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☑ **Αποτελέσματα Πιθανολογικού Υπολογισμού Εδαφικών Παραμέτρων.**

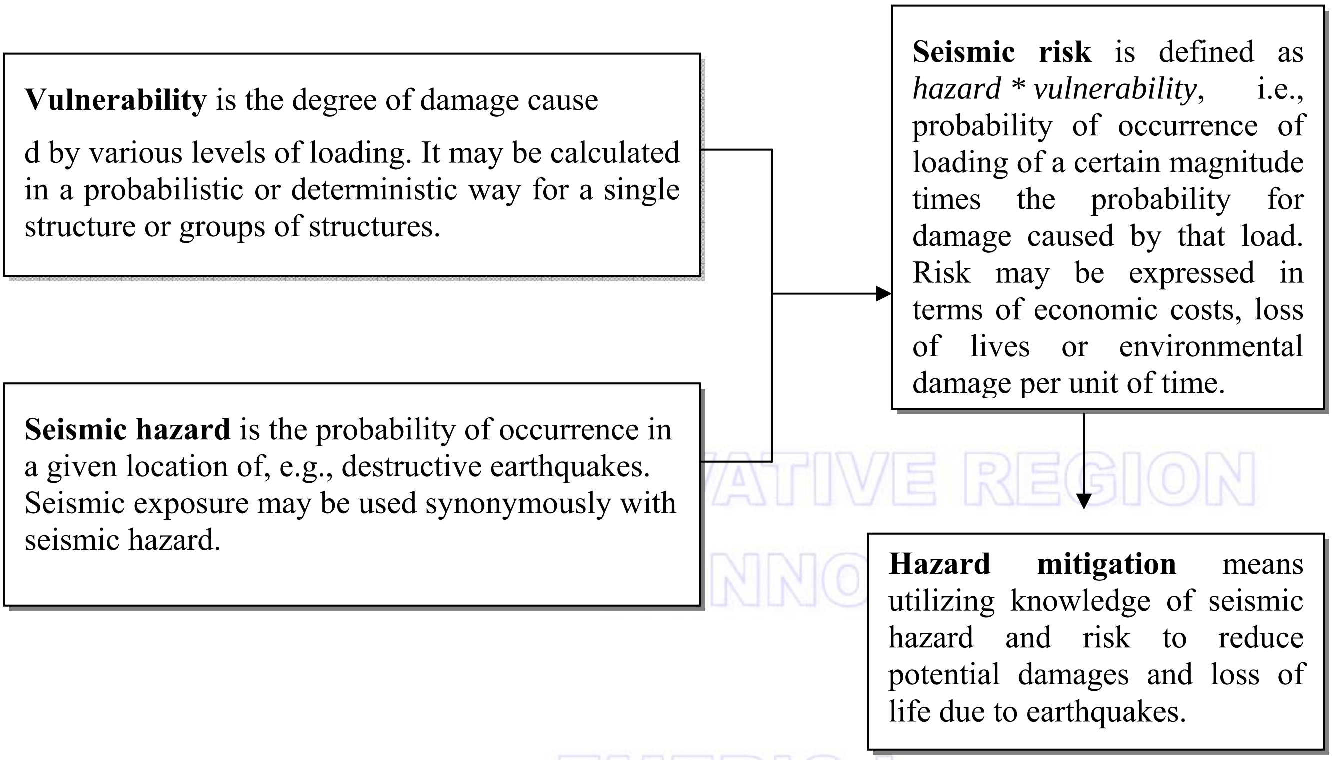
☑ Φασματική Απόκριση Υπεδάφους σε Επιλεγμένα Σημεία. (Παραδόθηκε τον Ιούλιο 2005)

☑ Πρότυπο Κατανομής Σεισμικών Ταχυτήτων. (Παραδόθηκε τον Ιούλιο 2005)

INTRODUCTION

Earthquakes are responsible for most of the casualties related to natural disasters, and the tolls are steadily increasing in line with an increasing *vulnerability* due to population increase, urbanization and industrial development. Studies of *seismic hazard* and *risk* have given significant advances in earthquake *mitigation* capabilities recently. In the meanwhile, short term earthquake prediction remains an elusive goal which may not be fulfilled in the very near future. What is available, however, is statistically based forecasts of approximate earthquake strength, place and time intervals between earthquakes (hazard analyses). For some individual faults, long term prediction of their behavior may be close at hand.

Seismic hazard is defined as the probable level of ground shaking associated with the recurrence of earthquakes. The assessment of seismic hazard is the first step in the evaluation of seismic risk, obtained by combining the seismic hazard with local soil conditions and with vulnerability factors (type, value and age of buildings and infrastructures, population density, land use). Frequent, large earthquakes in remote areas result in high seismic hazard but pose no risk; on the contrary, moderate earthquakes in densely populated areas entail small hazard but high risk. Minimization of the loss of life, property damage, and social and economic disruption due to earthquakes depends on reliable estimates of seismic hazard. National, state and local governments, decision makers, engineers, planners, emergency response organizations, builders, universities, and the general public require seismic hazard estimates for land use planning, improved building design and construction (including adoption of building codes), emergency response preparedness plans, economic forecasts, housing and employment decisions, and many more types of risk mitigation.



Vulnerability is the degree of damage caused by various levels of loading. It may be calculated in a probabilistic or deterministic way for a single structure or groups of structures.

Seismic hazard is the probability of occurrence in a given location of, e.g., destructive earthquakes. Seismic exposure may be used synonymously with seismic hazard.

Seismic risk is defined as *hazard * vulnerability*, i.e., probability of occurrence of loading of a certain magnitude times the probability for damage caused by that load. Risk may be expressed in terms of economic costs, loss of lives or environmental damage per unit of time.

Hazard mitigation means utilizing knowledge of seismic hazard and risk to reduce potential damages and loss of life due to earthquakes.

Figure 1

The basic elements of modern probabilistic seismic hazard assessment can be grouped into four main categories:

1. *Earthquake Catalogue*: the compilation of a uniform database and catalogue of seismicity for the historical (pre-1900), early-instrumental (1900-1964) and instrumental periods (1964-today).
2. *Earthquake Source Model*: the creation of a master seismic source model to describe the spatial-temporal distribution of earthquakes, integrating the earthquake history with evidence from seismotectonics, paleoseismology, mapping of active faults, geodesy and geodynamic modeling.
3. *Strong Seismic Ground Motion*: the evaluation of ground shaking as a function of earthquake size and distance, taking into account propagation effects in different tectonic and structural environments.
4. *Seismic Hazard*: the computation of the probability of occurrence of ground shaking in a given time period, to produce maps of seismic hazard and related uncertainties at appropriate scales.

Seismic hazard depicts the levels of chosen ground motions that likely will, or will not, be exceeded in specified exposure times. Hazard maps commonly specify a 10% chance of exceedance (90% chance of non-exceedance) of some ground motion parameter for an exposure time of 50 years, corresponding to a return period of 475 years. The following map depicts Peak Ground Acceleration (PGA) with a 10% chance of exceedance in 50 years for a firm soil condition. PGA, a short-period ground motion parameter that is proportional to force, is the most commonly mapped ground motion parameter because current building codes that include seismic provisions specify the horizontal force a building should be able to withstand during an earthquake. Short-period ground motions affect structures with corresponding short-period resonance vibrations (e.g. one-to-three story buildings, the largest class of structures in the world).

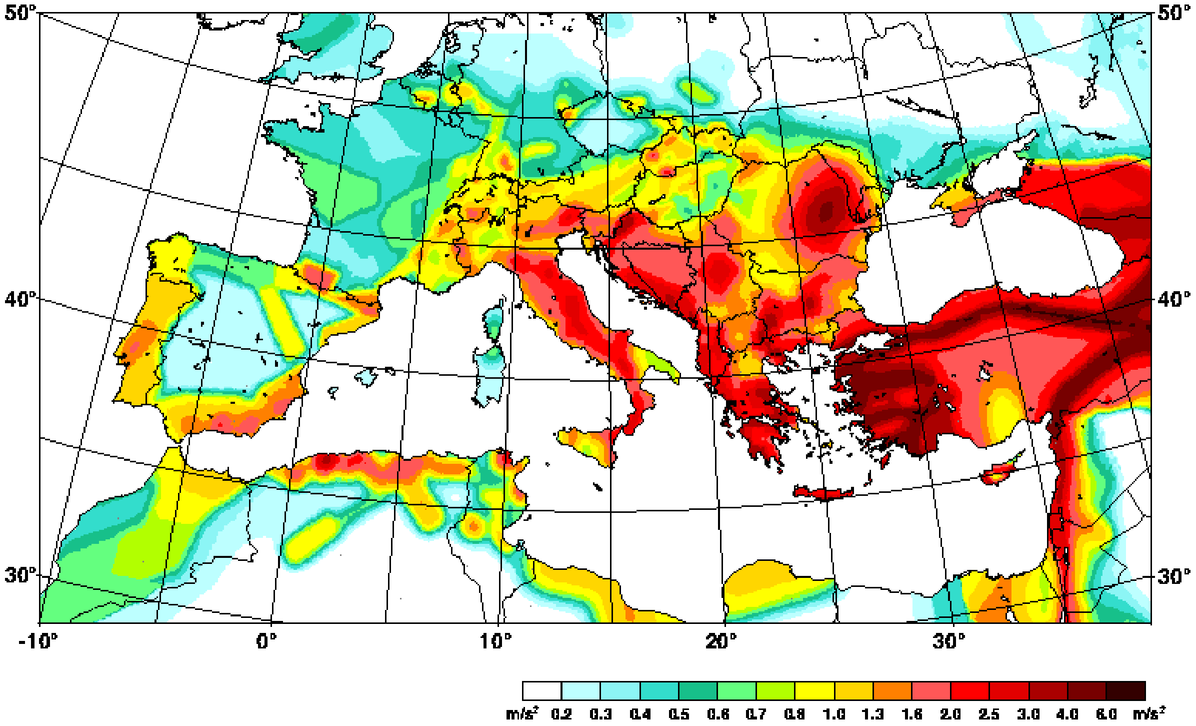


Figure 2 The map colors chosen to delineate the hazard roughly correspond to the actual level of the hazard; the cooler colors represent lower hazard while the warmer colors represent higher hazard. Specifically, white to green correspond to low hazard (0-8% g, where g equals the acceleration of gravity), yellow and orange to moderate hazard (8-24% g); reds to high hazard (> 24% g).

SOME THEORETICAL ASPECTS ABOUT SEISMIC HAZARD ANALYSIS

Probabilistic Seismic Hazard Analysis

The main objective of the earthquake hazard computation is to develop earthquake criteria in terms of bedrock outcrop equal probability design spectra, for given annual probabilities to be exceeded, e.g. of $2x10^{-3}$ (500 years return period) and 10^{-4} (10,000 years return period). This objective is achieved through an earthquake hazard assessment based on a probabilistic computational procedure permitting the characterization of input models in terms of logic trees, where the probability distributions of the input parameters, and thereby their uncertainties, can be specified. The main computational elements comprise an earthquake ground motion model deduced from available geological and seismological data.

Method

The foundations of probabilistic engineering seismic hazard analyses were established by Cornell, who recognized the need for seismic hazard to be based on a method which properly accounted for the intrinsic uncertainties associated with earthquake phenomena. Since then, both seismological and geological techniques and understanding applied to seismic hazard analysis have improved steadily, so that current practice is now able to utilize information from a variety of both seismological and geological data sources with due considerations for uncertainties. Significant improvements have also been achieved over the last 20 years on the modeling side.

While the standard practice for a long time was to present the results of seismic hazard analyses in terms of a single best estimate hazard curve, the growing awareness of the importance of parametric variability and the trend to consult expert opinion in matters of scientific doubt, led later to the formulation of Bayesian models of hazard analysis which seek to quantify uncertainty in parameter assignment in probabilistic terms. This approach has been formalized into a logic tree methodology which represents the range of possible parameter values as branches of a computational tree which are individually weighted and whose contributions to seismic hazard are separately evaluated and statistically combined.

A flow chart describing the various steps involved in the probabilistic computation of seismic hazard at bedrock outcrop level is given in Figure 3, and the logic tree formalism used in the hazard analysis is explained in Figure 4.

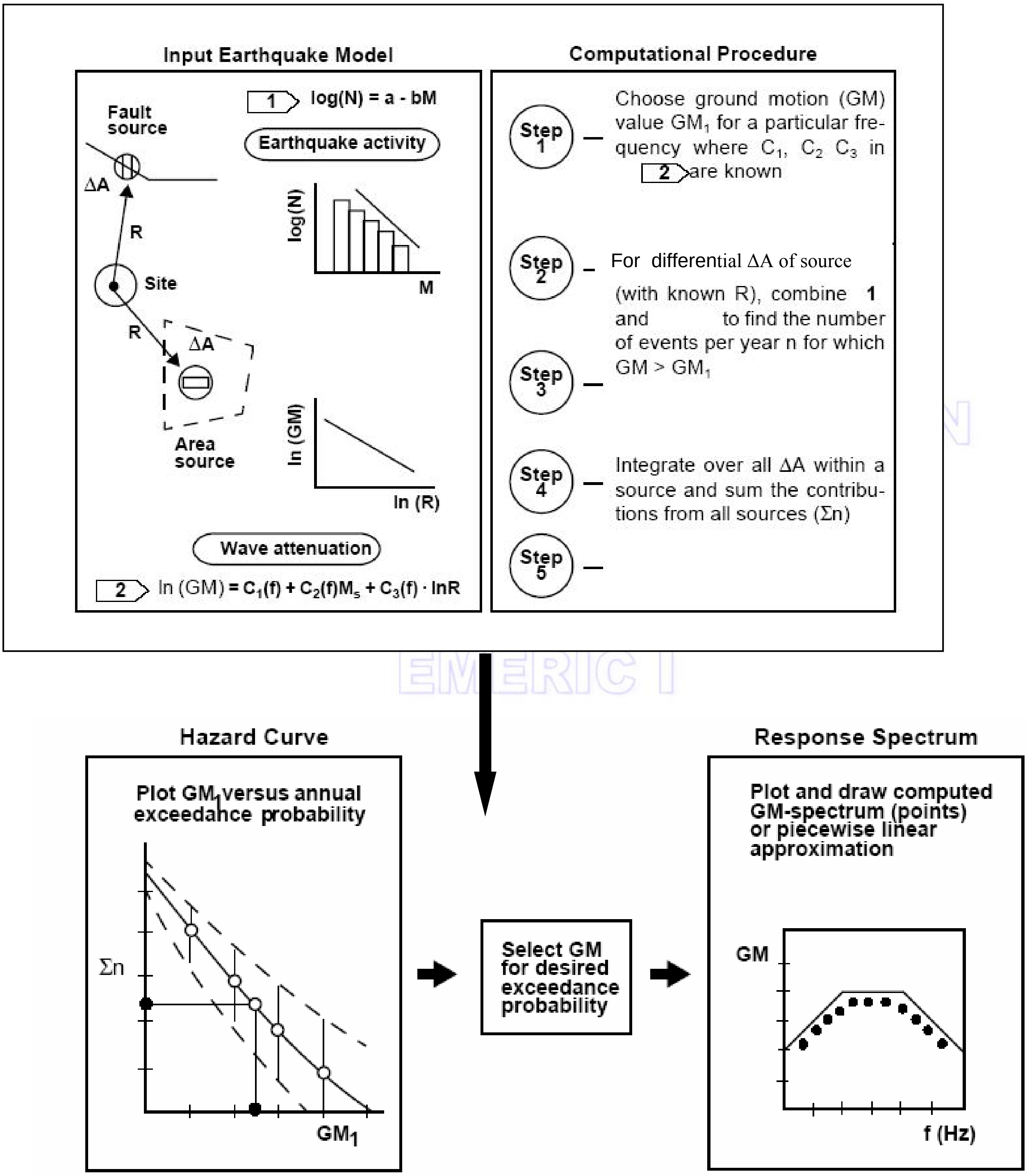


Figure 3 Simple layout of probabilistic earthquake ground motion (GM) hazard computation, and the associated equal probability hazard spectrum computation.

The model for the occurrence of ground motions at a specific site in excess of a specified level is assumed to be that of a Poisson process. This follows if the occurrence of earthquakes is a Poisson process, and if the probability that any one event will produce site ground motions in excess of a specified level is independent of the occurrence of other events. The probability that a ground motion level is exceeded at a site in unit time is thus expressed as:

$$P\,(Z>z) = 1 - e^{-\nu\,(z)}$$

Where $\nu(z)$ is the mean number of events per unit time in which Z exceeds z .
With N seismic sources, and seismicity model parameters S_n for each source n, the mean number of events per unit time in which ground motion level z is exceeded can be written as:

$$\nu(z) = \sum_{n=1}^{N} \nu_n(z|S_n)$$

$$\nu_n(z|S_n) = \sum_{i,j} \lambda_n(M_i|S_n)\; P_n(r_j|M_i S_n)\; G_n(z|r_j M_i S_n)$$

The functions λn , Pn and Gn model the inherent stochastic uncertainty in the frequency of occurrence and location of earthquakes, and in the attenuation of seismic waves. Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of the model parameters S_n. This source of uncertainty is accounted for by regarding the parameters S_n as random variables, whose discrete values are assigned with weights reflecting their likelihood. These discrete values represent branches in a logic tree for the seismic hazard model. At each node, probabilities are attached to the various branches. Consideration of the complete set of branches allows the probability distribution to be calculated.

Given that the mean number of events per unit time for which Z exceeds z is expressed for example as $1/T_R$, where T_R is the return period (inverse of annual exceedance probability), then the number of events in a time period T (e.g. the life time of a certain construction) for which Z exceeds z is given by T/T_R and the probability for Z exceeding z during that life time is given by:

$$P\,(Z > z) = 1 - e^{-T/TR}$$

For a life time T of 50 years and a return period T_R of 475 years (annual probability of exceeding 0.211 x 10^{-2}) the probability for Z exceeding z becomes 0.1, corresponding to 90% probability that this size ground motion is NOT exceeded in 50 years.

With several seismic sources, described through particular model parameters, the mean number of events per unit time in which the ground motion level z is exceeded can be expressed specifically, involving functions that model the inherent stochastic uncertainty in the frequency and location of earthquakes, and in the attenuation of the seismic waves.

Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of model parameters. This source of uncertainty is accounted for by regarding these parameters as random variables, whose discrete values are assigned weights reflecting their likelihood. These discrete values represent branches in a logic tree for the seismic hazard model (see Figure 2). At each node, probabilities are attached to the diverse branches, which are disjointed and exhaustive of possible choices. Consideration of the complete set of tree branches allows the probability distribution to be calculated.

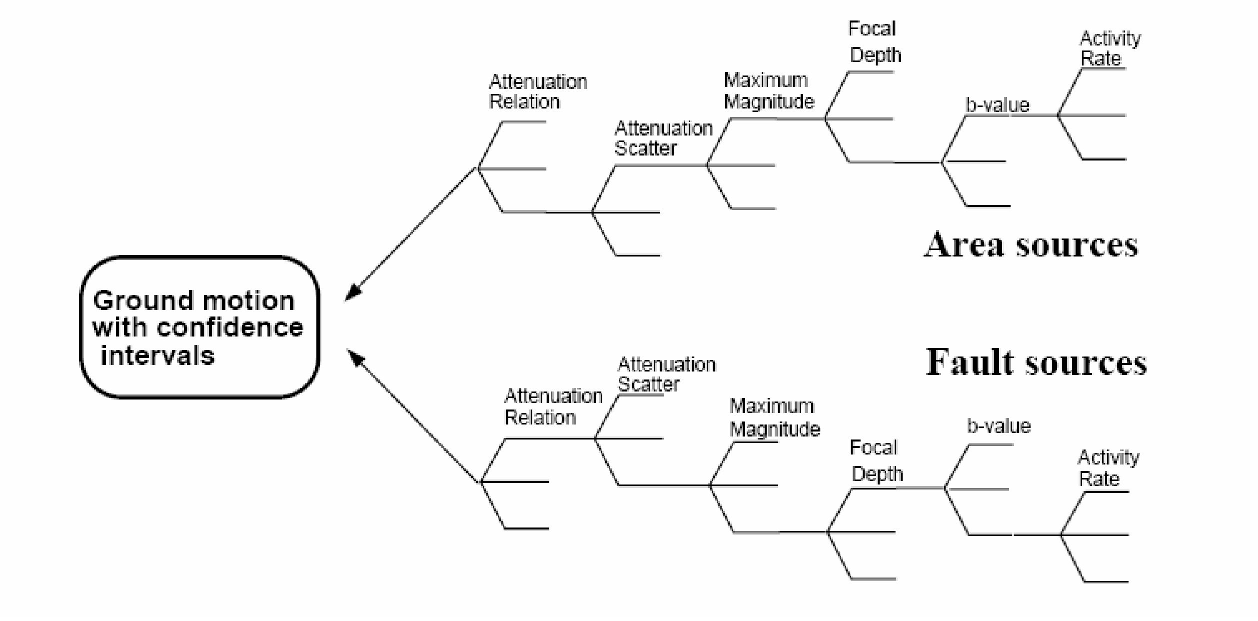


Figure 4 Logic tree branches for seismic sources.

Seismic vulnerability

Probabilistic vulnerability relationships are usually expressed either in matrix form, or in terms of probability curves that describe the probabilities that a given structure will sustain a certain degree of damage when exposed to a certain ground motion. Such probability curves are often termed vulnerability or fragility functions.

Vulnerability functions are described as probabilistic or deterministic. A typical vulnerability curve depicts the cumulative probability of damages (in defined damage states) for a given structure or type of structure. A typical vulnerability (or fragility) curve is shown below in Figure 5:

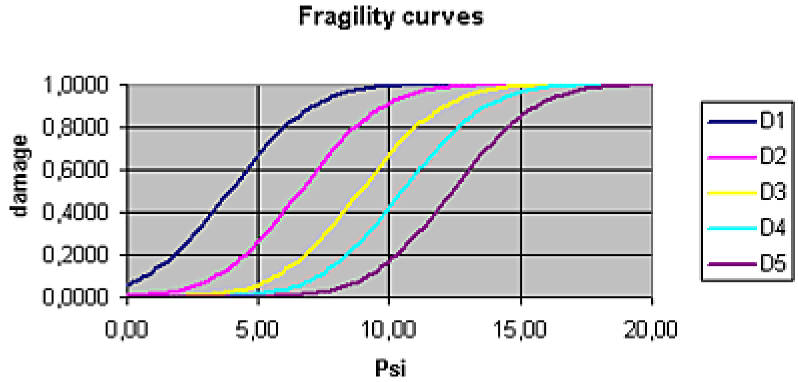


Figure 5 Vulnerability function for adobe (earth brick buildings).

There are two approaches commonly followed in vulnerability estimation:

- The deterministic: Through dynamic analysis of single structures and building types, the earthquake shaking performance can be computed. A typical example of this approach is HAZUS (Risk estimation software developed by the Federal Emergency Management Agency, FEMA).
- The empirical: Based on post-earthquake surveys data on damage for various building classes are collated and related to estimated or measured ground motion.

TECTONICS OF THE AREA OF SOUTHERN AEGEAN

One of the most prominent tectonic features of the Aegean Sea is the Hellenic Trench which consists of a series of sub-marine trenches (like the Pliny and Strabo trenches SE of Crete Island; The Ionian deep) with depths up to 5 km. The Hellenic Trench is parallel to the Hellenic Arc which consists of the outer sedimentary arc and the inner volcanic arc. The average distance between them is 120 km. The sedimentary arc (Hellenides Mts, Ionian Islands, Crete, Rhodos) connects Dinarides and Hellenides Mts to the Taurides Mts in southwestern Turkey. The Sea of Crete with maximum depth 2 km lies between the sedimentary arc and the volcanic arc. The front part of the African oceanic lithosphere is subducting under the continental Aegean Sea lithosphere as part of the collision process of Africa–Eurasia plates. This leads to the formation of an inclined seismic zone—a Benioff zone (Papazachos and Comninakis, 1971; Papazachos, 1990)—dipping to NE to a depth of about 150–200 km. The Aegean–Africa interaction is among the most studied (McKenzie, 1978; Taymaz et al., 1990, 1991; Jackson, 1994; Kiratzi and Papazachos, 1995 among many others).

Many researchers have studied the focal mechanisms of earthquakes of the Aegean region and the adjacent lands (McKenzie, 1972, 1978; Shirokova, 1972; Ritsema, 1974; Papazachos, 1975; Anderson and Jackson, 1987; Liotier, 1989; Kiratzi and Langston, 1991; Taymaz et al., 1990, 1991; Taymaz and Price, 1992; Hatzfeld et al., 1996; Baker et al., 1997; Bernard et al. 1997; Louvari et al., 1997; Louvari, 2000; Jost et al., 2002) using either first-motion polarities or teleseismic waveform modelling.

Benetatos et al. (2004) studied the spatial and mainly depth distribution of focal mechanisms of earthquakes in the southern Aegean Sea. They used body waveform modelling to determine the mechanisms for 28 earthquakes of the period 1977–2002. They exhausted the presently available IRIS data set for the intermediate depth earthquakes which do not occur often and they are very important in the studies of seismic hazard analysis for the southern Aegean Sea islands and land areas, since the generation of large events is forecasted from acceleration models of seismicity (Papazachos et al., 2002; Tzanis and Vallianatos, 2003).

The active tectonics of the southern Aegean Sea, a region of intense shallow and intermediate depth seismicity can be summarized as follows:
(a) NW–SE compression with thrusts along the outer central Mediterranean Rise; (b) reverse and low angle thrust faulting at depths up to 40 km with P axis having a constant direction which is almost perpendicular to the strike of the arc, in the western and central parts and parallel to the arc in the eastern part; (c) normal faulting with E–W trending T-axes showing along—arc extension at depths up to 40 km; and (d) strike–slip faulting with P-axes parallel to the strike of the arc for events deeper than 40 km. Of special interest is the area between the island of Zante and the western coasts of Peloponnese where shallow and deeper events are of strike–slip faulting. The eastern part of the Hellenic arc exhibits a different behaviour than the western and central part. In the eastern part P-axes for both shallow and deeper events have the same NE–SWparallel to the arc trend. This is not the case in the western and central part of the arc where there is a clear discrimination between shallow and deeper events. In the eastern part the angle of the subducting plate is steeper than the other parts and the T - axes are well aligned along dip of the subducting plate. If for

the deeper than 40 km events the _E–W trending planes are assumed as the fault planes, then the western parts of the arc (Kythira, Milos islands) are connected to dextral strike–slip motions while the eastern parts (near Rodos Island) are connected to sinistral strike–slip motions.

SEISMIC HAZARD ASSESSMENT IN THE AREA OF SOUTHERN AEGEAN, GREECE

As it has already been mentioned 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 it is a prerequisite for seismic risk reduction and urban planning. Greece is located in a very seismogenic region; it occupies the sixth position (with Japan in the first one) among the seismically active countries of the world. In cities, the level of seismic risk is extremely high due to large population, the relatively high vulnerability of structures and the large economic value exposed to earthquake activity. For these reasons, the mitigation of earthquake damage and loss of lives has been recognized as a major problem and the seismic hazard in Greece has been and still is widely studied using a number of different techniques and seismic quantities.

During the last two decades, seismologists have made significant advances in the areas of seismic hazard assessment. These advances have been prompted by the installation of modern seismological networks and the understanding of problems related to fault rupture, estimation of local site effects, tectonics of a specific area, characteristics of the strong ground motion.

More than forty scientific articles about seismic hazards in Greece have been published during the last twenty five years. These studies cover mainly problems related to expected macroseismic intensities (e.g., Galanopoulos and Delibasis, 1972; Papazachos et al., 1985; Papaioannou, 1986; Papoulia and Slejko, 1997,) and peak-ground accelerations, velocities, and strong-motion duration (e.g., Algermissen, et al., 1976; Drakopoulos and Makropoulos, 1983; Papazachos et al., 1990, 1992, 1993; Theodulidis, 1991; Margaris, 1994).

A composite result of the previous publications is a map where Greece is separated in four zones of equal seismic hazard, which was proposed by four seismological research institutions (Papazachos et al., 1989) and constitutes part of the New Seismic Code of Greece (NEAK) since 1995. Most of the previous attempts to assess seismic hazard in Greece were based on Cornell's (1968) method and its modification by McGuire (1976). These methods require regionalization of the seismogenic sources in Greece and the surrounding area and determination of attenuation relations.

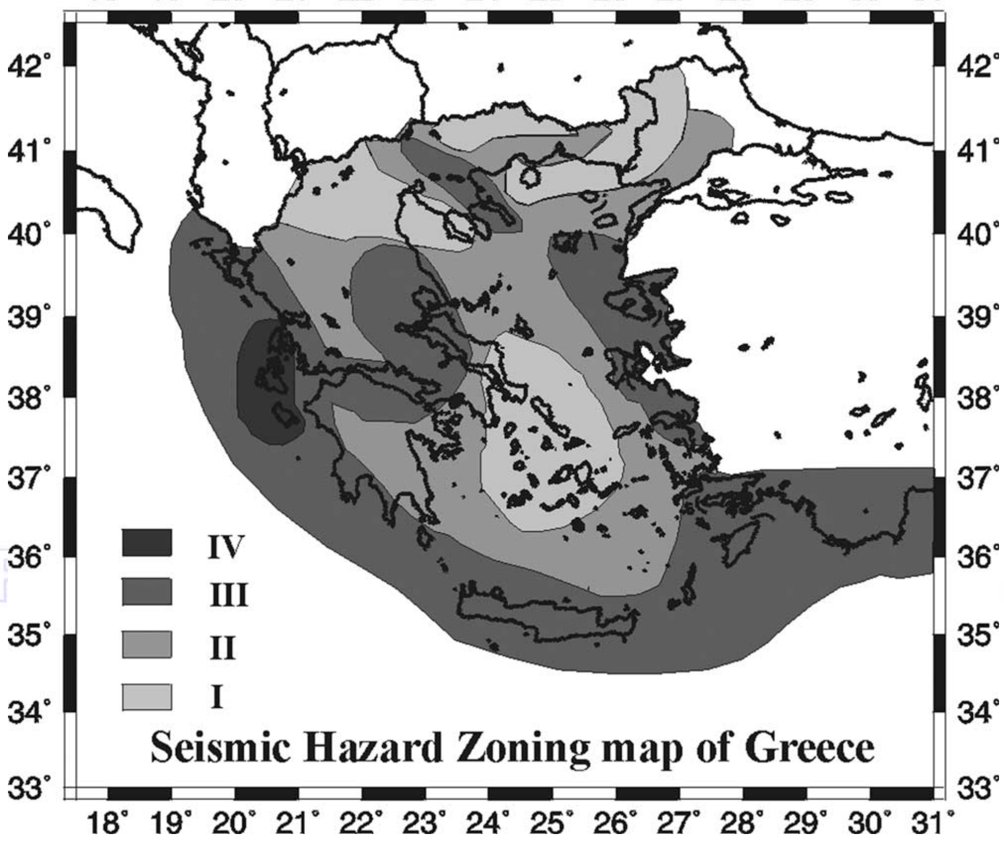


Figure 11 Seismic hazard zoning map of Greece adapted from the New Greek Seismic Code NEAK). NEAK addresses average horizontal p.g.a. values (%g) for a mean-return period of 475-year and adopts four zones: Zone I 12%g, Zone II 16%g, Zone III 24%g, Zone IV 36%g

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. 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. 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).

Mäntyniemi et al. (2004) tried to assess the level of seismic hazard for the city of Heraklion as well as its surrounding areas, using peak ground acceleration as the hazard parameter. The city of Heraklion in Crete is situated in the Hellenic trench-arc system and has experienced severe damage following both shallow and intermediate-depth earthquakes. The event of 21st July 365 had an estimated magnitude of Mw = 8.3, which is, until now, 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).

Additionally, 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 Imax =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 = VIII MM), 16 February 1810 (I = IX) and 12 October 1856 (I = IX). During modern times, Heraklion was damaged by among others the 23 May 1994 earthquake of magnitude Mw = 6.1 and focal depth of h = 80 km. The assigned intensity in the city was I = VII on the MM scale (Papazachos and Papazachou, 1997).

Mäntyniemi et al. (2004) applied the methodology for probabilistic seismic hazard assessment (PSHA) developed by Kijko and Graham (1998, 1999). 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 computations, the maximum magnitude was estimated for the broad areas surrounding the cities using a formula derived by Kijko and Graham (1998), and the magnitude recurrence in the broader 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 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.

Earthquake data used 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<60 km) and intermediate-depth (60 < h <180 km) events. The earthquake size is given on a scale equivalent to the moment magnitude (Papazachos et al., 1997)].

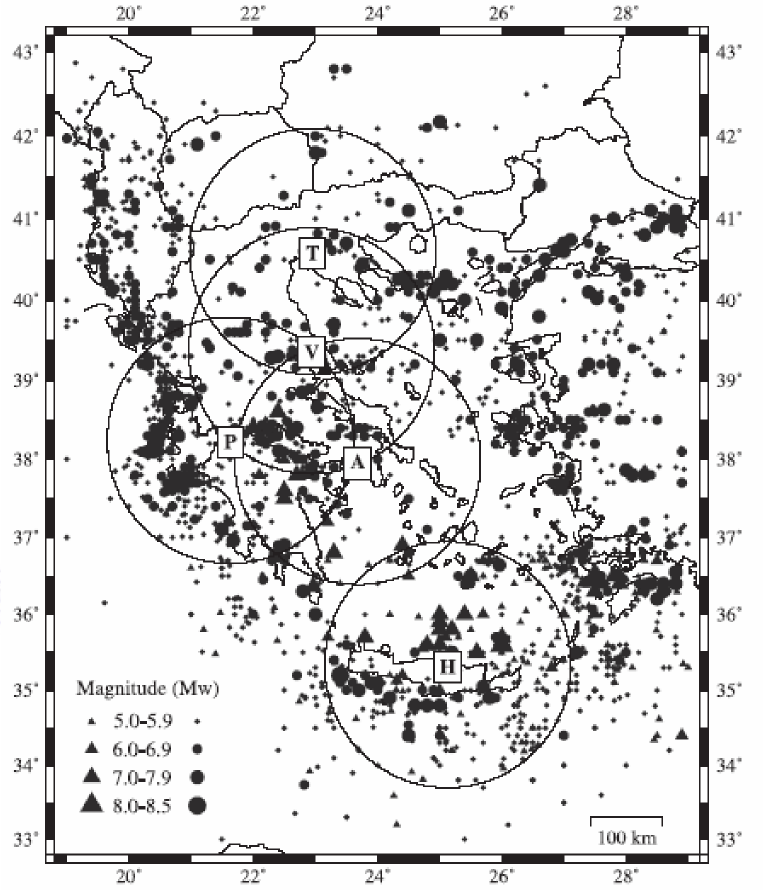


Figure 6 Epicentre map of the earthquake data for Greece and its vicinity. (foreshocks, aftershocks and earthquake swarms were removed from the initial data)

The whole catalogue of shallow earthquakes for the area between latitudes 33.0_43.0ºN and longitudes 19.0_29.0ºE is considered complete for the following time periods: after 550 B.C. for M≥8.0, after 1501 for M≥7.3, after 1845 for M≥6.0, after 1911 for M≥5.0, after 1950 for M≥4.5, after 1964 for M≥4.3 and after 1981 for M≥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). The above error estimates were used as guidelines when determining magnitude uncertainties during different time periods and dividing the instrumental catalogues into sub catalogues each one having a minimum threshold of magnitude. The thresholds of completeness were also verified.

For the city of Heraklion the earthquake data were taken for a radius of 180 km from their centres. It has to be noticed that 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.

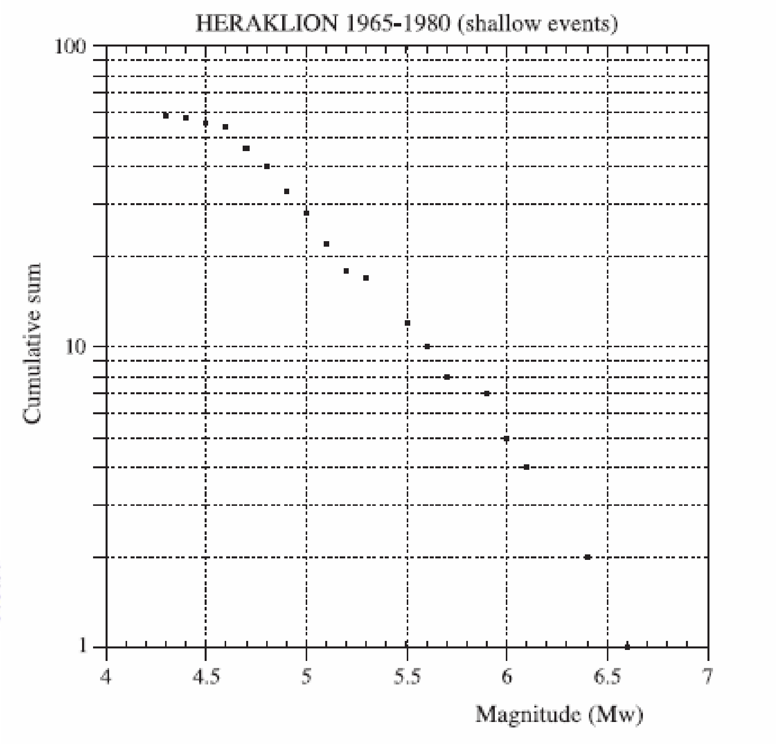


Figure 7 The sample of the shallow earthquakes around Heraklion between 1965 and 1980 is plotted as a cumulative sum of events vs. magnitude. Assuming the linearity of the magnitude– frequency relationship, the plot implies that the threshold of completeness is around magnitude 4.6, higher than the above guideline found in literature for the whole catalogue. The numbers of earthquakes used in the calculations is 430.

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 city of Heraklion. 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 b 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. The maximum magnitude 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 mmax (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

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

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. This attenuation law provides acceleration values in units of cm/s^2.

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

$$\ln(a) = c_0 + c_1 \cdot M_w + c_2 \cdot \ln(D + 30) + c_3 \cdot S$$

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.

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 and λ_S refers to the activity rate of earthquakes that cause a PGA value α at the site exceeding some threshold value a_{min} of engineering interest.

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. 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 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 reduces to the estimation of the site-specific mean seismic activity rate λS.

Tables 1–3 and Fig. 8 contain the main results for the area-specific part of seismic hazard assessment.

City	b	λ_A (for M>= 4.5)	$\hat{m}_{max}$	m_{max}	n_e
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**

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.

(Mw)	5.0	5.5	6.0	6.5	7.0	7.5	8.0
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**

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 Heraklion during 50 and 100 years.

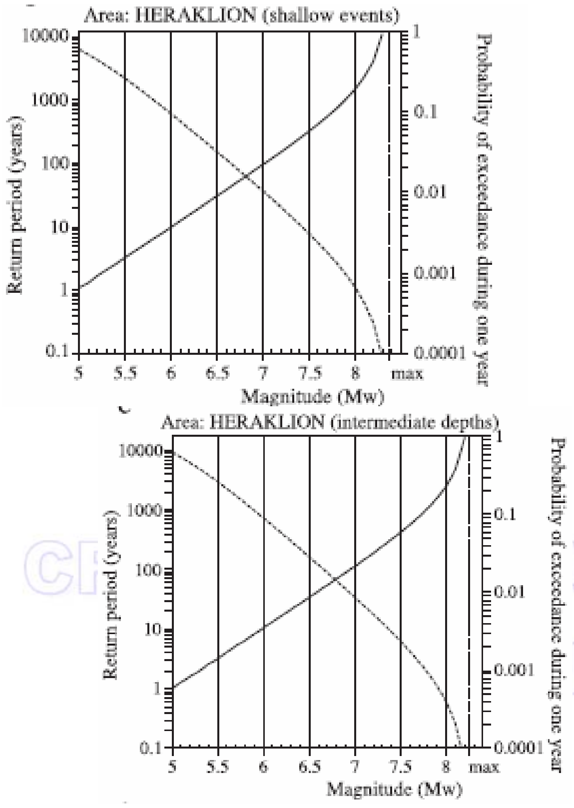


Figure 8 Mean return periods and probabilities of exceedance of the given magnitudes during 1 year for the earthquakes in the areas surrounding the city of Heraklion.

It can be easily understood from the above tables 1 and 2 the area surrounding Heraklion in the Hellenic trench-arc system has an extremely high seismic potential. The maximum magnitude estimated for shallow seismicity, $\hat{m}_{max}$ = 8.37 (±0.31), is a remarkable high value. The other 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).

Makropoulos and Burton (1985a) assessed seismic hazard in Greece using Gumbel's third asymptotic distribution of extreme values and earthquake strain energy release. 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. The shallow seismicity around Heraklion displays the same features except that for the magnitude Mw = 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.

For magnitudes above Mw = 6 (155 years of complete reporting) and Mw =

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.

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 mmax at a distance of 15 km from the site, and the mean value given by attenuation relation. The PGA values thus calculated were 0.53 g for the shallow and 0.39 g for the intermediate-depth earthquakes around Heraklion. In accordance with the area-specific results, the highest values were found for Heraklion.

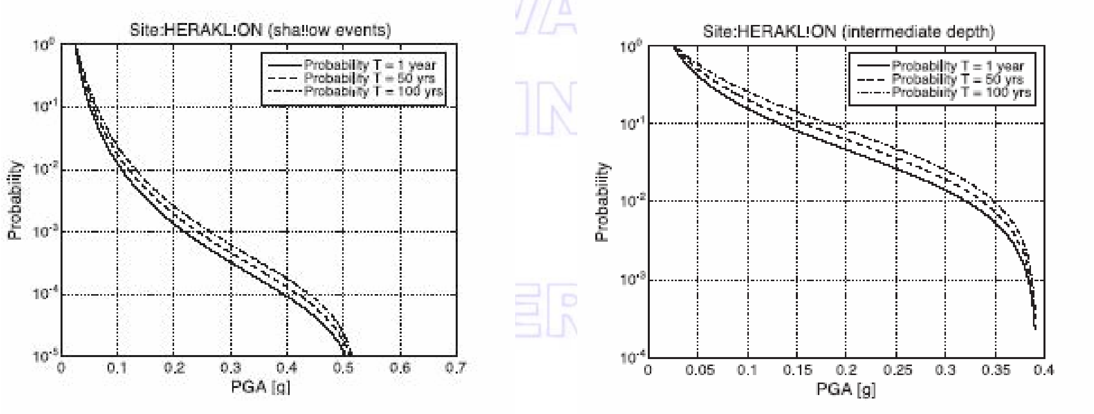


Figure 9 Probabilities that the given peak ground acceleration values will be exceeded during one year and 50 and 100 years at the sites of Heraklion, shallow events and Heraklion, intermediate-depth earthquakes.

Site effects play an important role in ground motion. In Heraklion is alluvium the dominant type of soil. 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 Mw = 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).

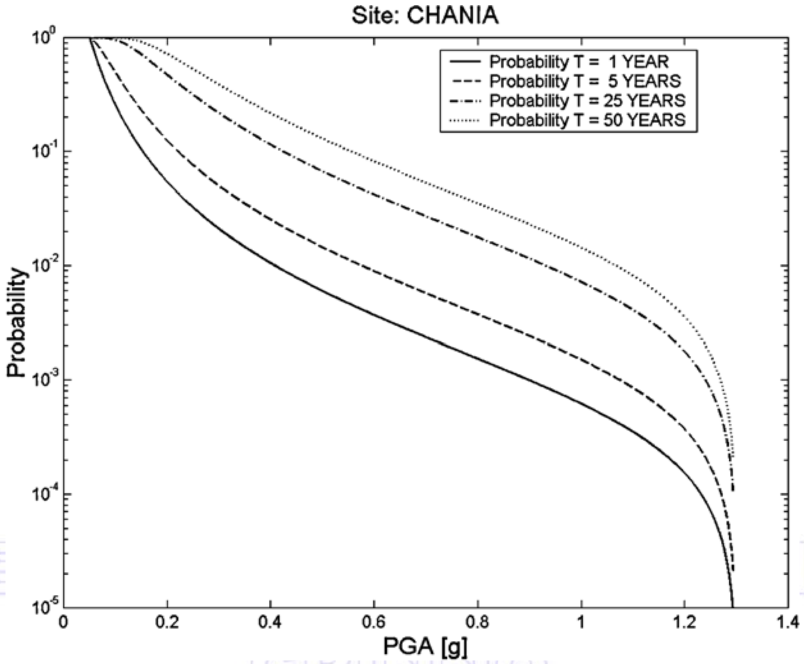
Previous studies also comprised assessments of the expected ground-motion in terms of PGA. Makropoulos and Burton (1985b) presented values which have 70% probability of not being exceeded in a given time interval. During 50 and 100 years, these values were

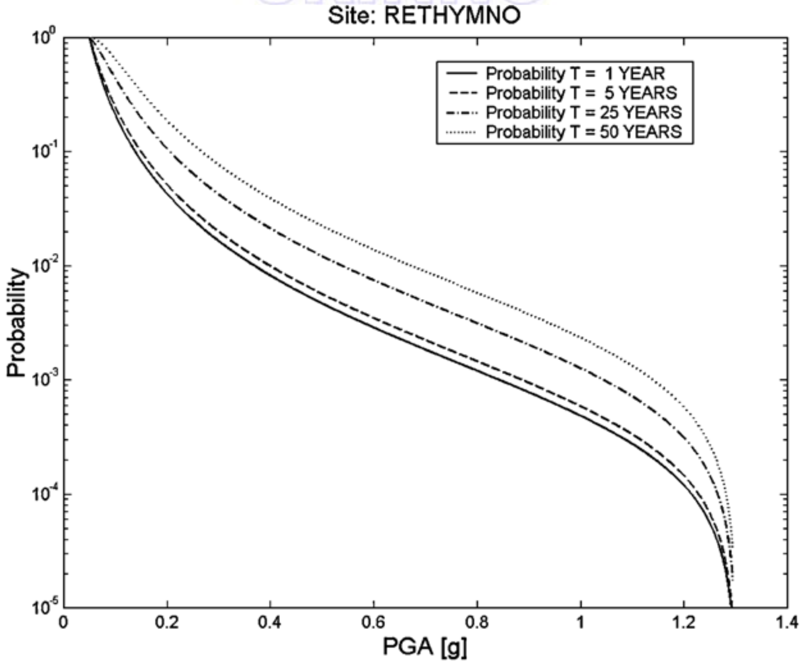
0.073 g, respectively, for Heraklion. Papazachos et al. (1995) specified seismic hazard in

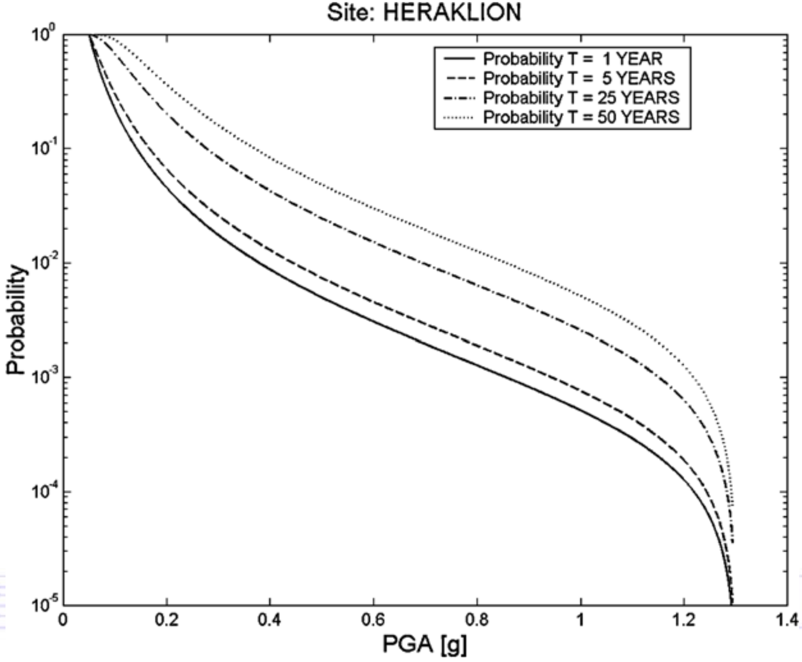
Heraklion in terms of expected values of horizontal PGA values for different time periods. The obtained values were 0.087 and 0.123 g for return periods of 50 and 100 years, respectively.

A probabilistic seismic hazard analysis has been also applied by Tsapanos (2003) to the sites of the main cities (Chania, Rethymno and Heraklion) of Crete island, Greece, to compute probabilities of exceedance of specified values of peak ground acceleration (PGA) and to estimate maximum possible PGA at each site. These cities are sited in the area of the subduction of Eurasia and Africa's lithosphere. The maximum observed magnitudes for the three cities occurred during the historical era. Chania is located about 70 km from the largest known earthquake in Greece with magnitude 8.3 generated in 365 AD, Rethymno is within a distance of about 95 km from the epicentre of the earthquake of 1629 of magnitude 7.3, while Heraklion is situated at a distance of about 60 km from the epicentre of the event of 1508 of magnitude 7.5. Details for the effect of these earthquakes on the island of Crete can be found in Papazachos & Papazachou (1997).

The methodology allows the use of historical or instrumental data, or a combination of both. The instrumental part of the data can be divided into sub catalogues with each having an individual minimum threshold magnitude for completeness. Also incorporated into the procedure were recently published maximum possible magnitudes for each site (6.48, 5.21, 7.52 for Chania, Rethymno and Heraklion, respectively) and an attenuation law for shallow seismicity in Greece $[\ln(PGA) = 3.52 + 0.70M_w - 1.14 \ln(R^2 + h_0^2)^{1/2} + 0.12S \pm 0.70]$, where R and h_0 are, respectively, the epicentral distance and focal depth in kilometres, S is 0, 1 or 2 depending on soil conditions and PGA is in units of $cm \cdot s^{-2}$. The maximum PGA for Heraklion varies from 0.130g (S = 0, rock) to 0.165g (S = 2, soft). All three sites are coastal, and alluvium is the dominant soil type, for which S = 2. Probabilities that a given PGA will be exceeded at least once during time intervals of 1, 5, 25 and 50 yr were also computed. Additionally, maximum PGA values associated with 'design earthquakes' were computed. For earthquakes at epicentral distances of 10±5 km, median values of maximum PGA were 0.23g, 0.09g and 0.42g at Chania, Rethymno and Heraklion, respectively.


Site: CHANIA
Probability T = 1 YEAR
Probability T = 5 YEARS
Probability T = 25 YEARS
Probability T = 50 YEARS
Probability
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
PGA [g]


Site: RETHYMNO
Probability T = 1 YEAR
Probability T = 5 YEARS
Probability T = 25 YEARS
Probability T = 50 YEARS
Probability
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
PGA [g]



<u>Figures 10a, b, and c</u> Seismic hazard for the cities considered: Chania, Rethymno and Heraklion, respectively. The seismic hazard is expressed as the probability of exceedance of a specified value of PGA at least once during a given time interval of 1, 5, 25 and 50 yr.

Papazachos et al. (1995) specified seismic hazard in Heraklion in terms of expected values of horizontal PGAs for different time return periods. The obtained values were about 85 cm $s^{-2} \approx 0.087$g and 121 cm $s^{-2} \approx 0.123$g for return intervals of 50 and 100 yr, respectively. Previous studies also comprise assessments of the expected ground-motion in terms of PGA.

Makropoulos & Burton (1985) presented values that have a 70 per cent probability of not being exceeded in a given time interval. Over T = 50 and 100 yr, these values are 64 cm $s^{-2} \approx 0.065$g and 72 cm $s^{-2} \approx 0.073$g, respectively, for Heraklion. Horizontal PGA values of 46 cm s^{-2} (≈0.047g) and 45 cm s^{-2} (≈0.046g) were recorded in Heraklion and Chania, respectively, at corresponding epicentral distances of 45 and 65 km, following the 1994 May 23 earthquake of magnitude Ms = 5.8 and focal depth of h = 79 km (Margaris et al. 1995). The same authors found that the site effect in Heraklion caused an increase of about 2 units in the intensity of the earthquakes. This earthquake caused damage at Heraklion and Chania (Papazachos & Papazachou 1997). In a detailed study Tsapanos (2001) estimated the earthquake hazard parameters (m_{max}, λ and β) in cells of 0.4X0.4 deg^2, in which Crete island and the adjacent area was divided. Based on these parameters he assessed seismic hazard as the annual probability of exceedance of a specified value of magnitude and the mean return periods (in years) that are expected for a given magnitude. These maximum possible magnitude are listed in Tables 3 and 4.

	a_{max} (0.5)	a_{max} (0.84)	$m_{max} \pm SD$
Chania	**0.44**	**0.91**	**6.48 ± 0.18**
Rethymno	**0.18**	**0.37**	**5.21 ± 0.19**
Heraklion	**0.92**	**1.91**	**7.52 ± 0.31**

Table 3 Median $a_{max}(0.5)$ and upper 84 per cent confidence limit amax(0.84) of maximum credible PGA (in units of g) at the sites of the three cities. The strongest possible magnitude, m_{max} (Tsapanos 2001), which is considered as the 'design' earthquake and is obtained by the application by the KSB estimator, with epicentre at the site of the city.

In Table 3 we observe that for the city of Heraklion $a_{max}(0.84) = 1.91$, which is about the double the acceleration due to gravity, and this is caused by the attenuation formula used, which seems to be so sensitive and does not fit well with the epicentral distance $R_0 = 0$. This is a good paradigm of how careful we have to be in the interpretation of the calculated PGA at very short distances. In order to obtain reliable results Kijko & Graham (1999) suggested these distances should be greater than or equal to 10 km as it is shown in Table 4. The New Greek attenuation law takes into account the factor of the soil conditions. All the presently investigated sites (cities) are located on the seashore. Therefore, alluvium is the dominant soil type, for which the soil classified factor, S, is 2. It is well known (Papazachos & Papazachou 1997) that earthquakes in Greece cause damage when the peak ground acceleration exceeds 90 cm s^{-2} (≈0.09g) but because of the different types of soil conditions in the affected areas this value is not valid.

	10 km		**20 km**		**30 km**		$m_{max} \pm SD$
	a_{max} (0.5)	a_{max} (0.84)	a_{max} (0.5)	a_{max} (0.84)	a_{max} (0.5)	a_{max} (0.84)	
Chania	**0.23**	**0.51**	**0.12**	**0.26**	**0.08**	**0.17**	**6.48 ± 0.18**
Rethymno	**0.09**	**0.20**	**0.05**	**0.11**	**0.03**	**0.07**	**5.21 ± 0.19**
Heraklion	**0.42**	**0.95**	**0.26**	**0.56**	**0.17**	**0.36**	**7.52 ± 0.31**

Table 4 Median $a_{max}(0.5)$ and upper 84 per cent confidence limit $a_{max}(0.84)$ of maximum credible PGA (in units of g) at critical epicentral distances of 10, 20 and 30 (±5) km of the three cities. The strongest possible magnitude, mmax (Tsapanos 2001), which is considered as the 'design' earthquake is obtained by the application of the KSB estimator.

Recent research work on active tectonics in this area (Smith et al., 1994, Oral et al., 1995, Papazachos et al., 1998, 1999a; Papazachos, 1999a) allows a better seismic Moreover, recent research work on the macroseismic field of this area (Papazachos and Papaioannou, 1997, 1998) provides improved attenuation and scaling relations for the macroseismic intensities and allows the determination of the site effects on the strong-ground motion of all the inhabited areas. For the previously mentioned reasons, an attempt is made by Papaioannou and Papazachos (2000) in order to improve both seismic zonation and attenuation relations for a more reliable assessment of time-independent seismic hazard in all 125 sites that appear in the New Seismic Code of Greece. In order to have a better geographical cover of the area they have included some additional sites and so the final number of the investigated sites is 144.

Previous work on seismic zonation in the Aegean and surrounding area (Algermissen et al., 1976; Papazachos, 1980; Hatzidimitriou, 1984; Papazachos et al., 1985; Makropoulos et al., 1988; Papazachos and Papazachou, 1997), work on seismicity (Stavrakakis and Tselentis, 1987; Papazachos, 1990; Hatzidimitriou, et al., 1994; Papazachos, 1999b) and active tectonics (Smith et al., 1994; Oral et al., 1995; McClusky et al., 1999; Papazachos et al., 1998, 1999b) as well as geological and geomorphological information, were used to separate Aegean and surrounding area in 67 seismogenic sources of shallow earthquakes (Figure 12).

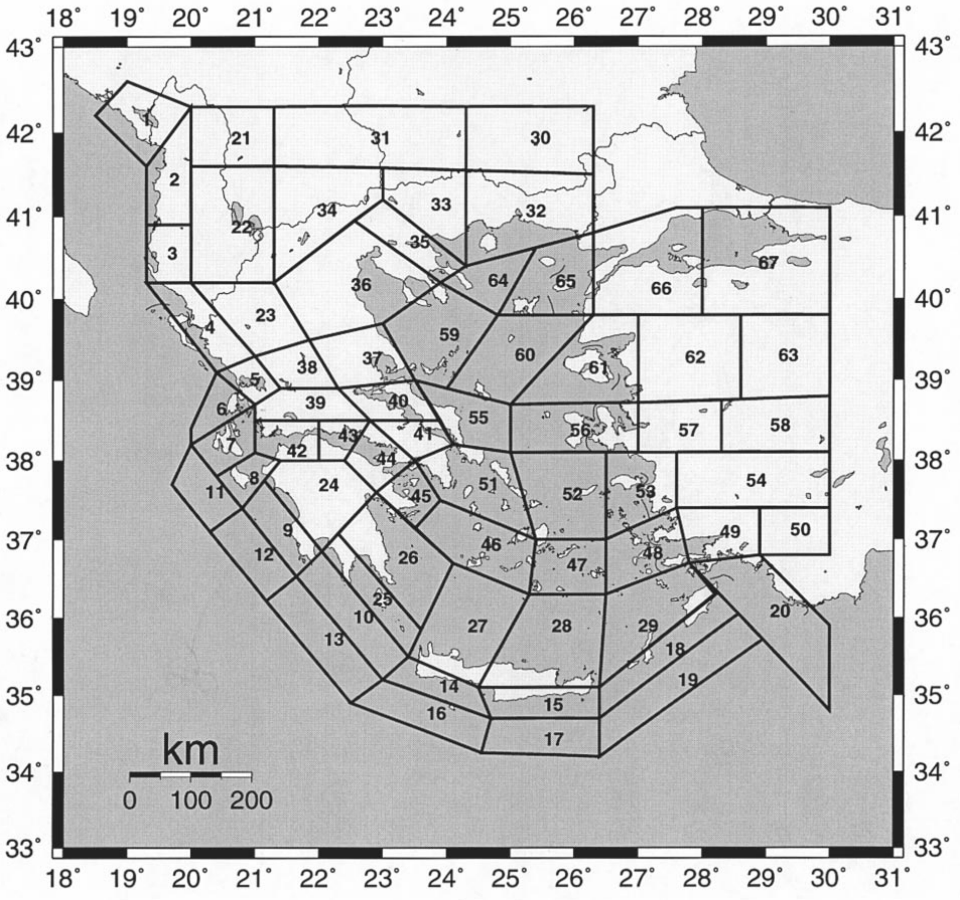


Figure 12

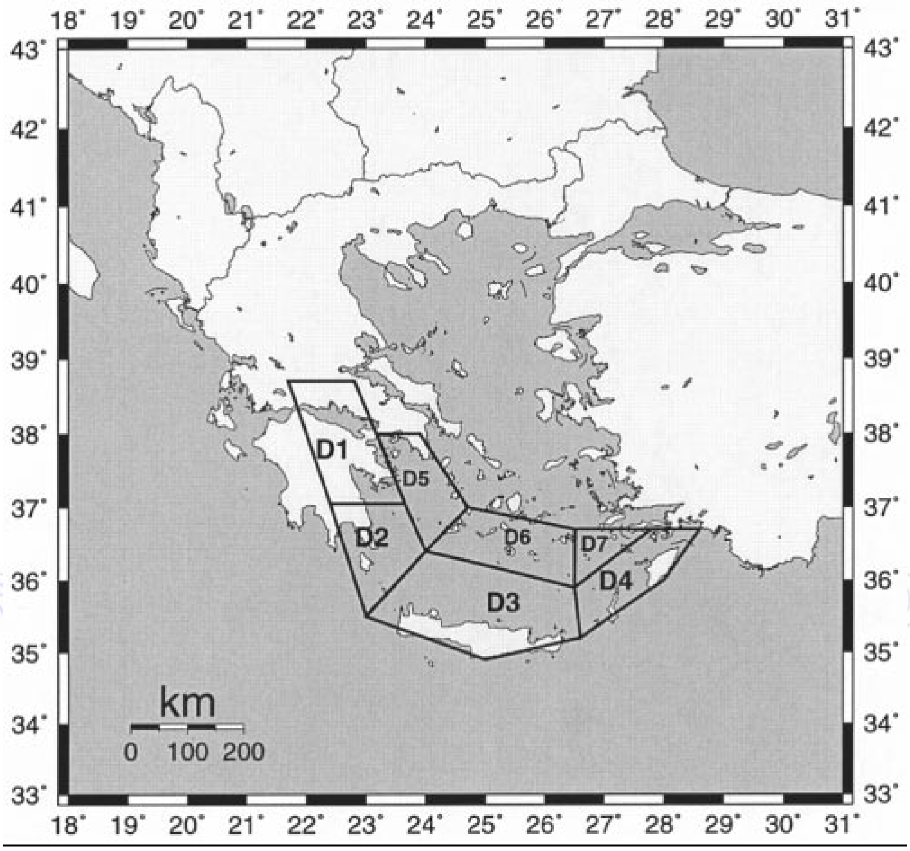


Figure 13 shows the seven seismogenic sources of the intermediate depth earthquakes in the southern Aegean (Papazachos and Papaioannou, 1993). The first four seismogenic sources are underlain by the shallow part (60 km ≤h ≤ 100 km) of the Benioff zone, and the other three are underlain by the deeper part (100 km , h ≤ 160 km) of the Benioff zone.

Table 5 gives the seismicity parameters for each of these seven seismogenic regions, which are necessary in order to estimate the seismic hazard due to intermediate- depth earthquakes at any site in the area of Greece.

Code	Name	b	a	Area, A, (km^2)	M_{max}	Rate, r, $M \geq 5.0$
D1	**Tripolis**	**0.56**	**2.28**	**19117**	**7.5**	**0.302**
D2	**Cythera**	**0.56**	**1.80**	**14362**	**7.5**	**0.100**
D3	**Heraklio**	**0.56**	**2.35**	**34673**	**7.8**	**0.355**
D4	**Rhodos**	**0.56**	**2.28**	**13718**	**7.5**	**0.302**
D5	**Methana**	**0.75**	**2.75**	**11317**	**7.0**	**0.100**
D6	**Thera**	**0.75**	**3.08**	**16349**	**7.0**	**0.214**
D7	**Nisyros**	**0.75**	**2.87**	**5141**	**6.2**	**0.132**

In order to assess the seismic hazard at a site, it is necessary to know the attenuation of the seismic intensity between the site and the seismogenic sources, which affect the site. The relations which are usually applied for this purpose, using the McGuire's (1976) code, are of the Cornell (1968) type:

$$I=b_2\ M + b_3 \log(\Delta + b_4) + b_1$$

where M is the magnitude of the earthquake, I is the macroseismic intensity at distance Δ (in km), and b_1, b_2, b_3 are constants that are determined by the available data.

Several attempts have been made to calculate the parameters of the above equation by the use of data of shallow and intermediate depth earthquakes in the area of Greece (Papaioannou, Papaioannou, 1984, 1986; Tassos, 1984; Papoulia and Stavrakakis, 1990; Theodulidis and Papazachos, 1992). Very recently Papazachos and Papaioannou (1997) used a large sample of macroseismic data concerning 284 shallow earthquakes to calculate the parameters. These earthquakes occurred in the Balkan area between 1901 and 1995 and had magnitudes between 4.1 and 7.8. The following equation was derived:

$$I = 1.43M - 3.59\log(\Delta + 6) + b_1$$

where I is the macroseismic intensity in the MM scale, M is the corresponding moment magnitude of the earthquake, and Δ is the epicentral distance. Using the value of b_1= 2.26, that holds for Greece, the standard deviation would be then equal to 0.87.

The parameter b_1 depends on several factors (macroseismic scale used, etc.) but mainly represents a site-effect term. This parameter cannot be calculated for every specific site where a structure will be constructed but it can be calculated for a broad site, that is, for the broader area covered by a city, town, and even a village. For this reason Papazachos et al. (1997a) used macroseismic information to calculate the value of parameter b1 for 144 sites, of which 126 are included in the NEAK. According to these results each value of the parameter b_1 corresponds to the mean value of the calculated b_1 estimates (applying equation 2) using reported intensities within a distance of 7 km from the examined site. These values of b_1 for every site (including the geographical coordinates) are listed in Table 6. Last equation implies that the shape of the isoseismals is a circle, that is, the energy source for every event is a point and there is no azimuthal variation of the released energy, which is not usually the case. In order to incorporate in the present hazard analysis the anisotropic radiation of the energy released, we followed the formulation of Papazachos (1992) and an implementation for this due to Margaris (1994) of the McGuire (1976) computer program. According to this formulation a factor, S, for the anisotropic radiation of the energy must be considered for the attenuation of the macroseismic intensities. This factor depends on the ellipticity,e, of the isoseismals, the azimuth of the major axis of the elliptical isoseismals, f, and the azimuth for each site/ direction we are studying. Extended information on the factor S and its application can be found in Papazachos, (1992) and Papazachos and Papaioannou (1997). According to Papazachos et al. (1999b), the major axis of the isoseismals is strongly influenced by the strike of the causative fault..

Site Name	φ0 ºN	λ0 ºE	b_1	c_2	I_{475}	P_{td}
AGIOS NIKOLAOS	35.177	25.719	2.42	3.865	6.83	0.302
AMORGOS	36.813	25.887	2.05	4.011	7.06	0.171
AREOPOLIS	36.663	22.381	2.41	4.477	7.50	0.285
CHANIA	35.511	24.017	2.94	4.425	7.40	0.374
IRAKLEION	35.344	25.118	2.91	4.280	7.22	0.300
KALAMATA	37.030	22.097	2.51	4.356	7.28	0.203
KANTANOS	35.277	23.699	2.92	5.555	8.65	0.432
KASTELLI	35.060	24.901	2.72	4.717	7.71	0.347
KASTELORIZO	36.078	29.710	3.40	4.961	8.15	0.295
KISSAMOS	35.494	23.616	2.42	4.347	7.34	0.337
KOS	36.896	27.306	2.88	4.761	7.72	0.320
KYPARISSIA	37.247	21.663	2.61	4.605	7.55	0.187
KYTHIRA	36.145	22.982	2.72	4.817	7.84	0.411
LEONIDION	37.163	22.848	2.56	3.929	6.77	0.275
MEGALOPOLIS	37.414	22.114	2.73	4.482	7.43	0.143
MESSINI	37.180	21.913	2.81	4.622	7.55	0.242
MILOS	36.729	24.417	3.03	4.160	7.12	0.240
MOIRAI	35.043	24.868	2.56	4.577	7.57	0.333
MONEMVASIA	36.679	23.048	2.44	3.882	6.77	0.303
PAROS	37.080	25.152	2.67	2.67	3.566	6.50
PYLOS	36.913	21.696	2.17	2.17	4.540	7.51
RETHYMNON	35.360	24.484	2.83	2.83	4.279	7.20
RODOS	36.429	28.240	2.47	2.47	4.139	7.25
SITEIA	35.193	26.104	2.72	4.151	7.10	0.324
SPARTI	37.063	22.414	2.72	4.800	7.81	0.284
THIRA	36.412	25.436	2.87	4.740	7.83	0.298
VAMOS	35.394	24.200	2.60	4.185	7.16	0.317

Table 6

For the attenuation of the intensity of the intermediate depth earthquakes in the southern Aegean the following relation has been used:

$$I = 1.69M - 3.34\log(\Delta + 30) + ct$$

where Δ is the epicentral distance. The value of the parameter ct is equal to 0.78 (Papaioannou, 1984; Papazachos et al., 1993) for the shallow part (sources D1–D4; 60 km $\leq h \leq$ 100 km) of the Benioff zone, which dips at a low angle (Papazachos, 1990). For the deeper part (sources D5–D7; 100 km , $h \leq$ 180 km), which dips at a higher angle, the
value of the parameter ct is equal to 10.69 (Papazachos et al., 1993).

Time-Independent Seismic Hazard in Greece

The seismic hazard (macroseismic intensity, in MM scale, as a function of the annual probability of exceedence or its reciprocal the mean return period) at the selected sites was calculated by a modification of the EQRISK program (McGuire, 1976) in order to use various attenuation relationships for every seismic source-site path.

The mean value of the macroseismic intensity (in MM scale) corresponding to a mean return period of 475 years was calculated by the use of the values Tm and the results are shown on Table 7. In the same table, the corresponding peak-horizontal-ground acceleration, γ_m, and peak-horizontal-ground velocity, u_m, are given.

	Zone I	**Zone II**	**Zone III**	**Zone IV**
Macroseismic Intensity	**6.6**	**7.3**	**7.6**	**8.2**
	Peak Horizontal Acceleration (%g)			
Papaioanou & Papazachos (2000)	**13**	**20**	**25**	**37**
Adopted in NEAK	**12**	**16**	**24**	**36**
Peak Horizontal Velocity (cm/sec)	**9**	**16**	**20**	**32**

Table 7 Average Macroseismic Intensities, Average Horizontal Peak- Ground Acceleration, cm, and Average Horizontal Peak-Ground Velocity for Mean-Return Period of 475 Years and for Each of the Four Zones of Equal Seismic Hazard Considered
in the New Greek Seismic Code (NEAK).

Peak ground acceleration hazard evaluation using the Makropoulos & Burton (MB) attenuation model

The MB attenuation model for Greece was derived from a few well-known formulae which had resulted from worldwide studies; this was because the limited number of strong motion records then available in Greece did not permit a regional study of attenuation of ground vibration. This model or formula is given by

$$a = 2164\, e^{0.7MS}\, (r + 20)^{-1.80}$$

where a cm/s^2 is p.g.a., M_S is the earthquake magnitude and r is hypocentral distance in km. This attenuation law is an average of eight independent attenuation laws used to describe the attenuation of p.g.a. by various authors in the mid-1970s. This average law was demonstrably compatible with the few observations of strong ground motion then available in Greece. In most of what follows the horizontal p.g.a. a_h is used. The earthquake records (1900–1999, $M_S \geq 5.5$) and (1964–1999, $M_S \geq 4.0$) are taken as best samples of complete data for Greece and these are usually adopted as the magnitude thresholds appropriate for analysis.

Acceleration seismic hazard at six cities from the MB model

The results for p.g.a.s which have 70 or 90% probability of not being exceeded in T-years, where T is 25, 50, 100 and 200-year, for six important cities and Revithoussa in Greece are listed in Table 8 . The return periods T' corresponding to T-year events with probabilities P of non-exceedance are listed in Table 9, to help interpretation of these hazard levels, noting that T'=1 /(1 -$P^{1/T}$). Generally, the p.g.a. values for data 1964–1999 are slightly smaller than the corresponding values for data 1900–1999.

Acceleration values emboldened in Table correspond to results from analysis of the earthquake catalogue for 1900–1999 with a 5.5M_S threshold, the best data span available, and to forecasts of the 50-year event with 90% non-exceedance probability (one chance in ten of exceedance). This corresponds to the event with an average return period of 475-year, which has become an arbitrarily accepted and typical norm for hazard comparisons.

Among these six cities, Athens, Corinth and Patras are located in the central belt dominated by the Gulf of Corinth Seismic Zone. The representative acceleration, $a_{P,T}$= $a_{0.9,\ 50}$ for Patras (data 1900–1999, threshold $M_S \geq 5.5$, T=50-year with P=90%) is about 130 cm.s^{-2}. This is quite a high value. The corresponding $a_{0.9,50}$ p.g.a. value for Athens is 126 cm.s^{-2}, with a lower value of 94 cm.s^{-2} resulting if only the more recent data are considered (1964–1999, $M_S \geq 4.0$). The corresponding representative $a_{0.9,50}$ p.g.a. value for Heraklion (Crete) and Rodhos are located in the southeastern part of the Hellenic Seismic Arc. The representative $a_{0.9,50}$ p.g.a. value for Heraklion is 70 cm.s^{-2} and for Rodhos is 93 cm.s^{-2}, apparently low values, given the substantial seismicity of the arc, but such values arise because they are associated with earthquake focuses at Intermediate depth, a factor which is allowed for through the attenuation model.

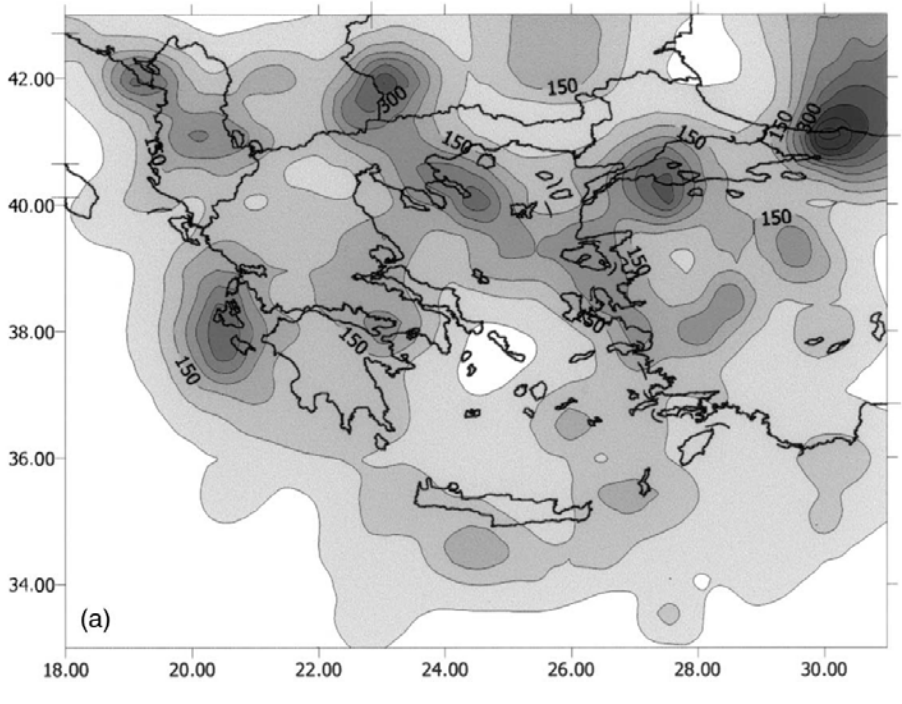
City	T = 25-year	T=50-year	T =100-year	T=200-year	Comment
Heraklion, 35.35N, 25.18E	**55.93**	**63.73 ***	**71.52**	**79.32**	**MB**
	41.76	**46.95**	**52.14**	**57.33**	**$M_S \geq 4.0$, 1964-1999, 70%**
	48.37	**56.23 ***	**64.09**	**71.95**	**$M_S \geq 5.5$, 1900-1999, 70%**
	50.89	**56.08**	**61.28**	**66.47**	**$M_S \geq 4.0$, 1964-1999, 90%**
	62.20	**70.06**	**77.92**	**85.78**	**$M_S \geq 5.5$, 1900-1999, 90%**

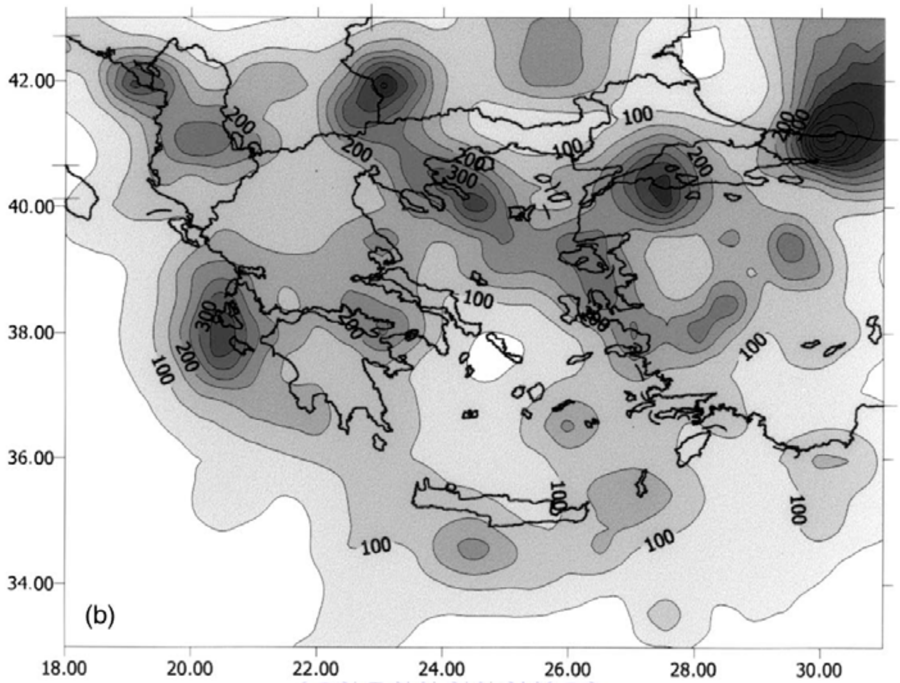
Table 8 Peak ground accelerations,cm.s^{-2}, which have 70 and 90% probability of non-exceedance in T-year, based on the Makropoulos and Burton model.

The overall change to results of site-specific seismic hazard analyses caused by an addition of 21 years of high quality earthquake catalogue data may be summarized through inspection of the values marked ‘ * ’ in Table 8. These changes are typically of order 10%. Only two of these major cities show an increase with an extra 21 years of data. These are Athens and Corinth which are associated with the earthquakes of Athens 1999 and Corinth 1981, respectively, during 1979–1999. The changes in this p.g.a. statistic are: Athens +7.5%, Corinth +13.1%, Heraklion -11.7%, Patras -10.1%, Rodhos -4.0%, Thessaloniki -8.3%.

Average return periods T'-year corresponding to T-year events with 70 and 90% probabilities of non-exceedance				
	T= 25-year	**T= 50-year**	**T= 100-year**	**T= 200-year**
T' at 70%	**70**	**140**	**280**	**560**
T' at 90%	**238**	**475**	**950**	**1900**

Table 9 Average return periods T’-years corresponding to T-years events with 70 and 90% probabilities of non-exceedance.




42.00
40.00
38.00
36.00
34.00
(b)
18.00
20.00
22.00
24.00
26.00
28.00
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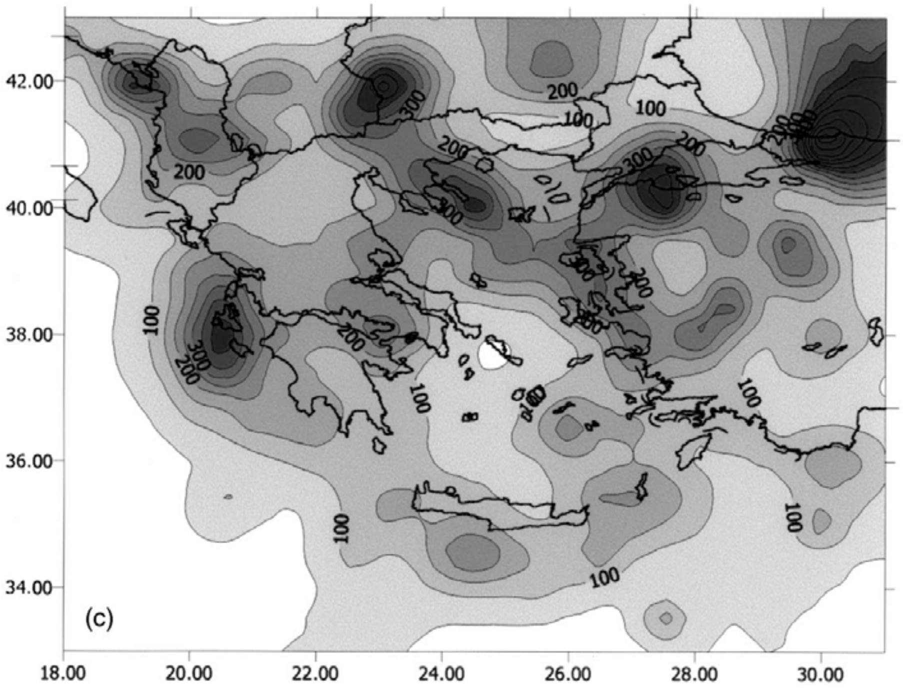
100
200
300


42.00
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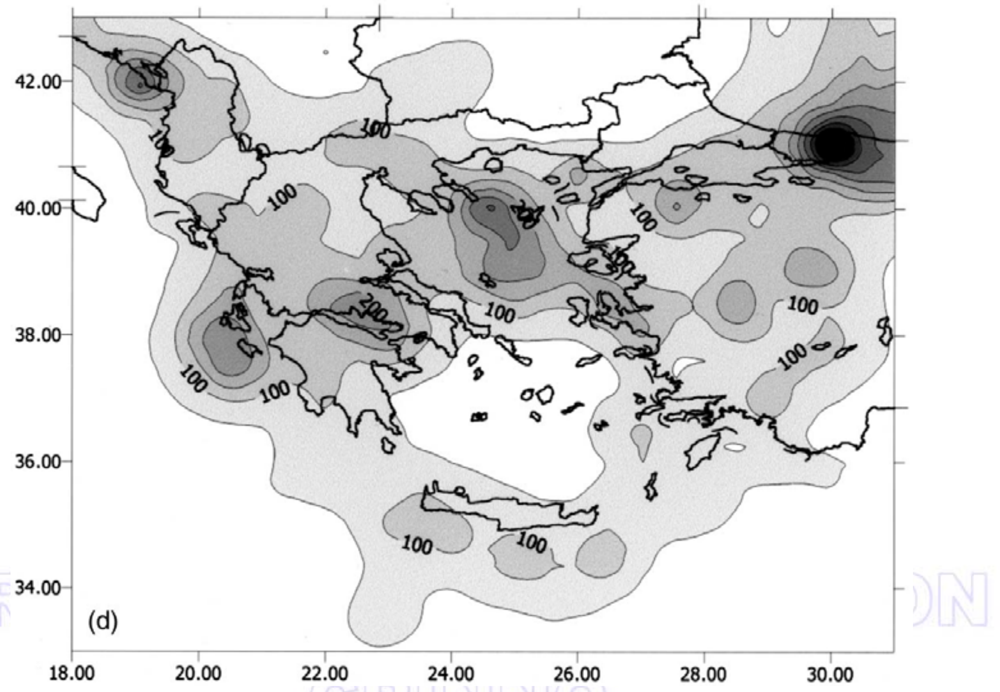
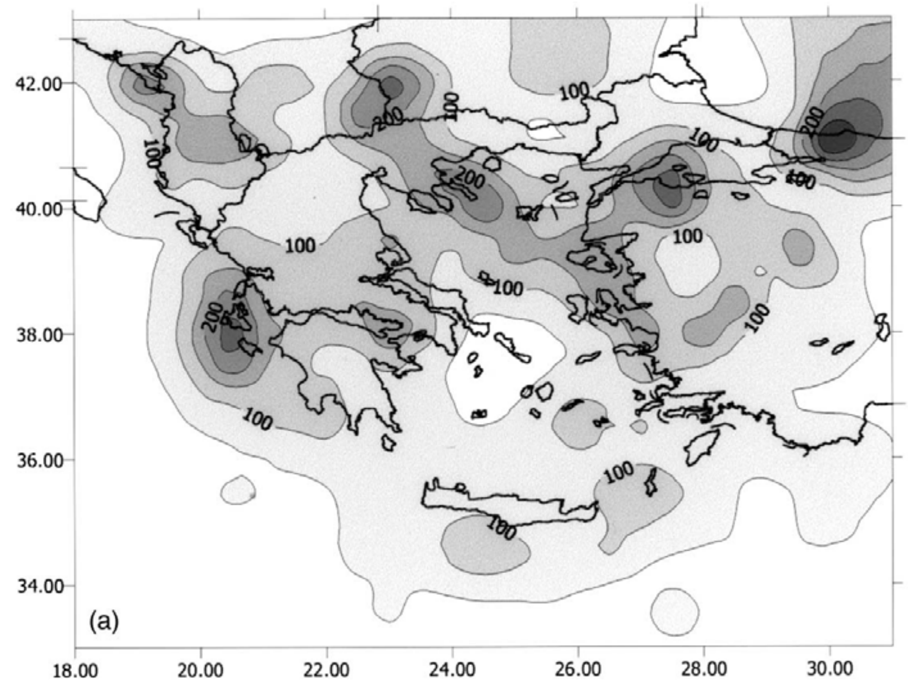


Figure 14 Seismic hazard maps for Greece using the MB attenuation relationship. Contours are expected maximum p.g.a.s (p.g.a. cm.s^{-2}) with 90% probability of not being exceeded (p.n.b.e.) during time periods: (a) 50-year; (b) 100-year and (c) 200-year, using data 1900–1999 with MS ≥ 5.5; (d) is 90% p.n.b.e. during 50-year using data 1964–1999 with MS ≥ 4.0.



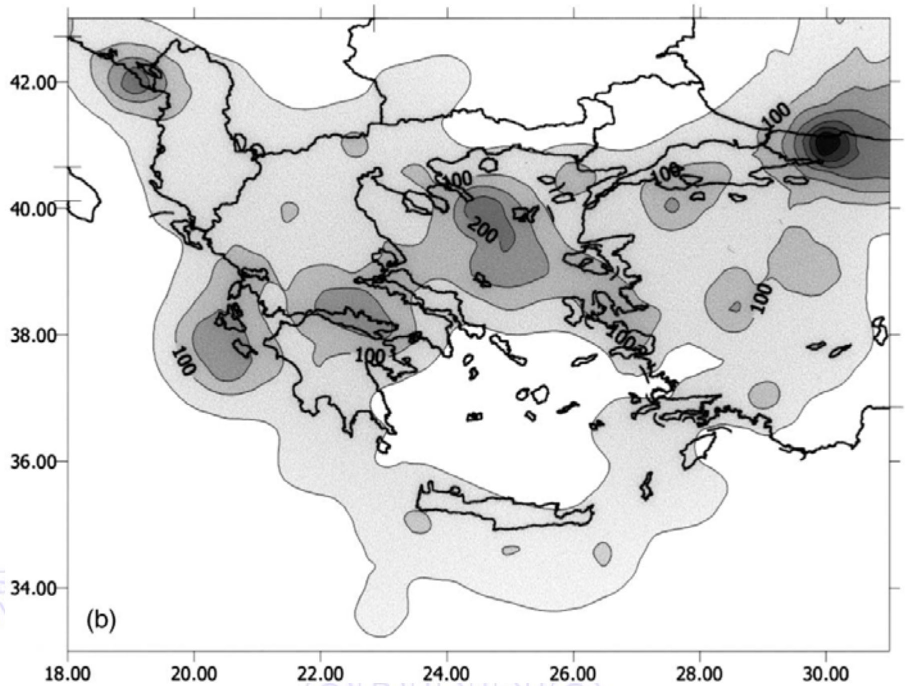


Figure 15 Seismic hazard maps for Greece using the MB attenuation relationship, illustrating contours of expected maximum p.g.a. cm.s^{-2} with 70% p.n.b.e. during 50-year: (a) using data 1900–1999 with $M_S \geq 5.5$; (b) using data 1964–1999 with $M_S \geq 4.0$.

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