0632

PROBABILISTIC SEISMIC HAZARD MAP ON THE FRENCH NATIONAL TERRITORY

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SUMMARY

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 (Evaluation Probabiliste de l'Aléa Sismique / Probabilistic Seismic Hazard Assessment), under the aegis of the AFPS (Association Française de Génie Parasismique / French Association for Earthquake Engineering), including organisms like BRGM, IPSN, EDF and GEOTER, is to propose a probabilistic seismic hazard map for the French metropolitan national territory for conventional structures.

The compilation of this map involved two stages : the first one consists in determining a seismotectonic zonation at the scale of the country. The second stage, presented in this article, uses the seismotectonic zonation to compute the probabilistic map. The Cornell probabilistic method was chosen because readily available to the different participants of the Working Group. Such studies are very sequential and can be split up into different steps : seismicity files from neighbouring countries complement the catalogue of seismicity, constituted of both instrumental and historical data. Statistical analysis permits to establish the date threshold and corresponding magnitude threshold, for which catalogue completeness can be assumed. Then, the parameters, which characterise the seismic activity of each source-zone, are determined. A general attenuation relationship, giving acceleration related to the magnitude and distance is chosen for national territory. Finally calculations are performed on a grid of points covering the national territory. The values obtained are translated into maps showing the values of spectral acceleration corresponding to a 475 years return period, commonly used for current constructions.

The paper insists on the uncertainties associated with all the parameters needed at each step of PSHA (Probabilistic Seismic Hazard Assessment) and which can influence the final results. More precisely, sensitivity analysis is achieved on : seismotectonic zonation's boundary, maximal magnitude and mean depth attributed to each zone, attenuation relation, and seismic parameters. Finally, confrontations with PSHA obtained in neighbouring countries are done.

INTRODUCTION

In the field of seismic risk studies, the french present seismic regulations are based on strictly deterministic approach, which takes into account both seismological zonation and the greatest known seismic event or "reference earthquake", without regarding their recurrence time. In the context of French Working Group EPAS, created in 1995 by the AFPS, the probabilistic approach is developed in order to better assess the regional seismic hazard on the whole French territory. In fact, this probabilistic approach permits to add the quantitative notion of earthquake return period for specific magnitude.

This paper follows the classical succession of the necessary steps for Probabilistic Seismic Hazard Analysis (PSHA) : definition of a seismotectonic zonation, constitution of a complete earthquake catalogue,

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characterisation of the seismic activity of each zone, choice of an attenuation relationship, and then calculation of the seismic hazard itself. It is completed in 1999 by a sensitivity analysis on the parameters and a comparison with results of neighbouring countries.

SEISMOTECTONIC ZONATION DEFINITION

Works conducted in 1997 and 1998 permitted to lead to a consensus seismotectonic zonation between the different members of EPAS Working Group (Autran et al., 1998). However, some points to be corrected appeared when this zonation was taken into account for the PSHA.

- The activity of some seismic zones is weakened because of their integration in zones with low seismic activity (as Basel area or Ligure zone).

- Some zones regarded as aseismic are integrated in more active zones (as Bresse area).

- Others present a seismicity composed of moderated events, but in too short number to establish a distribution relationship of magnitudes (as Bordeaux area).

Thereby, some limits were modified privileging the seismic activity level with respect to structural criterions.

Finally, the French reference zonation includes 39 source zones (Fig. 1).

EARTHQUAKE CATALOGUE

Knowing that a given site is subjected to the effects of earthquakes coming from neighbouring areas, the calculation of 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 historical and instrumental earthquakes catalogue from countries bordering France : England (Musson, 1994), Belgium (catalogue of the Observatoire Royal de Belgique), Germany (Leydecker, 1999), Switzerland (catalogue of the ETH Zurich), Italy (catalogues of the Protege Finalizzato Geodinamica and of the Istituto Nazionale di Geofisica) and Pyrenean data file (Souriau & Pauchet, 1998). In this work, the seismic catalogue is contained between 5°W and 10°E in longitude and between 41°N and 52°N in latitude.

As this work aims at a cartographic drawing of isovalues of acceleration obtained from magnitude and distance to the earthquake, we choose to work in magnitude. Therefore when no magnitude was available, the epicentral intensities were converted into "equivalent magnitudes" using the Levret (1994) relationship. Then, as a result of an observed divergence with LDG/CEA (Laboratoire de Détection et de Géophysique) magnitudes, a correction is established from low magnitude recent earthquakes.

Moreover, the model chosen is the Poisson one (cf. following chapter on recurrence relationship) for which one of the basic hypothesis is spatio-temporal stationarity of seismic activity. Therefore, foreshocks and aftershocks of main events have to be removed.

The final earthquake catalogue contains 2673 events between 813 and 1998 with magnitude greater or equal than 3.5 (Fig. 1).

CHARACTERISATION OF SEISMIC ACTIVITY

Recurrence relationship

As seismic activity of France is moderate, we have decided to use the stationary Poisson model and the truncated exponential relationship as magnitudes distribution relationship, i.e. relationship describing the magnitude distribution for homogeneous samples and for a given magnitude threshold (Dominique et al., 1998). The truncated Gutenberg-Richter relationship needs to introduce an upper bound magnitude M_m, for which the probability of exceedance is zero.

Seismic activity parameters

The annual seismicity rate ‘a’ and the ‘b-value’ of the Gutenberg-Richter relationship are key-parameters for PSHA because they characterize the seismic activity of each source zone.

They are assessed using the "maximum likelihood" statistical method proposed by Weichert (1980). When the number of earthquakes in a source zone is less than six, no calculation of λ and β is done. We simply give a seismic background for which the annual surfacic rate of seismic events with magnitude greater or equal than 3.5 is specified to $0.1*10^{-5}/\text{km}^2$ and the b-value of the Gutenberg-Richter relationship is put to 1.

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 know well the process occurring in the genesis of an earthquake and to gather all the available data concerning the considered area. At last, this notion is more significant for source faults than for source area, where it is rather uncertain to assess the maximum slip rate or the size of the maximum rupture area. In some part of south-eastern France, the maximum magnitude is assumed to be equal to the ‘paleoseismic magnitude’ deduced from field observations.

When such knowledge is unavailable, the upper bound is defined adding one half unit of magnitude to the magnitude of the maximum historically known earthquake for each source.

Finally, a lower bound to this maximum magnitude is fixed equal to 5.5. Indeed, a 5.5 magnitude earthquake is supposed to be able to occur in each zone even in very low seismic zone such as Burgundy, Corsica or the Basque country.

ATTENUATION EQUATION

Attenuation equation 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 choose has been established for the whole Europe by Ambraseys (1995) from acceleration (a) records generated by 219 shallow events (h < 25km) with surface-wave magnitude (M_S) between 4.0 and 7.3 and focal distance (R) between 1 and 310 km :

$$\log_{10}(a) = -1.06 + 0.245M_S - 0.00045R - 1.016\log_{10}(R) + \sigma P \tag{1}$$

where a in ‘g’ ; $\sigma = 0.25$; P = 0 for 50%-percentile curve and P = 1 for 84%-percentile curve.

Local magnitude M_L values are generally higher than the ones of surface-wave magnitude M_S for values lower then 6. Therefore, a correction deduced from the comparison of magnitudes proposed by Heaton et al. (1986) was introduced in the relationship (1) :

$$M_S = (M_L - 1.8)/0.7 \tag{2}$$

Moreover, the activity level λ was assessed again for a local magnitude threshold of 4.5 (i.e. $M_S = 4$) in order to be in the relationship validity domain.

PROBABILISTIC SEISMIC HAZARD ASSESSMENT

The model, the ‘a’ and ‘b-value’ parameters, the upper bound magnitude and the 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 peak ground acceleration (p.g.a.) for return period equal to 475 years. This return period corresponds to a probability of 10% in 50 years that this acceleration will be exceeded (figure 2).

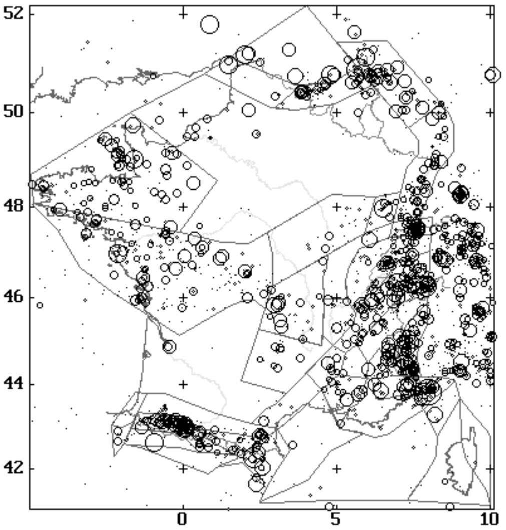

Figure 1 : Surimposition of zone sources and seismicity

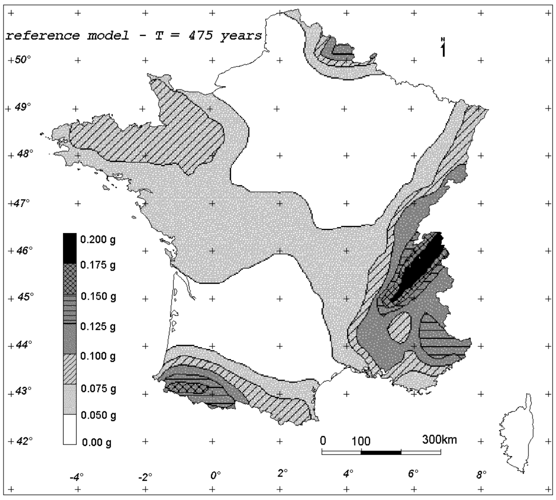

Figure 2: Map of acceleration isovalues corresponding to 475 years return period

The uncertainty factors are numerous and parameters used for assessing the seismic hazard can be spoilt by errors. These errors are due to : location and magnitude determination of earthquakes, conversions from intensity to magnitude and between different magnitude and/or intensity scales, removal of foreshocks and aftershocks, delineation of seismic source zone, determination of upper bound magnitude M_m , calculation of the 'a' and 'b-value' seismic activity parameters, attenuation equation (it is the only uncertainty to be taken into account by EQRISK code) with the choice of mean depth. 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. Despite these uncertainties, the results can give the trends of the hazard in France. Moreover, a sensitivity analysis permits to put in evidence values limits.

SENSITIVITY ANALYSIS

The idea is to study the influence of parameters on hazard : source zones boundaries, 'a' and 'b-value' seismic activity parameters, upper bound magnitude, choice of attenuation equation and mean depth. All the tests were done one after another from the reference model.

Zonation influence

A surimposition of zonation and hazard map shows that the acceleration isovalues curves follows well the boundaries of the zone which generate them. This underlines the importance of their geometry.

At first, a zone was created in the Swabian Alb region. Indeed, as this region has a high seismic activity, it could have increased acceleration levels of the nearest zone on the French territory, i.e. the Jura and the upper Rhine Graben. Now, two successive calculations with and without this zone show quite similar results. Therefore, this zone has no influence on the hazard in France and it was removed.

Likewise, the zone of Bordeaux, which knew some moderate events, was removed. The lack of events did not permit the calculation of the G-R relationship parameters. The assignation of a seismic background does not modify the acceleration level of that zone.

At last, some boundaries with poor structural proofs were tested : their setting up is based mainly on area with significant seismicity in comparison with neighbouring zones. In fact, removing some small zones with significant seismicity leads to a weakening of seismic hazard where they are located (case of the Vosges or the Basel zone). Likewise, the Bresse-Bas Dauphine zone was cut in two parts to emphasize the aseismic characteristic of the Bresse area.

Seismic activity parameters influence

A test was run out with seismic parameters assessed using the "maximum likelihood" statistical method adapted by Kijko and Sellevol (1992), by considering a magnitude uncertainty equal to 0.5. The activity parameters λ assessed by this method are equal or smaller from 10 to 50% than the ones assessed by the Weichert method, which were similar to those obtained by fitting the truncated Gutenberg-Richter relationship to the maximum magnitude. As a consequence, the values of acceleration are lower up to 0.05 g. The higher differences are observed in the more active areas.

Tests were also executed with b-value equal to 0.8, 1 and 1.2 with a constant annual rate of activity. The acceleration values decrease with the rise of b. Nevertheless, differences in values are less than or equal to 0.01 g which is not very significant. The b-value has only low influence on final acceleration values.

Finally, the uncertainty given by Weichert method on annual rate of activity ‘a’ given by Weichert method was taken into account : all the activity rates were increased by their respective uncertainties. This leads to very small variations of acceleration values (less than 0.1 g). Taking into account of this uncertainty has very few influence on the final result.

Upper bound magnitude influence

In reference model, most attributed maximum magnitudes M_m are lower than or equal to 6.5. One test was run out with an upper bound magnitude of 6.5 and then two more with an increase of 0.5 and 1 unit on the upper bound magnitude.

When all maximum magnitudes are fixed to 6.5, it can be observed than the values of acceleration increase by a maximum quantity of 0.03 g in the zones where reference maximum magnitude is lower than 6.5 and decrease in the contrary case.

A rise of 0.5 on the maximum magnitude leads to an increase of 0.01 g : central and occidental Pyrenees, large south-eastern area including the Alps, Rhine Graben, Fagnes (France-Germany frontier) and north-west part of Armorican Massif. An increase equal to 0.02 g is observed in the Jura and in Bearn.

A rise of 1 on the maximum magnitude leads to the same trends, but with an increase of acceleration values generally higher than 0.02 g : occidental Pyrenees, Alps, Rhine Graben, Fagnes and north-west part of Armorican massif. These values are sometimes higher than 0.04 g : Jura, Bearn and Tricastin.

Logically, acceleration values in a zone increase with maximum magnitude assigned. This property is emphasised in high activity zones. It is important to underline that these increases would be much higher for longer return period.

Attenuation equation influence

A test was carried out with the relationship established by Tento et al. (1992) from accelerometric data (a) recorded in Italy of 40 events with local magnitude (M_L) between 4.0 and 6.6 and with focal distance (R) between 3.2 and 170.0 km :

$$\log_{10}(a) = -0.946 + 0.226M_L - 0.00094R - \log_{10}(R) + \sigma P \qquad (3)$$

where a in ‘g’ ; $\sigma = 0.29$; P = 0 for 50%-percentile curve and P = 1 for 84%-percentile curve.

The activity level ‘a’ was assessed again for a local magnitude threshold of 4 according to the relationship validity domain.

With this relationship, the acceleration values are higher from 0.02 g to 0.1 g : the difference increases with the acceleration values.

A second test was run out with the attenuation relationship established by Mohammadioun and Pecker (1993) from 23 events (56 records) of California with local magnitude (M_L) between 5.0 and 7.7, with focal distance (R) between 3 and 136 km recorded on rocky site ($V_S > 750$ m/s) :

$$\log_{10}(a) = -0.945 + 0.17 M_L - 0.72 \log_{10}(R) + \sigma P \tag{4}$$

where a in 'g' ; $\sigma = 0.27$; P = 0 for 50%-percentile curve and P = 1 for 84%-percentile curve.

The activity level λ was assessed again for a local magnitude threshold of 5 according to the relationship validity domain.

The levels in zones with small activity are higher (up to 0.04 g) with the Mohammadioun & Pecker relationship than those obtained with the Ambraseys relationship but the highest values remain in the same range, sometimes slightly smaller with the Mohammadioun & Pecker relationship (up to 0.02 g).

On the one hand, considering the shape of the attenuation relationship adopted, depth can change the acceleration level especially for short distances. On the other hand, it is very difficult to assign a mean depth for each zone.

By using the Ambraseys relationship, a test was run out with a depth of 10 km for all zones and then another one modifying depth of some zones for which the determination of depth was doubtful.

As awaited, a depth increase from 5 to 10 km leads to higher variation of the acceleration values (greater than 0.03 g) than a passage from 15 to 10 km (-0.01 to -0.02 g). The acceleration variation increases with the decrease of the depth.

Spectral accelerations

By using the Mohammadioun & Pecker relationship, spectral acceleration have been caculated for several values of periods : 0.1, 0.2, 0.3 and 1 s (i.e. frequency : 10, 5, 3.33 and 1 Hz) with a critical damping ratio of 5%.

In agreement with what we thought, the highest acceleration values are obtained for a period of 0.3 s and 0.2 s. We can observe a ratio of 2.5 to 3.0 between these values and the p.g.a. values, which is in conformity with the Newmark (1976) coefficients. For all different periods, the same general trend of seismic area is still observed, in respect with the p.g.a. reference model.

CONFRONTATION WITH PSHA OF NEIGHBOURING COUNTRIES

A comparison is conducted with the neighbouring countries or regions : England (Musson 1997), Belgium (de Crook 1989), Germany-Austria-Switzerland (Grünthal and Mayer-Rosa 1998), Italy (Romeo and Pugliese 1998), Catalonia (Secanell et al 1998). This confrontation should not only be on the final hazard map, but also at each step of the PSHA : zonation adopted, parameters and method used for the hazard calculation and the type of representation itself. Indeed, we quickly realize that each team makes its own choices.

For zonation, in France, we decided to take into account both structural data and seismicity. It seems that countries as Belgium, Italy or Catalonia adopted the same reasoning. On the other hand, in England or Germany, seismicity was the main criterion : zones are generally smaller and so more numerous.

In most countries, SEISRISK III code is used instead of EQRISK. To make comparison easier, a hazard calculation for France is made with a modified version of this code.

Comparisons on final results have been made with Catalonia, Italy, Germany-Austria-Switzerland and England.

- The study in Catalonia was made in intensity. Comparing two sets of results (intensity versus magnitude) is not easy. There is no straight correlation between intensity and acceleration : a lot of parameters play a part (focal distance, signal spectral content). Roughly, it can be considered that a VII intensity corresponds to an acceleration of 0.04-0.16 g (Medvedev, 1962) or to an averaged value of 0.13 g (Trifunac, 1975). On the one hand, where Spanish team gives an intensity of VII, in France we have an acceleration of 0.08-0.1 g. It seems that our values are in the same range or slightly lower. The same progressive decrease of acceleration values from central Pyrenees to the East Coast can be observed in both maps.

- In Italy, large ranges of value are used for the representation of results. Nevertheless, in the Alps, acceleration values are between 0.05 and 0.15 g in both maps. It can also be noticed that in both case, a pocket of acceleration higher than 0.15 g appears in north Alps in the region between 7- 8° E in longitude and 46-47° N in latitude. Then, the acceleration values seems to be near.

- Studies in Germany-Austria-Switzerland and France give very similar results in northeast of France. In the Rhine Graben, acceleration values are between 0.08-0.1 g in both maps. Moreover, a small pocket of values higher than 0.1 g is to be noticed in the Remiremont area. Finally, acceleration values decrease quickly from the Rhine Graben (0.08-0.1 g) to Parisian Basin (<0.04 g).

- At last, concerning England, French map gives acceleration values smaller than 0.04 g which are observed in the British one.

So, french acceleration values coincide quite well with the ones of neighbourhood countries on boundaries.

CONCLUSION

This work, achieved as part as the Working Group EPAS (Probabilistic Seismic Hazard Assessment), under the aegis of AFPS (French Association for Earthquake Engineering), leads to a map of the isovalues of peak ground acceleration corresponding to a return period equal to 475 years, or acceleration values corresponding to a annual probability of exceedance of 10% in 50 years.

This work permits to extract the main trends giving the awaiting accelerations (and uncertainties) for a return period corresponding to those used for conventional structures. The highest values of acceleration in the range of 0.18-0.2 g are observed in the Pre-Alps near Switzerland. The zones of Occidental Pyrenees, Alps, East of French Riviera and Remiremont-Vesoul are clearly evident, with acceleration values between 0,12 and 0,16 g up to 0,18 g locally.

Moreover, zones with very low seismicity like Burgundy, Bresse, Massif Central and Tricastin are put in evidence as well Parisian Basin, Aquitaine Basin and Corsica.

At last, some parameters influence is put in evidence. Determination of zonation boundaries, depth and maximum magnitude assigned to each source zone and choice of attenuation relationship must be done with care.

The confrontation of our results with those of neighbouring countries shows a good agreement on the whole frontiers area.

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