COMPARISON OF TWO METHODS OF SEISMIC RISK ASSESSMENT IN FRANCE

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ABSTRACT :
Two methods of seismic risk assessment are compared. The first one is based on historical data. It considers statistics of earthquakes of epicentral intensities I_0 = V to IX and statistics of areas affected by intensities lower than or equal to I ($I<=I_0$). The risk is estimated in terms of annual probability of occurrence of given damage degrees. Typical outputs are that, in average for masonry buildings, probability of a degree 2 damage is around 10^{-4} ; 10^{-5} for a degree 3. The second method is based on convolution of seismic hazard data and masonry building fragility curves. Seismic hazard is described in the form of 3 different maps of the metropolitan France. These maps are outputs of probabilistic seismic hazard assessments of France and provide PGA values for a 475 year return period (PGA values for other return periods are extrapolated on the basis of classical relationship between PGA and return periods). Fragility of masonries is described in the form of a classical log normal distribution of the probability of exceedance of a given damage versus the PGA (median value 'a' and variability 'β'). A sensitivity study is carried out on the median value corresponding to damage degrees 2 and 3. For realistic values of 'a' and 'β', one of the maps leads to an tremendous overestimate of the risk, as compared to the historically observed risk, another one leads to an underestimate while the third one is in the middle. This approach could be used for reducing uncertainties in probabilistic seismic hazard assessment in low-moderate areas where sufficient historical data are available.

KEYWORDS:
Seismic risk, historical seismicity, probabilistic seismic hazard assessment, fragility curves, France

1. INTRODUCTION

Probabilistic seismic hazard assessment (PSHA) is a more and more popular technique, either for the evaluation of hazard on a specific site, as widely use by the nuclear industry or for establishing hazard maps at the scale of a country or even at a much larger scale. However, it appears that PSHA techniques are not yet mature enough to provide outputs that are reasonably insensitive to expert judgements. The case of France exemplifies this lake of maturity: three different maps where established, in 2002, 2004 and 2006, leading to huge variability in the hazard assessment of the metropolitan French territory. An other European example was also presented recently showing an hazard estimate in the north of Switzerland significantly larger than in Slovenia *(OECD 2008)*, what is fully contradictory with the global picture of seismic hazard in Europe.

In November 2006, the OECD-NEA (Nuclear Energy Agency) convened an expert meeting on Seismic Probabilistic Safety Assessment. According to the OECD-NEA practice, recommendations were made by the experts in order to improve engineering practices of the subject under consideration. At this occasion a series of recommendation were made about PSHA implementation, including that "PSHA results should be compared to all available observations, especially for return periods where records are available, in order to get an objective comparison and to improve the confidence in the results, at least in that range of return periods." (*OECD 2007*) In a country like France, and in many other countries, reliable historical records are available on a rather long period of time (around a millennium). The purpose of this paper is to present a methodology to process both historical data and PSHA outputs so as to make them comparable and meet the OECD-NEA recommendation. The methodology is exemplified on the case of the metropolitan France and could be easily applied to other countries with a similar historical background.

2. SEISMIC RISK BASED ON HISTORICAL SEISMICITY

2.1 Areas yearly affected by a given intensity

2.1.1 Principle of calculation

We consider a territory on which the seismic activity is homogeneous (in space) and stationary (in time). Taking the example of intensity V, we denote A_V the average area of this territory yearly affected by an intensity equal to or larger than V. Conceptually, would we have at our disposal comprehensive macro-seismic data on a very long period of time (T years), calculating A_V would be easily achieved as follows : For every event i, occurring during the period of time T, we denote $\mathcal{A}_{i,V}$ the area affected by an intensity larger than or equal to V. Then

$$A_V = \mathcal{A}_V / T \quad \text{with} \quad \mathcal{A}_V = \Sigma\, \mathcal{A}_{i,V} \tag{1}$$

Practically we do not have at our disposal the above-mentioned ideal comprehensive information. However, taking the example of the French territory, we can build on historical data as follows: We denote :

- n_{I0} ($I_0 \geq V$) the number of events of epicentral intensity I_0, felt in France during a reference period of time T, practically a century.
- $A_{I0,V}$ the average area affected by an intensity larger than or equal to V for an event of epicentral intensity I_0.

Then an estimate of $\mathcal{A}_V$ reads :

$$\mathcal{A}_V = \Sigma\, n_{I0}\, A_{I0,V}, \quad I_0 = \text{V to IX} \tag{2}$$

and can be introduced in Eqn. 1 to get an estimate of A_V . Other A_I can be estimated similarly.

2.1.2 Application to the metropolitan French territory for I=V

On the basis of available data, the period of time 1895-1994 has been selected as the best documented, representative of a century of seismicity. In particular, events with an epicentre out of the French territory but felt in France are mentioned in *Lambert et al.*, (1996) and *Sisfrance* (2005), and counted in the table 1 (numbers are rounded-up).

Table 1 : Average number of events ($I_0 \geq V$) felt per century on the metropolitan French territory

Epicentral Intensity, I_0	V	V-VI and VI	VI-VII and VII	VII-VIII and VIII	VIII-IX
Number of events, n_{I0}	350	150	70	10	1

For the purpose of calculating $A_{I0,V}$ values, a catalogue of 140 isoseismical maps, edited under the leadership of *A. Levret* (*Levret and al. 1996*), was processed. We do not present in this paper the detail of the statistical processing, including the treatment of extreme events *(Labbé 2007a and 2007 b)*. A major output is that, for a given epicentral intensity, areas affected by an intensity higher than or equal to V are log-normally distributed. Average values of these areas are presented in the table 2.

Table 2 : Average area affected by an intensity ≥V for a given epicentral intensity

Epicentral Intensity, I_0	V	V-VI and VI	VI-VII and VII	VII-VIII and VIII	VIII-IX
Average affected area(km²)	180	1020	5300	16300	103000
Area inside the French metropolitan territory	120	620	2940	8790	21800

Applying the Eqn. 2 formula with data included in the tables 1 and 2 leads to : A_V = 4500 km² on the metropolitan France

2.1.3. Other intensities and variability of seismic activity in the territory

In the above presentation of the proposed methodology, we referred to the metropolitan French territory. Generally speaking metropolitan France is an area of low to moderate seismicity; however in a more refined approach, the seismic activity on this territory cannot be regarded as homogeneous. It is possible to identified zones with a reasonable homogeneous seismicity. In the frame of this study, the territory was divided into two zones : a 'less prone to earthquake zone' and a 'more prone to earthquakes zone'. According to information provided by *Lambert et al., (1996)*, the later zone comprises 15% of the territory (on the basis of an administrative zoning as presented on the Fig. 1) and concentrates 56% of the activity. For both zones, areas affected by intensities V to VIII are reported in the table 3.

Table 3. average annual value of areas (km²) affected by a given intensity (or higher)

	V	VI	VII	VIII
French metropolitan territory (538 000 km²)	4500	470	58	3,7
more prone to earthquakes zone (79 000 km²)	2500	260	32,5	3,7
less prone to earthquakes zone (459 000 km²)	2000	210	25,5	0

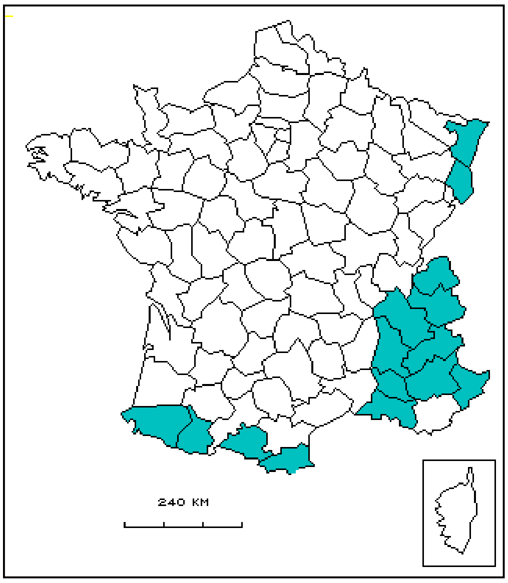

Figure 1 : The more prone to earthquake zone of the metropolitan French territory (dark area), delimited on the basis of the French administrative zoning.

2.2 Annual probability of a damage of grade 2 or 3 on masonry buildings

The macroseismic scale EMS98 classifies types of buildings according to their sensitivity to seismic input motion and introduces a definition of damage grades (see the appendix 1). According to this scale, the proportion of masonry buildings that undergo a grade 2 or a grade 3 damage is related to the intensity as reported in the table 4. (The damage grade is denoted D ; D=2 means damage grade 2)

Table 4 : Damage rate to masonry buildings *vs* Intensity

	VI	VII	VIII
D=2	some	many	most
D=3	/	some	many

Definition of terms *some*, *many* and *most* is based on fuzzy set techniques. It leads to quantify the terms as follows: *some* is equivalent to 8%, *many* to 35% and *most* to 80%

In order to evaluate the probability that a building undergoes a given damage grade, the probability it is exposed to an intensity VI VII or VIII should first be established. This piece of information is directly derived from data presented in the table 3. For instance, in average on the metropolitan territory the annual probability that a building is exposed to an intensity VII or higher is equal to 58 / 538000 = 1,1 10^{-4}. In the more prone to earthquakes zone it is equal to 32,5 / 79200 = 4,1 10^{-4}.

Table 5 : Annual probability that a masonry building undergoes a grade 2 or 3 damage on the basis of historical seismicity data

	D=2	D=3
Average value in the metropolitan territory	1,1 10^{-4}	1,1 10^{-5}
Average value in the more prone to earthquakes zone	4,5 10^{-4}	4,9 10^{-5}

3. SEISMIC RISK BASED ON HAZARD DATA AND FRAGILITY CURVES

3.1. Methodology

2.1.1 Principle of calculation

In the frame of this work, it is admitted that seismic hazard is described in the form of an hazard map derived from a probabilistic seismic hazard assessment of the territory under consideration. According to the usual practice, the map at our disposal provides Peak Ground Acceleration (PGA) values associated to a given return period. On any site of the territory, the annual probability that the observed PGA is greater than a is denoted $P_e(a)$[1]. Consequently the annual probability that a PGA with a value comprised between a and a+da occurs on this site is equal to $p_e(a)$ da, so that :

$$p_e(a)\,da = -P_e'(a)\,da\ . \tag{3}$$

Regarding a given type of buildings, its fragility is described by the probability it suffers a damage of degree D (or larger) in case it undergoes a seismic input motion, the PGA of which is equal to a. This conditional probability is denoted $P_{f,D}(a)$. The annual probability that a building of the considered type suffers a damage of degree D (or larger) is derived as follows :

$$p_D = \int_0^{\infty} p_e(a) P_{f,D}(a)\, da\ . \tag{4}$$

2.1.2. Classical forms of P_e et $P_{f,D}$ functions

It is frequently considered that $P_e(a)$ can be represented by a function of the form:[2]: $P_e(a) = (a/A)^{-n}$ (practically n is in the order of 2 or 3), leading to :

$$p_e = n / A\ (a/A)^{-(n+1)} \tag{5}$$

It is also generally accepted that building fragility is log-normally distributed. It means that the population of PGAs corresponding to a damage grade greater than or equal to D is log-normally distributed ; its median value is denoted a_D and the standard deviation of its natural logarithm β_D, leading to:

$$P_{f,D}(a) = \Phi\left[\frac{1}{\beta_D} \mathrm{Ln}\left(\frac{a}{a_D}\right)\right] \quad \text{with} \quad \Phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} \exp(-t^2/2)\, dt \tag{6}$$

[1] $P_e(a)$ is linked to the return period on the site, T(a), by : $P_e(a)=1-\exp(-1/T(a))$, or $P_e(a)=1/T(a)$ for rare events.
[2] Formally this formula cannot be a probability because it gives values larger than 1 in case a is lower than A; it means practically for very small PGAs. However the contribution of these very small PGAs to p_D is negligible, so that the proposed formula pertains. (On a formal view point this is valid for the annual rate of exceedance, which is the inverse of the return period).

On the basis of these assumptions, it is possible to derive an analytical formula of p_D :

$$p_D = \left(\frac{A}{a_D}\right)^n k_D \quad , \quad k_D = \exp\frac{n^2\beta_D^2}{2} \tag{7}$$

3.2. Application to the metropolitan France, considering masonry buildings

3.2.1. Hazard and fragility data

Three hazard maps are considered, every of them deemed corresponding to a 475 y. return period : the MEDD-2002 map (*Martin and al., 2002*), the LDG-2004 map (*Marin and al., 2004*) and the AFPS-2006 (*Martin and al., 2005*). For a given site, the PGA value read on the map is denoted a_{475}. The average value of a_{475} is reported in the table 6 for each map. The discrepancy is significant and reveals a dramatic variability in the evaluation of the seismic hazard in France, depending on the authors.

Table 6 : Average value of a_{475} for the three maps under consideration.

MEDD-2002 map	LDG-2004 map	AFPS-2006 map
0.95 ms^{-2}	0.14 ms^{-2}	0.48 ms^{-2}

At every site of the territory, $P_e(a)$ is given in the form indicated by Eqn. 8.

$$P_e(a) = \frac{1}{475}\left(\frac{a_{475}}{a}\right)^n \quad . \tag{8}$$

There is a lack of fragility data for conventional masonry buildings in France. Fragility data retained in the present study come from the Risk_UE project. This European project addressed the seismic risk assessment for 7 cities of the Southern Europe. Risk_UE established a methodology for building classification and characterization of their fragility by types. Masonry buildings were examined by the Skopje University, which, for this type of buildings in Balkans, published values of a_D et β_D reported in the table 7[3] (*Risk_UE 2004*)[4]. We have selected damage grades 2 and 3 so as to get results comparable to those derived from historical seismicity.

Table 7 : Fragility data for masonry buildings

Damage grade	a_D	β_D
D=2	1,76 ms^{-2}	0,50
D=3	2,83 ms^{-2}	0,55

Table 8 : k_D values for n=2 and n=3

	n=2	n=3
D=2	1,65	3,08
D=3	1,83	3,90

3.2.3. Calculated risk

Finally the risk is calculated according to the formula of Eqn. 9. The last parameter that have not yet been quantified is n. n values are discussed in the appendix 2. In order to provide the reader with an order of magnitude of the final result, k_D values corresponding to n=2 and n=3 are presented in the table 8.

[3] Buildings of the type M1-2 in the Risk_UE terminology

[4] Later on, a decision was made in the conduct of the Risk_UE project to describe the hazard, not only on the basis of the PGA, but also on the basis of associated response spectra. Consistently, fragility curves were expressed as functions of the building top displacement in place of functions of the PGA.

$$p_D = \frac{1}{475}\left(\frac{a_{475}}{a_D}\right)^n k_D \tag{9}$$

On the basis of the Eqn. 9, p_D values where calculated for the three maps introduced in the section 3.2.1. Average values of p_D where derived, for the metropolitan French territory as a whole and for the more prone to earthquake zone[5]. Outputs of these analyses are presented in the table 9. Comparison with outputs of historical seismicity are discussed in the next sections.

Table 9 : Annual probability that a masonry building undergoes a grade 2 or 3 damage on the basis of hazard maps and fragility data (p_D values for D=2 and D=3)

Average value in	MEDD-2002 map		LDG-2004 map		AFPS-2006 map	
	D=2	D=3	D=2	D=3	D=2	D=3
metropolitan territory	$15\ 10^{-4}$	$45\ 10^{-5}$	$0.32\ 10^{-4}$	$1.1\ 10^{-5}$	$2.8\ 10^{-4}$	$4.5\ 10^{-5}$
more prone to earthquakes zone	$45\ 10^{-4}$	$160\ 10^{-5}$	$1.65\ 10^{-4}$	$5.9\ 10^{-5}$	$1.6\ 10^{-4}$	$51\ 10^{-5}$

4. PARAMETRIC STUDY ON HAZARD AND FRAGILITY INPUTS

The significant gap that appears between the risk estimate based on historical data and the risk estimate based on convolution of hazard and fragility can be interpreted as an evidence of a wrong hazard assessment. However it should also be observed that fragility data were not established for masonries built in France ; possibly they are not suitable for France. For this reason a parametric study on the two inputs “hazard” and “fragility” was carried out as follows:

- Concerning fragility, it is assumed that a_D can take values different from those proposed by Risk_UE documentation.
- Concerning hazard, it is assumed that the return period, T, associated to a given map is not necessarily 475 years.

The parametric study consisted of calculating couples $\{a_D,T\}$ that, on the basis of the methodology presented in the section 3, result in a calculated risk consistent with the historically observed risk calculated in the section 2.

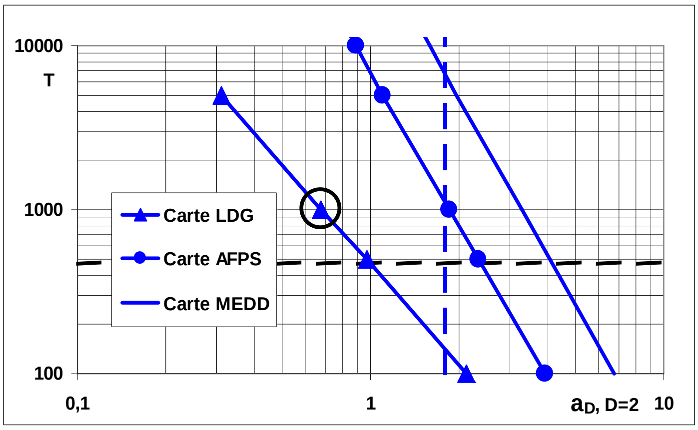

Figure 2 Return periods (years) and mean value of fragility (ms^{-2}) compatible with the historically calculated risk.

[5] Practically the more prone to earthquake zone is variable from a map to the next one. For each map the boundary of this zone was determined on the basis of a criterion on the PGA. The boundary PGA is so that the area included in the more prone to earthquake zone is the same as (or very close to the one) calculated in the section 2 (79200 km^2) .

In the frame of this paper, we present results obtained when processing the probability of damage grade 2 on the metropolitan French territory. Practically, the parametric study presented hereunder consisted of answering the following question: On the basis of the section 3 procedure, which value of a_2 and which return period affected to the X map (X= MEDD-2002 or LDG-2004 or AFPS-2006) result in a p_2 value equal to $1{,}1\ 10^{-4}$ in average on the metropolitan French territory (value calculated in section 2). Answer is not unique ; couples $\{a_2\ ,\ T\}$ resulting in $p_2 = 1{,}1\ 10^{-4}$ are presented in the Fig. 2. As a matter of example, the circled point on the figure means that the following assumptions {the LDG-2004 map corresponds to a 1000 y. return period and a_2 is equal to 0,7 ms^{-2} } results in $p_2 = 1{,}1\ 10^{-4}$.

5. CONCLUSIONS

A conclusion drawn from the Fig. 2 can be expressed as follows: Would fragility data for masonry walls used in this study be confirmed (vertical doted line), then, instead of 475 years, the return period of the MEDD-2002 map would be approximately around 5000 years, while, instead of 475 years, the return period of the LDG-2004 map would be around 100 years ; the AFPS-2006 map appearing in between.

Conversely, would the return period of the MEDD-2002 map be actually 475 years (horizontal doted line), it should be concluded that masonries built in France are twice more resistant than those built in the Balkans. This conclusion is very unexpected because, due to the fact that the Balkan area is much more prone to earthquake than France, traditional buildings are expected to be better designed in this regard.

Regardless the a_2 value, the Fig. 2 enables to draw conclusions on the likelihood of the different maps. For instance, would the return period of the MEDD-2002 map be actually 475 years, it should be concluded that the return period of the LDG-2004 map is around 30 years. And conversely, would the return period of the LDG-2004 map be actually 475 years, it should be concluded that the return period of the MEDD-2002 map is around 50 000 years. Both conclusions seem exaggerate.

Eventually, on the basis of available data for fragility of masonry buildings, it has to be concluded that the AFPS-2006 map is the more in compliance with historical seismicity of the metropolitan French territory.

Beyond the case of metropolitan France, the opinion of the author is that the proposed methodology could be successfully implemented in any country with a similar sufficiently documented historical seismicity. Fragility data consolidated for the conventional buildings of the type encountered in the country under consideration would be highly desirable. The author is convinced that checking the seismic risk value derived from hazard and fragility data against the seismic risk derived from historical seismicity, as presented in this communication, is a possible manner of complying with the recommendation of the OECD presented in the introduction. It is also a promising way of reducing uncertainties in PSHA implementation.

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APPENDIX 1 : Classification of damage to masonry buildings according to European Macroseismic Scale (EMS 98)

Grade 2 : Moderate damage (slight structural damage, moderate non-structural damage)
Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.

Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)
Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).

APPENDIX 2 : Comments on n value to be included in the P_e function

The formula adopted for $P_e(a)$ means that PGAs (denoted by a) and return periods (denoted by t) are linked by a relationship of the type $(t/t_0) = (a/a_0)^n$. This relationship should be plotted as straight line in a logarithmic coordinates. Actually it is not exactly the case. Examination of hazard curves leads to the conclusion that n value depends on t (or on a) in a manner that fits the following formula:

$$n = n_{475} + \Delta n \log(t / 475) \quad (10)$$

Practically, in the present study, n was not recalculated at every point of the maps. For each map average values of n_{475} and Δn were calculated and used at every point of the territory when dealing with the map under consideration.