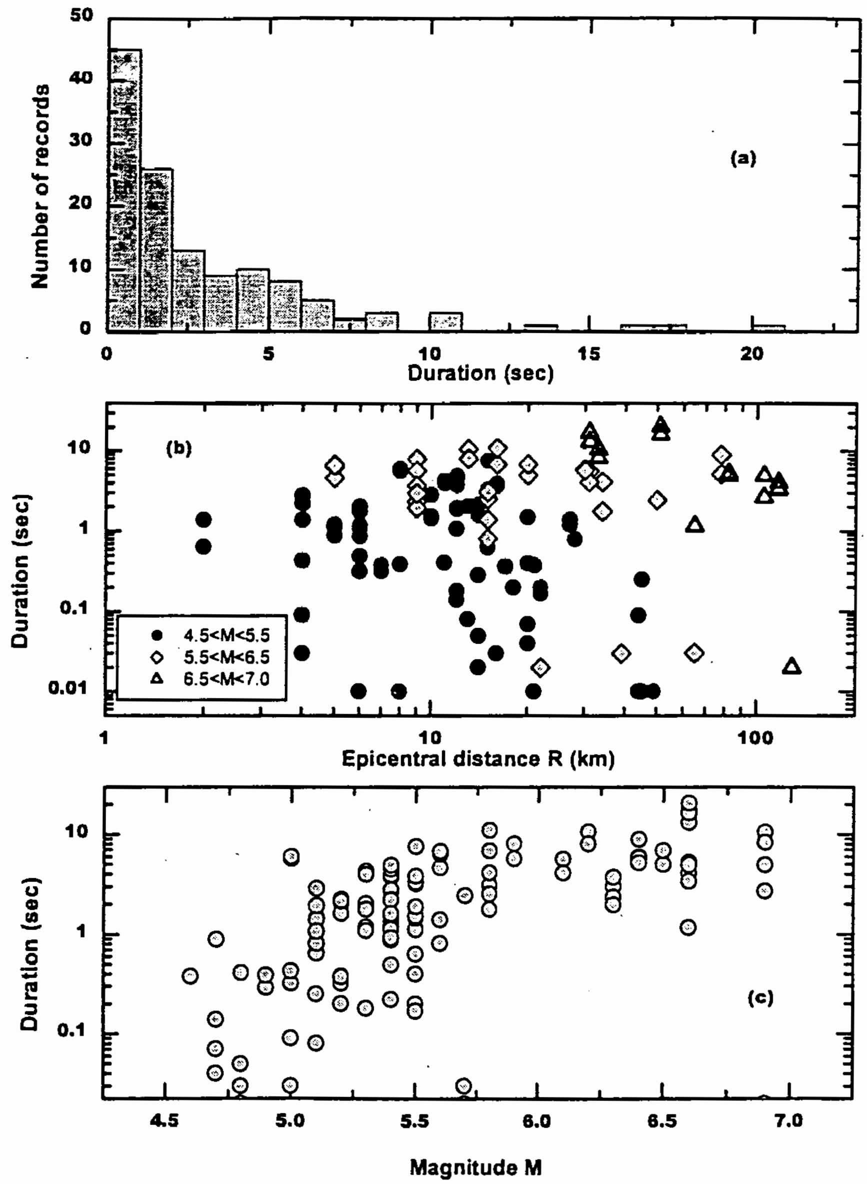

Fig. 3. (a) Distribution of calculated values of bracketed duration 5%g, (b) distribution of the same values versus epicentral distance and (c) distribution against earthquake magnitude.

et al., 1992; Novikova and Trifunac, 1994; Trifunac and Novikova, 1995]. The general form of the attenuation relation is:

$$\ln D = c_1 + c_2 M + c_3 \ln(R + R_0) + c_4 L + c_5 S + \sigma_{\ln D} P \tag{1}$$

where D represents the bracketed duration (in seconds), M is the earthquake magnitude, R is the epicentral distance (in kilometers), R_0 is a coefficient used to take into account the effect of the saturation of the values of D with distance, L is the level of acceleration for which the bracketed duration is calculated (in g) and finally S is the variable used to describe the soil conditions at the recording site. S, takes three different values: zero, one and two for soft alluvium deposits, intermediate soil conditions and tertiary or older rock respectively. P is 0 for 50 percentile and 1 for 84-percentile level of non-exceedence, assuming normal distribution of the residuals and $\sigma_{\ln D}$ is the residuals' root mean square resulting from Eq. (1). The inclusion of soil conditions as an independent parameter was decided in order to clarify an apparent contradiction between the findings of early works [e.g. McGuire and Barnhard, 1979] and more recent works [e.g. Kawashima and Aizawa, 1989; Papazachos *et al.*, 1992] regarding the importance of site characterization on duration. In particular, the former study showed the significance of incorporating soil conditions on duration empirical predictions while the later works have found that duration is practically independent of soil characterization. Recording sites were classified into three categories "soft alluvium", "intermediate" and "rock" soil conditions. The grouping was carried out based on the stiffness of the material at the accelerographic site, geological description and the available geotechnical data (V_{s30}, N_{SPT} etc.). This soil classification followed a methodology proposed by Trifunac and Brady [1976] and applied by Theodulidis and Papazachos [1992] for Greek strong-motion data. In addition, recent geotechnical information for a few accelerographic sites was taken into account in this classification [Klimis *et al.*, 1999].

The values c_i represent the coefficients of the attenuation relation under determination and were calculated with the application of multiple regression analysis. The method used to calculate the coefficients c_i, is the multi-linear regression analysis [Papoulis, 1990; Everitt, 1991; Bevington and Robinson 1992; Press *et al.*, 1992]. This method solves the problem of defining a function of the form:

$$y = c_1 w_1 + c_2 w_2 + \cdots + c_m w_m \tag{2}$$

which fits the data:

$$w_{1i}, \ldots, w_{mi}, \quad y_i i = 1, \ldots, n$$

where, n is the number of available strong-motion records. Each record corresponds to a single set of values for the variables D, M, R, S and L.

The solution of the above problem, is the function which minimizes the sum:

$$Q = \sum v_i^2 \tag{3}$$

where $v_i = y_i - (c_1 w_{1i} + c_2 w_{2i} + \cdots + c_m w_{mi})$.

Following this mathematical procedure the problem of determining coefficients, c_i, eventually reduces to the solution of a system of algebraic equations. The inclusion of the coefficient R_0 results in a system of non-linear equations, which is difficult if not impossible to solve. The procedure followed in this study is to assume distinct values for R_0 that lie inside a range of expected values. In this way, the

Table 3. Coefficients of the proposed attenuation relation [Eq. (1)].

	C_1	C_2	C_3	C_4	C_5	C_6	$\sigma_{\ln Y}$
Including the soil conditions variable, S	−1.88	2.05	−2.05	30	−0.05	−27.74	1.50
Without the inclusion of variable S	−1.88	2.05	−2.05	30	—	−27.75	1.49

system of algebraic equations becomes linear and is easily solved. The coefficient R_0 has been defined by investigating the standard deviation values of Eq. (1) through successive regression analyses with $R_0 = 0, 5, 10, \ldots, 40$. The value, which is finally chosen to represent R_0, is the one that minimises the standard deviation of the equation. By following this procedure, the value of R_0 was found equal to 30. This value $R_0 = 30$ is in a good agreement with values which have been derived from similar analyses regarding effective acceleration [Mortgat, 1979; $R_0 = 25$] or duration of strong-motion [Kawashima and Aizawa, 1989; Yayong and Minxian, 1990; $R_0 = 30$]. Table 3 shows the values of the coefficients of the attenuation relation. As it is clearly seen, the value of the coefficient c_5, for the variable S is very low. This means that bracketed duration is practically independent of the soil conditions at the recording site, provided that a simple soil description index like the one adopted herein is used. For further confirmation, a binary variable S (zero for alluvium and one for rock site conditions) was also used. The resulting coefficient c_5 was found equal to 0.09 while all remaining coefficients were almost identical to the values given in Table 3. The coefficients of the empirical relation were recalculated without taking into account the soil conditions parameter and they were found identical to the previously calculated values, as shown in Table 3. For this reason, the final relation does not include the soil condition parameter at the recording site.

In order to evaluate the reliability of the empirical relation, a residual analysis was performed. The residuals were plotted against the independent variables of the attenuation relation shown in Fig. 4. These plots are used in order to identify any trends that would indicate an inadequacy of the selected model leading to a modification of the functional form. Although a mild negative bias can be observed regarding low threshold values, this trend becomes negligible for higher threshold values, which are of practical interest. Consequently, the relation was considered acceptable. It is worth noting here, that this form of the empirical prediction of duration has been successfully used by McGuire and Barnhard [1979], Kawashima and Aizawa [1989], Margaris et al. [1990] and Papazachos et al. [1992].

Finally, the derived relation was compared with similar relations reported in two of the above-mentioned works. Specifically, a comparison was made with the relation proposed by Papazachos et al. [1992] in Greece and the one proposed by Kawashima and Aizawa [1989] in Japan. The latter work in fact, proposed two

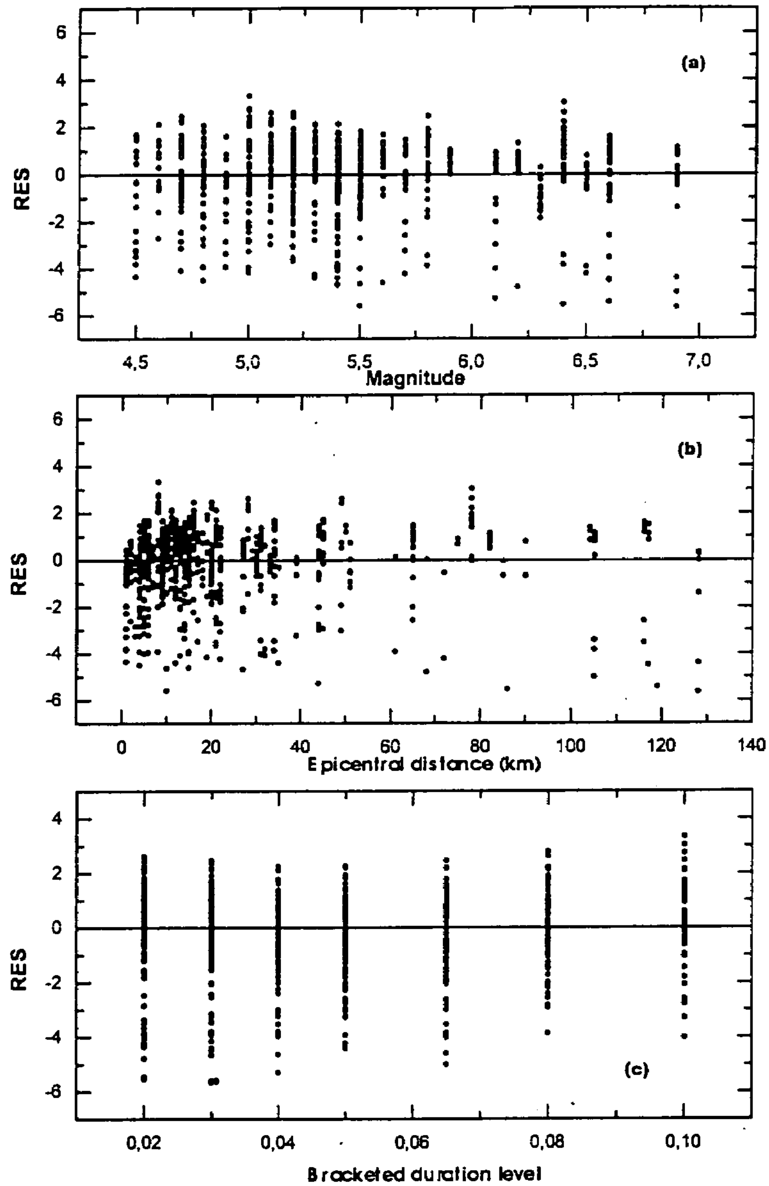

Fig. 4. Distribution of residuals of the calculated attenuation relation vs. earthquake magnitude (a), epicentral distance (b) and bracketed duration level (c).

different relations: one for the level of 50 cm/s^2 and one for the level of 100 cm/s^2 (roughly 5 and 10%g). Papazachos *et al.* [1992] proposed a relation that contains a parameter concerning the level of ground acceleration for which the bracketed duration is being calculated. It should be noted that all definitions of magnitude used (M_w, M_s and $M_{\rm JMA}$) in the above works are comparable for magnitude range

5 to 7 and shallow earthquakes, covering the bulk of the available data [Katsumata, 1996; Papazachos *et al.*, 1997]. In Figs. 5 and 6, the values of bracketed duration predicted by these three relations, are plotted against the epicentral distance for a constant magnitude of 6.5 and for two different levels of acceleration (5 and 10%g). From these two figures it can be seen that the relation proposed in the present study, is different from the one proposed by Papazachos *et al.* [1992]. In particular, the proposed relations predict higher durations for epicentral distances up to 30 km and lower durations for greater distances. These deviations are probably due to the substantially richer data set available herein compared to Papazachos *et al.* data set. The aforementioned conclusion is further supported from the fact that similar deviations have been reported in a comparison between Greek and Japanese empirical predictions of strong-motion duration [Papazachos *et al.*, 1992; Fig. 5). It is noteworthy that the Japanese empirical predictions [Kawashima and Aizawa, 1989] were based on a very rich data set comprising 197 accelerograms. ($5 < M < 8$ and 5 km $< R <$ 500 km). A part of these data were also used by Theodulidis and Papazachos [1992] to enrich the Greek dataset in order to derive empirical predictions for pga, pgv, pgd and 5%-psv spectra. This fact necessitates the comparison between Greek and Japanese empirical predictions.

Despite certain quantitative differences, the general trend of the relation proposed in the present study, show a satisfactory qualitative agreement with the trend of the relation proposed for Japan. In contrast, the differences between the Papazachos *et al.* empirical prediction and the Japanese predictions are both quantitative and qualitative.

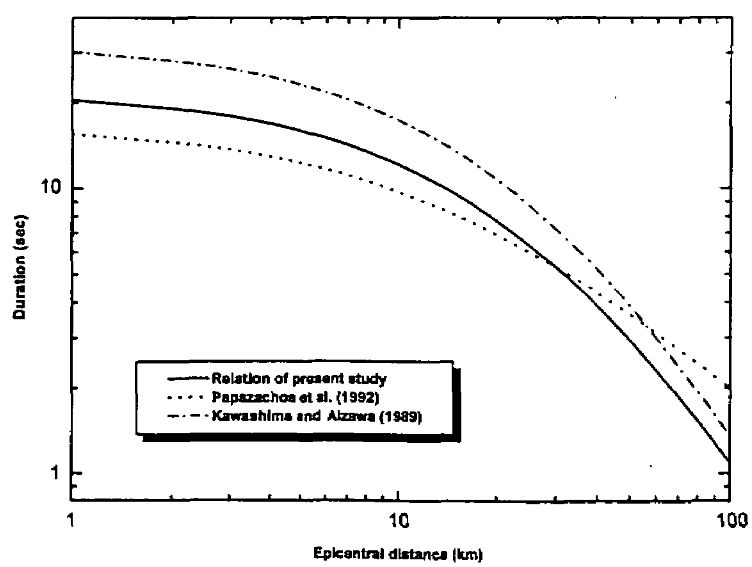

Fig. 5. Comparison between the attenuation relation of the present study and two existing relations for a constant magnitude of 6.5 and for a level of bracketed duration of 5%g.

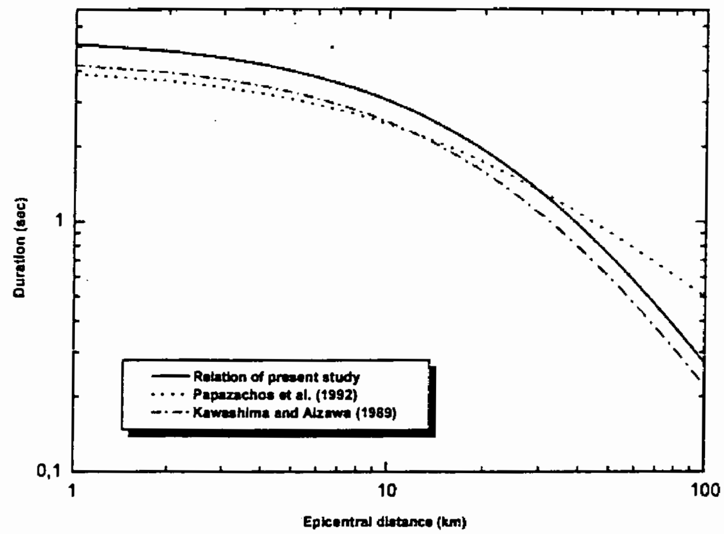

Fig. 6. Comparison between the attenuation relation of the present study and two existing relations for a constant magnitude of 6.5 and for a level of bracketed duration of 10%g.

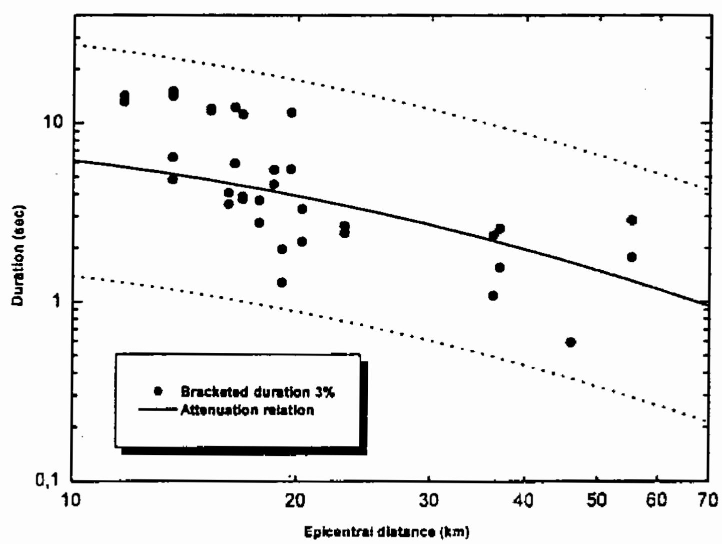

Fig. 7. Observed bracketed duration values for a level of 3%g from the 7/9/99 earthquake in Athens (solid circles). The solid line corresponds to the attenuation relation proposed in the present study. The dashed lines define the standard deviation interval.

Considering that, (in addition to the rich data set), the relation proposed by Kawashima and Aizawa [1989] was calculated using both shallow and intermediate depth earthquakes covering a more extended range of magnitudes and epicentral distances, one can conclude that the relation of the present study clearly improves the existing one for Greece.

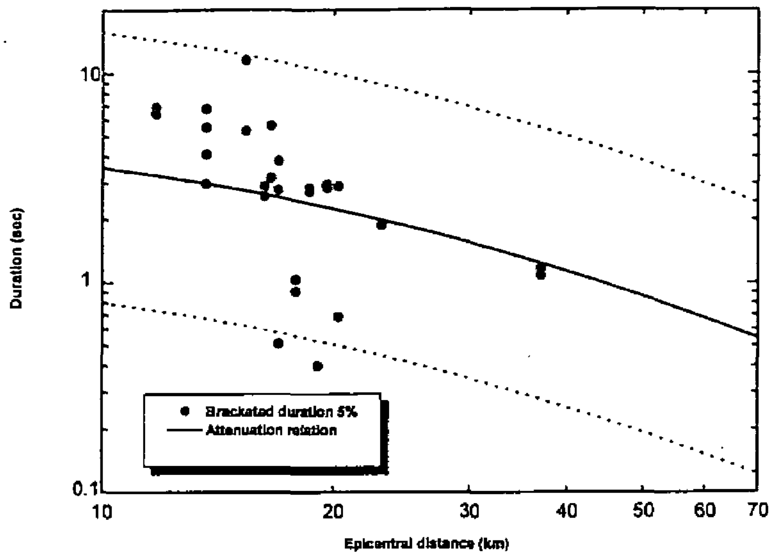

Fig. 8. Observed bracketed duration values for a level of 5%g from the 7/9/99 earthquake in Athens (solid circles). The solid line corresponds to the attenuation relation proposed in the present study. The dashed lines define the standard deviation interval.

The relation has been further tested by comparing its predictions with the corresponding results from the strong-motion records of the Athens earthquake of 7-9-1999 [Koliopoulos and Margaris, 2001]. These records were not included in the database used for the evaluation of the empirical relation and thus the comparison of the computed values of strong-motion duration of these recordings with the theoretical values predicted by the attenuation relation serves as a good test of the accuracy of the proposed relation. Figures 7 and 8 show the measured values of strong-motion duration for two different levels 3 and 5% of g along with the empirical theoretical attenuation curves ± one standard deviation. It is obvious that, given the statistical uncertainty, the proposed attenuation relation predicts the calculated values with acceptable accuracy.

4. Seismic Hazard Assessment for the Area of Greece

Using the new attenuation relation for strong-motion duration, a probabilistic seismic hazard analysis was performed in Greece [McGuire, 1976; Margaris and Papazachos, 1994]. The most recent model regarding geographical distribution of seismotectonic zones in Greece was used, as has been proposed by Papaioannou and Papazachos [2000]. In particular, 67 shallow and 7 intermediate seismic sources are used, which include seismicity information, maximum observed magnitudes and radiation coefficients. Regarding the distinction between shallow and intermediate depth seismic sources, the model implements the seismic hazard analysis adopting two characteristic depths namely 10 km and 80 km for shallow and intermediate seismic sources respectively. Moreover the above mentioned intermediate depth seismic sources are characterised by high seismic activity with magnitude between 6.2 and 7.8 [Papaioannou and Papazachos, 2000].

At first, calculations were made for the 136 different sites throughout Greece, which are included in the Greek Seismic Code, in order to examine the potential use of strong-motion duration in such an analysis. According to the Greek Seismic Code, the territory is divided in four different categories of seismic hazard (Fig. 1). The maximum expected values of bracketed duration were calculated for two different levels of acceleration, $L = 5\%g$ and $L = 10\%g$ and for eight different values of return period, 10, 25, 50, 80, 100, 200, 476 and 952 years. The results obtained for the aforementioned 136 sites were subsequently categorized according to the seismic hazard category in which they belong, according to the Seismic Code of Greece. Finally, the average values of the maximum expected bracketed durations were estimated for each category. These average values are plotted in Fig. 9 against the return periods. It can be seen that the four different curves corresponding to the four different categories of equal seismic hazard, are parallel to each other and follow the same shape starting from the first category, exhibiting the lowest seismic hazard category, up to the fourth category with the highest seismic hazard. The division into four different categories of seismic hazard of Greece as proposed by the Greek Seismic Code, has been made using the parameters of macroseismic intensity and peak ground acceleration. From the previous observation stems the conclusion

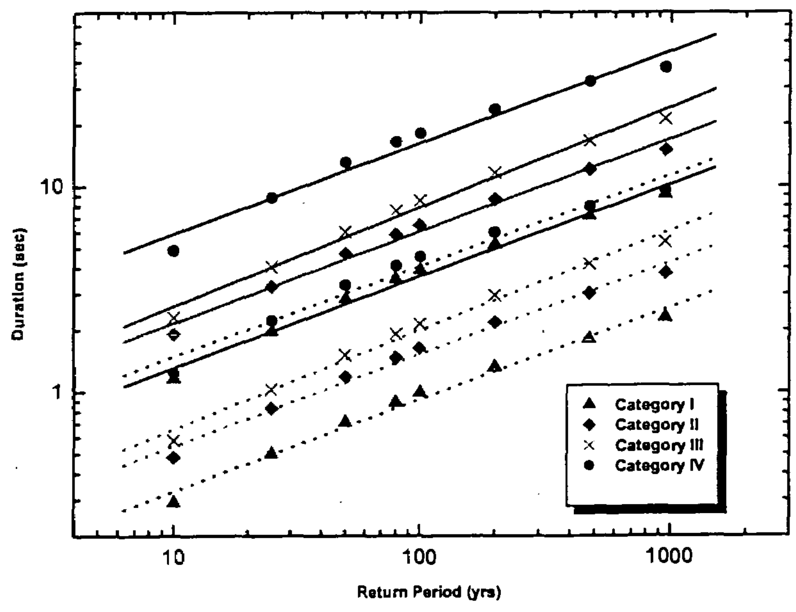

Fig. 9. Maximum expected values of bracketed duration for levels of $5\%g$ (continuous curves) and $10\%g$ (dashed curves), regarding the four categories of equal seismic hazard of the Greek Seismic Code.

that the same division also applies for the case of bracketed duration, which exhibits similar geographic distribution.

The next step was to estimate the seismic hazard of strong ground motion duration for a grid of points covering the entire Greek region. In this way, a new attempt to classify Greek territory into categories of equal seismic hazard was made, using the bracketed duration as the strong-motion parameter. The grid spacing was 0.2 degrees while the bracketed duration for the level of 10%g was used. The maximum expected values of bracketed duration were estimated for the eight values of return period, mentioned above. The level of 10% of g has been chosen because it was considered more appropriate for seismic design, since only strong earthquakes that exhibit high damage potential will contribute non-zero values for this particular level of measurement. In order to be able to check the results of the seismic hazard analysis of strong-motion duration, a similar analysis was performed for the peak ground acceleration using the attenuation relations proposed by Thedoulidis and Papazachos [1992; Eq. (8)], one for shallow and one for intermediate depth earthquakes. Both relations include a parameter describing the soil conditions at the recording site, unlike the attenuation relation of bracketed duration. For this reason, the estimation of seismic hazard of peak ground acceleration was performed assuming intermediate soil conditions at the recording sites. The results of these two analyses were used to divide Greece into four different categories of equal seismic hazard. The methodology used was the one proposed by Papazachos *et al.* [1985]. Specifically, a certain value of the strong-motion parameter is given as a criterion and the total number of maximum expected values of the strong-motion parameter for each point of the grid and for all values of return period is used in order to divide the area under consideration into categories of equal seismic hazard. The four categories derived in each case are shown in Figs. 10 and 11. A sample of seismic hazard results for different mean return periods including the most significant cities in Greece is presented in Fig. 12.

The conclusion from the inspection of the two maps in Figs. 10 and 11 is that the geographical distributions of the seismic hazard based on bracketed duration and peak ground acceleration follows roughly the same pattern. The main difference between the two appears at the area extending along the southern Aegean (Hellenic trench) where, in the case of bracketed duration, the second category covers a much larger area compared to the case of peak ground acceleration. The reason for this is that this area is governed by intermediate depth earthquakes that show an increased duration compared to the shallow ones. It should be noted that, although the proposed empirical predictions [Eq.(1)] are based (with only one exception) on shallow seismic events, nevertheless the focal depth is taken into account as an input to seismic hazard assessment [McGuire, 1976]. Another difference appears in the area of the northern Aegean trench (which consists the westward continuation of the northern Anatolian strike-slip fault). Again in the case of bracketed duration, the third category extends at a slightly larger area compared to the case of peak ground acceleration. This area is dominated by strong earthquakes ($M \geq 7.0$), and as a

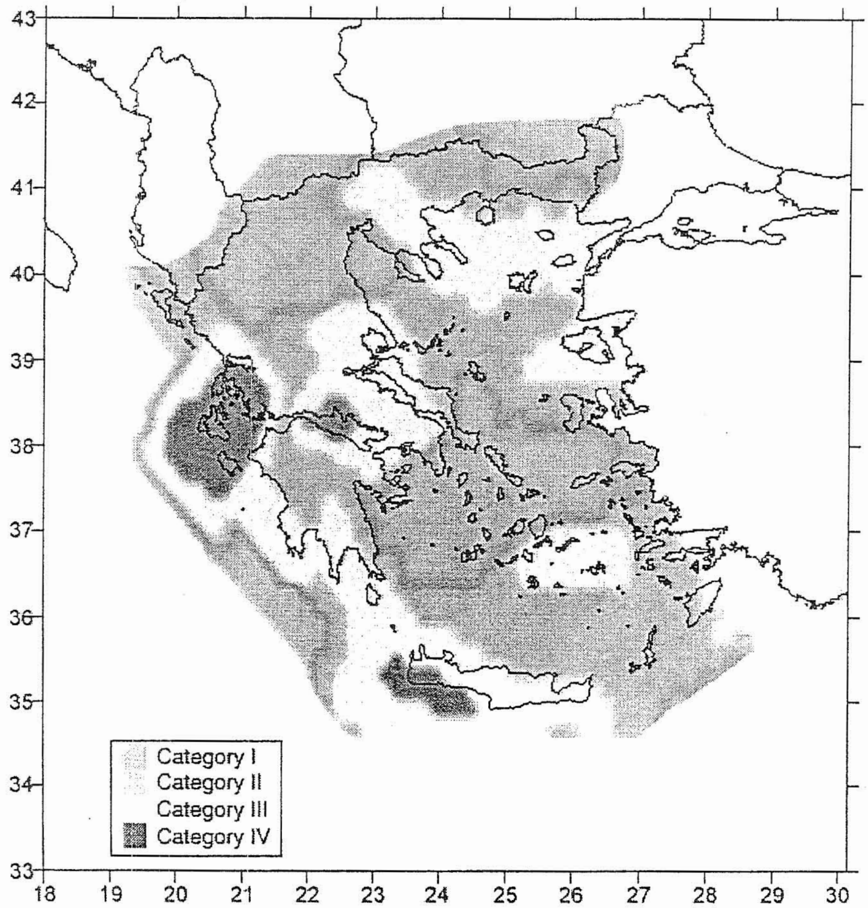

Fig. 10. The four categories of equal seismic hazard for Greece based on bracketed duration for a level of 10%g.

result, the expected values of strong-motion duration are significantly larger. These differences reveal that strong earthquakes contribute more to a duration-based seismic hazard assessment, compared to an acceleration-based hazard assessment. For example, an increase of magnitude from 5.5 to 6.5 for a design distance $R = 20$ km, causes 200% increase in terms of PGA (from 65 cm/s^2 to 200 cm/s^2), while in terms of 5%g Bracketed Duration causes 670% (from 1 s to 7.7 s). It should be mentioned that a similar conclusion is derived from a comparison between elastic input energy-based and elastic response spectra-based seismic hazard assessments, [Chapman, 1999].

In the next step, an attempt was made to combine the two previous maps into a single one. For this reason, an empirical relation was derived to associate the bracketed duration for the level of 10%g with the peak ground acceleration. Implementing this relation, the calculated values of bracketed duration can be transformed

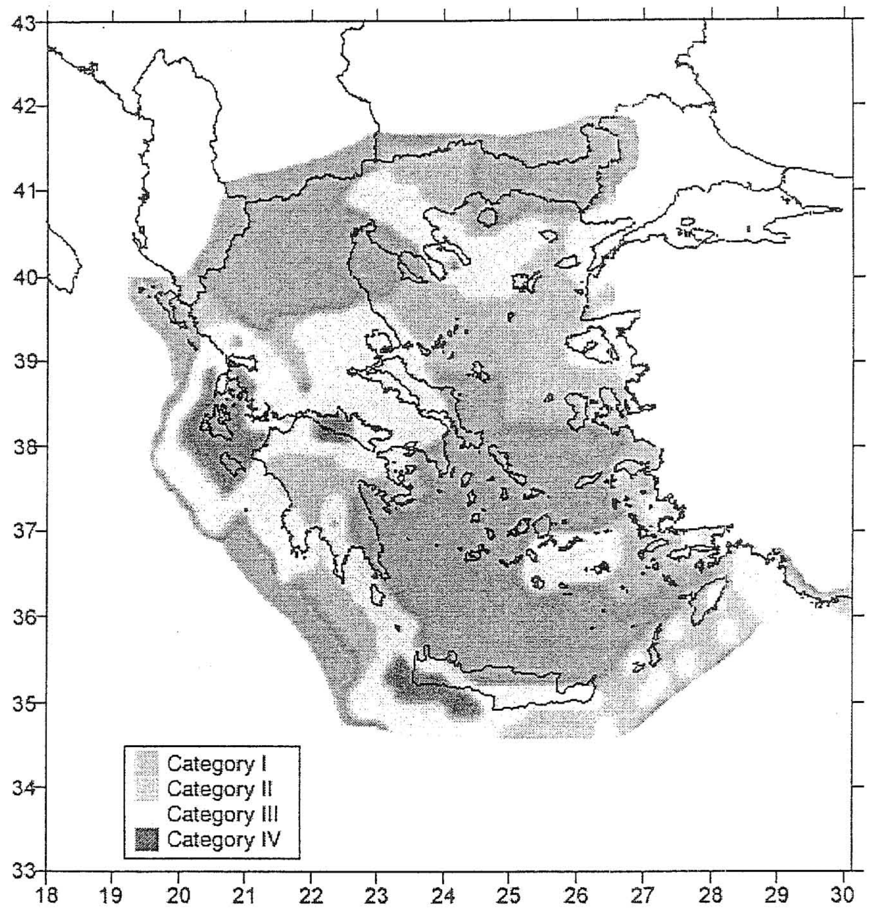

Fig. 11. The four categories of equal seismic hazard for Greece based on peak ground acceleration.

to values of peak ground acceleration. The combined map will then result from the average values of peak ground acceleration. The resulting relation reads:

$$\ln D_{10} = -7.45 + 1.41 \ln a_m \tag{4}$$

where D_{10}, stands for the bracketed duration for the level of $10\%g$ and a_m is the peak ground acceleration. The corresponding standard deviation is equal to $\sigma = 1.35$. Because the total number of observed values of bracketed duration for the level of $10\%g$ was not sufficiently large, values of bracketed duration for lower levels of acceleration, scaled to the level of 10% of g, were also used. The scaling of bracketed duration of lower threshold levels to the duration of level of 10% of g was done by using the theoretical attenuation relation. The values of bracketed duration, D_1 and D_2, for two different levels of bracketed duration, L_1 and L_2, for the same record (i.e. keeping the same values of magnitude, M and epicentral

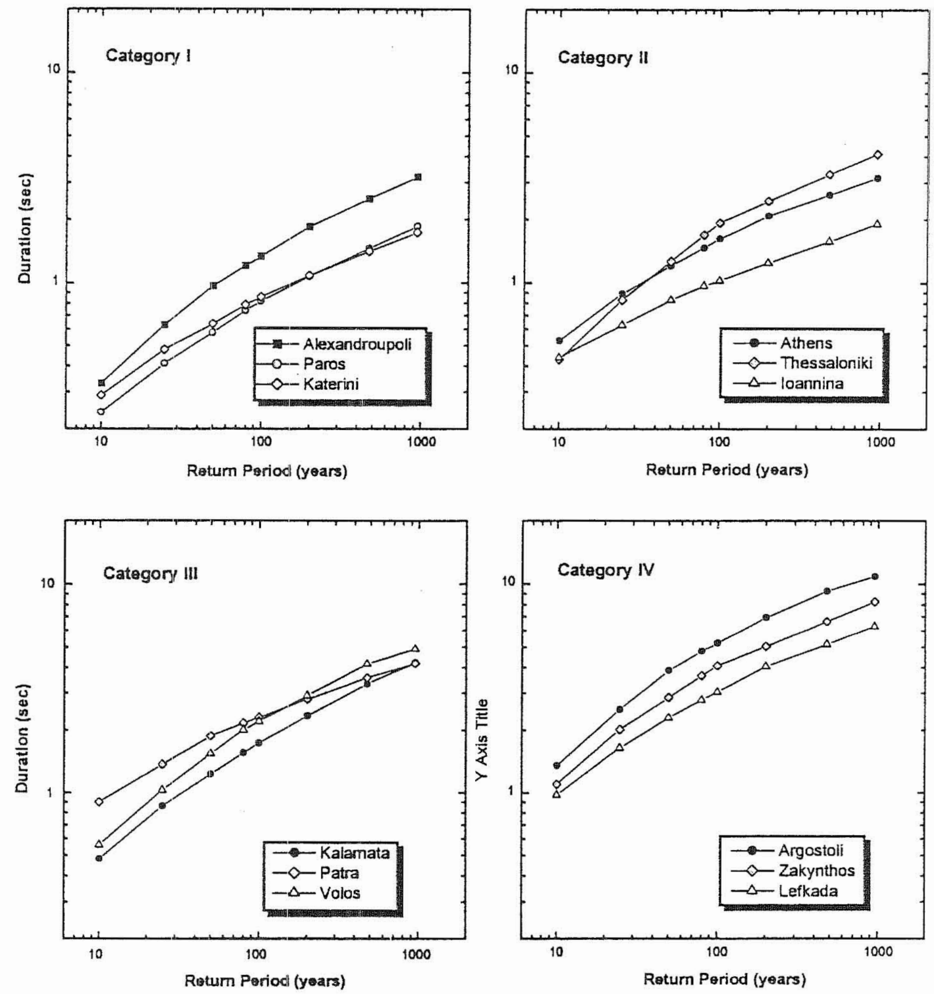

Fig. 12. Seismic hazard results for different mean return periods including the most significant cities in Greece.

distance, R) according to the attenuation relations are:

$$\ln D_1 = -1.88 + 2.05M - 2.05\ \ln(R + 30) - 27.75L_1$$

$$\ln D_2 = -1.88 + 2.05M - 2.05\ \ln(R + 30) - 27.75L_2\,.$$

Performing the necessary algebra, the following relation is derived:

$$D_2 = D_1 e^{27.75(L_1 - L_2)}\,. \tag{5}$$

Using the above equation for the records that exhibited zero values of bracketed duration for the level of 10% of g, all non-zero values of duration corresponding to lower threshold levels were scaled to the level of 10% of g and the average of these scaled values was used for the calculation of the Eq. (4). The aforementioned

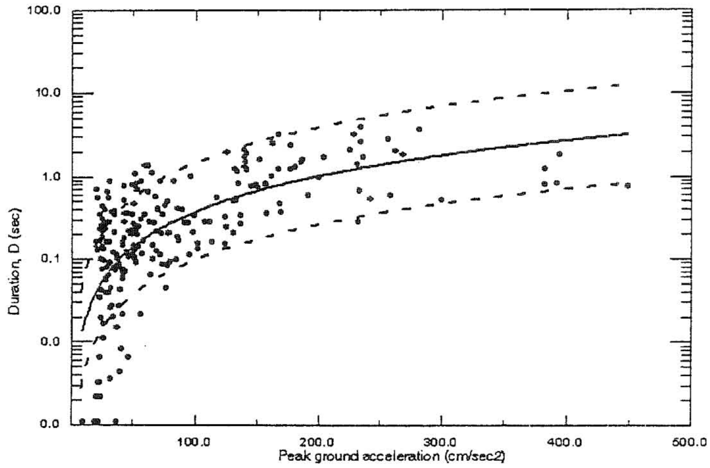

Fig. 13. Relation between bracketed duration for a level of 10%g and peak ground acceleration.

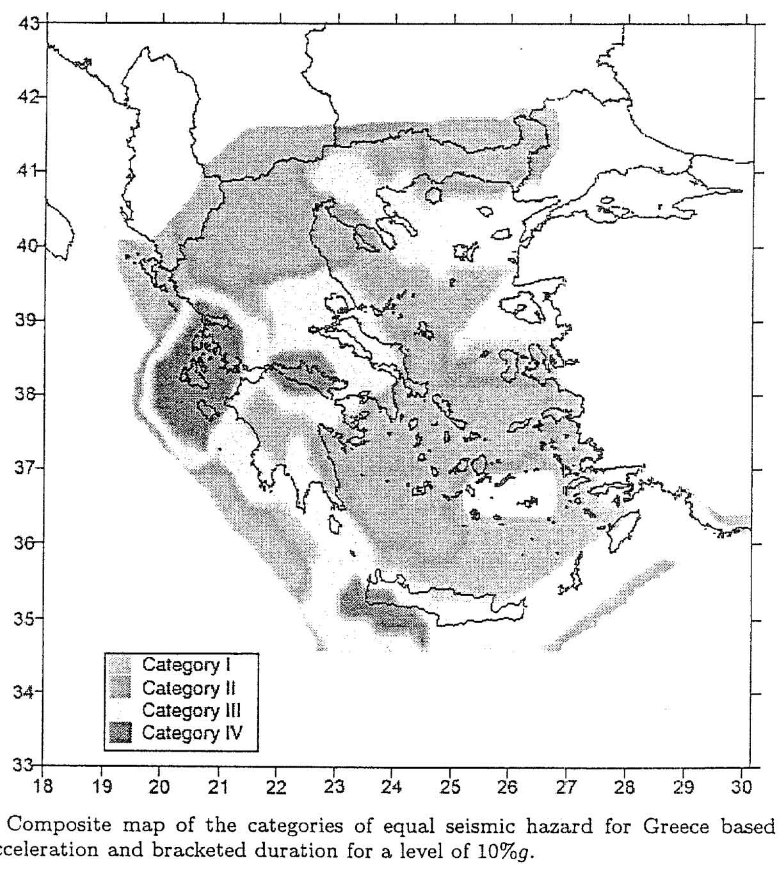

Fig. 14. Composite map of the categories of equal seismic hazard for Greece based on peak ground acceleration and bracketed duration for a level of 10%g.

relation is plotted with the observed values in Fig. 13. The data show a large scatter, reflected in the computed high value of standard deviation in Eq. (4).

By implementation of the above relation, the calculated average maximum expected values of strong-motion duration were transformed to peak ground acceleration values. The average values between the actual and the scaled were finally used in order to divide Greece into categories of equal seismic hazard using the same methodology mentioned at the previous stage. The results shown in the map of Fig. 14 consist the final proposal for classifying Greece into areas of equal seismic hazard. This proposal may prove useful in future attempts of improving the current Greek Seismic Code. In Figs. 15 and 16, the mean maximum expected values ($\pm$ standard deviation) of bracketed duration and peak ground acceleration are plotted versus the respective return periods. The mean values were computed from 2052 examined sites in Greece after their classification into the four seismic categories.

Comparing the map of Fig. 14 with the map that constitutes part of the current Greek Seismic Code (Fig. 1), it can be seen that the distribution of the two lowest seismic hazard categories is roughly the same. The major differences appear in the geographical distribution of the two higher seismic hazard categories. The fourth category, which exhibits the highest seismic hazard, in Fig. 14 covers a more extended area compared to the map of the current Seismic Code and also appears in two other parts of Greece (southeastern Crete and the area near Patras). Also the third category covers a larger area in Fig. 14 since it covers the largest part of the Hellenic arc (it appears in north Greece at the area of the North Aegean trough,

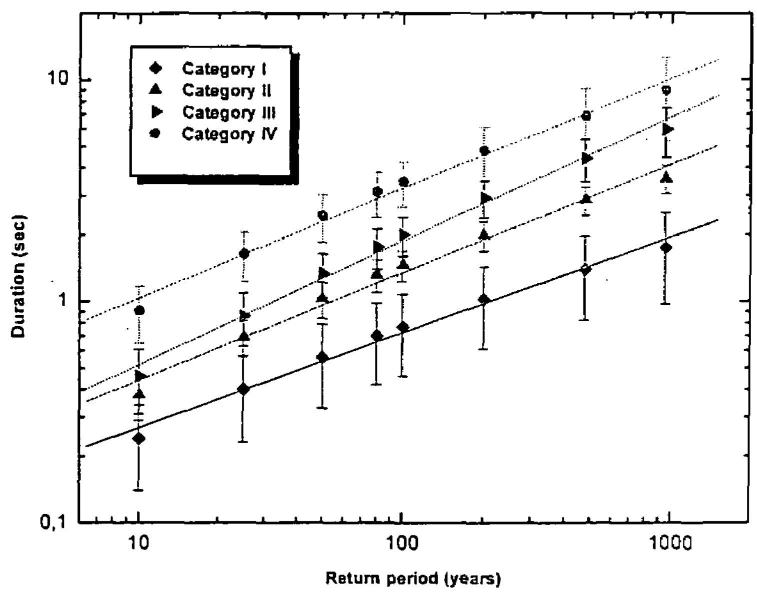

Fig. 15. Maximum expected values of bracketed duration for a level of 10%g, vs. return period, for the categories of Fig. 14.

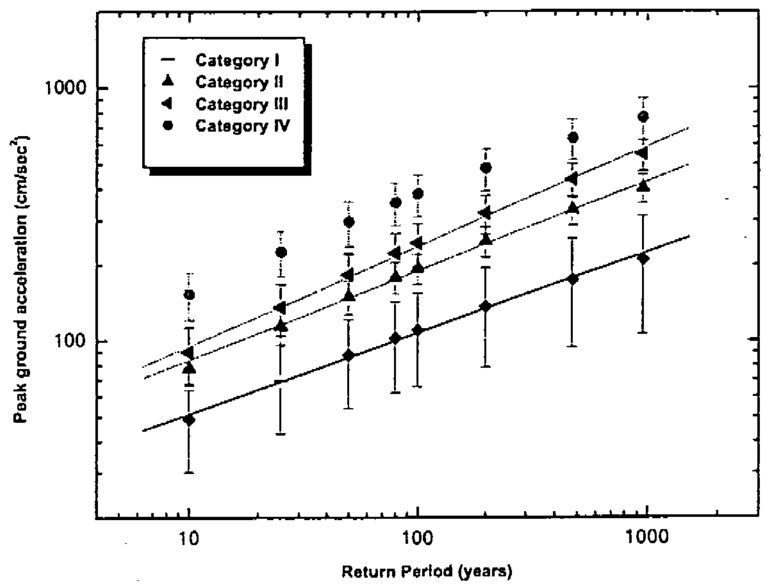

Fig. 16. Maximum expected values of peak ground acceleration vs. return period, for the categories of Fig. 14.

in Southern Aegean at the area of intermediate depth earthquakes and in most of central Greece).

5. Conclusions

In the preceding sections the duration of strong-motion in Greece was studied along with its potential use as a parameter for seismic hazard analysis in Greece. From the results of these analyses, the following conclusions can be deduced:

The correlation of the measured duration values with both magnitude and epicentral distance is not very strong. In general, duration shows a significant scatter, a fact that was also mentioned in previous studies [McGuire and Barnhard, 1979; Kawashima and Aizawa, 1989] and seems to be a characteristic of the selected measure of duration. However, as it can be seen from Fig. 3, bracketed duration in general increases with the increase of earthquake magnitude and the decrease of epicentral distance. Based on available strong-motion data in Greece, an empirical prediction for bracketed duration is proposed with a validity range in terms of magnitude between 4.5 and 6.9 and in terms of distances between 1 and 128 km.

No significant relation between bracketed duration and soil conditions was found and thus no parameter describing soil conditions was included in the proposed attenuation relation. This does not necessarily mean that the measured values of bracketed duration are independent of soil conditions, but that a simple definition like the one used herein may not adequately describe them. A more comprehensive definition of soil conditions should be adopted in future works, which will take into account the depth of the overlying layer of sediments and/or the shear wave velocity.

The results from seismic hazard assessment based on strong-motion duration, are consistent with the results derived from similar analysis based on peak ground acceleration. However, the seismic hazard maps that resulted in both cases show small, yet significant, differences from the corresponding that constitutes part of the Greek Seismic Code. Notably, these differences concern the areas in which the higher seismic hazard categories extend. These categories appear now to cover larger areas than assumed before and these differences are a consequence of two factors. The differences between the ground acceleration hazard maps are mainly due to the new improved seismotectonic model adopted here. Yet, the differences between duration-based seismic hazard and acceleration-based hazard assessment, both using the same seismotectonic model, are due to the fact that strong earthquakes contribute more to a duration-based hazard assessment.

It is one of the aims of an ongoing work between Greece and Italy to confirm our findings regarding the role of a duration-based hazard assessment. It is hoped that the implementation of the proposed methodology will lead to the improvement of current Seismic Codes.

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