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PSHA outputs versus historical seismicity; example of France

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1. Introduction

The purpose of this paper is to compare two different approaches for estimating the seismic risk on a territory, with application to the metropolitan French territory (Corsica excepted).

The risk can be defined as the annual probability of occurrence of certain damage degrees (according to EMS98 scale definition) on certain types of buildings. In the context of the seismicity of metropolitan France, and in view of addressing historical seismicity, the risk is measured in this paper as the annual probability of occurrence of damage degrees 2 and 3 on conventional masonry buildings.

The first method considered in the paper is based on historical data, while the second one is based on convolution of seismic hazard data and fragility curves. In the later, seismic hazard is described in the form of three different maps of metropolitan France. These maps are outputs of PSHA studies; they provide PGA values for a 475 year return period.

2. Seismic risk assessment based on historical seismicity

2.1 Areas affected by a given intensity

2.1.1 *Principle*

In view of processing historical data from a series of earthquakes, i is the sequential number of an event and $\mathcal{A}_{i,V}$ denotes the area inside the iso-intensity V line for this event.

On an hypothetical territory with stationary activity, observed on a very long period of time, T, and with a perfectly documented historical seismicity, the average area affected annually by an Intensity V or greater[1] would be calculated as follows : $\mathcal{A}_V$ denoting the sum of all the $\mathcal{A}_{i,V}$ on the period of time T, the average area affected annually by an Intensity V or greater is equal to :

$$A_V = \mathcal{A}_V/T$$

Practically this straightforward procedure is not applicable because we do not have at our disposal such ideal data. However the following historical data can be processed:

– n_{I0} ($I_0 \geqq V$) : number of earthquakes of epicentral intensity I_0 felt on the territory per century.[2]
– $A_{I0,V}$: average area affected by an Intensity $\geqq$ V for an event of epicentral intensity I_0.[3]

On these bases estimates of $\mathcal{A}_V$ and A_V are calculated as follows:

[1] Intensity V is an example ; the procedure is similar for every intensity.
[2] In the case of metropolitan France, a significant percentage of these events have their epicentres outside the territory.
[3] Only the part of this area inside the French territory pertains for risk assessment.

$\mathcal{A}_V = \Sigma\, n_{I0}\, A_{I0,V}$, I_0= V à IX and $A_V = \mathcal{A}_V/100$.

The same procedure applies for other $\mathcal{A}_I$ areas, I= VI to IX.

2.1.2 *Application the Metropolitan French Territory*

References available for establishing a statistics of events felt in France [1] [2] are analysed and discussed in Ref [4]. Outputs of this analysis are presented in table 1.

Epicentral Intensity I_0	V	V-VI & VI	VI-VII & VII	VI-VIII & VIII	VIII-IX
Number of events	350	150	70	10	1

Table 1. *Average number of events felt in France per century versus their epicentral intensities ($I_0 \geqq V$)*

In order to calculate $A_{I0,V}$, average area affected by an Intensity ≧ V for an event of epicentral intensity I_0, a series of 140 isoseismical maps [3] established by IPSN was processed. A statistical analysis of every set of events corresponding to a given epicentral intensity was carried out. (A more refined analysis is presented in [4], while the treatment of extreme events is discussed in [5]). An output is that in every set, $\mathcal{A}_{i,V}$ values fit a log-normal distribution. Mean values of these distributions are presented in table 2. In the case of metropolitan France, it is rather frequent that a significant part of $\mathcal{A}_{i,V}$ is out of the national territory (seismic activity is concentrated in border regions). The impact on $A_{I0,V}$ values is also presented in table 2.

Epicentral Intensity I_0	V	V-VI & VI	VI-VII & VII	VII-VIII & VIII	VIII-IX
$A_{I0,V}$ (km²)	180	1020	5300	16300	103000
$A_{I0,V}$ inside Metropolitan France(km²).	120	620	2940	8790	21800

Tableau 2. *Average area with Intensity ≧ V versus epicentral Intensity*

Series of values presented in tables 1 and 2 lead to A_V = 4500 km². A similar processing was also carried out for Intensities VI, VII and VIII, leading to values of A_{VI} A_{VII} and A_{VII} also presented in the first line of table 3.

The metropolitan French territory is not homogeneous in terms of seismic activity. It is possible to split it in zones from very still to rather active. For the purpose of seismic risk estimate, we have considered only two zones, qualified as "exposed" and "less exposed" in table 3. The area of the exposed zone is only 15% of the territory but the zone concentrates 56% of the activity.

Zone \ Intensity	V	VI	VII	VIII
Metropolitan France (538000 km²)	4500	470	58	3,7
Exposed zone (79200 km²)	2500	260	32,5	3,7
Less exposed zone	2000	210	25,5	0

Tableau 3. *Annual mean values of areas (km²) affected by an intensity at least equal to the value indicated at the top of the column (in metropolitan France, and distribution in exposed and less exposed zones).*

2.2 Risk exposure assessment for masonry buildings

In a first step, assuming that population density, and consequently building density, is not correlated with seismic hazard, annual probability that a building (of any type) experiences a given intensity can be derived from the estimated areas reported in table 3. For instance, in average on the Metropolitan French territory, the annual probability that a building experiences an Intensity VII is equal to 58 / 538000 = $1{,}1\ 10^{-4}$. In exposed areas, it is 32,5 / 79200 = $4{,}1\ 10^{-4}$.

In a second step, annual probability that a damage grade 2 or 3 is experienced by a type of building depends on its vulnerability class, such as defined in the EMS98 scale [7]. According to this scale, and considering damage grades 2 and 3 for conventional masonry buildings,

- Intensity VI implies that *a few* of them suffer damage of grade *2.*
- Intensity VII implies that *many* of them suffer damage of grade 2 and *a few* of them damage of grade *3.*
- Intensity VIII implies that most of them suffer damage of grade 2 and *many* of them damage of grade *3.*

Definitions of *a few*, *many* and *most* are relating to fuzzy set concept and leads to quantified of *a few* as 8%, *many* as 35% and *most* as 80%.

Eventually, taking into account contributions of Intensities VI, VII and VIII (Intensity V does not contribute) to damage grades 2 and 3, the annual probability that a conventional masonry building experiences at least such a damage can be estimated as follows :

	Grade 2	Grade 3
In average in Metropolitan France	$1{,}1\ 10^{-4}$	$1{,}1\ 10^{-5}$
In average in exposed zone	$4{,}5\ 10^{-4}$	$4{,}9\ 10^{-5}$

Table 4. *Annual probability of damage grades 2 and 3 on conventional masonry buildings, as resulting from historical seismicity data.*

3. Seismic risk assessment based on PSHA outputs and fragility curves

3.1. Formula for seismic risk calculation

3.1.1. *Principle*

Reference is made here to the classical methodology for seismic risk assessment, such as discussed in IAEA or OECD documents [12] [13]. It is assumed that the PGA is a suitable parameter for rating seismic hazard on a site. The PGA value is denoted a, and $P_e(a)$ is the annual probability that a PGA value larger than a is recorded on the site[4]. Consequently, the annual probability that a PGA is recorded in the range a - a+da is equal to $p_e(a)$ da, so that:

$$p_e(a)\ da = -\ P_e'(a)\ da\ .$$

Fragility of buildings of a given type is described by the percentage of buildings of this type that, under a PGA equal to a, suffer a damage grade at least equal to D (according to EMS98 scale definitions). This

[4] Relation between $P_e(a)$ and the return period T(a) reads : $P_e(a)=1-\exp(-1/T(a))$; it means $P_e(a)=1/T(a)$ for rare events.

percentage is also the probability that a building of the considered type suffers at least a damage D under the PGA a ; it is denoted $P_{f,D}(a)$.

Then the annual probability that such a building suffers at least a damage D reads :

$$p_D = \int_0^\infty p_e(a) P_{f,D}(a) da \ .$$

3.1.2. *Usual p_e et $P_{f,D}$ functions*

It is widely admitted that $P_e(a)$ can be expressed as[5][6]: $P_e(a) = (a/A)^{-n}$, where A is a corner value. Consequently p_e takes the form:

$$p_e = n/A\ (a/A)^{-(n+1)}$$

It is also widely admitted that log-normal distributions are suitable for describing building fragilities. In the following formula, a_D is the median value of a, corresponding to damage D, and β_D is the associated standard deviation of the natural logarithm of a.

$$P_{f,D}(a) = \Phi\left[\frac{1}{\beta_D} \mathrm{Ln}\left(\frac{a}{a_D}\right)\right] \qquad \text{with} \quad \Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp(-t^2/2)\, dt$$

On the basis of these assumptions, the annual probability that a building of the type under consideration suffers at least a damage D can be calculated and expressed as follows:

$$p_D = \left(\frac{A}{a_D}\right)^n k_D \ , \ k_D = \exp\frac{n^2 \beta_D^2}{2}$$

3.2. Application to traditional masonry buildings in France

3.2.1. *PSHA maps of France*

Three different Seismic Hazard Maps (SHM) of the French territory are considered. The three of them are providing the 475 year return period PGA on the French territory, denoted a_{475}. They were respectively issued in 2002, 2004 and 2006 and are identified in this paper as SHM-2002 [8], SHM-2004 [9], and SHM-2006 [10]. In every location of the continental French territory, taking into account an a_{475} values that depends on the map under consideration, $P_e(a)$ and p_D reads:

$$P_e(a) = \frac{1}{475}\left(\frac{a_{475}}{a}\right)^n \text{, and } p_D = \frac{1}{475}\left(\frac{a_{475}}{a_D}\right)^n k_D \ .$$

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[5] In principle this formula is not correct. It cannot be a probability because it leads to values larger than 1 for a values lower than A.. This formula would be more suitable for the annual rate of exceedance of a (This rate is exactly the inverse of the return period). However it is admitted here that we are considering rather long return periods, so that the annual probability of exceedance and the rate of exceedance may be regarded as equal.

[6] Practically n value is around 2 or 3.

3.2.2. *Fragility data*

The EMS98 building classification was adopted by the R&D European project Risk_UE. In the framework of this project a methodology was set up in order to establish fragility curves by building types. Traditional masonry buildings were considered by Skopje University, which proposed a series of a_D and β_D values [11][7] , including a_D and β_D values for damage grades 2 and 3 that are presented in Table 5. In this table k_D values corresponding to n=2 and n=3 are also indicated (n values are discussed in the Appendix). Whether these fragility curves are suitable for traditional masonries built in metropolitan France is a matter of discussion. Possibly, compared to France, larger exposure to seismic risk might have maintain a better "seismic risk culture" in Balkan. In such a case, a_D values applicable to metropolitan France should be lower than presented in table 5.

Damage grade, D	a_D	β_D	k_D (n=2)	k_D (n=3)
2	1,76 ms^{-2}	0,50	1,65	3,08
3	2,83 ms^{-2}	0,55	1,83	3,90

Table 5. *Fragility features for conventtional masonry buildings [11] and associated k_D values*

3.2.3. *Outputs*

Eventually, seismic risk estimates associated to the three SHMs under consideration are summarized in table 6. Comparing these outputs with the above estimate based on historical seismicity (table 4) is of major interest and some conclusions can be drawn from this comparison.

	Grade 2	Grade 3	Grade 2	Grade 3	Grade 2	Grade 3
Metropolitan territory	15 10^{-4}	45 10^{-5}	0.32 10^{-4}	1.1 10^{-5}	2.8 10^{-4}	4.5 10^{-5}
Exposed zone	45 10^{-4}	160 10^{-5}	1.65 10^{-4}	5.9 10^{-5}	1.6 10^{-4}	51 10^{-5}
	SHM-2002		SHM-2004		SHM-2006	

Table 6. *Annual probability of damage grades 2 and 3 on conventional masonry buildings, as resulting from convolution of PSHA and fragility data.*

4. Conclusions

In this paper a methodology was presented, and exemplified on the case of metropolitan France, about comparison of two different approaches of seismic risk. The seismic risk is evaluated as the annual probability that a certain damage grade is experienced by a building of a given type. The first approach processes historical seismicity data while the second one is based on the convolution of PSHA outputs and fragility data. Outputs of these two approaches can be compared in case the considered type of building is traditional masonry, historically built in France, and the damage grades are rated 2 and 3, which corresponds to damages rather frequently observed. This comparison enables to check consistency of PSHA outputs against historical seismicity.

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[7] building type M1-2 according to Risk_UE methodology.

Fragility curves used in this analysis were not derived from French data. They were obtained in the framework of the European project Risk_UE by researchers from Skopje University. However, regardless possible discussions about a_D values, it is possible, on the basis of the methodology presented in this paper, to draw some conclusions about the three SHMs considered in this paper: The gap between historically observed risk and risk derived from SHM-2002 is so large that we can conclude without doubt that SHM-2002 [8] overestimates significantly seismic hazard on the metropolitan French territory, by a factor of 10 or more in terms of return periods. SHM-2006 [10] still appears pessimistic while SHM-2004 [9] appears somewhat optimistic. Would a_D values suitable for metropolitan France be slightly lower than those proposed for Balkan countries, SHM-2004 would even appear as satisfactory consistent with historical seismicity.

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