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An estimate of probabilistic seismic hazard for five cities in Greece by using the parametric-historic procedure

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Abstract

A probabilistic procedure was applied to assess seismic hazard for the sites of five Greek cities (Athens, Heraklion, Patras, Thessaloniki and Volos) using peak ground acceleration as the hazard parameter. The methodology allows the use of either historical or instrumental data, or a combination of both. It has been developed specifically for the estimation of seismic hazard at a given site and does not require any specification of seismic sources or/and seismic zones. A new relation for the attenuation of peak ground acceleration was employed for the shallow seismicity in Greece. The computations involved the area- and site-specific parts. When assessing magnitude recurrence for the areas surrounding the five cities, the maximum magnitude, $m_{\max}$, was estimated using a recently derived equation. The site-specific results were expressed as probabilities that a given peak ground acceleration value will be exceeded at least once during a time interval of 1, 50 and 100 years at the sites of the cities. They were based on the maximum peak ground acceleration values computed by assuming the occurrence of the strongest possible earthquake (of magnitude $m_{\max}$) at a very short distance from the site and using the mean value obtained with the help of the attenuation law. This gave 0.24 g for Athens, 0.53 g for Heraklion (shallow) and 0.39 g Heraklion (intermediate-depth seismicity), 0.30 g for Patras, 0.35 g for Thessaloniki and 0.30 g for Volos. In addition, the probabilities of exceedance of the estimated maximum peak ground acceleration values were calculated for the sites. The standard deviation of the new Greek attenuation law demonstrates the uncertainty and large variation of predicted peak ground acceleration values.

Keywords: Probabilistic seismic hazard assessment; Seismicity of Greece; Peak ground acceleration; Attenuation law

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1. Introduction

Seismic hazard assessment involves the computation of long-term probabilities for the occurrence of earthquakes of a specified size in a given area during a given time interval and is a prerequisite for seismic risk reduction and urban planning. Greece is located in a very seismogenic region; when estimating and comparing seismic hazard for fifty of the most seis-

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mically active countries of the world, Tsapanos and Burton (1991) ranked Greece in the sixth position with Japan in the first. In cities such as the Greek capital, Athens, the level of seismic risk is high due to a large population, the relatively high vulnerability of structures and the large economic value exposed to earthquake activity (Papadopoulos and Arvanitides, 1996). The seismic hazard in Greece has therefore been widely studied using a number of different techniques and seismic quantities. Site-specific hazard analyses have been conducted among others by Papazachos et al. (1995), who investigated seismic hazard in the city of Heraklion in the Island of Crete. Papoulia and Slejko (1997) estimated seismic hazard for the towns of Argostoli, Leukas and Corfu in the Ionian Islands, Western Greece, using local macroseismic intensities. Papaioannou and Papazachos (2000) assessed both time-independent and time-dependent seismic hazard for 144 broad sites (cities, towns, villages) of Greece in terms of expected intensities at each of these sites, and Lyubushin et al. (2002) estimated seismic hazard in terms of maximum values of peak ground acceleration (PGA) for six sites (Griva, Konitsa, Kozani, Aeghio, Killini and Kalamata) using a Bayesian procedure. Tsapanos et al. (2003) estimated the levels of seismic hazard at the sites of seven Greek cities in terms of probabilities that a given PGA will be exceeded at least once during a time interval of one, 50 and 100 years at those sites by using the parametric-historic procedure developed by Kijko and Graham (1998, 1999).

This study focuses on the cities of Athens, Heraklion, Patras, Thessaloniki and Volos and their surrounding areas, the most densely populated and industrialised in Greece. All of them have suffered from the consequences of moderate-to-strong magnitude earthquakes. In spite of the long written history of the country, the earthquake of 7 September 1999 that hit the metropolitan area of Athens was somewhat surprising as it originated in an unidentified seismogenic structure between other known faults of large or medium size (Papadopoulos et al., 2000). Although the 1999 event was only of magnitude $M_s = 5.9$, it was the first earthquake known to have claimed casualties within the city of Athens and the most costly natural disaster in the modern history of Greece.

The city of Heraklion in Crete is situated in the Hellenic trench-arc system and has experienced damage following both shallow and intermediate-depth earthquakes. The event on 21 July 365 had an estimated magnitude of $M_w = 8.3$, which is the largest in the seismological record of Greece, and occurred in the vicinity of Crete (Papazachos and Papazachou, 1997), where the number of towns destroyed exceeded 100 (Guidoboni et al., 1994). The worst effects of the earthquake of 8 August 1303, one of the largest seismic events in the Mediterranean area, were felt in Crete, where the maximum macroseismic intensity has been estimated at $I_{max} = \text{XI}$ on the MCS scale (Guidoboni and Comastri, 1997). Heraklion was badly devastated by this earthquake and the related tsunami. The earthquake on 29 May 1508 is another strong shock known to have affected Heraklion (Ambraseys et al., 1994). Other destructive historical earthquakes there include the events of 1 July 1494 (intensity in Heraklion assessed at $I = \text{VIII}$ MM), 16 February 1810 ($I = \text{IX}$) and 12 October 1856 ($I = \text{IX}$). During modern times, Heraklion was damaged by among others the 23 May 1994 earthquake of magnitude $M_w = 6.1$ and focal depth of $h = 80$ km. The assigned intensity in the city was $I = \text{VII}$ on the MM scale (Papazachos and Papazachou, 1997).

The city of Patras in Central Greece is surrounded by some of the most seismically active seismogenic structures in the country. Earthquakes of assigned intensities of $I = \text{VIII}$ MM or greater in Patras occurred for example on 27 July 1714, 30 January 1785 and 23 January 1804 (Papazachos and Papazachou, 1997). Although of only moderate magnitude ($M_s = 5.4$), the earthquake of 14 July 1993 in Patras caused notable property damage (Karakostas et al., 1994). The city of Thessaloniki in Northern Greece experienced the consequences of a large shallow earthquake at an epicentral distance of 30 km on 20 June 1978 (Soufleris and Stewart, 1981; King et al., 1981; Papazachos et al., 1982). The societal and economic impact of this earthquake in the city was considerable (Karakos et al., 1983). The main shock belonged to a sequence of earthquakes lasting for several months; the available seismicity observations indicate similar occurrences in the past (Papazachos et al., 1979). The sequence of 1759 included a magnitude 6.5 shock in the vicinity of Thessaloniki, where its effects were estimated at $I = \text{IX}$ on the MM scale (Papazachos and Papazachou, 1997). Other seismic episodes of a similar type occurred in 1902 and 1932. The earthquake sequence of summer 1980 in the Magnesia region of Central Greece was of concern to the city of Volos because the main shock of magnitude $M_s = 6.5$ occurred in its vicinity (Papazachos et al., 1983). Some nearby villages suffered the heaviest damage.

The purpose of the present study was to assess the level of seismic hazard for the Greek cities of Athens, Heraklion, Patras, Thessaloniki and Volos using PGA as the hazard parameter. The methodology for probabilistic seismic hazard assessment (PSHA) developed by Kijko and Graham (1998, 1999) was applied. This technique has especially been developed for PSHA at a specified site. It does not rely on the definition of seismic sources or/and seismic zones, which may involve subjective judgement. Either incomplete historical or complete instrumental earthquake catalogues, or a combination of both, can be used as input data. As the first part of computa-

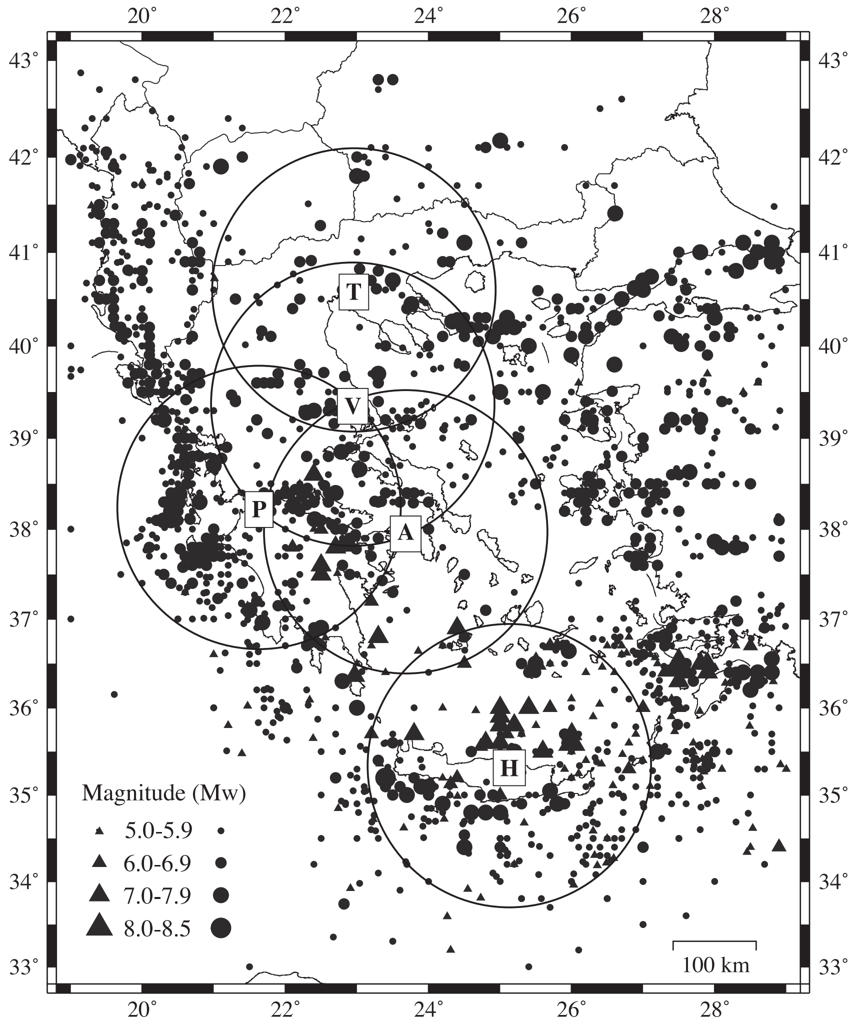

Fig. 1. An epicentre map of shallow (circles) and intermediate-depth (triangles) main shocks of magnitude $M_w = 5$ or greater for the territory of Greece and its vicinity between 550 B.C. and 1999. The data were taken from the data bank of the Geophysical Laboratory of the Aristotle University of Thessaloniki. The earthquake size is given on a scale equivalent to the moment magnitude. Letters mark the location of Athens, Heraklion, Patras, Thessaloniki and Volos. The circles show areas taken for a radius of 180 km from each city.

tions, the maximum magnitude, $m_{\max}$, was estimated for the broad areas surrounding the cities using a formula recently derived by Kijko and Graham (1998), and the magnitude recurrence in these areas was assessed following the approach described in Kijko and Sellevoll (1989, 1992). When computing the site-specific part, the new relation for the attenuation of PGA was employed for the shallow earthquakes in Greece (Margaris et al., 2001). The site-specific results were expressed as probabilities that a given PGA value will be exceeded at least once during time intervals of one, 50 and 100 years at the sites of interest. The maximum values of PGA were estimated by assuming the occurrence of the strongest possible earthquake (of magnitude $m_{\max}$) at a very short distance from the site and using the mean value of the maximum PGA obtained with the help of the attenuation law. In addition, the complementary probabilities of exceedance of the expected maximum PGA values were calculated.

2. Earthquake data

The earthquake data were taken from the data bank of the Geophysical Laboratory of the University of Thessaloniki (Papazachos et al., 2000). Abundant information of Greek earthquakes is available in this data bank, starting in 550 B.C. and comprising both shallow ($h \leq 60$ km) and intermediate-depth ($60 < h \leq 180$ km) events. The earthquake size is given on a scale equivalent to the moment magnitude (Papazachos et al., 1997). Fig. 1 is an epicentre map of the earthquake data for Greece and its vicinity. For the purpose of the present study, foreshocks, aftershocks and earthquake swarms were removed from the initial data using a relationship derived by Papazachos and Papazachou (1997), in which the duration of the aftershock sequence depends on the magnitude of the main shock.

The whole catalogue of shallow earthquakes for the area between latitudes 33.0 – 43.0°N and longi-

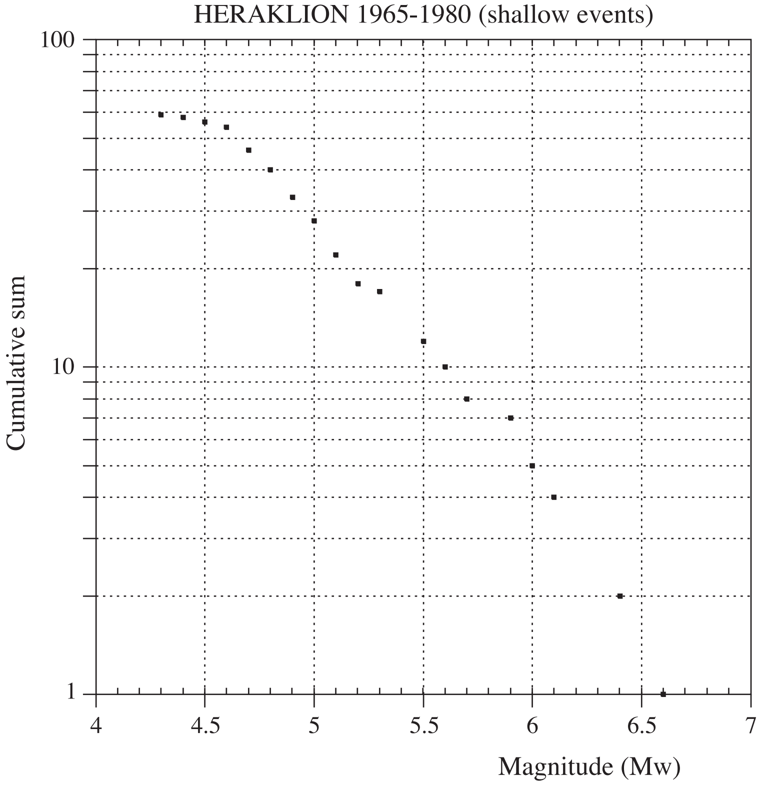

Fig. 2. A plot showing the cumulative sum vs. magnitude for an earthquake sample from 1965 to 1980 for the area surrounding Heraklion.

tudes 19.0 – 29.0°E is considered complete for the following time periods: after 550 B.C. for $M \geq 8.0$, after 1501 for $M \geq 7.3$, after 1845 for $M \geq 6.0$, after 1911 for $M \geq 5.0$, after 1950 for $M \geq 4.5$, after 1964 for $M \geq 4.3$ and after 1981 for $M \geq 4.0$ (Papazachos et al., 2000). In the historical data between 550 B.C. and 1910 the uncertainty of magnitude is assessed at ± 0.35 magnitude units if the number of available macroseismic observations is ten or above. The errors in the data recorded instrumentally since 1911 are in the interval of ± 0.25 magnitude units (Papazachos and Papazachou, 1997).

For the cities of Athens, Heraklion, Patras, Thessaloniki and Volos the earthquake data were taken for a radius of 180 km from their centres. In case of Heraklion, both shallow and intermediate-depth earthquakes, that is two different groups of events, were taken into consideration, because this city is known to have been damaged also by intermediate-depth earthquakes. Only shallow earthquakes were considered for the other four cities. The above error estimates were used as guidelines when determining magnitude uncertainties during different time periods and dividing the instrumental catalogues into subcatalogues each one having a minimum threshold of magnitude. The thresholds of completeness were also verified: Fig. 2 gives an example in which the sample of the shallow earthquakes around Heraklion between 1965 and 1980 is plotted as a cumulative sum of events vs. magnitude. Assuming the linearity of the magnitude–frequency relationship, the plot implies that the threshold of completeness is around magnitude 4.6, higher than the above guideline found in literature for the whole catalogue. The numbers of earthquakes used in the calculations for each area can be found in Table 1.

Table 1
The estimated parameters b, area-specific activity parameter λ_A for magnitude value 4.5 and above, maximum magnitude $\hat{m}_{max}$ and the maximum magnitudes observed in the areas during the time span of available earthquake data

City	b	λ_A (for $M \geq 4.5$)	$\hat{m}_{max}$	m_{max}	n_e
Athens	0.93 ± 0.02	1.56	7.23 ± 0.30	7.20	227
Heraklion (I)	0.96 ± 0.02	2.81	8.37 ± 0.31	8.30	261
Heraklion (II)	1.02 ± 0.03	3.22	8.25 ± 0.30	8.20	169
Patras	0.82 ± 0.02	2.10	7.51 ± 0.30	7.50	329
Thessaloniki	0.94 ± 0.02	1.28	7.74 ± 0.30	7.70	188
Volos	0.92 ± 0.02	1.78	7.51 ± 0.30	7.50	279

Heraklion (I) refers to shallow and Heraklion (II) to intermediate-depth events. The number of earthquakes, n_e, is the total number of events used in the area-specific calculations.

3. Theoretical considerations

The parametric-historic procedure developed by Kijko and Graham (1998, 1999) was applied in the present study to quantify the level of seismic hazard at the given sites. This methodology for PSHA has been classified as parametric-historic because it combines several components of the deductive (Cornell, 1968) and historical (Veneziano et al., 1984) procedures, which constitute two main categories of PSHA methods (McGuire, 1993).

From a computational point of view, the parametric-historic method involves the area-specific and site-specific parts. Firstly, in the area-specific computations, three parameters, namely the maximum magnitude, m_{max}, mean seismic activity rate, λ_A, and the b-value of the Gutenberg–Richter magnitude–frequency relation (or $\beta = b\ln 10$), are calculated for an area surrounding the site for which seismic hazard analysis is needed. The three parameters are determined simultaneously using an iterative scheme. When estimating λ_A and β two assumptions are made: the occurrence of earthquakes follows the Poisson distribution with activity rate λ_A and the doubly truncated Gutenberg–Richter relationship with parameter β. The maximum likelihood method is employed to estimate these parameters.

The maximum magnitude, m_{max}, can be evaluated by following a very general procedure which is capable of generating solutions in different forms, depending on the assumptions about the statistical distribution and/or the information available about past seismicity. The procedure can be applied also in the case when no information about the nature of the distribution of earthquake magnitude is available. In other words, the procedure is capable of generating an equation for m_{max}, which is independent of the particular frequency–magnitude distribution assumed. The procedure can also be used when the earthquake catalogue is incomplete, i.e. when only a limited number of the largest magnitudes are available (Kijko, 2002).

In the present study, the maximum magnitude, $m_{\max}$, was estimated for the areas of interest by using the Bayesian extension of the earlier formula (Kijko and Sellevoll, 1989, 1992), which was based on the assumption that earthquake magnitudes are distributed according to the classical Gutenberg–Richter relationship bound from above by the maximum regional magnitude $m_{\max}$ (Cosentino et al., 1977). More information on the applied procedure can be found in the original work by Kijko and Graham (1998) and Kijko (2002).

The second part of the parametric-historic procedure, the site-specific computations, require a knowledge of the attenuation of the selected ground-motion parameter, a, as a function of distance. In this work, the new attenuation law of PGA for shallow earthquakes in Greece, recently derived by Margaris et al. (2001), was employed. It can be written as

$$\ln(a) = c_0 + c_1 \cdot M_w + c_2 \cdot \ln(R^2 + h_0^2)^{1/2} + c_3 \cdot S \pm c_4, \tag{1}$$

where R is the epicentral distance (in km), $h_0 = 7$ km and the values of coefficients are $c_0 = 3.52$, $c_1 = 0.70$, $c_2 = -1.14$ and $c_3 = 0.12$, and the standard deviation of $\ln(a)$ is $c_4 = 0.70$, while S describes soil classification by assuming values 0, 1 or 2 corresponding to hard (rock), intermediate and soft (alluvium) conditions, respectively. The attenuation law of Eq. (1) provides acceleration values in units of cm/s^2. The standard deviation of the normal distribution of $\ln(a)$ was disregarded in computations, so that the PGA values obtained with the help of this law and reported in the next section were the mean values.

Intermediate-depth earthquakes occur along the Hellenic trench-arc system. Because Heraklion has suffered damage following these earthquakes, computations were performed also for this group of events within the same area. The attenuation relationship given by Papazachos et al. (1995) was used for intermediate-depth events. It takes the form

$$\ln(a) = c_0 + c_1 \cdot M_w + c_2 \cdot \ln(D + 30) + c_3 \cdot S, \tag{2}$$

where D is the epicentral distance (in km) and the coefficients are $c_0 = -1.08$, $c_1 = 1.34$, $c_2 = -1.15$ and $c_3 = 0.04$. Parameter S describes soil classification but takes values 1 (corresponding to rock), 0.5 (intermediate soil conditions) or 0 (alluvium).

The approach based on the concept of the "design" or "floating" earthquake (Krinitzsky et al., 1993) was used to derive the maximum PGA at the examined sites. This approach can be seen as a special case of the technique known as "scenario" earthquakes (Ishikawa and Kameda, 1993). The purpose of specifying such a "scenario" earthquake is to avoid surprises such as very high PGA values at the site originating from faults that have not been mapped. According to this procedure, $a_{\max}$ is the maximum value of PGA computed using the attenuation law and assuming the occurrence of the strongest possible earthquake (of magnitude $m_{\max}$) at a very short distance, say 10–25 km from the site. In this study, an arbitrary distance of 15 km was selected but, at the same time, a rigorous sensitivity analysis of the selected parameters was performed (see Eq. (3)).

Tinti and Mulargia (1985) suggested that any observed earthquake magnitude M is distorted with a normally distributed error that has a zero mean and standard deviation σ_M. The same assumption is made concerning the error in the determination of the epicentral distance R when the standard deviation of R is σ_R and $h_0 = 7$ km. For an earthquake of an observed magnitude M, located at a distance R, the value of the ln(PGA) is approximately normally distributed (Benjamin and Cornell, 1970) with the mean given by the RMS of Eq. (1) and the standard deviation similar to the one derived by Kijko and Graham (1999), that is

$$\sigma_{\mathrm{TOTAL}} = \sqrt{\sigma^2_{\ln(\mathrm{PGA})} + c_2^2 \sigma_M^2 + \sigma_R^2 \left(\frac{R}{R^2 + h_0^2} \right)^2}. \tag{3}$$

Following the applied formalism, the seismic hazard at the site of interest can be described by three parameters: $a_{\max}$, which is the maximum PGA at the site, parameter $\gamma = \beta / c_2$ and site-specific, mean activity rate λ_S. The coefficient c_2 is related to the PGA attenuation formula (1) and λ_S refers to the activity rate of earthquakes that cause a PGA value a at the site exceeding some threshold value $a_{\min}$ of engineering interest. It is assumed that the occurrence of earthquakes producing PGA a, where $a \geq a_{\min}$, at the site, follows the Poisson distribution with a mean activity rate λ_S.

To express seismic hazard in terms of PGA, the aim would be to calculate the conditional probability that an earthquake, of random magnitude occurring at a random distance from the site, will cause a PGA value equal to, or greater than, the chosen threshold value of $a_{\min}$ at the site. If the random earthquake magnitude, m, is in the range of $m_{\min} \leq m \leq m_{\max}$, where $m_{\min}$ is the minimum earthquake magnitude resulting in the exceedance of PGA value $a_{\min}$, it can be shown (Kijko and Graham, 1999) that the cumulative distribution function (CDF) of the logarithm of PGA at a given site takes the form

$$F_X(x) \ = \frac{\exp(-\gamma x_{\min}) - \exp(-\gamma x)}{\exp(-\gamma x_{\min})\exp(-\gamma x_{\max})}, \qquad (4)$$

where $x_{\min} = \ln(a_{\min})$, $x_{\max} = \ln(a_{\max})$ and $a_{\max}$ is the maximum PGA at the site. It should be noted that this CDF may have a different form if the attenuation relation has a functional form different from that in Eq. (1).

From an engineering point of view, the maximum PGA expected at a given site during a given time interval, t, is of special interest. The CDF of the logarithm of the largest PGA value, $x_{\max}$, observed at the site during time interval t, can be written as

$$F_X^{\max}(x \mid t) = \frac{\exp\{-\lambda_S t[1 - F_X(x)]\} - \exp(-\lambda_S t)}{1 - \exp(-\lambda_S t)}. \qquad (5)$$

Eq. (5) is doubly truncated: from below, $x_{\min} = \ln(a_{\min})$, and from above, $x_{\max} = \ln(a_{\max})$. The earthquakes that cause a PGA value a, where $a \geq a_{\min}$ at the site, are expected to follow the Poisson process with mean activity rate $\lambda_S(x) = \lambda_S[1 - F_x(x)]$, with $x = \ln(a)$.

The maximum likelihood method is used to estimate the site-characteristic seismic hazard parameters. If the observations are $a_1, \ldots, a_n$, that is the largest PGA values of n successive time intervals $t_1, \ldots, t_n$ recorded at the site, the likelihood function of the sample $x_1, \ldots, x_n$, where $x_i = \ln(a_i)$ and $i = 1, \ldots, n$, for a specified value $a_{\max}$ can be written as

$$L(\lambda_S, \gamma) = \prod_{i=1}^{n} f_X^{\max}(x_i \mid t_i), \qquad (6)$$

where $f_X^{\max}$ $(x_i|t_i)$ is the probability density function of the logarithm of the largest PGA value observed at a given site during a given time interval t. For a given value of $x_{\max}$ (or equivalently, the maximum PGA at the site), maximization of the likelihood function (6) leads to determination of the parameters λ_S and γ. The computations make use of the whole earthquake catalogue available, including both historical and instrumental observations. More details of the procedure can be found in Kijko and Graham (1999).

It should be noted that the above procedure for the estimation of unknown hazard parameters is used only when the b-value of the Gutenberg–Richter frequency–magnitude relationship is not known. In the case when the b-value is known, parameter γ is calculated as β/c_2 and the maximum likelihood search (Eq. (6)) reduces to the estimation of the site-specific mean seismic activity rate λ_S.

4. Results and discussion

4.1. Area-specific PSHA for areas surrounding the five cities

Tables 1–3 and Fig. 3 contain the main results for the area-specific part of seismic hazard assessment. Table 1 gives the computed parameter values and Table 2 the computed numbers of expected exceedances of the largest magnitudes in the areas adjacent to Athens, Heraklion, Patras, Thessaloniki and Volos during 50 and 100 years. Fig. 3 shows the mean return periods and probabilities of exceedance of the given magnitudes during 1 year for the earthquakes in the areas surrounding the five cities.

Table 1 shows the estimated b parameters, area-specific activity parameters, λ_A, for magnitude value 4.5 and above, estimated values of maximum magnitude $\hat{m}_{\max}$ and the maximum magnitudes observed in the areas during the time span of available earthquake data.

Table 2
The expected number of exceedances of the given magnitudes during 50 and 100 years in the broad areas surrounding the five cities

(Mw)	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Athens (50)	26–27	9–10	2–3	0–1	0–1	–	–
(100)	53–54	18–19	5–6	1–2	0–1	–	–
HeraklionI (50)	46–47	15–16	5–6	1–2	0–1	0–1	≈ 0
(100)	92–93	30–31	10–11	3–4	1–2	0–1	≈ 0
HeraklionII (50)	49–50	15–16	4–5	1–2	0–1	0–1	≈ 0
(100)	99–100	30–31	9–10	2–3	0–1	0–1	≈ 0
Patras (50)	40–41	15–16	5–6	2–3	0–1	0	–
(100)	81–82	31–32	11–12	4–5	1–2	0	–
Thessaloniki (50)	21–22	7–8	2–3	0–1	0–1	0	–
(100)	43–44	14–15	4–5	1–2	0–1	0	–
Volos (50)	30–31	10–11	3–4	1–2	0–1	0	–
(100)	61–62	20–21	7–8	2–3	0–1	0	–

Both shallow (I) and intermediate-depth (II) events were considered for Heraklion, whereas the numbers computed for other cities were based on only shallow events.

The obtained *b*-values are in the range from 0.82 (± 0.02) to 1.02 (± 0.03). The lowest value was obtained for Patras, which is the westernmost of the five cities investigated (Fig. 1). This does not agree with the systematic decrease of *b*-values for shallow earthquakes from southwest to northeast, that is from the outer side of the Hellenic arc to the inner part (Papazachos and Papazachou, 1997). The *b*-value computed for the group of intermediate-depth earthquakes was the highest, although the *b*-values estimated for these events by other authors tend to be low (cf. Papazachos and Papazachou, 1997).

The estimated maximum magnitudes do not differ significantly from the maximum magnitudes already observed in the five areas during the time span of the available earthquake data. They were estimated by using the K-S-B formula (see Kijko and Graham, 1998), which takes into account that the empirical distribution of earthquake magnitude can deviate from the assumed model, viz. the Gutenberg–Richter relation. The estimation was quite robust for the Greek earthquakes: convergence towards the exact value of $m_{\max}$ was also reached when some other estimators failed. Tests carried out using synthetic earthquake catalogues also indicated that this estimator tends to perform well (Kijko and Graham, 1998). The shape of the return period curves displayed in Fig. 3 was somewhat similar in all cases, as the curves bend rather sharply at the upper magnitude range; this feature looks most pronounced for Patras and Volos. A similar behaviour was also noted for the return periods relying on K-S-B estimators reported for a low-seismicity area in Mäntyniemi et al. (2001). The curves for the probabilities of exceeding the given magnitudes in 1 year exhibit the same kind of bend at the largest magnitude values.

In terms of earthquake size, the area surrounding Heraklion in the Hellenic trench-arc system has the highest seismic potential. The maximum magnitude estimated for shallow seismicity, $\hat{m}_{\max} = 8.37$ (± 0.31), was the highest of the values. The second largest maximum magnitude was obtained for intermediate-depth earthquakes in the same area; $\hat{m}_{\max} = 8.25$ (± 0.30). The expected numbers of exceedance of the given magnitudes for exposure times of 50 and 100 years were also the highest for shallow and intermediate-depth events around Heraklion (Table 2). The area surrounding Patras also has high occurrence rates of the given magnitudes, although less so than around Heraklion (Table 2). The areas around the city of Thessaloniki have the lowest occurrence rates of the given magnitudes, although the estimated maximum magnitude, $\hat{m}_{\max} = 7.74$ (± 0.30), is the third largest of the values. The lowest maximum magnitude, $\hat{m}_{\max} = 7.23$ (± 0.30), was estimated for the vicinity of Athens. The annual probability of an earthquake of the size of the 1999 event or greater is small, about 0.07, but well in excess of 0.9 around Athens during a time interval of 50 years.

Makropoulos and Burton (1985a) assessed seismic hazard in Greece using Gumbel's third asymptotic distribution of extreme values and earthquake strain energy release. They estimated an upper bound magnitude of $M_s = 6.80$ (± 0.39) for an area surrounding the City of Athens within a radius of 100 km from the city centre and a value of $M_s = 7.35$ (± 0.58) for a 150-km radius using Gumbel III. The corresponding values obtained from strain energy release were $M_s = 6.7$ (± 0.3) and $M_s = 7.1$ (± 0.3), respectively. These estimates were based on a data set covering the time interval from 1900 to 1978, during which the maximum observed earthquake magnitudes were $M_s = 6.6$ within 100 km and $M_s = 7.0$ within a 150-km distance from the city. The presently estimated

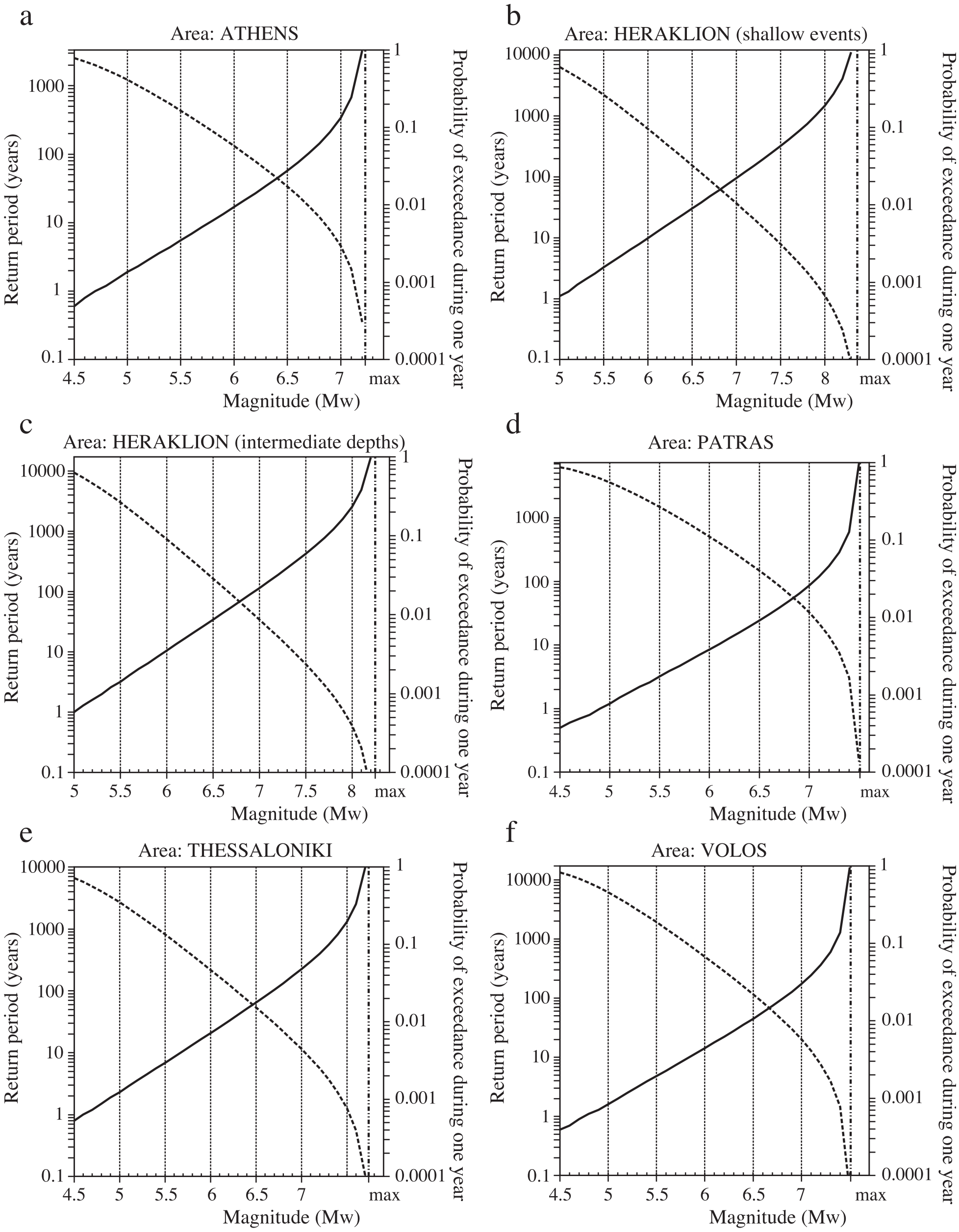

Fig. 3. Mean return periods (solid lines) and probabilities of exceedance of the given magnitudes during 1 year (dashed lines) for the earthquakes in the areas surrounding the cities of (a) Athens, (b) Heraklion, shallow and (c) Heraklion, intermediate-depth earthquakes, (d) Patras, (e) Thessaloniki and (f) Volos. The maximum magnitude (dash with two dots) was estimated for each area by using the K-S-B equation (see Theoretical considerations).

maximum magnitude for a 180-km radius around Athens is $\hat{m}_{\max} = 7.23$ (± 0.25) on the M_w scale, based on seismological records that cover about two and a half millennia with a maximum earthquake magnitude observed in 1894 and estimated at $M_w = 7.2$. The present estimate is larger than both the previous estimates for a 100-km distance but it is not far from the value obtained for a 150-km distance using strain energy release. The value obtained for a 150-km distance using Gumbel III distribution is the largest but it also has a very large degree of uncertainty.

The study of Makropoulos and Burton (1985a) also discussed magnitude recurrence in the areas surrounding the cities of Athens, Corinth, Heraklion, Patras, Rodhos and Thessaloniki within a radius of 100 and 150 km from the city centres. They used the computed Gumbel III parameters to estimate the mean return periods of the largest magnitudes in these areas. For the area of a radius of 150 km around Athens, they reported average return periods of 2.6 years for magnitude $M_s = 5.0$ and 4.3 years for magnitude $M_s = 5.5$, while the mean return period for magnitude $M_s = 6.0$ was 8.7 years, for $M_s = 6.5$ it was 26.0 years and for $M_s = 7.0$ they obtained 222.9 years. The return periods computed in the present study for magnitude $M_w = 5.0$ around Athens are in the range of 1.7–2 years (taking into account the standard deviation), between 5.1 and 6 years for $M_w = 5.5$, from 15.6 to 18.3 years for $M_w = 6.0$, from 53.3 to 62.5 years for $M_w = 6.5$ and for magnitude $M_w = 7.0$ in the range of 314.6–369.2 years. For Thessaloniki and Patras, the comparison yielded the same features, namely that the present estimates of return periods for $M = 5.0$ are shorter than those reported by Makropoulos and Burton (1985a) for a radius of 150 km, for $M = 5.5$ the results are shorter or about the same but longer for the bigger magnitudes. The shallow seismicity around Heraklion displays the same features except that for the magnitude $M_w = 7.5$ the present estimate and that given by Makropoulos and Burton (1985a) are not very different, the former being between 297.9 and 345.1 years and the latter 378.8 years. The comparison refers to different areas (a radius of 150 km vs. 180 km) but also to different time periods of observation, as Makropoulos and Burton (1985a) used 78 years of data.

Table 3
The computed (C) and observed (O) numbers of exceedances of the given magnitudes in the broad areas surrounding the five cities

Mag (Mw)	4.0	4.3	4.5	5.0	6.0	7.3	8.0
T (years)	19	36	50	89	155	500	2550
Athens C	86	86	78	48	9	–	–
O	65	79	99	82	30	–	–
HeraklionI C	161	157	141	83	16	3	2
O	118	162	187	122	13	3	1
HeraklionII C	198	185	161	89	15	2	1
O	162	156	137	48	16	4	1
Patras C	103	111	105	72	18	2	–
O	49	103	142	154	52	2	–
Thessaloniki C	72	71	64	38	7	1	–
O	74	84	49	70	23	3	–
Volos C	98	98	89	54	11	1	–
O	64	100	132	64	38	1	–

Time *T* is the time interval of completeness of the data above the respective magnitude. Heraklion (I) refers to shallow and Heraklion (II) to intermediate-depth events.

Table 3 shows the computed and observed numbers of exceedances of a selection of small-to-large magnitudes for the different areas. They correspond to time intervals of complete reporting of the respective magnitude, assuming that the thresholds of completeness assessed by Papazachos et al. (2000) for the whole Greek catalogue (given in Section 2) apply as such to its subcatalogues. This comparison can be seen as an attempt to illustrate how the model of earthquake catalogue used in the computations affected the input data. The observed earthquake magnitudes counted from the available catalogue were treated as accurate, whereas the model assumes that the observed magnitudes were distorted by a normally distributed error. Deviations between the two values can be noted especially for magnitude $M_w = 5$ (corresponding to complete reporting of 89 years), in which case the number of observed magnitudes is almost twice as big as the computed number except for Volos; for the intermediate-depth earthquakes around Heraklion the reverse holds true. For magnitudes above $M_w = 6$ (155 years of complete reporting) and $M_w = 7.3$ (500 years) the observed number of events also tends to be larger than the computed one. For the low magnitudes with brief time intervals of complete reporting the deviations tend to be smaller, which probably reflects the accuracy of more recent observations. This does not apply for Patras, however, where the number of observed magnitudes above $M_w = 4.0$ is only about half of the computed number. The comparison implies that the incorporation of magnitude error in the computations affected the output in such a way that the level of seismic hazard increases if magnitude uncertainty is disregarded.

4.2. Site-specific PSHA for the five cities

Fig. 4 shows the probabilities that the given PGA values will be exceeded during time intervals of 1, 50 and 100 years in the five cities. They decrease rather quickly with increasing PGA, so that the probability to exceed for instance a PGA value of 0.10 g is less than 0.04 and 0.15 g is less than 0.01 during 100 years

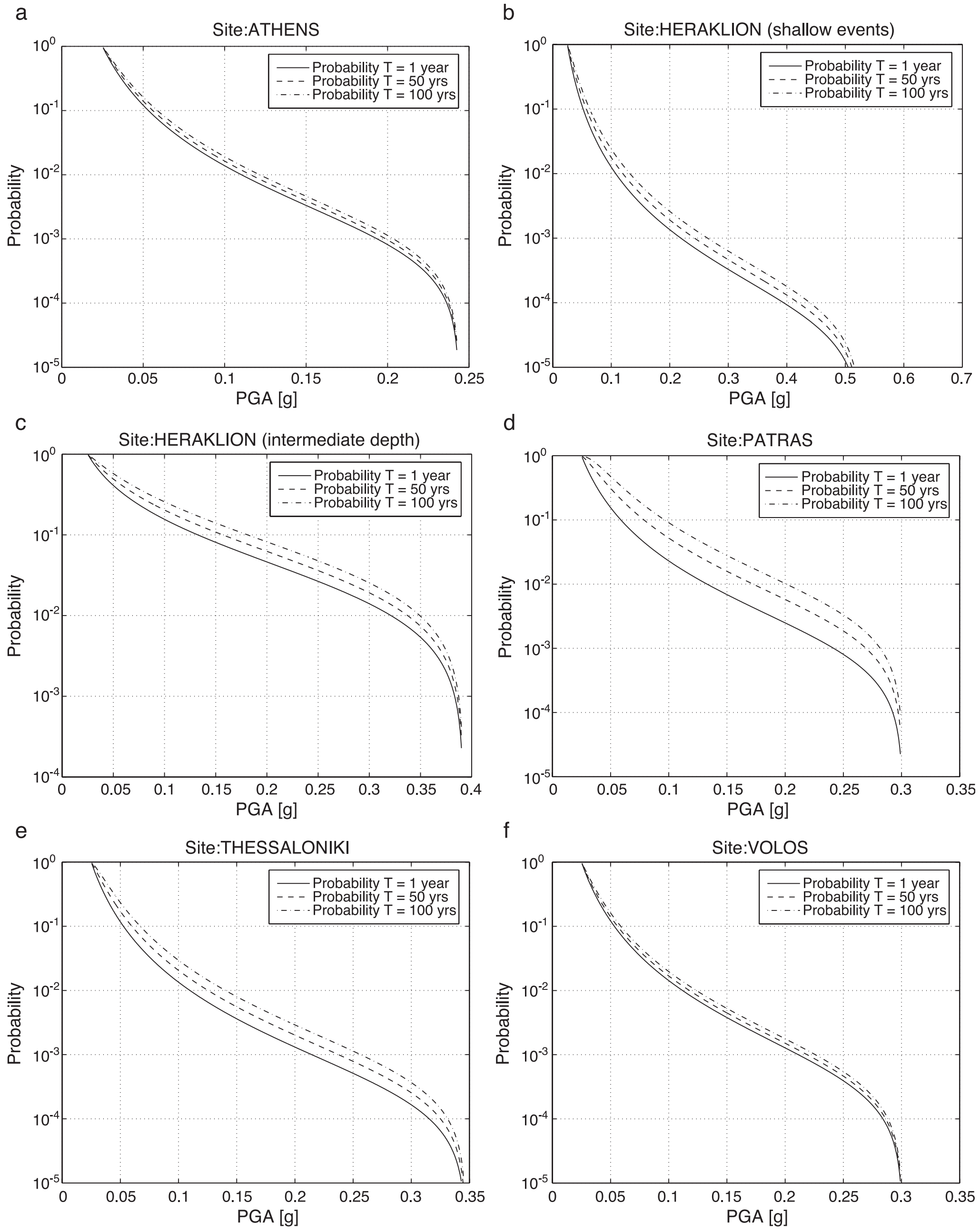

Fig. 4. Probabilities that the given peak ground acceleration values will be exceeded during one year and 50 and 100 years at the sites of (a) Athens, (b) Heraklion, shallow and (c) Heraklion, intermediate-depth earthquakes, (d) Patras, (e) Thessaloniki and (f) Volos.

for shallow seismicity at the five sites. The probabilities obtained for the intermediate-depth earthquakes are higher than those for shallow events, which can be attributed to the different attenuation laws used for the two groups of events. The results rely on the maximum PGA values, which were computed by consideration of the maximum magnitude, locating an earthquake of magnitude $m_{\max}$ at a distance of 15 km from the site, and the mean value given by attenuation relation (cf. Section 3). The PGA values thus calculated were 0.24 g for Athens, 0.53 g for the shallow and 0.39 g for the intermediate-depth earthquakes around Heraklion, 0.30 g for Patras, 0.35 g for Thessaloniki and 0.30 g for Volos. In accordance with the area-specific results, the highest values were found for Heraklion.

Fig. 5 is an illustration of the uncertainty of maximum PGA assessment. It gives the probabilities that an earthquake of maximum magnitude, as estimated for each area, occurs at a hypocentral distance of 15 (± 5) km from the respective site and produces a PGA value exceeding a given value. The computation of the shown probabilities involved the consideration of the total standard deviation, which consisted of the uncertainties for the maximum magnitude, distance and attenuation law used. This kind of computation can be seen as a probabilistic extension of the deterministic “design” earthquake approach.

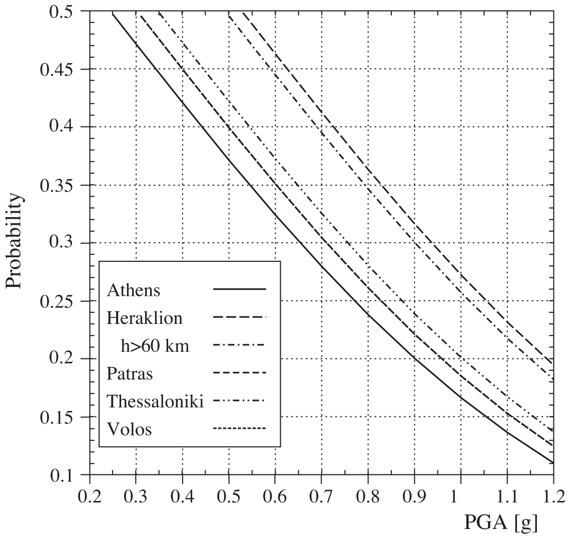

Fig. 5. The complementary probabilities that an earthquake of maximum magnitude, as estimated for each area, will occur at a hypocentral distance of 15 (± 5) km from the respective city and cause a peak ground acceleration (PGA) value exceeding the estimated maximum value at the sites Athens, Heraklion (both shallow and intermediate depths), Patras, Thessaloniki and Volos. The probabilities computed for Patras and Volos overlap.

If maximum PGA values are computed on the basis of what is known of past seismicity, accounting not only for the available magnitudes but also for the distance between the epicentre and the city, the results are rather moderate because none of the largest events in the past occurred very close to the cities. Even the event on 21 July 365 of an estimated magnitude of $M_w = 8.3$, which is the largest in the Greek earthquake catalogue, occurred at a distance of more than 100 km from Heraklion. However, the largest events may be accompanied by large location uncertainties. For example, Guidoboni and Comastri (1997) placed the epicentral area of the great earthquake of 8 August 1303 to the southeast of Crete, whereas according to Papazachos and Papazachou (1997) its epicentre was east of the Island of Rodhos. In the very near field of a shallow earthquake of an equivalent size to the 365 and 1303 events the computations yielded a PGA value in excess of 1.0 g.

Site effects play an important role in ground motion. Although all the presently investigated sites are located by the sea, soil conditions may vary considerably within the cities. For instance, the old part of Thessaloniki sits on rock, but because of the population increase, the part of the city built prior to the second world war has intermediate soil conditions and there is alluvium in the newest parts of the city. This kind of variety also exists in Athens and Volos. Only in Heraklion is alluvium the dominant type of soil. The intermediate soil conditions were selected when calculating the probabilities displayed in Fig. 4.

The era of directly measured earthquake-related ground-motion is considerably shorter than the available catalogue, and it is of interest to compare the actually observed ground-motion with calculated PGA values. For Athens, ample strong-motion data were gathered at the time of the 1999 earthquake and its aftershocks. According to Papadopoulos et al. (2000), the corrected PGA values related to the main shock ($M_s = 5.9$) measured at distances between 16 and 39 km varied from 0.5 g at the Monastiraki site downtown to 0.075 g at the Dimokritos site on rock.

Because of the extreme local conditions at Monastiraki, however, the value of 0.31 g recorded at the Sepolia station was regarded as the most representative value measured. This value exceeds the present estimate of 0.24 g. However, taking into consideration the standard deviation of the attenuation relation (1), the 84% confidence level of PGA becomes 0.49 g for Athens, which is about the same as the value actually observed at the Monastiraki site. The corresponding confidence levels for the other cities are 1.06 g for Heraklion (shallow earthquakes), 0.61 g for Patras, 0.70 g for Thessaloniki and 0.61 g for Volos.

A horizontal PGA value of about 0.047 g was recorded in Heraklion at an epicentral distance of 45 km following the 23 May 1994 earthquake of magnitude $M_w = 6.1$ and focal depth of $h = 80$ km (Margaris et al., 1995). This earthquake caused damage at Heraklion and Chania (Papazachos and Papazachou, 1997). Drakopoulos (1976) reported PGA values observed in Greece including two records at the strong motion station of Patras. They were related to the earthquakes of 29 January 1974 of magnitude $M_s = 4.3$ at an epicentral distance of 30 km and 4 April 1975 of magnitude $M_s = 5.7$ at a distance of 56 km. The observed values were 0.041 and 0.059 g, respectively. Following the 14 July 1993 event of magnitude $M_s = 5.4$, accelerographs located at two places in the city of Patras recorded horizontal PGA values of 0.144 and 0.180 g (ITSAK, 1997). The magnitude $M_w = 6.5$ earthquake of 20 June 1978 at an epicentral distance of about 30 km from Thessaloniki produced a maximum PGA value of 0.15 g in the city (Carydis et al., 1983). These observed values were caused by low-to-moderate magnitude events only. The Athens earthquake of 1999 demonstrated the effect of local site conditions.

Previous studies also comprised assessments of the expected ground-motion in terms of PGA. Makropoulos and Burton (1985b) presented values which have 70% probability of not being exceeded in a given time interval. During 50 and 100 years, these values were 0.094 and 0.107 g, respectively, for Athens, and 0.065 and 0.073 g, respectively, for Heraklion. The values corresponding to time intervals of 50 and 100 years were 0.146 and 0.167 g, respectively, for Thessaloniki, and 0.119 and 0.134 g for Patras. These values refer to other probability levels than those of the present study, but agree with the present ones in that the expected PGA values tend to be quite moderate. Papazachos et al. (1995) specified seismic hazard in Heraklion in terms of expected values of horizontal PGA values for different time periods. The obtained values were 0.087 and 0.123 g for return periods of 50 and 100 years, respectively.

5. Conclusions

The area-specific results for the broad areas surrounding the five cities were based on an earthquake catalogue covering two and a half millennia. The obtained parameters b and λ_A rely on the value of the maximum magnitudes estimated by using the K-S-B approach, which in turn were not very different from the respective maximum magnitudes observed within the areas during the span of the earthquake data. The shape of the return period curves was somewhat similar in all cases, as the curves bend rather sharply at the upper magnitude range. Comparison to previous studies is not straightforward because they were based on earthquake observations of a much shorter span, and comparisons to observed numbers of occurrences may be hampered by differences in the thresholds for complete reporting and errors in the oldest data, but the present estimates appear to feasible and justified in that magnitude uncertainty is taken into account.

The site-specific results for the five cities were expressed as probabilities that the given PGA values will be exceeded at least once during 1, 50 and 100 years. They were based on the maximum PGA values assessed using information about the maximum magnitude at a short distance from the city and the attenuation relationship and were 0.24 g for Athens, 0.53 g for the shallow and 0.39 g for the intermediate-depth earthquakes around Heraklion, 0.30 g for Patras, 0.35 g for Thessaloniki and 0.30 g for Volos. However, the computed probabilities decreased rather quickly with increasing PGA. This kind of behaviour appears to be in agreement with computations presented in previous studies. The available strong-motion data still cover a rather brief time spans and mainly resulted from low-to-moderate magnitude earthquakes. The Athens earthquake of 1999 was important in this respect, because it demonstrated how earthquakes of moderate magnitude pose a threat to urban conditions. The PGA value of 0.31 g measured at an epicentral distance of 16 km was regarded as the most representative value related to this event (Papadopoulos et al., 2000). It is above the value obtained by a computation scheme of the maximum magnitude and the mean PGA value obtained with the help of the attenuation law, but well below the 84% confidence level of the computed value. This shows the effect of the error term, ± c_4, of the attenuation law of Margaris et al. (2001).

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