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Part Two: Probabilistic approach: Seismic hazard map on the national territory (France)

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ABSTRACT: Seismic hazard assessment for the construction of earthquake-resistant buildings, in particular of critical facilities, in France follows traditionally a deterministic approach. The aim of the French Working Group EPAS, under the aegis of the AFPS (Association Française du Génie Parasismique / French Association for Earthquake Engineering), is to propose a probabilistic seismic hazard map for the french metropolitan national territory for conventional structure. The compilation of this map involved two stages: the first one, detailed in the previous abstract (Part I; Autran and al. 1998), consists in determining a seismotectonic zonation at the scale of the country. The second stage, presented in this abstract, uses the seismotectonic zonation to compute the probabilistic map giving the values of acceleration corresponding to a 475 yr return period.

1 INTRODUCTION

In the field of seismic risk studies, the french present seismic regulations are based on strictly deterministic approach, which takes into account both seismotectonical zonation (Combes and al., 1993; Terrier and al., in press; Bour and al., in press) and the greatest seismic events or 'reference earthquake', without regarding their recurrence time. In the context of french Working Group EPAS (Evaluation Probabiliste de l'Aléa Sismique / Probabilistic Seismic Hazard Assessment), created in 1995 by the AFPS (Association Française du Génie Parasismique / French Association for Earthquake Engineering), the probabilistic approach is developed in order to better assess the regional seismic hazard on the whole metropolitan french territory. This work has been possible thanks to the active participation and collaboration of several organisms, institutes and individual scientists, such as BRGM, CEA, EDF, GEOTER and ICC. In fact, this probabilistic approach permits to add the quantitative notion of earthquake return period for specific magnitude, which is difficultly seized with the deterministic approach (Terrier and al., in press; Bour and al., in press). For this reason, it helps the engineers and the decision-makers in their choice to fix the reference design seismic motion for conventional structures referring to specific return period.

This paper follows the classical succession of the necessary steps for Probabilistic Seismic Hazard Analysis (PSHA), i.e.:

- numerizing the seismotectonic units into sources zones;
- constituting a reliable and complete earthquake catalog;

- characterizing the seismic activity;
- calculating the seismic hazard itself and producing its graphical representation by mapping the iso-values of probabilities or ground motion parameters.

2 DELINEATION OF SEISMIC SOURCE ZONES

The seismotectonic zonation (Part I; Autran and al. 1998) has to be adapted to the probabilistic model of seismic sources. The sources zones are provided from seismotectonical units whose contours are geometric. Numerous corrections, modifications and adaptations shall have been given to the initial seismotectonical zonations (Combes and al., 1993; Terrier and al., in press; Bour and al., in press) before obtaining a useful delineation of seismic sources zones. In fact, in each of them, the seismic activity has to be homogeneous and to consist of sufficient number of earthquakes, in order to characterize the activity, by using an intensity distribution law. That is why some aseismic zones have been removed and others, inhomogeneous from the point of view of their seismic activity have been modified. Finally, new ones have been created.

Following these specifications, the Aquitaine Basin and Gulf of Lion - Camargue aseismic area have been removed. The necessity of complete earthquake catalog has needed other changes. For example, because of the northerly extension of the Lower Rhenan Basin which does not give better information on the statistical processing of data and on the seismic hazard of North France, this area has been also northerly bounded by the 51.5 N parallel of latitude. For the same reason, the Oriental Pyrenees have been arbitrarily southerly bounded by the 41.5 N parallel of latitude.

The Liguro-Provençal Basin is saved as it was in its south-western part. It is northerly bounded by the little "newly created" Ligure area, which permits to take into account the strong seismicity present in the North-East without "spreading" its influence on a whole area otherwise quasi-aseismic. This limitation can sligthly increase the level of the hazard at the North of Corsica.

Some seismic zone-sources have been added. That is the case of the Souabe Jura, whose the high seismic activity can influence significantly the hazard in Alsace, the Ligure zone (see just above) and the very little Bordeaux area which presents a specific located activity.

Finally, 38 sources zones derived from the initial seismotectonical zonation (Part I; Autran and al. 1998) are identified to represent the seismic behaviour of the french territory (Fig. 1). When the number of earthquake was too low in order to calculate reliable statistical results in terms of seismic activity or when the activity was nearly aseismic, a low seismic background has been allocated.

3 EARTHQUAKE CATALOG

Knowing that a given site is subjected to the effects of earthquakes coming from neighbouring areas, the calculation of the seismic hazard requires to define the maximal extent of the area in which earthquakes can have an influence on the site. Moreover, it is of the major importance to constitute for this area, the data file as exhaustive and homogeneous as possible. For the french territory, it needs the use of the earthquakes catalog from countries bordering France: Belgian, Dutch, German, Italian, Swiss instrumental and historical earthquake data file. The chosen threshold magnitude is 3.5.

In this work, the studied area was comprised between 5°W and 10°E in longitude and between 41°N and 52°N in latitude.

3.1 *Conversion*

Some earthquakes data files contain epicentral intensities (mainly for historical earthquakes), others in magnitude. In order to use the whole available data, we chose to keep only one of both parameters and to convert the other one.

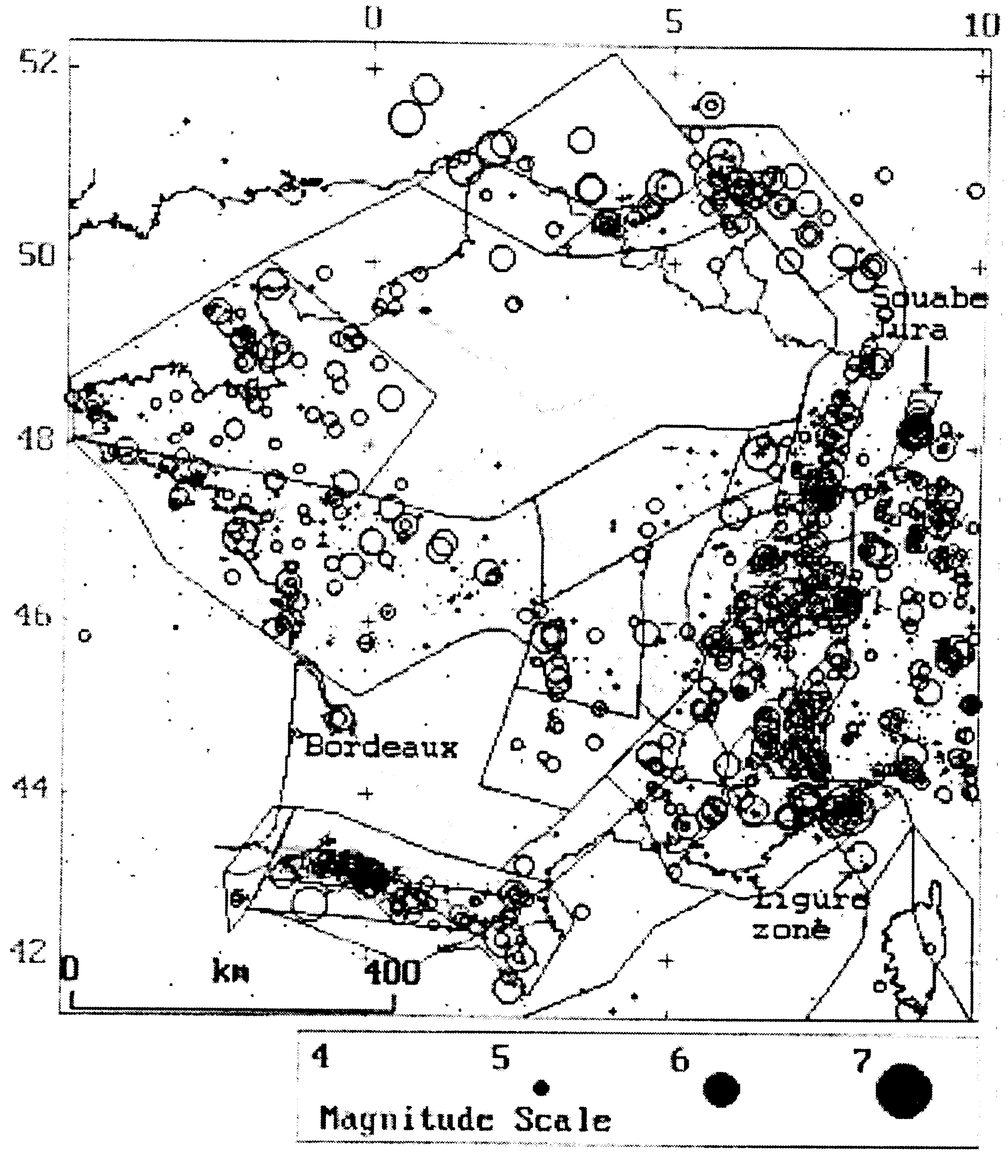

Figure 1. Seismic zone sources and seismicity data (M greater or equal than 3.5) used for PSHA.

The aim of this work was the cartographic drawing of iso-values of the maximum acceleration.That is very hazardous to deduce directly from epicentral intensity of an earthquake, from its depth if it is known and from its distance to the site, the maximum acceleration on it by using an attenuation equation. Such equations present in general too high dispersion. In contrary, numerous recent scientific publications give the maximum acceleration predicted on a site, function of the magnitude and the distance to the earthquake. We chose this approach and therefore converted the whole epicentral intensities into "equivalent magnitudes".

In all the cases, the M.C.S. (Mercalli, Cancani, Sieberg) intensities, issued from the italian catalog, are converted into M.S.K. (Medvedev, Sponheuer, Karnik) intensities, then into "equivalent magnitude". This conversion has been achieved by comparing, adjusting and selecting some conversion equation from the plot of 242 earthquakes recorded by both french and italian observatories. When numerous values of magnitude were calculated on different scales (M_L, M_D), we keep only the maximum of these values, following a conservative scope.

3.2 *Temporal stationarity hypothesis*

As it is required by using simple Poisson process, the hypothesis of spatio-temporal stationarity in the recurrence of future earthquakes needs the removal of foreshocks and aftershocks. It is complex to make this task automatically, because of the variability of the time period between dependant events occurrence. Therefore, this step needs a manual removal. In general, we used the following rule: the foreshocks occur in a time period less than two days before the mainshock and the aftershocks can continue until six months to more than one year after the mainshock. This removal of foreshocks and aftershocks is relatively easy to apply in France, where like in many areas, the seismic activity occurred by crisis spaced in time.

A specific process has been done for the swarms, for which the identification of one mainshock, among its foreshocks and aftershocks was particularly difficult because of:

- the homogeneity of the values of magnitudes of these clusters of earthquakes;
- a "serrated" seismic distribution (alternation of small and moderate earthquakes) during the time interval

In the case of a swarm, it is important to take into account the dissipated energy liberated during the seismic crisis. That is why it has been chosen to increase the highest magnitude of the swarm of one half unit when the swarm is important (long time and high frequency of events) and of 0.2 when we consider two significative earthquakes of same magnitude which occurred in a 72 hours time period.

The final earthquakes catalog contains 2998 events with magnitude greater or equal than 3.5, as it is shown in Figure 1.

4 CHARACTERIZATION OF SEISMIC ACTIVITY

4.1 *Recurrence relationship*

If the seismic activity of a fault or an area, i.e. its annual rate of seismicity above a specific threshold, varies during time, the stationary Poisson equation is rather not appropriate for describing this behaviour. In such case, we need to have recourse to more sophisticated temporal model, such as Markov-model process or renewal process, including the determination of parameters like the amplitude of cyclic fluctuations of the annual rate of seismicity, its frequency and phase. Unfortunately, such parameters are very difficult to assess in France, where the seismic activity is relatively low compared with other countries like Italy, where temporal models are developed and have been applied already. Therefore, we use the classical stationary Poisson process, defined by the following equation:

$$P(n,t) = \frac{(\lambda t)^n e^{-\lambda t}}{n!}$$

where P = probability than n earthquake(s) occurred during t years; λ = averaged annual rate of earthquakes with magnitude greater or equal than M_0; M_0 = lower bound below which the earthquakes are too low for engineering purposes (here $M_0 = 3.5$); t = lifetime of the structure or observation time in years; n = number of earthquakes with magnitude greater or equal than M_0 which occurred during the lifetime t.

To describe the probability to have an earthquake with a magnitude M' greater than a specified magnitude M, different relationships are available. Among them, the simple exponential distribution, the Weibull distribution and the truncated exponential recurrence relationship. We chose this last relationship which is coherent with the physical bound to the energy release giving a zero probability for very high magnitude earthquake, i.e. greater than the upper bound magnitude chosen:

$$P(M' \geq M) = \frac{e^{-\beta(M-M_o)} - e^{-\beta(M_m-M_o)}}{1-e^{-\beta(M_m-M_o)}}$$

where M_m = upper bound magnitude; β = parameter giving the decrease of seismic activity with the magnitude. ($\beta = b \ln 10$, where b is the b-value of the Gutenberg-Richter equation)

The reccurrence model of earthquake is then defined by the following equation giving the averaged annual number of earthquakes with magnitude M' greater or equal than M:

$$\lambda(M) = \lambda \times P(M' \geq M)$$

4.2 *Upper bound magnitude*

The upper bound magnitude M_m is deduced from the Maximum Credible Earthquake (MCE) which gives the physically upper bound magnitude to the energy released associated with an earthquake, taking into account the seismotectonic characteristics and properties of the studied region.

The assessment of this bound needs to well know the process occurring in the genesis of an earthquake and to gather all the available data concerning the considered area.

When such knowledge is unavailable, the maximal upper bounds are defined adding one half unit to the magnitude of the reference earthquake (Maximum Historically Credible Earthquake - MHCE) associated with the corresponding seismotectonical unit.

4.3 *Complete sampling catalog*

A sampling data is complete when its exhaustiveness (all available data have been collected) and its homogenousness (these data show a regular and if possible stationary seismic activity). Such determination is necessary for calculating the λ and β parameters. The χ^2 (khi-square) test is used to check the homogeneity of the catalog (Hendrickx, 1981). This test permits to determine the following threshold from which the earthquakes catalog can be assumed as complete:

Table 1. Threshold for complete earthquakes catalog

Magnitude threshold	3.5	4.5	5.0
initial date for complete sampling	1962	1870	1810

In fact, we normally check that the initial date for complete sampling with threshold magnitude equal to 3.5 corresponds well to the first instrumental data catalog in 1962. This underscores the importance of instrumental data and the lack of information in relation with small earthquakes before this date.

The number of events becoming insufficiant, it is impossible to apply the χ^2 test for thresholds greater than 5.0. Nevertheless, the Kijko & Sellevoll method (1989, 1992) allows us to take into account the "extreme part" of the catalog, including the strongest earthquakes, with magnitude greater than 5.0. This "extreme part" covers the time period from 858 to 1809, but do not represent in any case, a complete catalog.

Nevertheless, we must remind that this χ^2 test shows a general trend for the whole data file. It does not take into account the possible variations between the different seismic source zones. To show these differences would suppose to achieve the χ^2 test for each zone. But, the fewer number of events of these zones would give no significance to the test.

4.4 *Seismic activity parameters*

Because they characterize the seismic activity, λ and β are key-parameters for PSHA. We remind there that λ is the averaged annual rate of earthquakes with magnitude greater or equal to $M_o = 3.5$ and that β describes the decrease of the seismic activity with magnitude.

The statistical data processing of historical and instrumental seismicity on a given time period is essential before each PSHA. It allows to test the exhaustiveness, coherence and spatio-temporal representativity of data.

Three approaches have been used to determine the seismic activity parameters (λ and β): the adjustment to the Gutenberg-Richter relationship (1954) by the Mean Square Fit, the adjustment to the truncated Gutenberg-Richter relationship by the Mean Square Fit, the Kijko and Sellevoll (1989, 1992) method. The first one has the advantadge to be the simpliest and easiest to apply but is really not appropriated for such PSHA studies. The second one permits to take into account the upper bound magnitude M_m. The third one is the most complex and complete taking into account both several complete parts of catalog and the extreme part of catalog, and also the upper bound magnitude M_m. Another advantadge of this last method is the possibility to associate uncertainties to the magnitude, that we affected to 0.5 and to give some a priori value of λ and β.

When the number of earthquakes in a source zone was less than six, no calculation of λ and β was done. We simply give a seismic bakground for which the annual surfacic rate of seismic events with magnitude greater or equal than 3.5 was specified equal to $0.1\ 10^{-5}$ / km^2.

4.5 *Attenuation equation*

Attenuation equations of acceleration function of the distance can not be determined locally, because of the lack of recorded strong motions in France.

The attenuation equation we chose has been established for the whole of Europe by Ambraseys (1995) from 529 horizontal components of acceleration:

$$\log_{10}(a_h) = -1.06 + 0.245 M_s - 0.00045 R - 1{,}016 \log_{10}(R) + \sigma P$$

where $\sigma = 0.25$; P = 0 for 50%-percentile curve and P = 1 for 84%-percentile curve; R = focal distance; a_h = horizontal acceleration (in g's); M_S = surface wave magnitude.

The local magnitude (M_L) or duration magnitude (M_D) values are generally greater than those of surface wave magnitude (M_S) for magnitude less than 6.0. This difference can slightly overestimate the hazard, which is acceptable if we take into account the conversion errors (from MCS intensity to MSK intensity, from intensity to magnitude,...). In fact, EPRI (1989) and Van Dyck (1985) indicate that magnitude obtained from conversions should be increased because of their conversion uncertainties. If M(Io) is the reference magnitude obtained from a conversion equation and σ is the associated standard deviation, we should use:

$$M^* = M(Io) + \frac{1}{2} b . \ln(10) \sigma^2$$

This increase that we do not have inserted in our model is truthly mainly taken again by the attenuation equation, especially for the low magnitudes.

5 PROBABILISTIC SEISMIC HAZARD ASSESSMENT (PSHA)

The λ and β parameters, the upper bound of magnitude and attenuation equation have been calculated or chosen for each source zone. Then, the PSHA can be run on France.

A modified version of the well-known Mc-Guire (1976) EQRISK code, following the Cornell methodology has calculated the acceleration for a return period equal to 475 years, which corresponds to a probability of exceedance of 10% in 50 years for a given acceleration. The annual probability of exceedance is equal to $2.1\ 10^{-4}$.

The seismic hazard map shows in figure 2 the iso-values of peak ground horizontal acceleration for a return period equal to 475 years.

The uncertainties factors are numerous and the parameters used for assessing the seismic hazard can be spoilt by errors. These uncertainties are due to:

- location and magnitude of earthquakes;
- conversion (from MCS to MSK intensities, from intensity to magnitude);
- removal of foreshocks and aftershocks (difficulty to distinguish the mainshock in a swarn);
- delineation of seismic source zone;
- attenuation equation (it is the only uncertainty to be taken into account by EQRISK code);
- determination of upper bound magnitude;
- calculation of the λ and β seismic activity parameters.

We remind here that the uncertainties are sometimes mainly due to the lack of data. This point is the main problem for assessing the seismic hazard in area of low seismicity like in some parts of France.

In despite of these uncertainties, the results can give the trends of the hazard in France, even if it should be taken carefully.

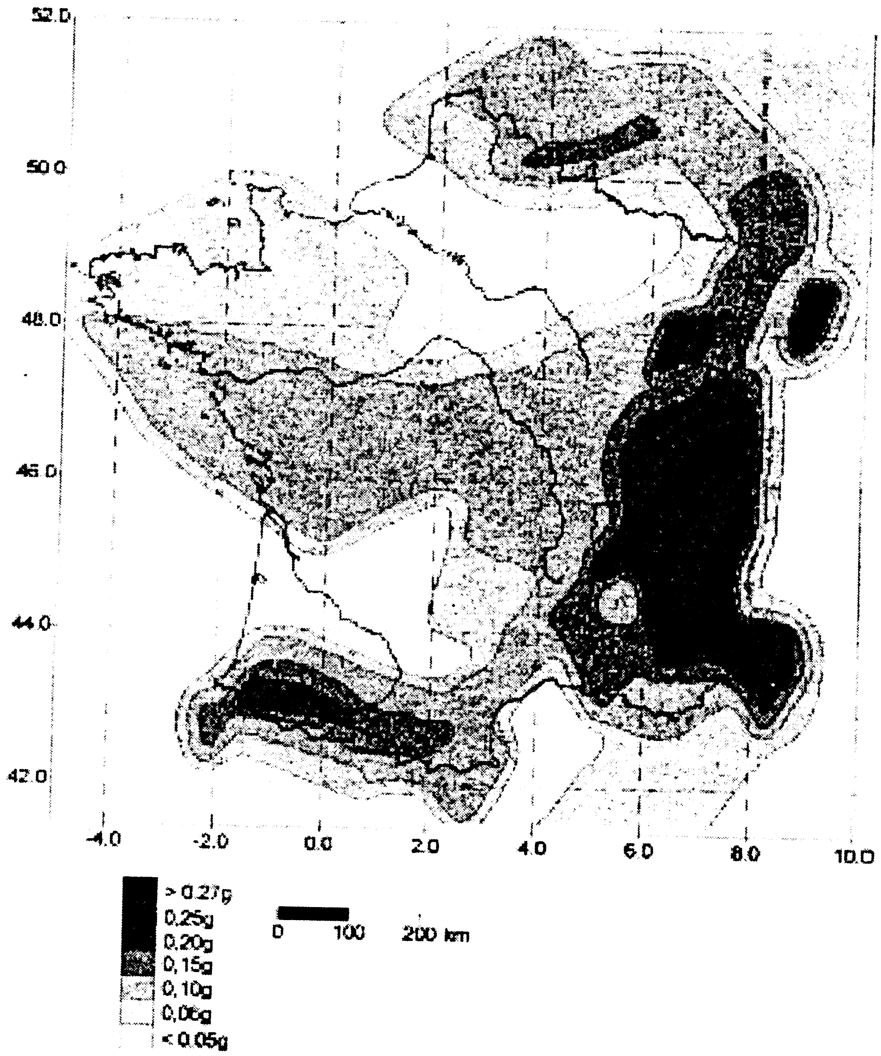

Figure 2. Preliminary map of acceleration iso-values corresponding to a 475 years return period.

6 RESULTS AND CONCLUSION

The Working Group EPAS (Probabilistic Seismic Hazard Assessment), under the aegis of AFPS (French Association for Earthquake Engineering), works for about two years on seismic zonation and hazard at the national scale. This paper shows the first results obtained for mapping the iso-values of maximum horizontal acceleration corresponding to 475 years return period (Fig. 2).

This preliminary work permits us to extract the main trends giving the awaiting accelerations for a return period corresponding to those used for conventional structures.

The Occidental Pyrenees, the Alpes and the Remiremont-Vesoul area stand out clearly with acceleration values bounded between 0.20g and 0.25g. In the least manner, the Upper Rhenan Basin, the Lower Rhône Valley and the North Artois Shear have accelerations closed to 0.15g. The German Jura Souabe N-S Fault zone is the most seismic active area with accelerations greater than 0.27g.

The Aquitaine Basin and Parisian Basin, considered as aseismic zones, have accelerations lower than 0.05g corresponding to the arbitrary fixed level of background seismicity.

We remind there that the values observed in coastal and some frontiers areas have no physical significance because of the lack of knowledge and confrontation with neighbouring coutries. Moreover, it should be pointed out that this work can not be used directly as it is for further studies aiming at assessing the hazard or risk level in France. Before this, it should be completed by necessary sensitivity analysis taking into account particularly the different hypothesis for delineating the zonation, choosing the parameters like λ, β, M_o, M_m, characterizing the seismic activity and also the attenuation equation which is of the major importance on the results.

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