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Seismic zoning studies in the area of Greece based on the most perceptible earthquake magnitude

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The Greek seismicity file developed by Makropoulos and Burton (1981) for earthquakes up to 1978 and extended up to 1983 (Makropoulos et al., 1986), is examined in terms of magnitude frequency using Gumbel's third type asymptotic distribution of extreme values. The forecasting parameters are obtained by subdividing Greek seismicity in a cellular manner. Combination of the Gumbel III earthquake occurrence statistics for each cell with acceleration attenuation law leads to perceptibility curves which give the probability of perceiving specific acceleration levels from each earthquake magnitude up to local upper bound magnitude w. These curves show a peak probability which occurs at similar magnitudes defined as the "most perceptible" earthquake. The range of these "most perceptible" earthquake magnitudes is for an M_S of about 5.3 to 7.2.

The results are presented as contouring maps for two average depths of 10 km and 20 km respectively. The features of the contoured perceptibility maps are compatible with existing hazard maps of Greece based on different approaches. This, coupled with the fact that these values may be used as a criterion for choosing engineering design time histories, shows the usefullness of the method for seismic zoning problems.

Proučavanje seizmičkog zoniranja na području Grčke na osnovi magnitude najbolje opažljivog potresa

Podaci u datoteci o seizmičnosti Grčke (Makropoulos i Burton, 1981) za potrese do 1978. i prošireni do 1983, proučeni su na osnovi čestine magnituda koristeći Gumbelovu asimptotičku razdiobu ekstremnih vrijednosti trećeg tipa. Parametri potrebni za proračun definirani su podjelom grčke seizmičnosti na karakteristična područja. Kombiniranjem III Gumbelove razdiobe događanja potresa za svako područje sa zakonitosti prigušenja akceleracije dobiju se krivulje koje prikazuju vjerojatnost opažanja specifičnih nivoa akceleracije za svaku magnitudu, sve do lokalne gornje granice magnitude, w. Maksimalna vjerojatnost na tim krivuljama javlja se za slične magnitude, definirane kao magnitude "najbolje opažljivog" potresa. Njihov raspon kreće se za M_S od oko 5.3 do 7.2.

Rezultati su na kartama prikazani izolinijama za prosječne dubine žarišta od 10 i 20 km. Značajke karata opažljivosti su u suglasju s postojećim kartama hazarda za Grčku koje su dobijene drugačijim postupcima što, zajedno s činjenicom da se izračunate vrijednosti mogu upotrijebiti kao osnova za odabir projektnih vremenskih nizova, pokazuje korisnost ove metode za rješavanje problema seizmičkog zoniranja.

1. Introduction

Seismicity and seismic hazard mapping in terms of earthquake epicentre and average recurrence intervals of different magnitude levels are an important aspect of overall seismic hazard analyses. However, this alone is not sufficient for an assesment of the hazard and consequently of the risk of a certain area. It is also necessary to predict the levels of ground motion associated with earthquake occurrence. To this end it is necessary to include attenuation relations for the region of interest. Such an extension of the method will not only immediately make available simple physical estimates of the levels of ground vibration, but will also allow comparison of seismic hazard distributions expressed both in magnitude recurrence and ground motion models.

Greece has the highest seismic activity in Europe with about 2% of the whole world's seismic energy release (Båth, 1983a). Fig. 1 shows the spatial distribution of earthquakes in the area of Greece with magnitude $M \geq 5.5$ for the period 1900 - 1983. Hence models of the above categories have already been applied in an attempt to map the seismicity and seismic hazard of the area .

Thus, Galanopoulos (1968) calculated the seismic hazard expressed as the recurrence rates of shallow earthquakes in each square degree of Greece. Comninakis (1975) defined the seismic hazard in terms of the most probable annual maximum magnitude from the Gutenberg-Richter cumulative frequency-magnitude a and b values per square degree. Algermissen et al. (1976) used Shebalin et al. (1974) catalogue to compile seismic hazard maps of the Balkan region. Båth (1983b) examined earthquake frequency and energy released in Greece using Makropoulos and Burton (1981), MB, catalogue. Using the same catalogue, Drakopoulos and Makropoulos (1983) compiled hazard maps depicting magnitude and acceleration with 90 % probability of not being exceeded in 50 and 100 years period. Finally, Makropoulos and Burton in two recent papers (1985a , 1985b), using the MB catalogue and the Gumbel first and third type asymptotic distribution of extreme values (Gumbel, 1966), compiled several seismic hazard maps in terms of magnitude and peak ground acceleration values for different probability levels and return periods.

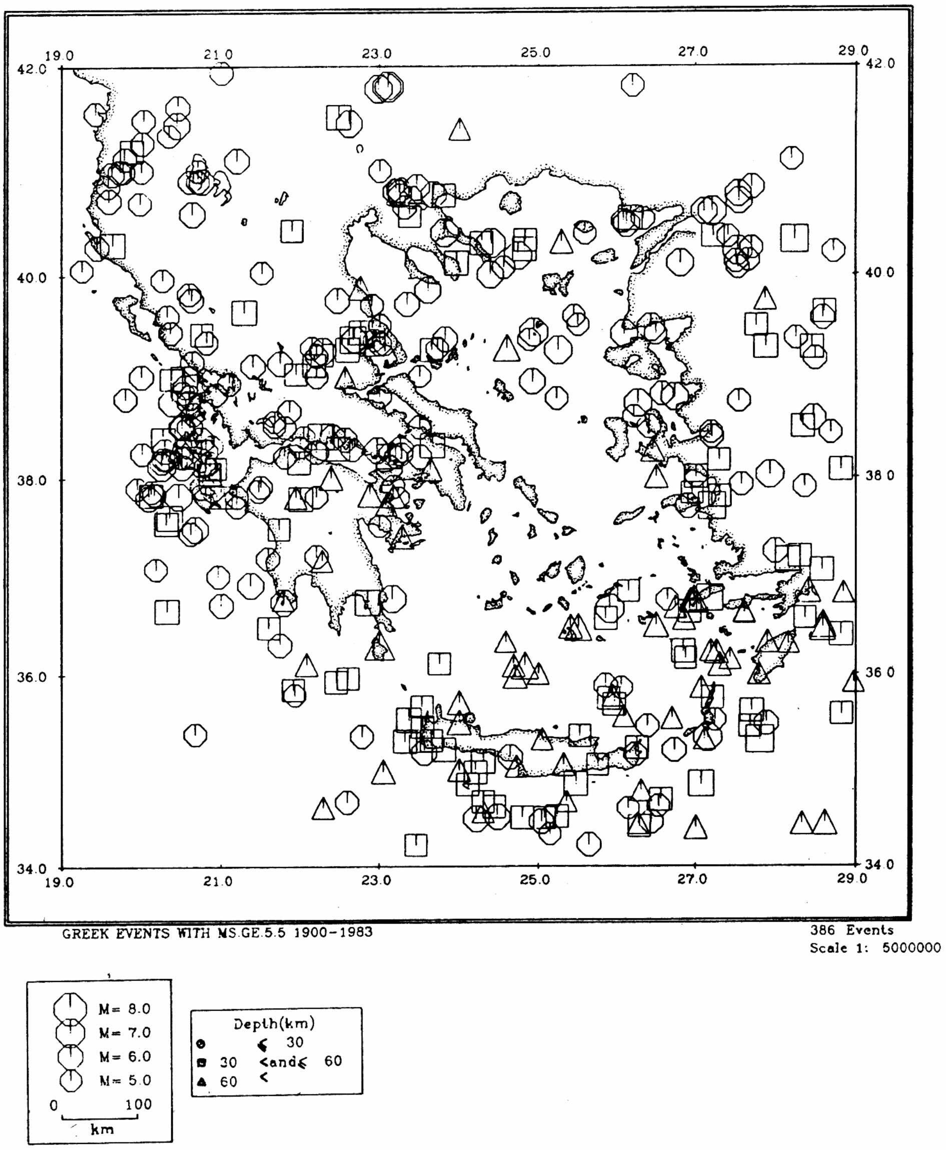

Figure 1. Spatial distribution of earthquakes in the area of Greece with magnitude $M_S \geq 5.5$ during the period 1900-1983.

In the present study, a further step towards the design earthquake parameters is taken by combining the probability of earthquake occurrence with an acceleration attenuation law by means of the equation :

$$P_p(A/M) = P_c(A)\,P_e(M) \tag{1}$$

where $P_p(A/M)$ is the probability of the magnitude M earthquake[1] occurring and causing perceptible ground motion with acceleration at least at level A. $P_e(M)$ is the probability of a magnitude M earthquake occurrence on which ground acceleration A is conditional, and $P_c(A)$ is an estimator of the probability that a point in the area under study is within the area for which an earthquake of magnitude M cause ground acceleration of at least the level A. (Burton et al., 1983, Burton et al., 1984).

An updated catalogue which covers period from 1900 to 1983 (Makropoulos et al., 1986) will be used here to evaluate the most perceptible earthquake magnitude in a cellular manner of 1.5° radius with a shifting step of 0.5°. Gumbel's third type asymptotic distribution of extreme values and the acceleration attenuation law derived in Makropoulos (1978) will be used to calculate $P_e(M)$ and $P_c(A)$ respectively. The results are presented in the form of contour maps for two average hypocentral depths of 10 km and 20 km. The methodology is briefly outlined below.

2. Methodology

2.1. Extreme value theory

In order to estimate the probability of occurrence of a magnitude M, $P_e(M)$ of equation (1), the asymptotic distribution of extreme valus (Gumbel, 1966) will be used. While the method has been described in detail in the above references, a brief description of the third type asymptotic distribution, Gumbel III, used in the present study, will be attempted here.

The Gumbel III distribution of extremes takes the form

$$G^{III}(M) = \exp\{-[(w-M)/(w-u)]^{1/\lambda}\} \tag{2}$$

where w is an upper bound of magnitude limit, u is the characteristic value associated with unit time (e.g. one year) and λ is a measure of the distribution curvature. $G^{III}(M)$ is the probability that magnitude M is an annual extreme. Methods of estimating Gumbel III parameters along with a computer program have been described by Makropoulos and Burton (1986). The same procedure is followed here.

In the present study, the probability of a magnitude M earthquake occurrence, $P_e(M)$ in equation (1), is taken as the differential probability $dG(M)/dM$, the probability density function derived from $G^{III}(M)$ of equation (2).

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[1] Magnitudes throughout are taken as surface wave type M.

2.2 Perception of ground motion

The estimation of the probability $P_C(A)$, see eq. (1), that a point in the area covered by the earthquake subcatalogue (e.g. an area of 1.5° radius) is within the area for which an earthquake of magnitude M causes ground peak acceleration of at least the level A, is taken to be the ratio of the area at an acceleration A or greater to the total area considered.

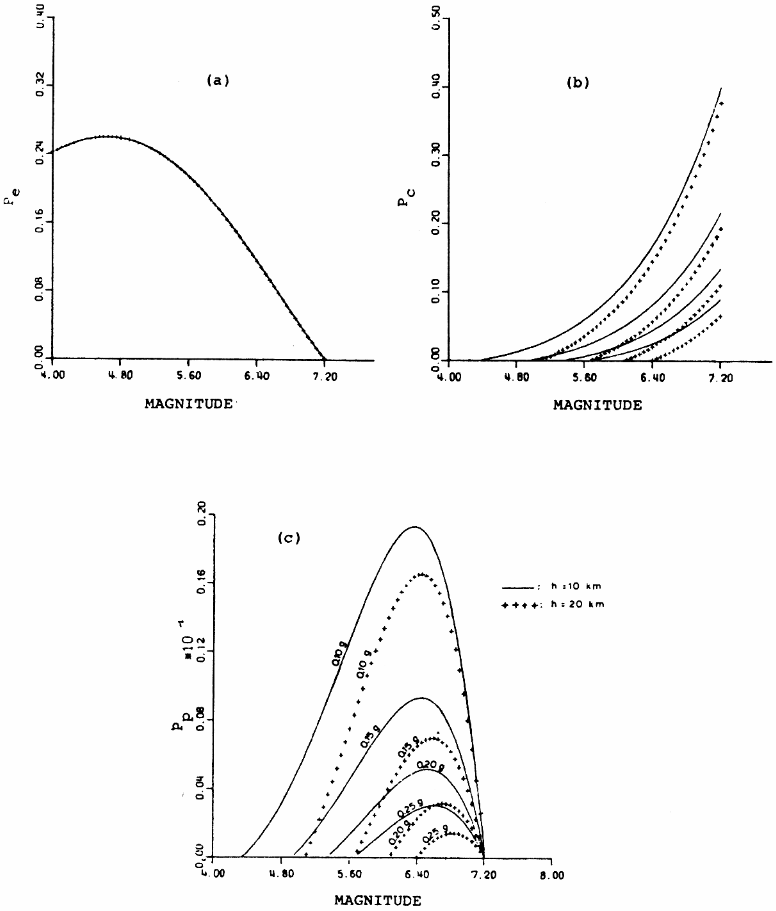

Figure 2. Example of perceptibility analysis in Volos, Central Greece, based on the Gumbel's III asymptote and acceleration law for two different depths and for four peak ground acceleration values . (a) P_e (M), (b) P_c (M), and (c) $P_p(A/M)$. For explanation see text.

In order to calculate the radius and consequently the area which during the occurence of an earthquake of magnitude M will experience peak ground acceleration A or greater, the acceleration attenuation formula derived by Makropoulos (1978) and further discussed in Makropoulos and Burton (1985b) is used. That is:

$$A = 2164\, e^{0.7M} (R + 20)^{-1.80} \qquad \text{in cm/sec}^2 \tag{3}$$

where A is the peak ground acceleration in cm/sec^2 and is related to the earthquake magnitude M and the focal distance R (km).

It will be seen subsequently that curves of perceptibility $P_p(A/M)$ versus a range of magnitudes M for different levels of peak ground acceleration are nested and show a peak at a particular magnitude range which is denoted as the "most perceptible" earthquake magnitude M_{mp}. This can be explained by the fact that for small magnitudes the $P_c(A)$ tends to zero. Similarly, for large magnitudes the $P_e(M)$ tends to zero and for Gumbel III the $P_e(M)$ are truncated at zero for $M \geq w$; hence $P_p(A/M)$ tends to zero. The intermediate maximum of the curve $P_p(A/M) = f(M)$ for different A levels defines a suite of most perceptible earthquake magnitude. Figure 2 illustrates the above explanation. It is an application of the method to the city of Volos (Central Greece). Note that the magnitudes are right bounded by the value of w which in this case was found to be 7.2 . As it can be seen from Figure 2c the most perceptible earthquake magnitude is 6.5 ± 0.2 and 6.6 ± 0.3 for $h = 10$ km and $h = 20$ km respectively.

2.3. *Integrated perceptibility*

The values of perceptibility calculated for each magnitude and acceleration level allow also an estimation of the annual probability of perceiving a particular level of acceleration at a point for all earthquakes up to magnitude M_i. This can be obtained by integrating the perceptibility curves through the magnitude range to M_i (Burton, 1981). Thus, for $-\infty \leq M \leq M_i$ we have

$$P_{ip}(A/M \leq M_i) = \int_{-\infty}^{M_i} P_p(A/M)\, dM \tag{4}$$

Then,

$$P_{ip}(A) = \int_{-\infty}^{w} P_p(A/M)\, dM \tag{5}$$

where w is the upper bound of magnitude occurence of Gumbel's III distribution.

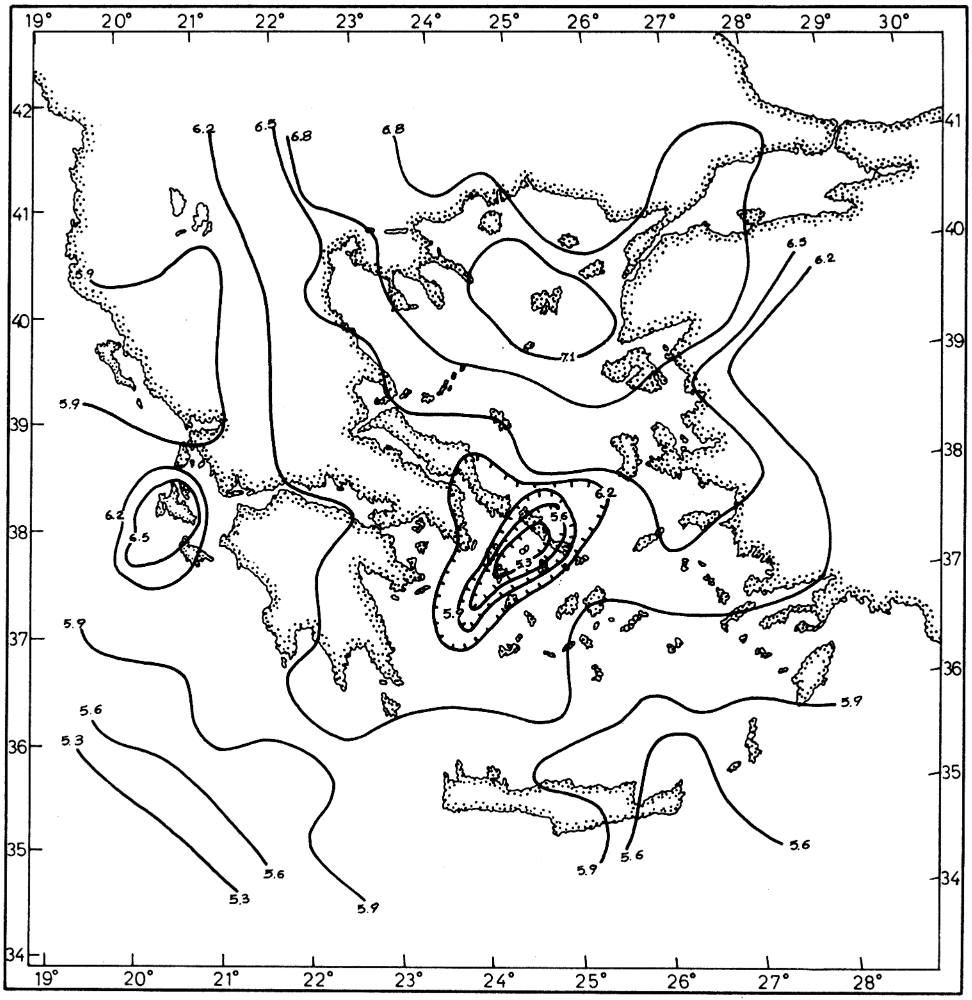

Figure 3. Magnitudes of the most perceptible shocks for the area of Greece corresponding to mean focal depth of earthquakes $h = 10$ km.

3. Application of the method

Greece is divided into cells of 0.5° latitude × 0.5° longitude and a mesh of grid points with spacing of 0.5° latitude, 0.5°longitude, is created for the whole area. All earthquakes occurring within a circle of 1.5° radius, with its centre at a particu-

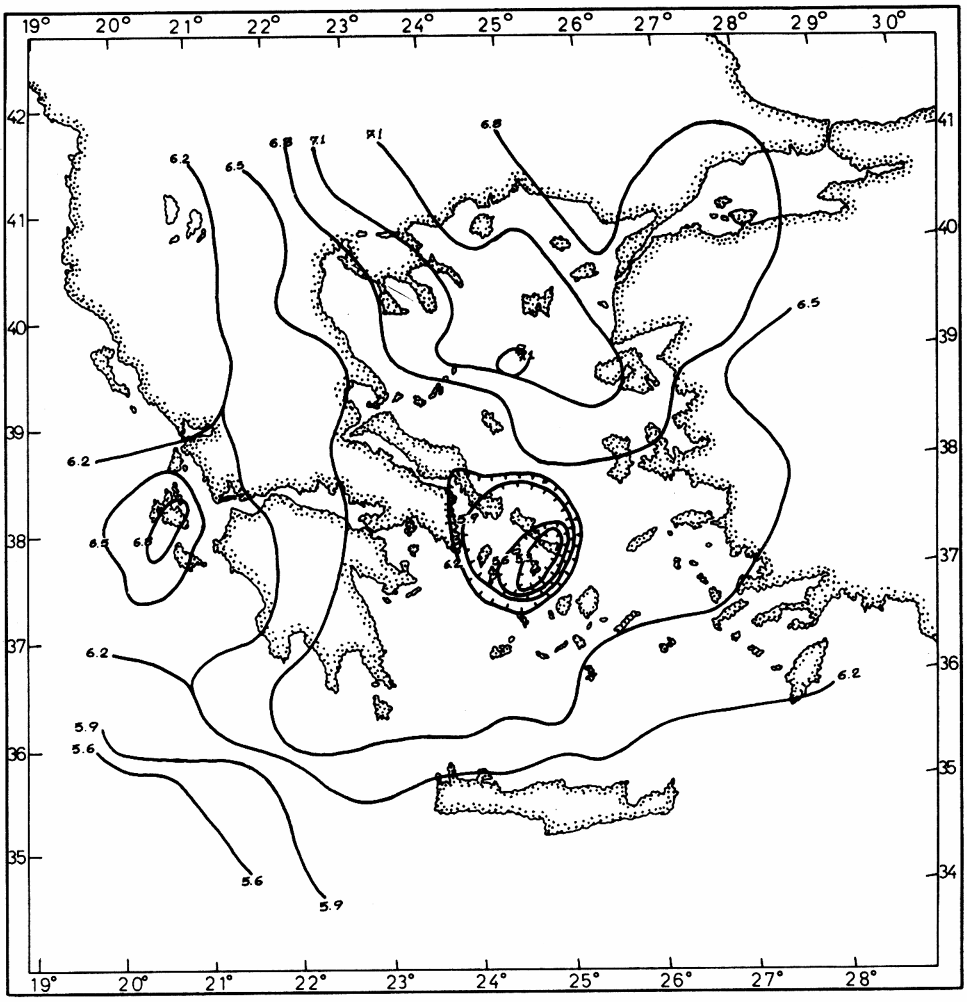

Figure 4. Magnitudes of the most perceptible shocks for the area of Greece corresponding to mean focal depth of earthquakes h = 20 km.

lar grid point are then collected from the new earthquake catalogue (Makropouols et al., 1986) and their annual maximum observed magnitudes are analysed with the Gumbel's III type asymptotic distribution. For every grid point the parameters w, u and λ of equation (2), are computed. Each set of parameters corresponds to an area which overlaps the adjacent one by about 80 % of the area. By differentiation of equation (2) the values of $P_e(M) = \mathrm{d}G(M)/\mathrm{d}M$ for magnitudes 4.0 up to w are estimated. Next, the values of $P_c(A)$ are estimated for the same range of magnitudes by calculating the area for which these magnitudes cause peak ground acceleration of at least the level 50, 100, 150, 200 and 250 cm/sec^2, as derived from the attenuation law of equation (3), and dividing this area by the total area of each cell (i. e. $A_{tot} = \pi R^2$ where $R = 1.5°$). Although the computational procedure allows any value of "effective depth" to be included in the area calculations through the equation (3) and one can choose values like Moho's boundary ($\cong$33km) and/or shallow - intermediate depth limit ($\cong$70) or the mean value of each cell, for practical engineering applications and considering the nature of the attenuation laws near to the source, in the present study values of effective depth of 10 km and 20 km are adopted. From these values the $P_{c10}(A)$ and $P_{c20}(A)$ are calculated and the values of $P_p(A/M)$ for each acceleration level and depth are then estimated by multiplication of $P_e(A)$ and $P_e(M)$ according to equation (1). Finaly, for each grid point, the values of the magnitude for which the perceptibility curves show a maximum are taken and averaged, therefore defining the " most perceptible earthquake magnitude", M_{mp}, for this particular focal depth.

4. Results and discussion

The values of M_{mp} for each grid point are contoured as in Figures 3 and 4 for the two depths respectively. From these figures several features are worth mentioning. The first is that both maps reflect the seismic regime of the area of Greece and show similar characteristics with maps compiled using different techniques (Drakopoulos and Makropoulos, 1983, Makropoulos and Burton, 1985 a, b). Thus the higher values of M_{mp} in both cases coincide with the areas of high seismic hazard previously mapped such as the (a) North Aegean - Eastern Chalkidike area, (b) Yugoslavia, (Cresna zone)-Greek border, (c) Ionian island, mainly Cephalonia island and (d) Marmara area in Turkey. Similarly, areas of lesser seismicity are also defined in these two figures , the most pronounced being the seismic block of Southern Euboea - Cyclades block.

However, the maps of Figures 3 and 4 present another form of seismic hazard parameter. The previous work was mainly dealing either with the maximum expected earthquake magnitude during the next T years at a specific level of probability (Makropoulos and Burton, 1985 a) or with the maximum expected acceleration (Makropoulos and Burton, 1985 b). The magnitudes shown in Figures 3 and 4 are derived from the combination of magnitude occurrence statistics with an acceleration attenuation law. Thus, they do not present maximum expected values but magnitudes of earthquakes which are most likely to occur and at the same time to cause destruction to the region and thus, emphasizing variations in the felt or damaging potential of each area. In that sense, the values of M_{mp} presented here may be more suitable for design purposes.

The design engineer may then allow for an appropriate range of magnitudes with chosen probabilities of occurrence, or related periods, by investigating properties such as the spectral characteristics of recent events in this magnitude range. To this end calculations on resonances of buildings or of mechanical coupling between buildings and ground become important as well as the changes in spectral characteristics with distance.

The estimation of the annual probability of perceiving a particular level of acceleration at a point for all earthquakes can be obtained by the application of eq. (5). This type of work for the area of Greece will be completed in another paper.

5. Conclusions

By combining results for magnitude recurrence derived from Gumbel's III type asymptotic distribution of extreme values, equation (1), with an acceleration attenuation law, equation (2), using the procedure described above and through the equation (3) the perceptibility values were estimated for five different acceleration levels and two values of effective depth of 10 km and 20 km. The values of most perceptible magnitude M_{mp} are then calculated for each cell. It is a striking feature that M_{mp} is similar for any level of ground motion being slightly higher for $h = 20$ km than for $h = 10$ km.

The results for the whole area of Greece are presented as contouring maps for two average depths of 10 km and 20 km respectively. It must be underlined that the obtained results are in relatively good agreement with similar ones depicting magnitude occurrences. However, the more interesting properties, from the engineering point of view, of the "most perceptible earthquake magnitude" discussed above, make this effort worth trying.

The values of M_{mp} presented in Figures 3 and 4 have, of course, certain limitations concerning their applicability. First, the attenuation law used here is an average law and thus does not reflect regional influence of geology and ray paths into energy attenuation. As regional attenuation laws of ground motion become available, they should be accommodated into the model allowing for more detailed local studies to be performed. Another limitation is that the $G^{III}(M)$ calculated from eq. (2) takes into consideration uniform distribution of earthquakes, which is not always the case. As it is well known from seismicity studies, the detailed spatial distribution depends on the seismotectonics of the area considered. Thus, although the general picture of Figures 3 and 4 is in agreement with the seismicity of the area as it can be seen from Figure 1, in order to avoid the above mentioned main limitations of the method we need local and detailed attenuation studies and a way of weighting the data in order to take into account spatial distribution of earthquakes. Such an effort is in progress.

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