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Analysis of seismic hazard in Catalonia (Spain) through different probabilistic approaches

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ABSTRACT: In order to analyse the seismic hazard in Catalonia a new parametric catalogue, in terms of macroseismic intensities, has been produced. A seismotectonic zonation of the area under study and surrounding regions, which takes into account the geologic and seismic data, is also proposed. From this input data, an estimation of the seismicity of the various seismotectonic sources has been made using both stationary and non-stationary models. The stationary models used are: the well known double truncated relation, of Guttenberg and Richter, and the extreme value model, developed by Gumbel. The non stationary Poisson model used was developed by Savy (1978). Given that the earthquake occurrence models do not show important non-stationarities, a hazard analysis, using the McGuire (1977) approach, has been carried out with the parameters from the stationary model. A sensitivity study, using the Montecarlo technique show relatively small uncertainties.

1 INTRODUCTION

Several studies on seismic hazard assessment, carried out some years ago (Egozcue et al., 1991; Mayer-Rosa et al., 1993), pointed out the need for better input data, particularly in regions, such as Catalonia, where seismicity is moderate. With this aim, a research, oriented towards the revision of the earthquake catalogue and the definition of an "objective" seismotectonic frame, was undertaken in the last years. A new regional seismic hazard assessment, taking into account updated data, is proposed.

From these input data, an estimation of the seismicity of the different seismotectonic sources has been made. Because of seismicity being moderate, different models have been used to estimate the rate of occurrence of major earthquakes. Both stationary and non-stationary models have been used. The stationary models used are: the well known double truncated relation of Guttenberg and Richter and the extreme value model, developed by Gumbel (1954). The non-stationary model used was initially developed by Savy (1978). A revised model was successfully used in Taiwan (Hong & Guo, 1995).

2 INPUT DATA

To analyse the seismic hazard in Catalonia, a catalogue containing information both from this region and from the surroundings is needed (figure 1). This catalogue should include two areas which can increase the seismic hazard in Catalonia: the Eastern half of the Iberian Peninsula and the South of France, with an important seismicity in the Central Pyrenees.

Data from earthquake catalogues (I.G.N., 1991; BRGM-CEA-EDF, 1994; Fontserè & Iglésies, 1971; and Suriñach & Roca, 1982) have been compiled. A new working file has been obtained, containing the parametric data of each earthquake according to its respective information source.

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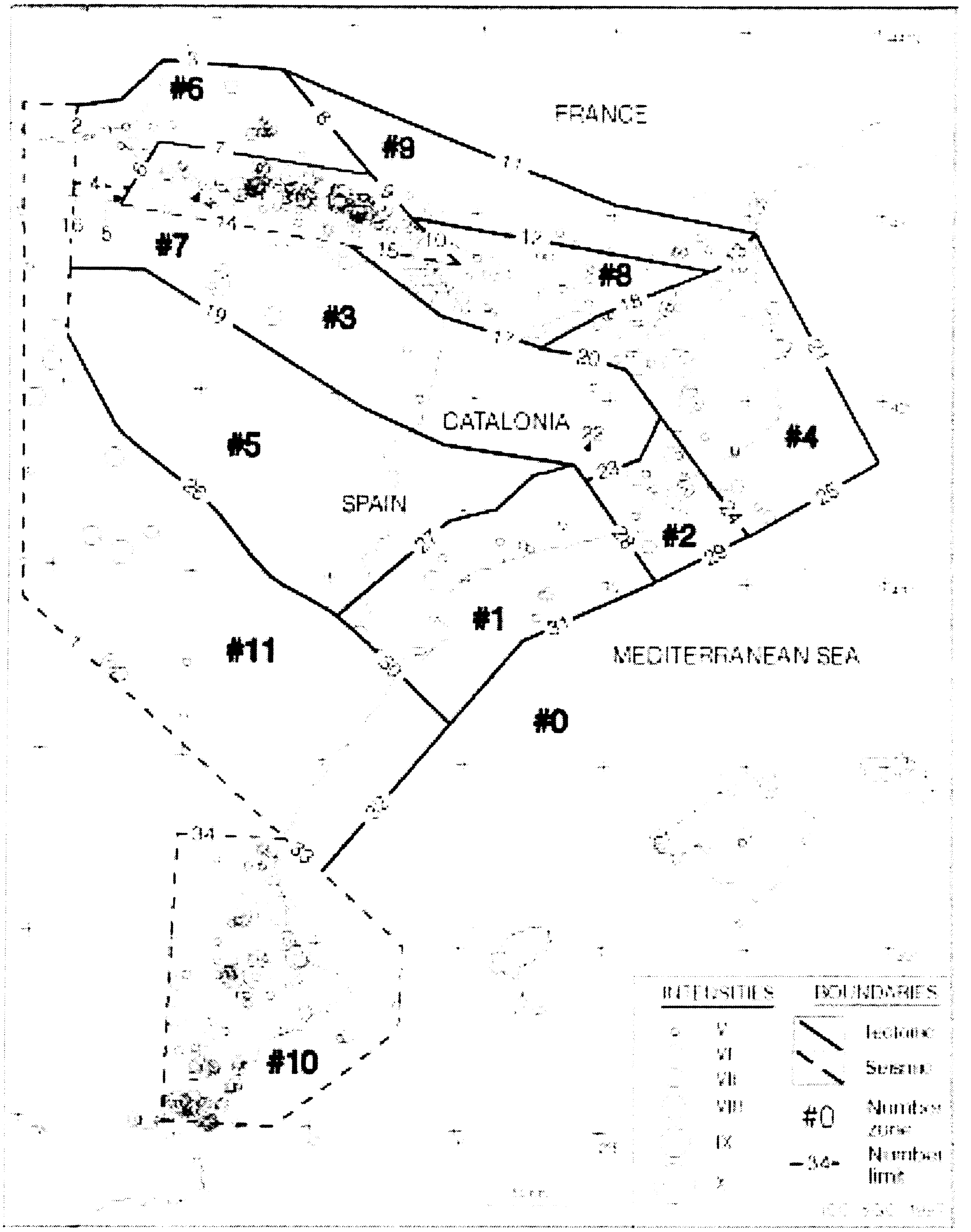

Figure 1. Seismicity and seismic zonation for Catalonia.

A critical comparison (Susagna et al., 1996) of the different information sources, together with the inclusion of new specific studies (i.e. Olivera et al., 1994 and Susagna et al., 1994) led to the creation of a new revised catalogue for the area under study. A special effort has been devoted to the revision of earthquakes with epicentre near the border line between Spain and France. The epicentres from this catalogue are plotted in Figure 1, together with the seismotectonic zones considered.

In areas where seismic activity is moderate, it is useful to introduce the concept of seismotectonic zone rather than active faults. The basic hypothesis is that the heterogeneity of the continenta crust could explain the distribution and other characteristics of the seismicity. So, the tectonic zonation is the first step towards seismotectonic zonation. This zonation takes into account the most representative parameters of the crustal structure, mainly coming from the inherited geological structure, but does not include the analysis of recent and present day tectonics (post-Miocene). The methodology proposed by Grellet et al. (1993) for this first step has been applied, with some modifications due to the differences in scale and geological context. The variations in different parameters for selected themes allow the individualisation of homogeneous zones (Fleta et al., 1996).

An initial seismotectonic zonation may be obtained, for probabilistic analysis purposes, from the tectonic zonation complemented by the seismicity distribution. A seismotectonic zonation with eleven zones is proposed in Figure 1. The zones proposed for the border line area are in agreement with the preliminary zones established in France (Autran, in press). Only three zones out of these eleven are defined only by seismicity distribution criteria.

3 DIFFERENT SEISMICITY MODELS

In order to assess the seismic hazard within a probabilistic frame, several models of earthquake occurrence have been considered.

3.1 *Stationary Poisson Model*

A first approach is based on a Poisson stationary process, using all the seismic data available.

The following double truncated relation (Goula and Godefroy, 1985) is used in each one of the considered zones:

$$\Pr(I \geq i) = \alpha * (\exp(-\beta * (i - i_0)) - \exp(-\beta * (i_{max} - i_0))) / (1 - (\exp(-\beta * (i_{max} - i_0))) \quad (1$$

where Pr(I>i) is the annual probability of exceeding a value of intensity i, i_0 is the minimum epicentral intensity considered, i_{max} is the maximum epicentral intensity allowable in each zone, α is the mean annual activity rate for intensities equal to or greater than i_0, and the value β is related to the slope of the Guttenberg-Richter law. The minimum intensity considered in this study is V (M.S.K.) and the maximum intensity allowed in each seismic zone depends upon the geological and seismic conditions of each source.

Before calculating the seismicity parameters α and β, a completitude analysis study on the seismic catalogue has been performed. This completitude analysis was developed using graphic representations for each zone. These graphics take into account the number of earthquakes of each one of the intensity levels which occurred in different periods of time. The maximum completitude period considered was 750 years.

The seismicity parameters α and β were computed following the maximum likelihood method proposed by Weichert (1980). The most active zones result to be : the Central Pyrenees (zone 7) and the zone located at the South of Catalonia (zone 10). Special attention is paid to zones 1, 2 and 4 due to the fact that the greater part of the population lives within them.

3.2 *Extreme Values Approach*

A second approach to the earthquake occurrence model is based on the extreme value method, which considers only the most important event occurred (Gumbel, 1954).

The seismic data of the most active zones in Catalonia were adjusted according to a Gumbel I distribution:

$$G^1(y) = \exp(-e^{-A(y-U)}) \quad (2)$$

where A and U are the parameters of the function, and to a Gumbel III distribution:

$$G^3(y) = \exp(-\left(\frac{w-y}{w-u}\right)^{K} \quad (3)$$

where w, K and u are the parameters of the function. The w parameter has a seismotectonic meaning as it is related to the maximum epicentral intensity expected to occur in a region.

Both distributions were adjusted using a linear regression analysis. In the Gumbel III distribution, the w parameter was fixed at $i_{max}+1$.

Different time intervals were used to adjust the available data (5, 10, 20 and 50 years). It was observed, when choosing the time interval, that long intervals do not provide sufficient data and short intervals present the problem of void intervals. The analysis showed that the best adjustment of the available data was achieved when the interval is fixed at 10 years.

Another problem is to decide how void intervals should be considered. A few possibilities exist: to eliminate these intervals; to replace them by an i_{min} interval; to assign a random value between i_{min} and i_{max}, etc. It was proved that the best adjustment was obtained by replacing void intervals by i_{min}, depending upon the seismotectonic zone. The Gumbel I distribution gave return periods slightly shorter than the Guttenberg-Richter law. On the other hand, Gumbel III gave return periods a bit longer than the Guttenberg-Richter law. This is consistent with the definitions of both distributions. Figure 2 shows the comparison between the activity rate of the zone 2 obtained by means of the extreme value methods and by the truncated Guttenberg-Richter law. As can be seen, no large differences exist between the different distributions, except for intensities of around i_{max}.

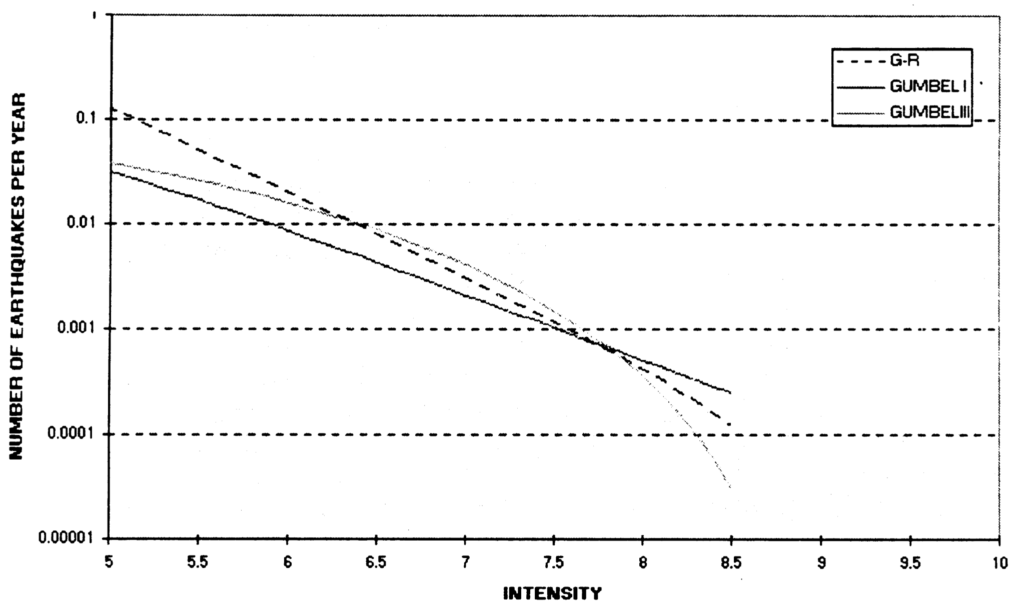

Figure 2. Comparison betweeen the probabilities of occurrences given by Guttenberg and Richter, Gumbel and Gumbel III for Barcelona.

3.3 *Non Stationary Poisson Model*

Another approximation to the earthquake occurrence model is a non-stationary Poisson process, initially developed by Savy (1978) and recently modified by Hong & Guo (1995). The model proposes a seismicity occurrence following a Poisson law including a temporal dependence of the mean occurrence. So, when a long period of time has elapsed without a great earthquake, its probability of occurrence is larger than in the years following a major event.

The counting process proposed by this model is based on the assumption of independent increments and, at most, one occurrence at any moment in time. It differs from a stationary Poisson model by the fact of having a varying average occurrence time. In this type of model, the number of arrivals in the time interval (t_1-t_2), $N(t_2)$-$N(t_1)$, is a random variable with a probability mass function (Hong and Guo, 1995):

$$P[N(t_2) - N(t_1) = n] = \frac{\int_{t_1}^{t_2} \gamma(t)dt}{n!} * \exp(-\int_{t_1}^{t_2} \gamma(t)dt) \quad (4$$

where the activity rate is time dependent:

$$\gamma(t) = \mu\lambda t^{\lambda-1} \quad (5)$$

and the return period:

$$T(t) = \frac{1}{\mu\lambda t^{\lambda-1}} \quad (6)$$

are time dependent. The mean and the standard deviation are used to determine the parameters μ and λ.

The initial idea was to carry out an analysis of this kind in every studied zone, when the data were sufficient. Therefore, a dynamic map of earthquake occurrence should be obtained and, in consequence, a dynamic hazard map. The results show that only the analysis with intensities equal to or larger than six are possible. However, the standard deviation is, in these cases, important. This fact is due to the lack of data when working with individual seismotectonic zones.

In order to avoid large errors, an analysis for the whole Catalan territory was carried out. Then, the period of recurrence for only intensity VIII was studied.

Figure 3 shows the variation of the return periods obtained with the non-stationary Poisson model for different times elapsed since the occurrence of the last earthquake of intensity VIII. It can be noticed that, for the years following a major earthquake, the return period for an earthquake of the considered intensity is very long. This shows a low probability of occurrence of earthquakes after a big one, as expected. However, it can be noticed that the return period decreases slowly when the time elapsed since the last event increases with a near asymptotic trend to 85 years (which is the return period obtained through Guttenberg and Richter approach). Therefore, our catalogue gives no evidence of a non-stationary tendency.

4 PROBABILISTIC HAZARD ASSESSMENT

The procedure used for the probabilistic assessment of earthquake hazard is essentially based on the Cornell (1968) method, later modified by McGuire (1976) and adapted to the possibility of using the Sponheuer attenuation law (Goula and Godefroy, 1985).

The seismicity is considered to be distributed over homogeneous seismic sources, each of them characterised by the values of the parameters computed using a stationary Poisson model process. This choice is justified because earthquake occurrence models above analysed (paragraph 3) show small differences among their results.

The method computes the probability of exceeding a certain intensity, at a given site, due to the different seismic sources and taking into account the pertinent attenuation laws.

The seismic hazard map, presented in Figure 4, was obtained by using the mean values for the different frequency parameters estimated for each seismic zone. The Sponheuer (1960) attenuation law was used.

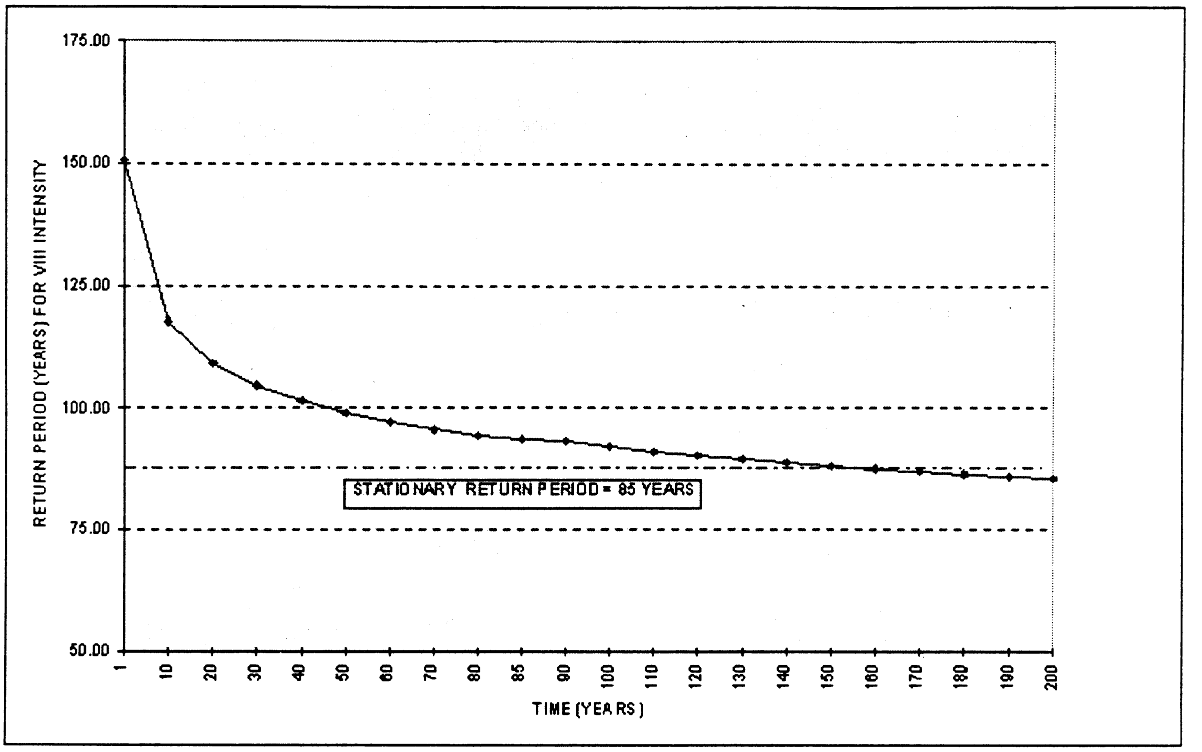

Figure 3. Non stationary return period for epicentral intensity VIII and for the whole area of study.

A very low value (0.001 km^{-1}) of the anelastic attenuation coefficient was found for the whole region and a range of earthquake depths between 5 and 15 km is adapted to the available macroseismic data. This map shows the intensity level (as a continuous parameter) corresponding to a return period of 500 years. The obtained intensities range from less than VI in the South to VII-VIII in the North Western part of Catalonia.

A sensitivity analysis was carried out in order to investigate the influence of the parameters uncertainties in the parameter values on the stability of the results. A Montecarlo method was used to determine the confidence of the results. The parameters controlling the seismicity were considered, for each seismotectonic zone, as a probability distribution function. Therefore, we consider:

- α and β as a Gaussian probability distribution with average and standard deviation obtained through the Weichert (1980) method.
- The depth and the length of the seismic source as a Gaussian probability distribution. The average of the depth corresponds to the value used to determine the seismic hazard and the standard deviation depends on the depth. The average value and the standard deviation for the length of the seismic sources were deduced from i_{max}.
- The maximum possible intensity in each zone, i_{max}, was considered as a triangular probability distribution with $P(i_{max}=i_{obs})=0.25$; $P(i_{max}=i_{obs}+1)=0.5$ and $P(i_{max}=i_{obs}+2)=0.25$, where i_{obs} corresponds to the maximum intensity observed in the zone.

One hundred random values of each one of the former variables were generated for each seismotectonic zone. Then, 100 random samples were used in order to obtain the seismic hazard in six selected towns: Barcelona, Girona, Tarragona, Lleida, Olot and Vielha. It was proved that results did not differ when more than 100 random samples were used.

The output distributions obtained were characterised through the average value and the standard deviation.

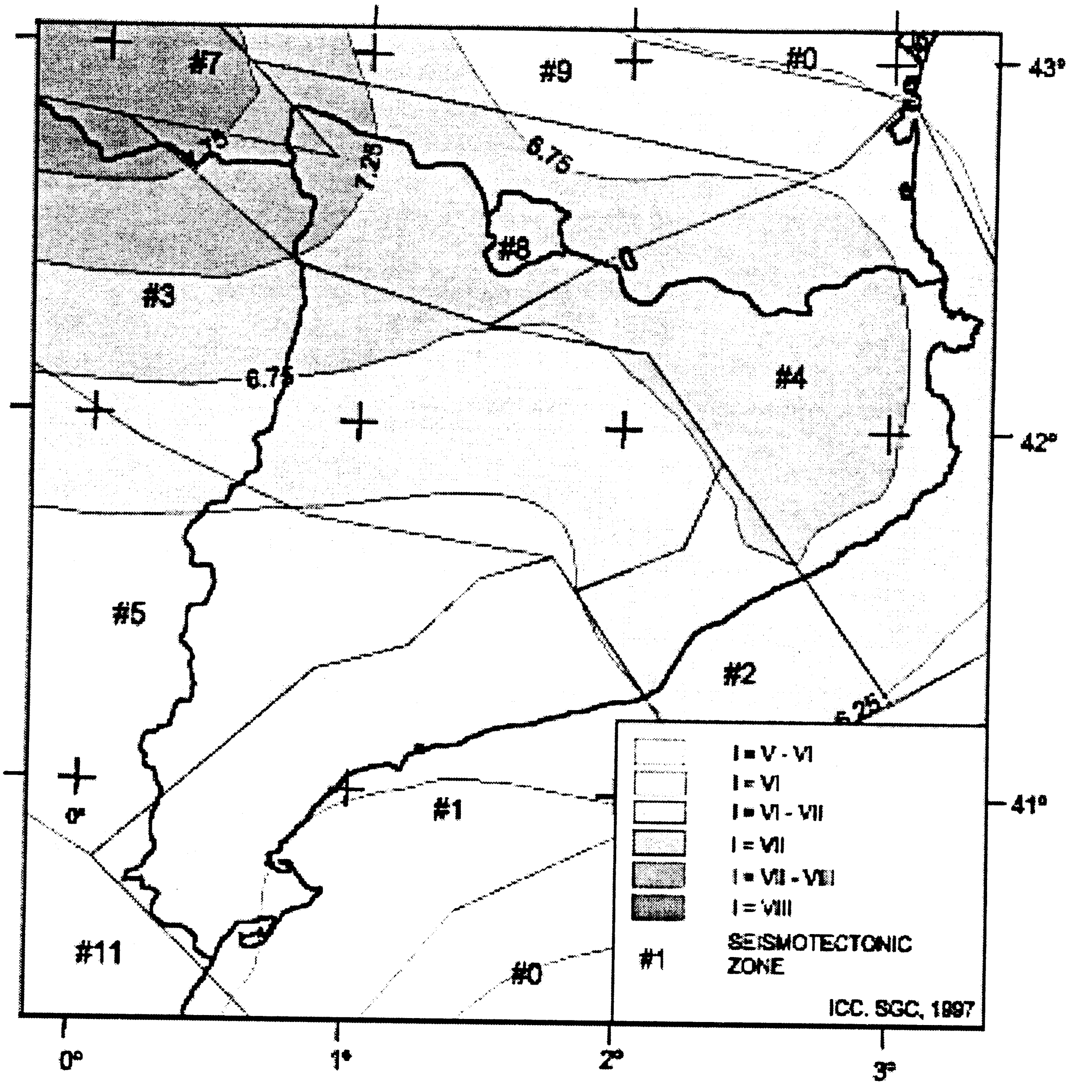

Figure 4. Intensity map for a return period of 500 years.

The chi-square proof shows an acceptable approximation to a Gaussian distribution in all towns studied, with a confidence of 95%. As an example, Figure 5 shows the comparison between the results obtained with the Montecarlo method and the expected Gaussian curve for Barcelona. Furthermore, the standard deviation with respect to the mean value of intensity obtained with the analysis of the seismic hazard is in the order of 0.3 degrees in the towns analysed, a fact which indicates the con fidence of the results.

5 CONCLUSIONS

A new seismic hazard assessment for Catalonia has been carried out taking into account a recently revised earthquake catalogue and a seismotectonic zonation, defined by tectonic zonation and seismicity distribution.

Different seismicity models of occurrence were applied to deduce the seismic behaviour of the Catalan territory. First, a double truncated relation of Guttenberg and Richter was used as a stationary Poissonian model. Secondly, two extreme value processes, developed by Gumbel (1954) were

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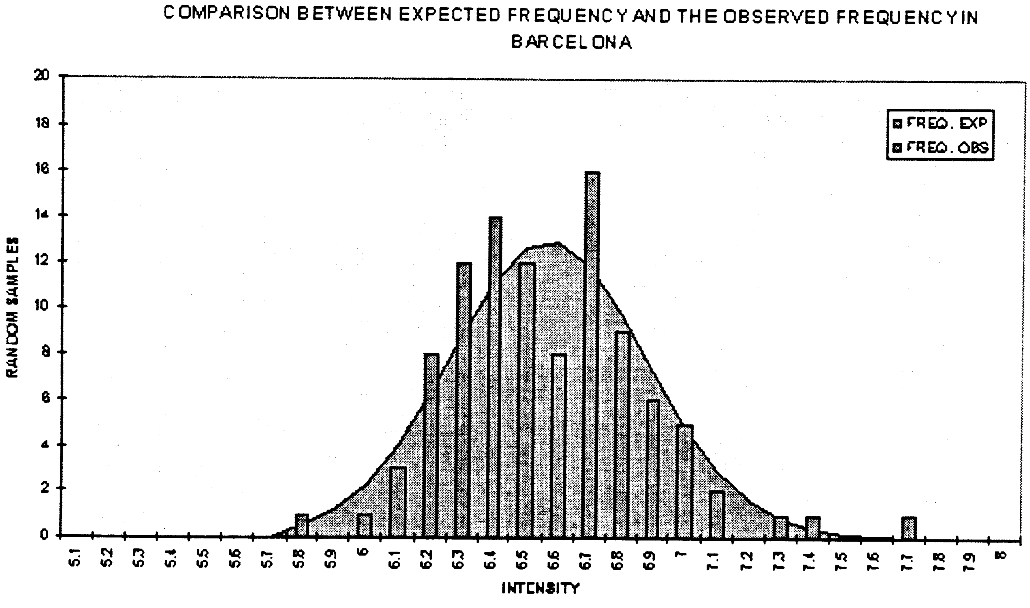

Figure 5. Comparison between the results obtained with the Monte Carlo method and the expected gaussianian curve of Barcelona.

used and showed, for high intensities, a good agreement with the return periods calculated through the stationary Poisson process. Finally, a non-stationary model, initially developed by Savy (1978) and modified by Hong and Guo (1995) was successfully used. It shows an almost stationary behaviour for the whole region. The return periods for intermediate intensities are very close to those obtained through the Guttenberg-Richter law. Therefore, the seismic hazard can be reliably assessed by standard procedures using stationary approaches.

A seismic hazard map, corresponding to a return period of 500 years is presented, showing intensities ranging from less than VI in the South to VII-VIII in the North Western part of Catalonia.

The sensitivity analysis, carried out in order to investigate the uncertainty in seismic hazard estimations, shows good results, with a 95% confidence in the chi-square proof. Assuming that several parameters used in seismic hazard calculations are a probability distribution and using a Montecarlo technique, a standard deviation of only 0.3 intensity degrees is obtained for all towns analysed.

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