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SEISMIC HAZARD PARAMETERS ESTIMATION IN GREECE AND THE SURROUNDING AREA BASED ON HISTORICAL AND INSTRUMENTAL DATA

Abstract. The maximum likelihood estimation of earthquake hazard parameters (maximum magnitude, activity rate, b-value) is obtained for several seismic source regions in Greece and the surrounding area, combining large historical earthquakes with complete instrumental data. From these parameters, the probability that different earthquake magnitudes will not be exceeded in a given time period is computed for each source. It is found that the highest probabilities are expected in the western (Cephalonia and Zakynthos islands) and southeastern (Carpathos, Rhodos and Crete islands) segments of the Hellenic arc, the Marmara Sea and the Northern Aegean Sea.

INTRODUCTION

The probabilistic method of seismic hazard analysis advanced by Cornell (1968) is mainly based on the delineation of potential seismic sources distributed around the site of interest, and the seismicity parameters (b-value, mean activity rate, maximum expected earthquake magnitude) of each source.

The most common method of summarizing past earthquake occurrence information in seismic hazard analysis is by means of a recurrence relationship.

A higher b-value means that a smaller fraction of the total earthquakes occurs at the higher magnitudes, whereas a lower b-value implies a larger such fraction.

Since the higher levels of motion at a site are dominated by the major earthquakes, knowledge of b is of great importance in seismic hazard analysis. However, b-value estimates may be different when different techniques are used (Aki, 1965; Utsu, 1965; Karnik, 1971).

Usually, the mean rate of earthquake occurrence is estimated from past seismicity data by assuming that the number of seismic events for the future follows the Poisson probability law. There is, however, a statistical uncertainty in the parameter λ. This uncertainty is reduced as the data increases, indicating that the volume of data has a significant effect on the quality of estimation.

Ambraseys (1978) pointed out that the estimation of maximum earthquake magnitude and its occurrence in space and time is the most difficult to assess of all seismic hazard parameters. The most common method of estimating the largest possible earthquake magnitude uses the theory of extremes which has been fully exploited by many investigators in various parts of the world (Lomnitz, 1966; Milne and Davenport, 1969; Karnik, 1971; Yegulalp and Kuo, 1974; Burton, 1979).

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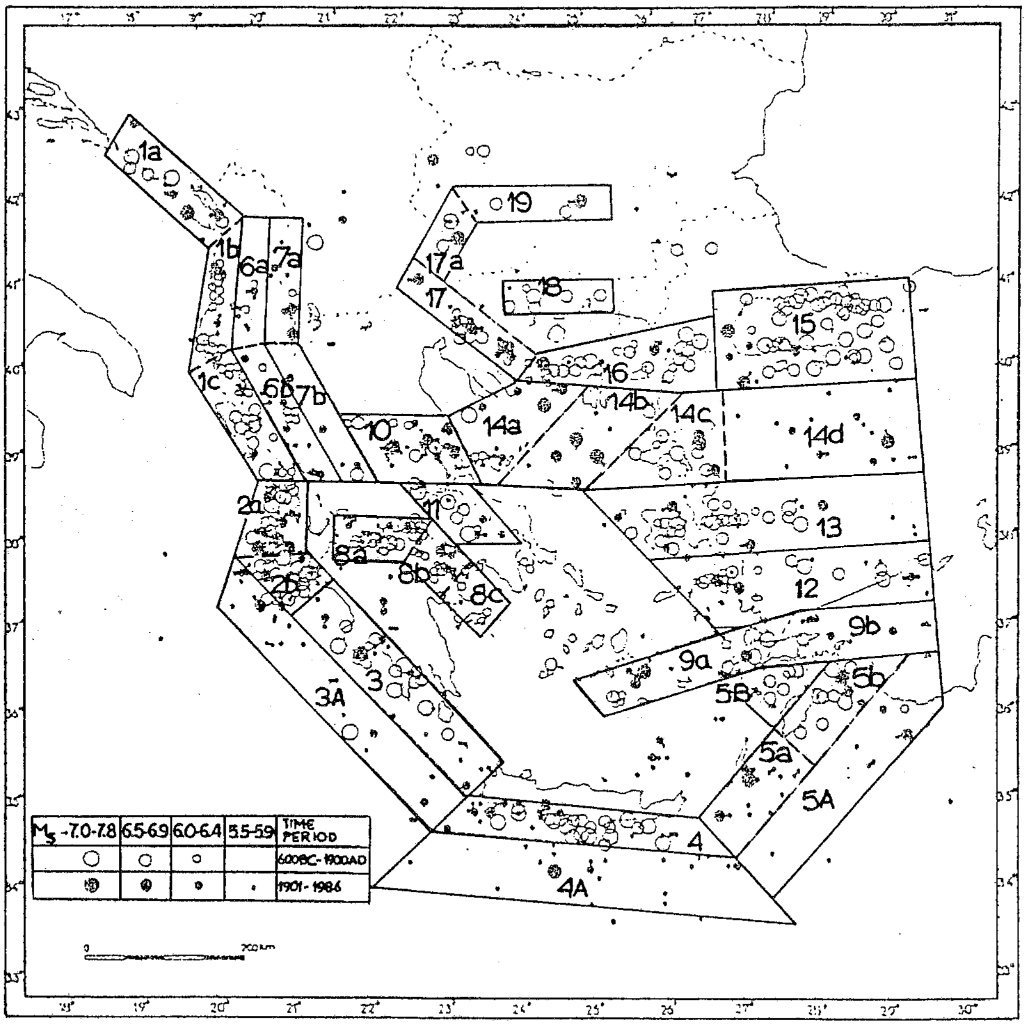

Fig. 1 - The seismic zones in the Aegean and surrounding area (from Papazachos, 1988).

Large uncertainties however arise in extreme value estimates of the three parameters b-value, return period, and maximum magnitude, in comparison with such estimates obtained from the full catalogue. Knopoff and Kagan (1977) and Kagan and Knopoff (1981) concluded that extreme value procedures are unsatisfactory for the determination of hazard parameters, being unreliable when for return periods greater than about one half the span of the earthquake catalogue. This indicates the need to incorporate either historical (non-instrumental) or other geophysical data in the complete instrumental earthquake catalogues, and much effort has been made by several investigators (Wesnousky et al., 1984; Anderson and Luco, 1983; Doser and Smith, 1982; Papastamatiou, 1980), by involving long-term slip rate data in seismic hazard estimation. It is widely accepted that a full use of all available data rather than just the extreme value extract still provides better estimates of the seismicity of a region. The problem really arises when more than one source of information on past occurrences is available.

Dong et al. (1984) used the maximum entropy principle to insert geological, historical and instrumental information of varying quality into a single minimally biased recurrence relationship. Anderson (1979), Molnar (1979), and Campbell (1977) proposed methods to obtain recurrence relationships from slip rates.

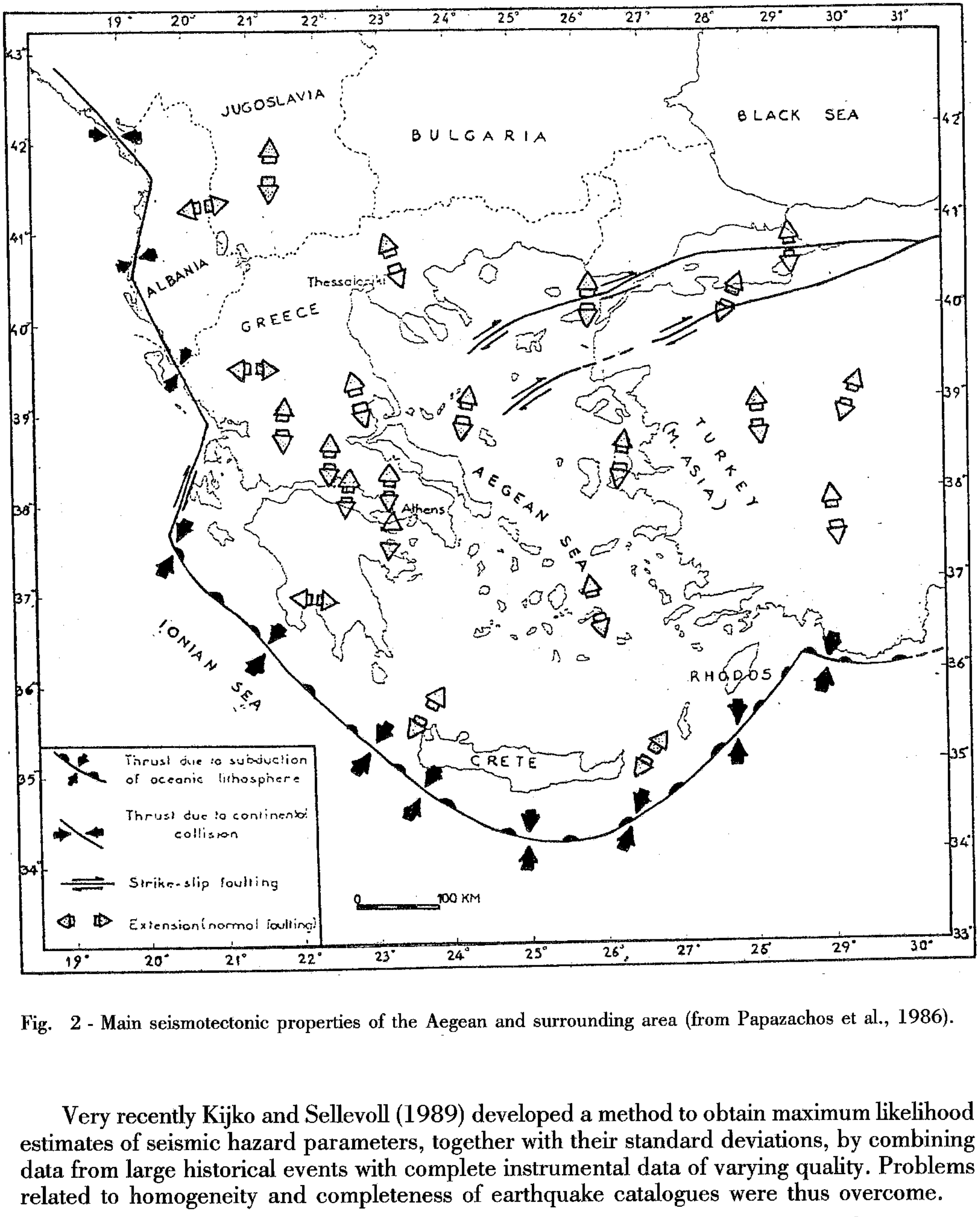

Fig. 2 - Main seismotectonic properties of the Aegean and surrounding area (from Papazachos et al., 1986).

Very recently Kijko and Sellevoll (1989) developed a method to obtain maximum likelihood estimates of seismic hazard parameters, together with their standard deviations, by combining data from large historical events with complete instrumental data of varying quality. Problems related to homogeneity and completeness of earthquake catalogues were thus overcome.

In the present analysis the above method is applied to compute the seismic hazard parameters for the main seismogenic sources in Greece and the surrounding area. Additionally, the non-exceedence probability of different earthquake magnitudes, in a given time, is estimated for each source.

Details and theoretical aspects of the method are found in Kijko and Sellevoll (1989), Fernandez-Garcia et al., (1989), Papadopoulos and Kijko (1991), and Slejko and Kijko (1991).

ESTIMATION OF HAZARD PARAMETERS FROM INCOMPLETE DATA

Considerable work on seismic zonation in and around Greece has been done in the past

Table 1 - Number of events over a threshold magnitude for the main seismogenic sources in Greece.

Source	Historical Events	Complete Part of Catalogue				
	23BC - 1800	1801-1910 (6.5)*	1911-1949 (5.2)	1950-1963 (4.8)	1964-1984 (4.5)	1985-1989 (4.0)
1a	4 (7.2)*	3	2	0	74	37
1b	8 (6.6)	6	6	7	26	9
1c	8 (7.0)	6	10	0	55	21
2a	17 (7.2)	6	35	53	135	11
2b	10 (7.2)	6	9	28	60	106
3	2 (7.0)	5	8	16	55	58
3A	1 (7.0)	0	6	35	106	85
4	13 (7.2)	3	18	7	95	52
4A	1 (7.1)	0	19	20	139	30
5a	-	0	19	12	68	40
5b	4 (7.2)	6	3	8	20	24
5A	-	0	13	4	30	8
5B	1 (7.0)	2	2	5	19	2
6a	-	0	9	3	38	5
6b	1 (6.1)	2	10	1	34	28
7a	1 (6.8)	0	8	1	6	4
7b	1 (6.5)	0	2	0	37	11
8a	9 (7.2)	6	13	7	63	25
8b	6 (7.0)	3	7	5	47	4
8c	1 (5.0)	2	3	0	9	1
9a	5 (6.8)	1	12	26	31	32
9b	1 (6.9)	0	10	10	36	9
10	13 (7.0)	0	9	39	47	11
11	5 (7.0)	4	8	1	40	9
12	5 (7.2)	12	7	10	74	17
13	12 (7.2)	10	14	9	51	28
14a	1 (6.0)	0	9	3	55	28
14b	5 (6.9)	0	1	4	68	18
14c	5 (6.9)	4	6	5	13	32
14d	-	0	16	7	173	19
15	39 (7.1)	6	10	17	24	12
16	13 (7.3)	8	3	7	22	16
17	6 (6.6)	1	10	4	31	8
17a	1 (6.9)	1	1	0	4	1

* Threshold magnitude
** Maximum observed magnitude

(Papazachos, 1980; Hatzidimitriou et al., 1985). Papazachos (1988) improved the delineation of the seismogenic sources in this area on the basis of the distribution of historical and instrumental data, as well as on geophysical and geological information, such as stress field, seismicity rates, b-value, orientation of isoseismals, and trends of geological zones. The proposed model, adopted in the present study, is illustrated in Fig. 1.

The main seismotectonic properties of the area under study, based on fault plane solutions, are shown in Fig. 2 (Papazachos et al., 1986). Horizontal compression dominates along the convex side of the Hellenic arc, where lithospheric subduction takes place, as well as along the western coast of Yugoslavia-Albania-Central Greece, where continental-continental collision occurs. Extensional movementes are present throughout the Aegean and surrounding area. Finally, strike-slip faulting occurs in the Ionian islands and in the northernmost part of the Aegean Sea.

Three different kinds of seismological data are used in the analysis: (i) large historical earthquakes for the period 473 BC - 1900 AC (Papazachos and Comninakis, 1982), (ii) instrumental data for the period 1901-1984 (Comninakis and Papazachos, 1986), and (iii) recent instrumental data for the period 1985-1989 (Bulletins of the National Observatory of Athens). Large historical earthquake information is also taken from a recently published catalogue (Papazachos and Papazachos, 1989).

The instrumental data for the different time periods are used by assuming a predetermined

Table 2 - **Seismic hazard parameters and non-exceedence probability of M=6, 7, with corresponding return period for the main seismogenic sources in Greece.**

Source	$b \pm \sigma b$	$\lambda \pm \sigma\lambda$ (for M=4.0)	$M_{max} \pm \sigma M_{max}$	Non-exceedence Prob. (in 20 years) M=6.0	M=7.0
1a	0.71 ± 0.05	3.19 ± 0.41	8.00 ± 0.44	0.16 (10) *	0.75 (73)
1b	0.64 ± 0.10	1.77 ± 0.37	6.74 ± 0.20	0.31 (15)	
1c	0.95 ± 0.12	5.15 ± 1.12	6.88 ± 0.72	0.36 (21)	
2a	0.93 ± 0.00	14.52 ± 0.86	7.60 ± 0.38	0.14 (9)	0.73 (72)
2b	1.17 ± 0.05	13.13 ± 1.27	7.24 ± 0.53	0.36 (20)	0.95 (620)
3	1.04 ± 0.07	7.20 ± 0.95	7.50 ± 0.52	0.35 (20)	0.93 (300)
3A	1.07 ± 0.15	14.07 ± 1.34	6.76 ± 0.24	0.22 (13)	
4	0.97 ± 0.05	9.56 ± 0.99	7.55 ± 0.40	0.16 (15)	0.85 (145)
4A	1.02 ± 0.00	10.43 ± 0.83	7.15 ± 0.22	0.22 (18)	0.95 (430)
5a	0.93 ± 0.00	7.21 ± 0.65	7.43 ± 0.46	0.18 (13)	0.87 (165)
5b	0.72 ± 0.00	1.92 ± 0.27	8.04 ± 0.37	0.28 (20)	0.81 (110)
5A	0.82 ± 0.12	2.25 ± 0.05	7.45 ± 0.42	0.41 (27)	0.92 (255)
5B	0.79 ± 0.14	1.14 ± 0.32	7.07 ± 0.23	0.63 (50)	
6a	1.00 ± 0.14	3.37 ± 0.83	6.37 ± 0.35	0.71 (57)	
6b	1.17 ± 0.10	4.27 ± 0.73	7.53 ± 1.23	0.71 (65)	
7a	0.53 ± 0.21	0.54 ± 0.21	6.62 ± 0.20	0.62 (42)	
7b	1.03 ± 0.17	2.85 ± 0.77	6.77 ± 0.29	0.70 (55)	
8a	0.99 ± 0.07	6.88 ± 1.21	7.55 ± 0.41	0.46 (28)	0.95 (360)
8b	0.98 ± 0.07	2.68 ± 0.51	7.34 ± 0.27	0.50 (42)	0.96 (725)
8c	0.72 ± 0.05	0.46 ± 0.02	6.33 ± 0.17	0.86 (150)	
9a	1.02 ± 0.00	5.09 ± 0.56	7.86 ± 0.34	0.44 (25)	0.92 (312)
9b	0.81 ± 0.10	2.37 ± 0.47	6.93 ± 0.21	0.42 (25)	
10	0.92 ± 0.05	4.63 ± 0.66	7.14 ± 0.22	0.34 (19)	
11	0.94 ± 0.08	2.45 ± 0.49	7.19 ± 0.24	0.58 (37)	
12	1.00 ± 0.06	5.54 ± 0.74	7.39 ± 0.24	0.39 (23)	0.93 (350)
13	0.93 ± 0.06	4.51 ± 0.65	7.37 ± 0.23	0.35 (20)	0.91 (300)
14a	1.23 ± 0.07	5.23 ± 0.79	7.40 ± 0.41	0.74 (65)	
14	1.09 ± 0.09	4.74 ± 0.74	7.51 ± 0.32	0.58 (40)	
14c	1.00 ± 0.09	2.80 ± 0.54	7.23 ± 0.26	0.63 (45)	
14d	0.98 ± 0.06	9.42 ± 1.00	7.22 ± 0.15	0.17 (10)	0.83 (110)
15	0.67 ± 0.04	2.53 ± 0.41	7.80 ± 0.22	0.15 (12)	0.72 (65)
16	0.72 ± 0.06	1.94 ± 0.37	7.61 ± 0.22	0.30 (20)	0.84 (130)
17	0.93 ± 0.00	2.44 ± 0.36	7.18 ± 0.24	0.57 (40)	
17a	0.78 ± 0.15	0.40 ± 0.20	8.55 ± 0.69	0.80 (100)	

* Return Period (in years)

threshold magnitude value. Thus, no procedure was applied to exclude aftershock events. More specifically, the complete catalogue (Comninakis and Papazachos, 1986) is divided into four subcatalogues, according to the completeness of data: (a) 1801-1910, with $M_S > 6.5$, (b) 1911-1949, with $M_S > 5.2$, (c) 1950-1963, with $M_S > 4.8$, and (d) 1964-1984, with $M_S > 4.5$. Earthquakes which occurred during the time period 1985-1989 are treated as an additional subcatalogue complete for magnitude 4.0 and above. Input parameters used in the analysis are summarized in Table 1.

DISCUSSION AND CONCLUSIONS

The most common procedure for estimating seismicity parameters uses the theory of extremes. The crucial problem however is the unacceptably large probable errors in such estimates. Additionally, the method is limited to homogeneous and complete data files. On the other hand, methods which utilize all available data give superior estimates of the seismicity parameters than do extreme value methods. Therefore, the incorporation of such information from different sources into the input parameters of the prababilistic seismic hazard analysis is of great importance.

Kijko and Sellevoll (1989) developed a method to obtain maximum likelihood estimates of seismic hazard parameters by combining data from large historical earthquakes with complete but short, and of varying quality instrumental catalogues. This method is applied to several seismogenic sources in Greece and the surrounding area, using different sources of data of varying quality, namely large historical earthquakes (incomplete data), and historical and instrumental data of varying completeness.

The maximum likelihood estimates of the mean rate of occurrence, b-value and maximum magnitude are obtained for each seismogenic soruce. The estimated parameters with their standard errors are summarized in Table 2. Based on these parameters and following the procedure proposed by Kijko and Sellevoll (1989), the non-exceedence 20-year probability for magnitudes 6.0 and 7.0, with corresponding return periods, is estimated and presented in the last two columns of Table 2.

The b-parameter of the frequency magnitude distribution ranges between 0.53 and 1.23 in the seismogenic sources considered. However, the most frequently obtained b values are about 0.9 ± 0.1, in accordance with those proposed by Hatzidimitriou et al. (1985). The mean yearly activity rate for magnitude $M > 4$ varies from about 2 events/yr (source 1b, 5b) to values exceeding 10 events/yr (2a, 2b, 3A, 4A). The maximum regional magnitude ranges between a minimum of 6.33 and a maximum of 8.55. The lowest value corresponds to the relatively aseismic zone of Saronikos gulf (source 8c). The significantly large value of maximum magnitude obtained for zone 17a can be justified in terms of the corresponding seismological data: very large events have taken place in this zone in the past (e.g. 1904 Kresna earthquake, $M = 7.7$).

In general, high probabilities ($>$80%) for the next 20 years are obtained for seismic sources 2a, 3A, 4, 5a, and 15. Seismic zone 2a has been recognized as a seismic gap (Papadimitriou and Papazachos, 1985), and exhibits the highest probability. Seismic zones 4, 3A, and 5a, which belong to the boundary of the Hellenic arc, also recognized as seismic gaps (Wyss and Baer, 1981a, 1981b), show very high probabilities, and are expected to have a significant seismic potential.

Stavrakakis and Tselentis (1987) computed the occurrence probabilities of moderate to large earthquakes in the investigated area, using instrumental data for the period 1901-1981 (Makropoulos and Burton, 1981), and applying Bayesian statistics, and they also obtained high probabilities for earthquakes with $M > 6.0$ in the sourthwestern part of the Hellenic arc (zones 3 and 3A).

Moreover, Papazachos et al. (1987) computed the occurrence probabilities of large earthquakes in the same area, using complete historical and instrumental data (Comninakis and Papazachos, 1986; Papazachos and Comninakis, 1982). The computations were done on the basis of the time of the last earthquake, the average repeat time, and its standard deviation.

A direct comparison of the results of the present study with those of previous ones cannot be achieved because of the different seismic source models, and hence different earthquake data used in the analysis.

Papadopoulos and Kijko (1991), applying the same methodology to the Greece area, gave an alternative interpretation of the obtained results, using a different earthquake data set. However, in the present application all available seismological data in Greece are considered, and the general behaviour of each seismogenic source is shown. The hazard parameters obtained may be further incorporated into traditional seismic hazard analysis to estimate the expected ground motion at different sites for each seismogenic source.

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