Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

A probabilistic assessment of seismic hazard in France

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ABSTRACT. A probabilistic approach is adopted in this feasibility study concerning seismic hazard in France, based on seismotectonic zoning of the country and a historical seismicity data file. The method includes several preliminary steps intended to determine different regional seismicity parameters: parameters involved in the laws governing earthquake distribution and attenuation of macroseismic intensity. Seismic hazard assessment for a site entails taking into account the contributions made by surrounding areas that have been characterized as described above. The results obtained for points corresponding to the nodes on a standard grid covering the entire country are presented as isointensity maps for a given probability and isoprobability maps for a given intensity. This type of representation, which can be improved on as new data become available, may contribute to the evaluation of the statistical hazard existing in a given region, although it cannot as yet, per se, constitute a design basis for specific structures.

INTRODUCTION

The study consists in estimating the probability that an earthquake with known significant parameters will affect a given site. The present survey is based on the identification of the seismic sources, an analysis of the distributions in space and time of the earthquakes associated with these sources, a consideration of the contribution of these different sources in assessing the probability of a selected parameter being exceeded for a given site. Seismic source determination depends on seismotectonic analysis which, for present purposes, is based simply on seismotectonic zoning. For each zone, the macroseismic intensity distributions will be studied, since these are the only data available for France that make possible the systematic inclusion of comprehensive historical seismicity data. Calculation of the probability of exceedence of a given intensity in a given place depends on seismic wave energy attenuation versus distance, which, in this study, was derived from the macroseismic intensities of historical earthquake .

1 BASIC DATA

1.1 Seismotectonic zoning

In the French seismotectonic context, characterized by moderate intraplate seismicity, it is extremely difficult in most cases to establish a unequivocal relationship between the seismicity observed (historical or instrumental) and identified faults. Zones must consequently be identified within which the geological and seismic characteristics are such that uniform seismogenic behaviour may be postulated. Such postulates cannot consistently be corroborated within the span of the historical earthquake observation period, partly because the data sample is too limited. For instance, we would recall that, prior to 1909, when an earthquake of magnitude 6 took place, the part of Pro-

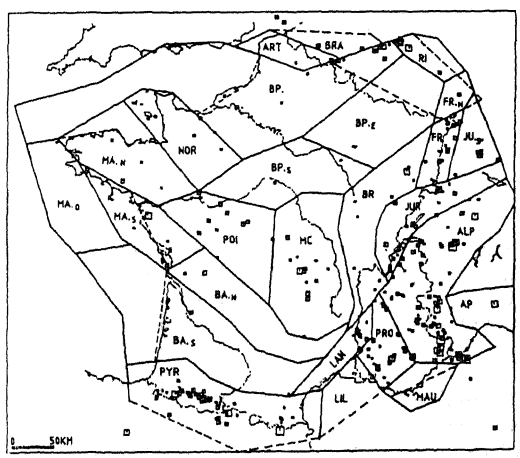

Figure 1. Seismotectonic zoning (I ≥ VI).

vence lying between the middle Durance and the Salon fault was inferred to be virtually aseismic.

The zoning used in the present survey, as defined by Grellet et al. (1991) and appearing in diagram form in Figure 1, relis primarily on the definition of zones with presumably uniform crustal structure and presenting an identical type of tectonic deformation. In these zones, recent and present-day deformations, including seismic mechanisms, must be consistent with the stress field.

1.2 Historical seismicity data

These data, relating to more than 5,000 historical earthquakes, are compiled in the SIRENE file. The events are characterized by their epicenters, the localities where their effects were observed, their macroseismic intensities on the MSK scale and a quality code rating of their estimation. For a given earthquake, analysis of the intensities I_r experienced at various distances from the epicenter (where the intensity is I_0) enables certain parameters to be defined.

Sponheuer (1960) obtains the following relationship:

$$\Delta I = I_0 - I_r = 3 \log [(h^2 + r^2)^{1/2} / h] + 1.3 \alpha [(h^2 + r^2)^{1/2} - h] \quad (1)$$

where h is the the focal depth, r the epicentral distance, and α, an anelastic attenuation coefficient.

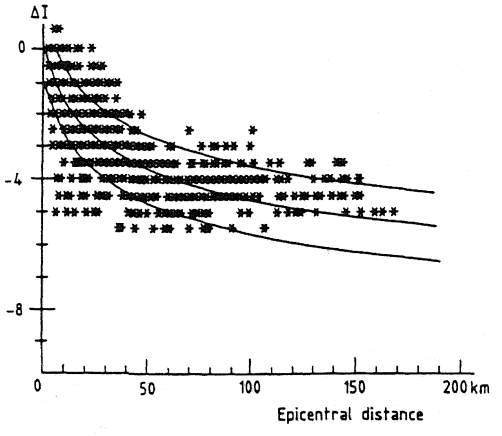

Figure 2. An example of regional attenuation law: Jura. The middle curve indicates the mean law, while the upper and lower curves are respectively the same plus or minus one standard deviation.

Using the least squares method to adjust function f (r, α, h) above with an experimental curve $\Delta I = f(r)$, the parameters α and h are determined. Regional attenuation laws have been analyzed by A. Levret (1987) (Figure 2). Three main types of area have been identified in France: 1) very superficial focal depth areas (about 5 km): Jura, Rhineland rift valley, Bresse and Provence regions, Pyrenees, Languedoc and Maures; 2) intermediate focal depth areas (about 10 km): Alps, Massif Central, Poitou region, the Aquitaine basin, the Paris basin and the Artois region, and 3) areas of greater focal depth (about 15 km): Normandy, the Armorican chain.

2 DATA PROCESSING METHOD

2.1 A general approach to the probabilistic assessment of seismic hazard

The annual probability that certain intensity values will be reached or exceeded on the site under examination is calculated by considering the cumulative effects due to the different seismic source zones peripheral to or containing the site. The analysis is performed by means of the MacGuire code (1976); it incorporates notably studies by C. A. Cornell (1968) and has been adapted by X. Goula (1980).

When earthquake frequency is known in terms of epicentral intensity for each zone and taking into account the attenuation laws of intensity between the source and the site, the intensities produced on the site considered can be calculated, together with the corresponding probabilities. By cumulating these probabilities for all the sources, we obtain the probabilities for the different intensity values likely to be experienced on the site.

2.2 Frequency laws for intensity per zone

The frequency of occurrence of earthquakes in terms of epicentral intensity is calculated by means of a computer program using the seismotectonic zoning system as input data. The historical seismicity file documents only those events for which the epicentral intensity attains a degree V at least on the MSK scale (for lesser intensities, the data are not exhaustive). The program outputs an intensity distribution table with classification, by half-degree increments, between degrees V and X per period of 50 to 950 years from the year 1000 on. The regional frequency distribution laws are thus determined for epicentral intensities of at least V.

In order to adjust the frequency laws, each occurrence of an earthquake at a given place and time is considered to be independent of what may have taken place prior to it and elsewhere. It is then possible to model earthquakes within a given zone by a random, stationary time and space process. The supposition is made that the occurrence process of earthquakes in a region can be mod-

elled by a Poisson law (with a parameter λ) that respects the representation of the observations. The parameter corresponds to the regional seismicity rate, i.e. the annual number of earthquakes with an epicentral intensity I_0 reaching or exceeding a certain threshold, in this case, degree V.

The probability of occurrence of n earthquakes during a period t is written:

$$P_t(n) = [e^{-\lambda t} (\lambda t)^n] / n! \quad (2)$$

In addition, for a set of earthquakes with intensities of at least I_0, supposing that the probability of an earthquake's exceeding an intensity I ($I > I_0$) is given by a relationship of the type:

$$F(I) = e^{-\beta (I - I_0)} \quad (3)$$

then the expectation with regard to the number of earthquakes where the epicentral intensity will reach or exceed I is:

$$n(I) = \lambda F(I) \quad (4)$$

In terms of decimal logarithms, we obtain the law:

$$\log n(I) = a - bI \quad (5)$$

where $a = \log \lambda + I_0 \beta \log e$ and $b = \beta \log e$. A normal log law is obtained.

Richter (1958) demonstrated that seismic data (magnitude or intensity) tend very generally to respect a law of this type, which substantiates a posteriori the assumption expressed in (3). The β variable may be interpreted as an indicator of the relative distribution of small and large events: the higher the value of β, the smaller the number of large events in the region considered. The λ and β parameters are estimated by the maximum likelihood method (Weichert, 1980) based on observed values. However, the intensity scales comprise a finite number of degrees, and a non-null probability of occurrence for events where the intensity exceeds the maximum degree on the scale considered is meaningless. Moreover, for moderate seismicity regions, the probability of occurrence of earthquakes becomes null as soon as a certain intensity is reached. In order to take these observations into account, the relationship can be modified to include the maximum intensity for each region :

$$F(i) = \frac{e^{-\beta (I - I_0)} - e^{-\beta (I_{max} - I_0)}}{1 - e^{-\beta (I_{max} - I_0)}} \quad (6)$$

if $I \leq I_{max}$ and $F(i) = 0$ if $I > I_{max}$. When I is close to I_0, the decimal logarithm of n (I) thus defined tends towards a type (5) relationship. But if an I_{max} is selected that increases the maximum epicentral intensity observed in each region by one or two degrees on the MSK scale, this will take into account uncertainties resulting from lack of available data on major events, while at the same time defining a safety margin. In order to infer distribution laws for high intensities, we consequently use a log normal law asymptotically truncated at the maximum observed intensity plus one or two degrees (Figure 3).

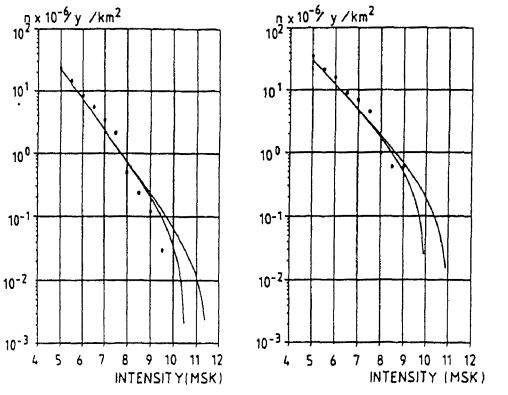

Figure 3. Frequency/intensity distribution for the Alps (left) and Provence (right).

2.3 *Seismic hazard assessment for a given site*

The MacGuire code (1976) is used to assess not only the probability that a certain intensity will be reached or exceeded on a certain site, but also the intensity likely to be reached or exceeded for a

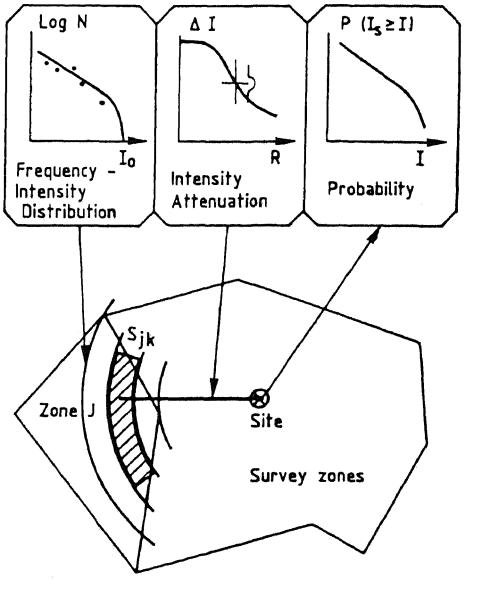

Figure 4. Calculation scheme of seismic hazard.

given level of hazard. Seismic hazard assessment for a given site takes into account the parameters characterizing the seismicity of the region where the site is located and those of nearby regions likely to affect the hazard level on the site considered (Figure 4).

Each source zone is defined by a polygonal area S_j, which is characterized by: 1) a log normal distribution law covering the cumulated number of events versus intensity, the parameters of which are λ, β and I_{max}, and 2) an intensity attenuation law, the parameters of which are the mean focal depth h and the anelastic attenuation coefficient α. The probability of an intensity I being reached or exceeded on the site is obtained by summing the probabilities related to each zone, taking into account the attenuation. It is expressed as follows:

$$P(I_s > I) = \sum_j P_j (I_s > I) = \sum_j [1 - e^{n_j (I)}] \qquad (7)$$

where n_j is the mean annual earthquake frequency in zone j giving rise to an intensity on the site exceeding or equal to I.

If zone j is divided into several sectors k, then

$$n_j (I) = \sum_k n_{jk} (I) = \sum_k (S_{jk} / S_j) \lambda_j F_{jk} (I) \qquad (8)$$

with

S_j	area of zone j
S_{jk}	area of sector k
λ_j	mean annual frequency in zone j
F_{jk} (I)	Probability of occurrence in zone k of an earthquake giving rise to an intensity exceeding or equal to I on the site, taking attenuation into account

2.4 Characteristics and limits of this assessment

Among the limitations inherent to the application of such a method, the following points should be mentioned. The assessment is based on zoning defined primarily by recent or current tectonic data, where observed seismicity is only considered as an indication of the types of mechanism involved and not as a quantitative activity index. This type of zoning may be excessively conservative in the context of a deterministic approach, where it will be assumed that a major earthquake could take place anywhere in the zone. In a probabilistic approach context, on the other hand, it tends to smooth over effects within the zone and in its immediate vicinity, since the observed seismicity rate is distributed over the entire area, with the consequent possibility of underestimation close to a "hot spot" and, conversely, of overestimation with respect to earthquakes which have actually been observed, in cases where the seismotectonic zone considered is bordered by active zones.

Certain drawbacks in particular are to be noted:

- The zones are characterized by parameters λ and β, obtained by fitting a theoretical curve on experimental points, with extrapolation to a higher intensity than those observed (I + 1) or (I + 2). This extrapolation may be relatively penalizing in the case of a low-gradient β curve zone (which theoretically corresponds to a relatively high proportion of significant earthquakes). An example of this is the Paris basin as defined in the zoning system used.
- Seismicity data relating to areas in the vicinity of territorial boundaries should be treated circumspectly, since they may differ from those obtained in adjacent countries. There is fairly little historical seismicity data for sea areas. A probabilistic assessment for a coastal area may on occasion correspond to a representation of source zones by only a half-mesh. A better approximation has been found to consist in assigning maritime provinces identical seismic characteristics to those of adjoining continental provinces having the same tectonic characteristics.
- In certain particularly low seismicity regions, the number of experimental points is insufficient for a theoretical curve to be fitted. To ensure inclusion of such regions, they are sometimes grouped with adjoining zones. It should moreover be borne in mind that the studies performed for the definition of amplitude attenuation laws were extremely localized, with the result that only mean focal depths could be taken into account for each region in the seismotectonic zoning system.

Among the parameters with which a significant degree of uncertainty may be associated, consideration is given to the influence of depth h, distribution slope β, and asymptotic distribution value I_{max}. In order to assess their influence on the probability calculation, a certain number of sites representing various levels of seismicity were selected. For each of these sites, we then assessed the rated probability and the influence of a specific parameter, using successively for the purpose: h × 2, $\beta - \sigma_\beta$, and I_{max} + 1. Figure 5 represents the sensitivity study for one of these sites.

With regard to the λ parameter, owing to the exhaustivity of the SIRENE data file, relevant indications may be considered as acknowledged data, at least as far as the national territory is concerned. However, SIRENE data for areas outside the national borders is incomplete, and assessments would assuredly be improved in the vicinity of these areas were the data banks used for this work in adjoining countries to be standardized. In this connection, it will be noted, for instance, that taking

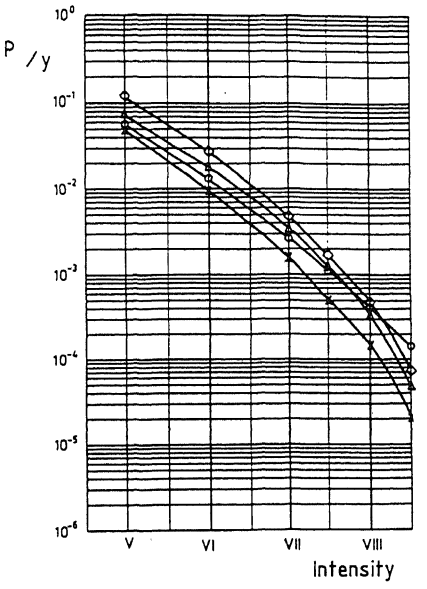

Figure 5. Sensitivity of the annual probability to different parameters: curve marked with x's: nominal values; curve marked with circles: I_{max} incremented by 1 degree; curve marked with triangles: $\beta - \sigma_\beta$; curve marked with a diamond shape: h multiplied by 2.

for the Swabian Jura a zero seismicity (λ = 0) as opposed to a seismicity identical to that of the lower Rhineland rift valley results in discrepancies of less than 20% in the probability calculation for sites in the latter province.

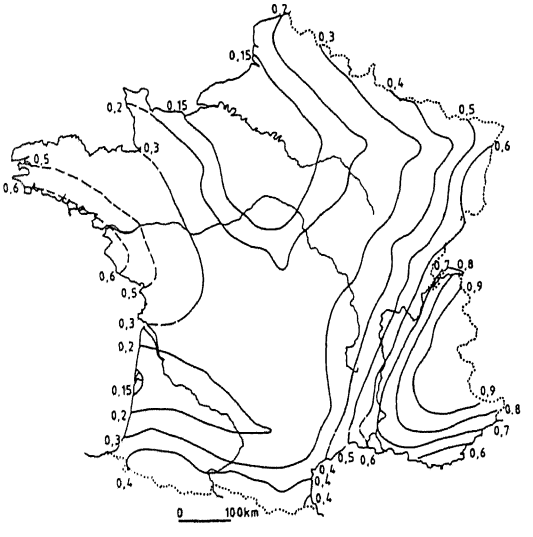

Figure 6. Isoprobability curves for I = V (values to be multiplied by 10^{-1}).

3 ELABORATION OF SEISMIC HAZARD MAPS

The probability values were calculated for points corresponding to the nodes on a 50 km-sided square mesh grid. Isoprobability curves are then plotted for a given intensity, together with isointensity curves for a given probability. For the present survey, maps were prepared for intensity V (Figure 6) and intensity VII (Figure 7) and for probability levels of 10^{-2} (Figure 8) and 10^{-3} (Figure 9).

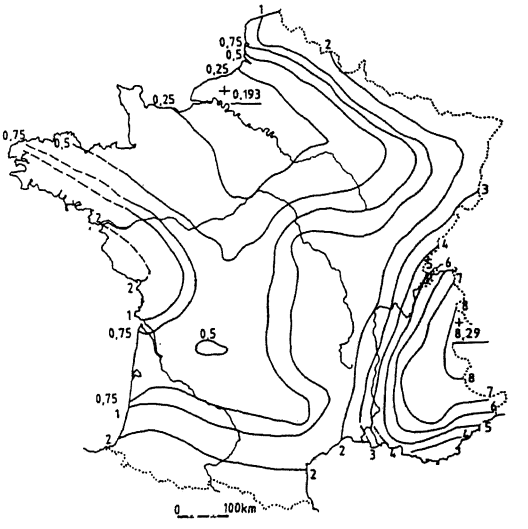

Figure 7. Isoprobability curves for I = VII (values to be multiplied by 10^{-3}).

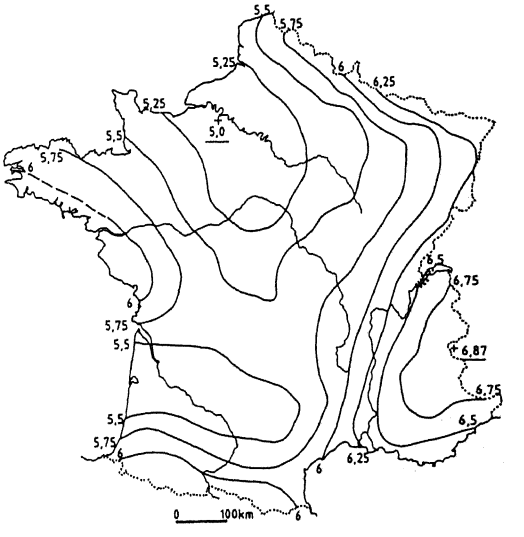

Figure 8. Isointensity curves for a probability of 10^{-2}.

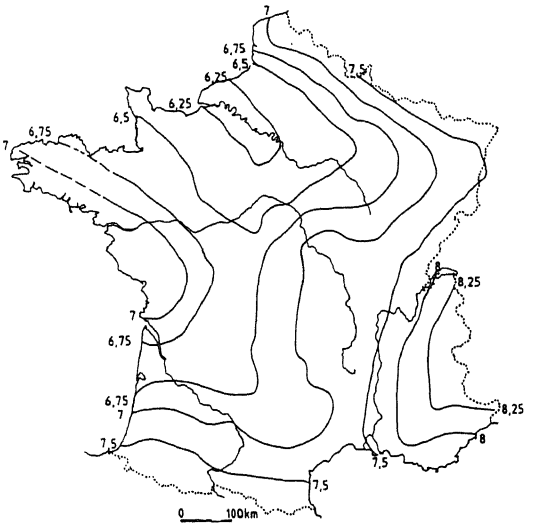

Figure 9. Intensity curves for a probability of 10^{-3}.

The investigation is entirely based on elements afforded by the SIRENE data file and could be subsequently supplemented. Meanwhile, we have taken into account the fact that the SIRENE data could not provide for the definition of province by province distribution laws for Belgium. The Belgian provinces are consequently considered as an agglomeration, including a part of them which belongs to the Paris basin in the seismotectonic zoning system. This local zoning modification seems justified by certain seismotectonic arguments (tectonic zoning, current seismic activity, deformations, etc.).

4 CONCLUSION

The seismic hazard maps (see figures) elaborated on the basis of the rated probability values calculated in this survey correspond to a co,structive utilization of the historical seismicity data contained in the SIRENE data file and of the national territory seismotectonic characteristics as formally presented in the zoning system described. These representations of the seismic hazard constitute, as they are, an approach to assessment of the seismic potentiality of the different regions, clearly delineating the configuration and activity of the various seismic zones in France. For further guidance, on the basis of specific studies and subject to the results of continuing research, the probability values may be estimated with an accuracy that is conditioned by the amount of data available. Subsequent improvements to the present survey will depend on a standardization of national seismicity data files compiled by other countries and on possible finer seismotectonic zoning which could be implemented as new data became available, notably in the field of quantification of deformations and their relationship with impact-brittle tectonics.

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