STATISTICAL AND SEISMOTECTONIC MODELS IN SEISMIC HAZARD ASSESSMENT: APPLICATION TO THE CITY OF THEVA, CENTRAL GREECE

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ABSTRACT

Two different methodologies for seismic hazard assessment are applied, and the obtained results are compared, at the present study. The first one (extreme value method) is based on pure statistical analysis of the seismological data, while the second one (Cornell's method) takes into consideration the general seismotectonic characteristics of the investigated region.

Both methods are applied to the city of Theva, Central Greece, in order to obtain a distribution of the expected seismic intensity and acceleration levels over a given duration of time. The analysis shows that the seismotectonic approach leads to considerably more reliable seismic hazard estimations.

Introduction

Generally, the methods used in seismic hazard assessment fall into two categories:

(i) those based on pure statistical models (extreme value statistics), without taking into consideration the seismotectonic characteristics of the investigated region (Drakopoulos and Makropoulos 1983, Makropoulos and Burton 1985, Papoulia et al. 1985). The reliability of these models strongly depends on the time duration of the seismological data. It has been shown that the return period of high magnitude earthquakes (M>7.0) can be accurately estimated only when the time period of observations is greater than 600 years (Anderson 1979). Therefore, the duration of data is the most important criterion using extreme value statistics.

(ii) The second category is based on the combination of the main seismotectonic characteristics with the recurrence model of small seismic sources in the investigated region (Algermissen and Perkins 1976, Papaioannou et al.

1985, Papazachos et al. 1985, Stavrakakis 1986, Stavrakakis et al. 1987). These models are referred as "point source models" (Cornell 1968), because they are based on the assumption that the total energy released during an earthquake is radiated from the focus (point) of the earthquake.

The choise of a model for seismic hazard analysis is usually based on the available data and the possibility of incorporating the maximum of information.

Thus, extreme value method can theoretically be applied to any region, assuming the existence of a complete and homogeneous catalogue, whereas the application of Cornell' s method requires detail knowledge of the seismotectonics of the region.

In the present study both methods are applied to the city of Theva for estimating the expected seismic ground motion over a given duration of time. The results of the two models are then compared, and their inherent uncertainties and limitations discussed.

Extreme Value Theory in Seismic Hazard Assessment

Introduction

Extreme value theory has been multiply used in seismic hazard studies, in many different parts of the world (Gumbel 1954, Nordquist 1945, Dick 1965, Epstein and Lomnitz 1966, Makjanic 1972, Makropoulos 1978, Burton et al. 1983, Makropoulos 1983, Drakopoulos and Makropoulos 1983, and others).

The most important advantages in the application of the theory of extreme values are the following (Lomnitz 1974):

(i) The maxima of a geophysical variable are homogeneous in time, and more accurately estimated.

(ii) The method does not take into account the parent distribution of the investigated parameter, its application being very simple.

The theory of extreme values is based on the assumptions (Gumbel 1966):

(i) The future seismic activity of an area is expected to be similar to that of the past years. This assumption is justified by the fact that seismicity is not equally nor randomly distributed, but occurred at certain areas, specifically along plate boundaries. This practically means that no essential variation in seismicity is to be expected within the time period of observations.

(ii) The maximum values of a geophysical variable are inter-independent. This assumption is reasonable, since high magnitude earthquakes are independent in space and time (Gumbel 1966, Lomnitz 1966).

Mathematical Formulation of the Model

The mathematical formulation of the model of extreme values has been discussed in previous studies, and therefore only a brief presentation of the three types of the asymptotic distributions will be made here.

Let I be a discrete variable describing the maximum seismic intensity. The three asymptotic distributions (Gumbel 1966) are given by

$$\Phi I(Imax)= \exp\{-\exp(-a(Imax-u))\},\quad a>0 \qquad (1)$$

$$\Phi II(Imax)= \exp\{-[(u-\varepsilon)/(Imax-\varepsilon)]k\},\quad k>0,\ u>\varepsilon>0,\ Imax>\varepsilon \qquad (2)$$

$$\Phi III(Imax)= \exp\{-[(\omega-Imax)/(\omega-u)]k\},\quad k>0,\ Imax<\omega,\ u<\omega \qquad (3)$$

where u is the characteristic maximum value of seismic intensity (mode) with 63% probability of exceedance, and

$$\Phi I(u)= 1/e \qquad (4)$$

ω is the upper bound of the third asymptotic distribution, meaning

$$\Phi III(\omega)= 1 \qquad (5)$$

ω is characteristic for the area of study, and is related to the maximum possible magnitude to be occurred.

Finally, parameter k is related to the geometrical shape of the distribution, showing the rate of approaching the upper bound.

Several methods have been proposed for the estimation of the parameters of the three asymptotic distributions (Kimball 1960, Stepp 1971):

Specifically, the parameters of the first asymptote are estimated using either the maximum likehihood or the least squares method, while those of the third asymptote can be estimated using the method of moments (Gumbel 1966, Yegulalp and Kuo 1974).

Application of the Model

Extreme value theory is applied to the city of Theva, in order to obtain a specification of maximum expected seismic intensity over a given duration of time.

The data used in the analysis are the macroseismic intensities, in MM scale, observed at the city of Theva within the last 86 years, taken from the following sources:

1) Annual Bulletins of the National Observatory of Athens, for the period 1900 - 1939.
2) Monthly Bulletins of the National Observatory of Athens, for the period 1950 - 1986.
3) Atlas of isoseismal maps for the Balkan region (Unesco 1978).
4) Atlas of isoseismals for earthquakes in Greece (1902 - 1981) (Papazachos et al. 1982).

The parameters of the earthquakes are taken from the catalogue Makropoulos and Burton (1981), and ISC bulletins.

Macroseismic intensities are investigated using both first and third asymptotic distributions. Thus, observed values are statistically elaborated applying HAZAN computer program (Makropoulos and Burton 1981). Figure (1) illustrates the intensity-probability distribution and the correspondent return period, while Tables I and II tabulate the most probable maximum intensity (mode), and the intensity with a certain probability of exceedance within the next T years, respectively.

Estimated hazard values, in terms of expected seismic intensities, seem to be underestimated in comparison with the observed values in the area of study. Moreover, it should be emphasized that the application of the first or third asymptote only slightly differentiates the expected hazard. However, the choise of the third asymptotic distribution is justified based on the following:

(i) For any particular event, maximum expected seismic intensity is a function of magnitude. Regarding earthquake magnitude, the upper bound of the third asymptotic distribution is correlated with the geometrical characteristics of fault and dynamic characteristics of the rupture. From empirical relationships of the form

$$I_{max} = a + bM \qquad (6)$$

it comes out that, since earthquake magnitude is upper limited, the same is expected to be with regards to maximum intensity.

(ii) Macroseismic intensity scales are based on the response of structures. Parallel to the continuous development of seismic codes, the upper bound of the third asymptotic distribution is given a greater physical meaning.

Cornell's model in Seismic Hazard Assessment

Introduction

The probabilistic assessment of seismic hazard using the seismotectonic approach involves four different stages: (i) delineation of seismic sources , (ii) determination of the recurrence model of earthquakes in each seismic source, (iii) consideration of attenuation of ground motion, and (iv) contribution of all potential sources to future seismic load at the site of interest.

Seismic source model

The delineation of seismic sources is based on the combination of the spatial distribution of earthquake epicenters with the main tectonic features in the area of study. Seismic sources, in which a good correlation between epicentral distribution and well defined fault zones occurs, are identified "linear", whereas, in case of no such correlation, sources are characterized "areal". The exact position of a fault in linear sources is defined by multiple regression analysis of epicenter coordinates in each source.

It is assumed that, when an earthquake occurs, the epicenter has an equal probability of occurring anyplace in each seismic source.

Recurrence model of earthquakes

The probabilistic model describing the occurrence of earthquakes is Poisson model, pressuming that earthquakes are independent events, in space and time, and their mean rate of occurrence is constant.

This assumption does not introduce any limitation in engineering practice, and has been widely adopted in almost all seismic hazard models.

The probability of occurrence of n events of a certain magnitude within the next t years is given by

$$P(n) = \exp(-vt)(vt)^n/n!, \quad n = 0,1,2,\ldots \qquad (7)$$

Then, Gutenberg-Richter's parameters are estimated by multiple regression analysis of data in each source of the proposed model.

Attenuation of ground motion

Attenuation of strong ground motion is a function of source characteristics, transmission path, geometrical spreading, absorption coefficient, and local site conditions. In practice, all these parameters are very difficult to be accounted for, and the estimation of the expected ground motion is usually based on empirical equations derived from regressions of observed motions against earthquake magnitude and distance from source to site.

The majority of seismic hazard models (Cornell 1968, McGuire 1978, Algermissen and Perkins 1976) assume a general function of the form

$$g_s = f(M,R) \qquad (8)$$

where g_s is the site ground motion, M is the earthquake magnitude, and R is the epicentral or hypocentral distance.

In the present study, macroseismic intensity distribution is examined using a mean attenuation law proposed for the area of Greece (Papaioannou 1984), while peak ground acceleration distribution is investigated using three different formulas (Makropoulos 1978, Papaioannou 1984, Papoulia 1988).

Seismic hazard estimation

On the basis of the recurrence model of earthquakes, seismicity, geometry and geographical position of each seismic source, and attenuation law, the return period for different levels of macroseismic intensity and peak ground acceleration is estimated. It is emphasized that estimated acceleration is referred at a base rock level for the city of Theva, its transformation to the ground needing further estimations.

Figure (2) illustrates the seismic epicentral distribution and the proposed seismic source model for the city of Theva. Source modelling is attained considering the main seismotectonic characteristics of the area (Mariolakos et al. 1985).

Specifically, because of the random epicentral distribution and the complicated tectonic regime, sources A_1 and A_2 are considered areal.

Source L_1, in the northwestern part of Evia, is identified linear, because seismic epicenters are approximately correlated with a small fault zone of NW-SE direction occuring in this area.

Earthquakes in source L_2 occur along the well defined major fault zone of Atalanti, therefore this is characterized linear.

The tectonic evolution of the Gulf of Corinth is mainly characterized by vertical movements along normal faults of E-W direction, many of which are still active today. Seismic epicenters are well distributed along this major fault zone, and source L_3 is also identified linear.

Finally, epicentral distribution is very dense in source L_4, very close to the city of Theva. This source is characterized linear following the direction of the seismic fault of Kaparelli-Platees, which occurred during the earthquake sequence of February-March 1981.

All characteristic parameters of the seismic sources of the proposed model are summarized in Table III, where b is the parameter of the exponential distribution of the recurrence model of earthquakes, estimated by regression analysis of the data of each source, RATE is the mean annual rate of events above a minimum magnitude, DEPTH is the mean focal depth, Mmin is the minimum considered earthquake magnitude, Fi represent the geometrical characteristics of sources, and Mmax is the maximum probable magnitude for each source estimated on the basis of statistical studies (Drakopoulos and Makropoulos 1983, Makropoulos and Burton 1984a).

All computations are made using the computer program written by Cornell (1968). The results of the analysis are summarized in Tables IV to V. Figures (3) to (4) illustrate the macroseismic intensity distribution and peak ground acceleration distribution, respectively.

Estimated macroseismic intensities are well correlated with the observed ones in the city of Theva.

The critical point, however, seems to be the "edges" of the investigated parameter. Specifically, low intensities are rather underestimated, while high intensities seem to be overestimated. This is probably due to the distribution of events in each seismic source. Moreover, the results are strongly dependent upon the attenuation model. The intensity attenuation formula used in the present study is an average one, valid for shallow events in the area of Greece, and therefore the results represent a mean return period for the area of study.

Regarding peak ground acceleration distribution, no direct correlation between estimated and observed values is possible, due to lack of strong motion data. Considering however the data of the earthquake sequence of February 1981, and correlating maximum ground acceleration with maximum expected macroseismic intensity, it is shown that estimated values are well approaching observed ones.

The influence of the attenuation relationships on the hazard results is emphasized using three different attenuation functions. This is particularly evident at the upper edge of the probability distribution (Figure 4). Improvement of hazard estimations requires that these empirical attenuation relationships are updated, and must therefore await more strong motion data.

Comparison of the Results of the two Models

The object of assessing seismic hazard analysis is to define the probability of exceedance of a certain level of seismic ground motion over a given duration of time. This can be attained either by using pure statistical models, like extreme value statistics or seismotectonic ones, like Cornell' s model, which further consider the seismotectonic regime of the investigated region, incorporating this information in the analysis.

The application of extreme value statistics is rather simple, requiring only an earthquake catalogue for the area of interest. The seismic parameter to be investigated can be either the earthquake magnitude and seismic moment or the peak values of ground parameters (acceleration, velocity, displacement, or seismic intensity).

The assessment of seismic hazard is based on statistical analysis of the seismological data. It is therefore obvious that, the reliability of hazard estimations is dependent on the completness of data and the time duration of the catalogue.

When the investigated parameter is the macroseismic intensity, further attention has to be given.

Theoretically, the range of values, on the basis of which the probability of exceedance is to be estimated, can vary between a minimum of 4.0 MM and a maximum of 12.0 MM. This range can be considered reliable for calculations, however, in practice, the maximum intensity value never occurs in Greek catalogues, whereas the minimum one is not accurately estimated. This considerably decreases the range for the interpolation of hazard values.

Finally, as mentioned before, the method does not take into account the seismotectonic characteristics of the investigated region.

On the other hand, the estimation of hazard using Cornell' s model involves the following requirements:

(i) Earthquake catalogue of the region
(ii) Seismotectonic characteristics
(iii) Seismicity of the source
(iv) Attenuation of ground motion from source to site.

On the basis of the geographical distribution of epicenters and the general seismotectonic characteristics of the region, the potential seismic sources are first delineated. The recurrence model of earthquakes in each source is then defined, and considering an attenuation law of the investigated parameter, the future seismic load is estimated at the site of interest.

The model seems to be sensitive to a certain number of parameters and physical relationships. It has been revealed (McGuire and Shedlock 1981) that the parameter b of the recurrence model of earthquakes, the rate of occurrence, the geometry of sources, as well as the attenuation relationship strongly affect the results of seismic hazard estimations.

Specifically, the parameter b is estimated by the analysis of observed data from each seismic source. However, the data base on a given source is often incomplete and nonhomogeneous in time, leading to large uncertainties in the estimation of b. This is a critical point in the application of the model.

Comparing the results of the two methodologies - Extreme Value Statistics, and Cornell' s model - it is first noticed that, the seismic hazard values, as obtained by the application of Cornell' s model, are higher and better approximating the observed values at the site of interest.

Moreover, the model predicts the seismic hazard combining the seismological and seismotectonic information in the study region, instead of considering only the maximum values of the investigated parameter, and is therefore considered more reliable.

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Captions of Tables

Table I : Most Probable Maximum Macroseismic Intensity for the next T years (T-year mode)

Table II : Macroseismic Intensity with P-probability of exceedance for the next T years

Table III : Macroseismic Intensity Results for a range of Return Periods, using Cornell' s model

Table IV : Peak Ground Acceleration Results for a range of Return Periods, using Cornell' s model

Figure Captions

Figure 1 : Intensity - Probability Distribution and correspondent Return Period for the city of Theva, Central Greece

Figure 2 : Seismic Epicentral Distribution and Proposed Seismic Source Model for the city of Theva, Central Greece

Figure 3 : Macroseismic Intensity Distribution for the city of Theva, using Cornell' s model

Figure 4 : Peak Ground Acceleration Distribution for the city of Theva, using Cornell' s model

TABLE I

Most Probable Maximum Macroseismic Intensity
for the next T years
(T-year mode)

T (years)		1	50	100
I (MM)	I-asymptote	3.5	7.0	8.0
	III-asymptote	3.0	6.5	7.5

TABLE II

Macroseismic Intensity with P- Probability of Exceedance
for the next T years

P	T(years)	1	50	100
0.90	I-asymptote	5.5	8.5	9.5
	III-asymptote	5.0	8.0	9.0
0.80	I-asymptote	5.0	8.0	9.0
	III-asymptote	4.5	7.5	8.5
0.70	I-asymptote	4.5	7.5	8.0
	III-asymptote	4.0	7.0	8.0
0.60	I-asymptote	4.0	7.0	8.0
	III-asymptote	3.5	6.5	7.5
0.50	I-asymptote	4.0	6.5	7.5
	III-asymptote	3.0	6.0	7.0

TABLE III

Seismic Hazard in Theva, Central Greece
Macroseismic Intensity Results for a Range of Return Periods
CORNELL 'S MODEL

Macroseismic Intensity (MM)	Return Period (years)
4.00	1
5.00	2
6.00	3
6.50	6
7.00	10
7.50	21
8.00	45
8.50	109
9.00	364

TABLE IV

Seismic Hazard in Theva, Central Greece
Peak Ground Acceleration for a Range of Return Periods
CORNELL 'S MODEL

Peak Ground Acceleration (gals)	Return Period (years)		
	Makropoulos 1978	Papaioannou 1984	Papoulia 1988
50	2	2	3
100	4	5	7
150	11	11	15
200	22	19	26
250	39	30	40
300	66	50	60
400	129	101	119
500	257	217	228

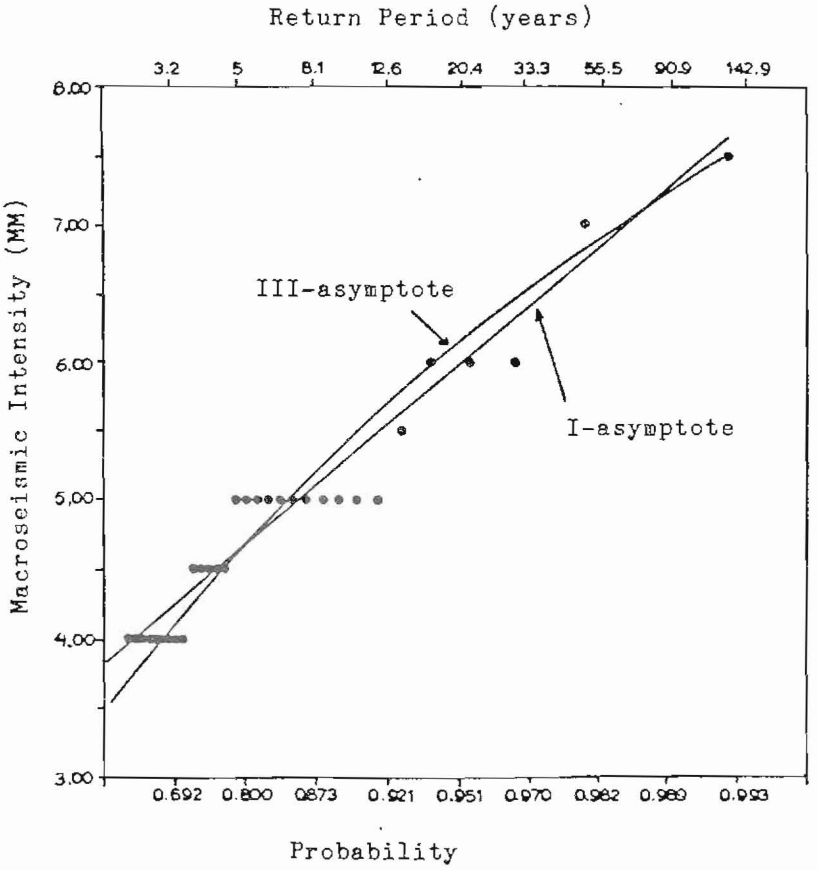
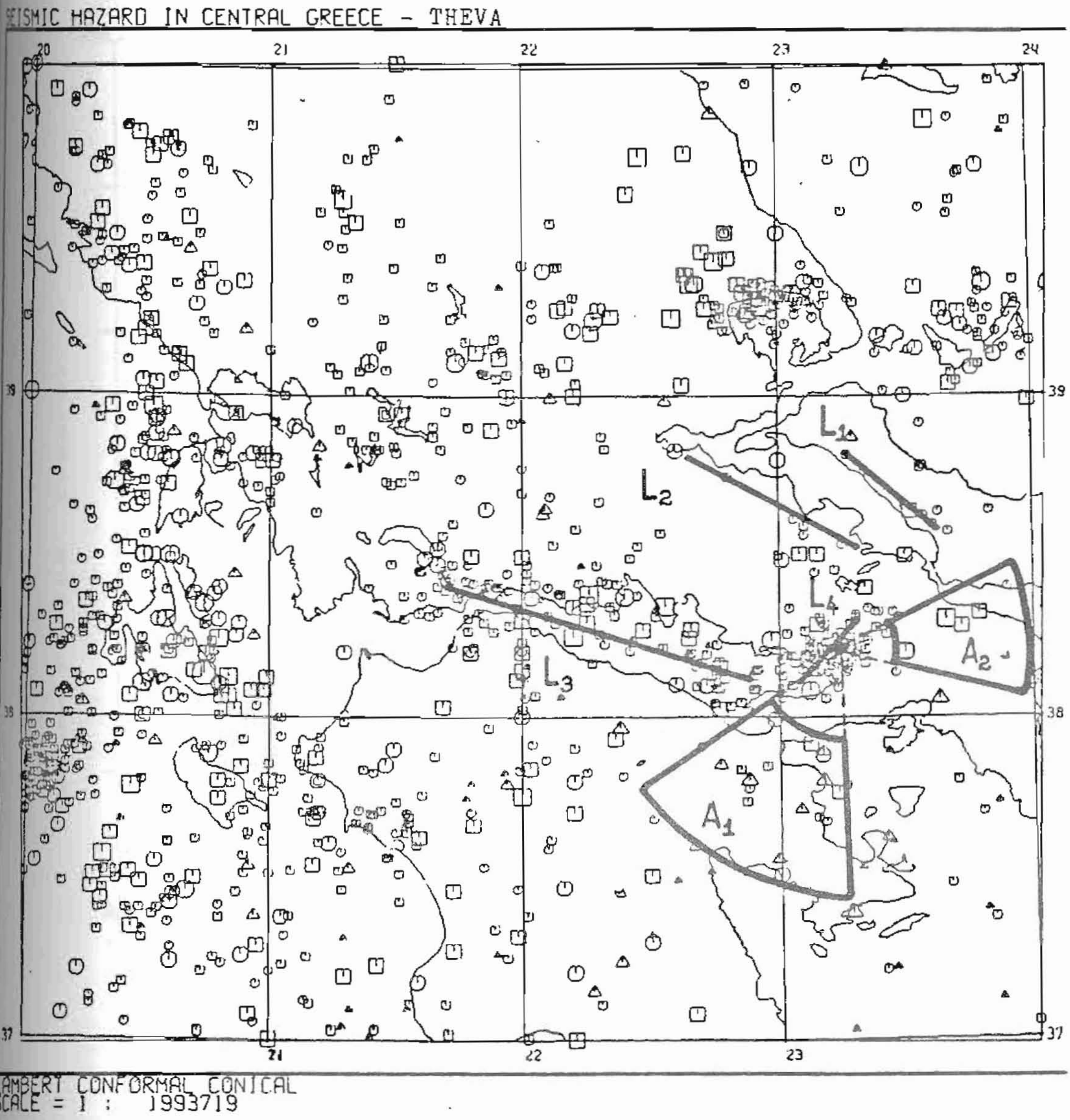

Return Period (years)
3.2
5
8.1
12.6
20.4
33.3
55.5
90.9
142.9
8.00
7.00
6.00
5.00
4.00
3.00
Macroseismic Intensity (MM)
III-asymptote
I-asymptote
0.692
0.800
0.873
0.921
0.951
0.970
0.982
0.989
0.993
Probability

Figure 1


SEISMIC HAZARD IN CENTRAL GREECE - THEVA

LAMBERT CONFORMAL CONICAL
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Figure 2

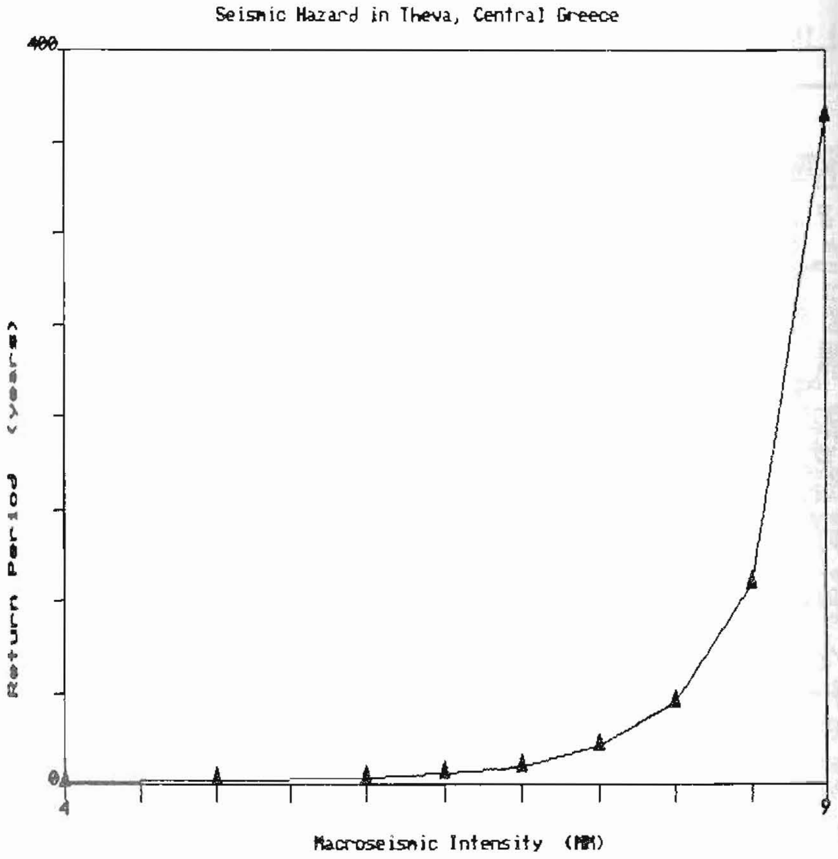
Seismic Hazard in Theva, Central Greece
400
0
Return Period (years)
4
9
Macroseismic Intensity (MM)

Figure 3

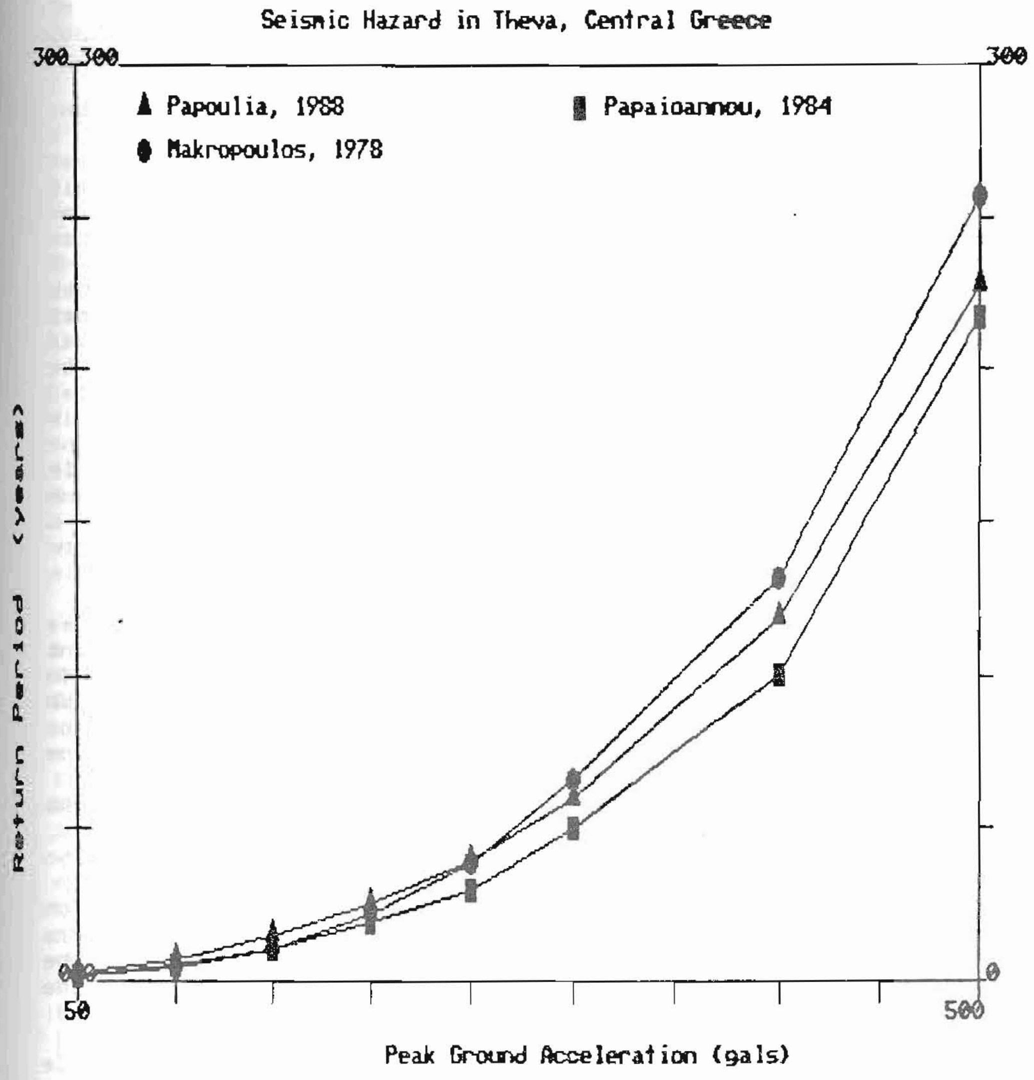
Seismic Hazard in Theva, Central Greece
Papoulia, 1988
Papaioannou, 1984
Makropoulos, 1978
300
300
300
0
50
500
Return Period (years)
Peak Ground Acceleration (gals)

Figure 4