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UPDATING OF A PSHA BASED ON BAYESIAN INFERENCE WITH HISTORICAL MACROSEISMC INTENSITIES

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Abstract

Since the basic work of Cornell, many studies have been conducted in order to evaluate the probabilistic seismic hazard (PSHA) at a given site or at a regional scale. In general, results of such studies are used as inputs for regulatory hazard maps or for risk assessments. Such approaches are nowadays considered as well established and come more and more used worldwide, generally in addition to deterministic approaches.

Nevertheless, some discrepancies have been observed recently in some PSHA, especially from studies conducted in areas with low to moderate seismicity. The lessons learnt from these results lead to conclude that, due to uncertainties inherent to such a domain (for example, the ground-motion prediction equations used in computing the hazard), some deterministic choices have to be made and, depending on expert judgments, may lead to strong differences in terms of seismic motion evaluation.

In this context, the objective of this paper is to present a methodology that can be used to take into consideration historical observations (such as macroseismic Intensities) in order to reduce epistemic uncertainties in a probabilistic seismic hazard assessment (PSHA). The method developed here is based on a Bayesian inference technique that is used in order to quantify the likelihood of the prior estimation and finally, update the PSHA.

Hazard curves (rate of occurrence of PGA), output of a given PSHA, are transformed into macroseismic Intensity through “PGA-to-intensity” relationships. Random and epistemic uncertainties included in such relationships are propagated in the overall updating process, as well as the random occurrence of events, over the period of observation.

The period of observation under consideration is the completeness period for each intensity data set.

The updating process is developed at a regional scale over a significant number of stations. The potential correlation between points of observation is also discussed and accounted for.

Finally, a case of application is proposed on the French metropolitan territory to demonstrate the efficiency of this updating method and draw perspectives for further applications.

Keywords: PSHA, Bayesian updating, PSHA testing, Macroseismic intensity

1. Introduction

Since the basic work of Cornell, many studies have been conducted in order to evaluate the probabilistic seismic hazard (PSHA) at a given site or at a regional scale. In general, results of such studies are used as inputs for regulatory hazard maps or for risk assessments. Such approaches are nowadays considered as well established and come more and more used worldwide, generally in addition to deterministic approaches.

Nevertheless, some discrepancies have been observed recently in some PSHA, especially from studies conducted in areas with low to moderate seismicity. The lessons learnt from these results lead to conclude that, due to uncertainties inherent to such a domain (for example, the ground-motion prediction equations used in computing the hazard), some deterministic choices have to be made and, depending on expert judgments, may lead to strong differences in terms of seismic motion evaluation.

In this context, the objective of this paper is to present a methodology that can be used to take into consideration historical observations (such as macroseismic Intensities) in order to reduce epistemic uncertainties in a probabilistic seismic hazard assessment (PSHA). The method developed here is based on a Bayesian inference technique that is used in order to quantify the likelihood of the prior estimation, and finally update the PSHA.

2. Background

Bayes theory on conditional probabilities was developed in the second half of the 18th century by Reverend Thomas Bayes and was strongly promoted by Pierre-Simon de Laplace in the early 19th century.

The use of Bayesian theorem of conditional probability (also known as Bayesian inference), which has drastically increased during the second half of the 20th century, is nowadays largely disseminated in a wide range of fields and applications (biology, pharmaceutical statistics, economics, finance, environmental and earth science, industrial statistics, mechanics …) [1].

The principle of Bayes theorem of conditional probabilities is simple to present (but not always simple to solve!). Based on a probabilistic assessment of a given parameter A (usually called as the prior estimation), Bayesian theorem consists in calculating the likelihood of the prior estimation using actual observations B of the parameter under consideration, cf. Eq. (1).

$$P(A|B) = \frac{P(B|A).P(A)}{P(B)} \tag{1}$$

Where:

P(A) is the prior estimation based on a probabilistic assessment
P(B|A) is conditional probability of the observed event B according to the prior assessment
P(B) is the total probability of the observed event B according to the prior assessment
P(A|B) is the expected updated (posterior) estimation

The application to our case will be developed in section 4.

3. Application of Bayes theorem in the field of earthquake engineering

In the field of earthquake engineering, Bayesian approaches are already largely used, in various aspects, such as seismology and structural dynamics. In seismology, the Bayesian inference is used in elicitation techniques [2], for comparison of PSHA hypothesis [3, 4] or for direct updating of GMPEs on local data [5, 6, 7].

In the last decade, many developments and applications were published in the field of PSHA testing and Bayesian updating, especially in the framework of OECD/NEA [8] and SIGMA Project [9, 10].

PSHA testing and Bayesian updating are now considered as state of the art and should be systematically implemented. This process is not antagonist with expert judgments, which are of course necessary to guaranty the robustness of the prior PSHA and the correct propagation of random and epistemic uncertainties. PSHA testing and Bayesian updating have to be considered as an additional step that allows actual observations at a given site to be taken into consideration to reduce epistemic uncertainties (i.e. uncertainties that could not be reduced by experts), taking into account random and epistemic uncertainties they intrinsically incorporate, OECD/NEA [11].

4. The innovating method developed in this paper

The method developed in this paper is based on the Bayesian updating process described in [12, 13]. In these previous references, instrumental seismicity is taken into consideration as observations to update the prior estimation.

In the current study, historical seismicity is taken into account to update the prior assessment.

4.1 Principle for incorporating historical observations

First of all, the approach needs a PSHA following the state of the art approach as input data. This prior estimation has to take into consideration all sources of random and epistemic uncertainties. This PSHA has to be carried out though a well documented procedure, which should explicitly describe the elicitation of experts' judgments, such as the so-called SSHAC procedure.

Hazard curves expressed in term of PGA (Peak Ground Acceleration) rate of exceedance will be considered as the prior estimation for the implementation of Bayes theorem of conditional probability. The hazard curve is used to determine an exceedance rate of a given macroseismic Intensity based on Intensity to PGA relationships.

Random and epistemic uncertainties are fully propagated, as described in the following sections.

Historical observations are expressed in term of macroseismic Intensity observed at the site under consideration.

Finally, the Bayesian theorem of conditional probability is applied for each single hazard curve of the prior estimation in order to calculate its likelihood and though to update its weight accordingly.

The likelihood function becomes the posterior weight of the hazard curves.

4.2 Prior estimation: PSHA complemented by PGA-to-Intensity relationships

Theoretically, any kind of observation and any period of observation, including instrumental seismicity, historical seismicity and paleoseismicity data can be used in such a process.

In this paper, we'll focus on historical seismicity. The objective is to determine an exceedance rate of a given macroseismic intensity based on the hazard curve under consideration. The principle of the method is described in [3] and extended in this paper as described below.

In order to use historical observations, PGA-to-Intensity relationships are used to transform PGA to macroseismic intensities, based on Eq. (2).

$$I = a.Log(PGA) + b \qquad (+/-\sigma) \tag{2}$$

Random and epistemic uncertainties are taken into consideration through the full propagation of the standard deviation of the PGA-to-intensity relationship and through the use of different PGA-to-Intensity relationships.

The goal is to determine the rate of exceedance of a given intensity from a given hazard curve expressed in term of PGA. The calculation is performed based on Eq. (3).

$$N_{I_i} = \sum_{A_{\min}}^{A_{\max}} (N_{A+\Delta A} - N_A).P_{I_i|A} \tag{3}$$

Where:

- N_{I_i} is the annual rate of exceedance of a given Intensity I_i
- N_A is the annual rate of exceedance of a given PGA A
- $P_{I_i|A}$ is the probability of a given PGA to produce the given intensity I_i according to (2), including σ (i.e. percentage of the contribution of the given PGA level to the considered class of intensity)
- ΔA is a discretization step small enough in order to get stable results of N_{I_i} (in this study, the range of PGA from 1 to 1000 cm/s² is discretized into 40 steps)

Finally, the annual exceedance rate is multiplied by the completeness period of the historical catalogue in order to determine the prior rate of exceedance of a given hazard curve in term of macroseismic Intensity.

The illustration of this process is given in Fig. 1 and Fig. 2.

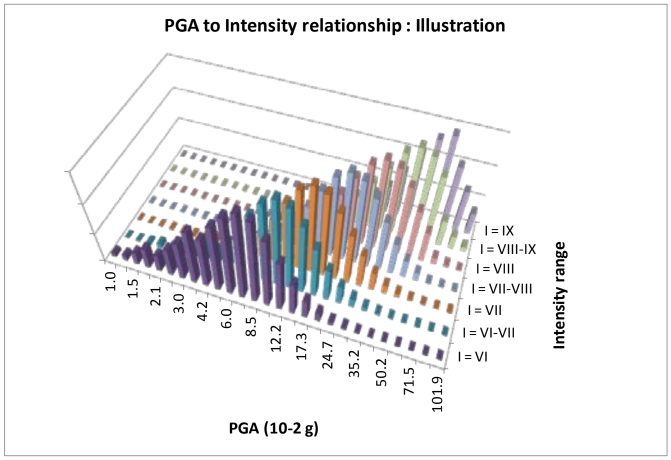

Fig. 1 - $P_{I_i|A}$: Probability of a given PGA to produce the given intensity (Illustration case)

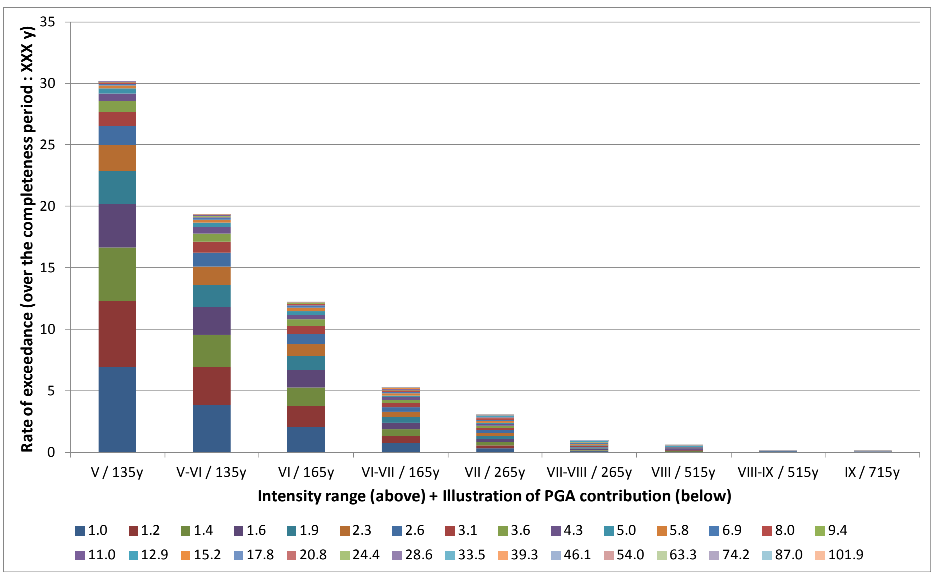

Fig. 2 - N_{I_i} : Rate of exceedance of a given hazard curve in term of macroseismic Intensity over the completeness period (illustration case showing contribution of PGAs)

This allows to express the prior PSHA estimation in term of rate of exceedance of a given Macroseismic Intensity. Through this process, the full range of uncertainties is propagated in order to guaranty that none of the possibilities are disregarded.

4.3 Historical observations consideration

The historical observations have to be well documented. This means that a historical database has to be available and its quality has to be high enough to allow to define completeness period and to be sure that it is possible to quantify the number of event that were felt on a given location over this completeness period.

Once the previous requirements are fulfilled, the historical observations are the number of historical events that produced a Macroseismic Intensity higher or equal to a given one. An application is presented in section 5.

We would like to mention that the historical observation which are used here are also usually used in the PSHA as input data (for earthquake recurrence parameters' determination for instance). This means that these data could be used twice in the process, which may be confusing. However, we are dealing here with a reduced number of historical observations compared with the huge number that are considered in the prior PSHA. Then, it can be easily shown that removing these observations from the set of data used in the prior PSHA would have no impact on the PSHA result. Then, there is no risk of giving them an arbitrary high weight in the overall process (by using them twice).

4.4 The updating process: Accounting for random occurrence of events

The updating process is based on Eq. 1. This formula, applied to our case, is shown in Eq. (4).

$$P(Model|Observation) = \frac{P(Observation|Model)}{P(Observation)}.P(Model) \tag{4}$$

Where:

P(Model) is the prior estimation, direct output of the PSHA based on a probabilistic assessment
P(Observation|Model) is the probability of the observed event according to the prior assessment
P(Observation) is the total probability of the observed event according to the prior assessment
P(Model|Observation) is the expected updated (posterior) estimation

This equation is applied to each single hazard curve of the prior PSHA (A_i) so that the updating process will allows to calculate a likelihood of each single hazard curve of that prior estimation, Eq. (5).

$$P(A_i|Observation) = \frac{P(Observation|A_i)}{P(Observation)}.P(A_i) \tag{5}$$

Where:

$P(A_i)$ is the prior weight of the hazard curve under consideration, which results directly from the weighting process of the PSHA under consideration, including expert judgment and epistemic uncertainties propagation
$P(Observation|A_i)$ is the probability of the observed event according to the prior assessment
$P(Observation)$ is the total probability of the observed event B according to the prior assessment

Calculation of P(Observation|A_i)

Based on the rate of exceedance calculated as described in Eq. (3), P(Observation|A_i) is calculated assuming a Poisson's occurrence model, Eq. (6)

$$P(Observation|A_i) = P(n,t) = \frac{e^{-\lambda.t}(\lambda(A_i).t)^n}{n!} \tag{6}$$

Where:

λ is the annual rate of exceedance of a given acceleration A_i
t is the period of time under consideration
n is the number of event with an acceleration higher that A_i

In order to perform this updating process at a regional scale using multiple sites of observation, the Poisson's occurrence model Eq. (6) is generalized through a negative binomial distribution that allows to account for correlation between stations of observation, as described in detail in [14] and shown in Eq. (7).

$$P(Observation|A_i) = P(n,t) = \exp\left[\ln\Gamma\left(\frac{\lambda(A)}{K-1}+n\right) - \ln\Gamma\left(\frac{\lambda(A)}{K-1}\right) - \ln\Gamma(1+n)\right].\frac{1}{K}^{\frac{A}{K-1}}\left(1-\frac{1}{K}\right)^n \tag{7}$$

Where:

lnΓ is the logarithmic gamma function
λ(A) is the cumulative rate of exceedance of a given acceleration A for all the stations under consideration
n is the number of events with an acceleration higher that A
K is the average number of sites impacted by one earthquake (this parameter is indicative of the correlation among stations. If K tends to 1, the negative binomial distribution goes towards a Poisson distribution).

Calculation of P(Observation)

P(Observation) is simply calculated through Eq. (8).

$$P(Observation) = \sum_{N} P(Observation|A_i) \quad (8)$$

Likelihood function and posterior estimation

Finally, the likelihood function, Eq. (9), becomes the updated weight of the hazard curve A_i under consideration, which allows to recalculate the range of (reduced) epistemic uncertainties of the PSHA, and becomes the posterior estimation.

$$\text{Likelihood of a given hazard curve:} \quad \frac{P(Observation|A_i)}{P(Observation)} \quad (9)$$

5. Application: French metropolitan territory

5.1 Description of the PSHA used for this application

In order to illustrate the efficiency of this method, the application is performed based on the French Metropolitan territory.

The prior PSHA is based on a previous study described in [4]. This study is not described in detail in this paper in order to concentrate on the Bayesian updating process. However, this PSHA includes the propagation of a large range of random and epistemic uncertainties, especially on the GMPEs and the random model as shown by Eq. (10).

$$Log(PGA) = \begin{pmatrix} a_1 \\ \pm\sigma_1 \end{pmatrix}.M + \begin{pmatrix} a_2 \\ \pm\sigma_2 \end{pmatrix}.M^2 + \left[\begin{pmatrix} a_3 \\ \pm\sigma_3 \end{pmatrix} + \begin{pmatrix} a_4 \\ \pm\sigma_4 \end{pmatrix}.M\right].Log\left(\sqrt{R^2 + \begin{pmatrix} a_5 \\ \pm\sigma_5 \end{pmatrix}^2}\right) + \begin{pmatrix} a_6 \\ \pm\sigma_6 \end{pmatrix} + \begin{pmatrix} \sigma \\ \pm\sigma_\sigma \end{pmatrix} \quad (10)$$

Where:

PGA is the Peak Ground Acceleration,

M is the magnitude,

R is the hypocentral distance,

Every parameter (a_1 to a_6) has its own uncertainty, even the random part σ.

This process allows to obtain hazard curves for a large number of locations. In our case, we are using the results obtained for 19 EDF Nuclear Power Plant locations, in order to use historical seismicity as observation, which is well documented for these sites. The location of EDF NPPs is shown in Fig. 3.

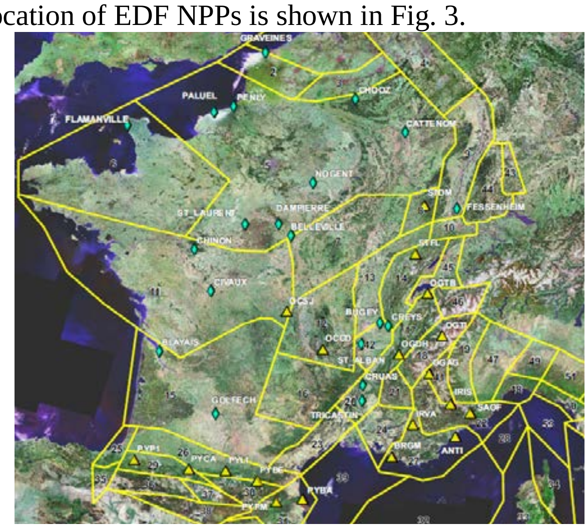

Fig. 3 – Location of the 19 EDF NPPs on the French Metropolitan territory (green diamonds)

NB: Yellow rectangles are French accelerometric networks stations not used in this study

For this paper, 42 hazard curves have been generated among the whole logic tree that contains much more than this number. This choice (only 42 hazard curves) was made in order to ease the interpretation and to better illustrate the updating process.

Fig. 4 shows the 42 hazard curves obtained at one site.

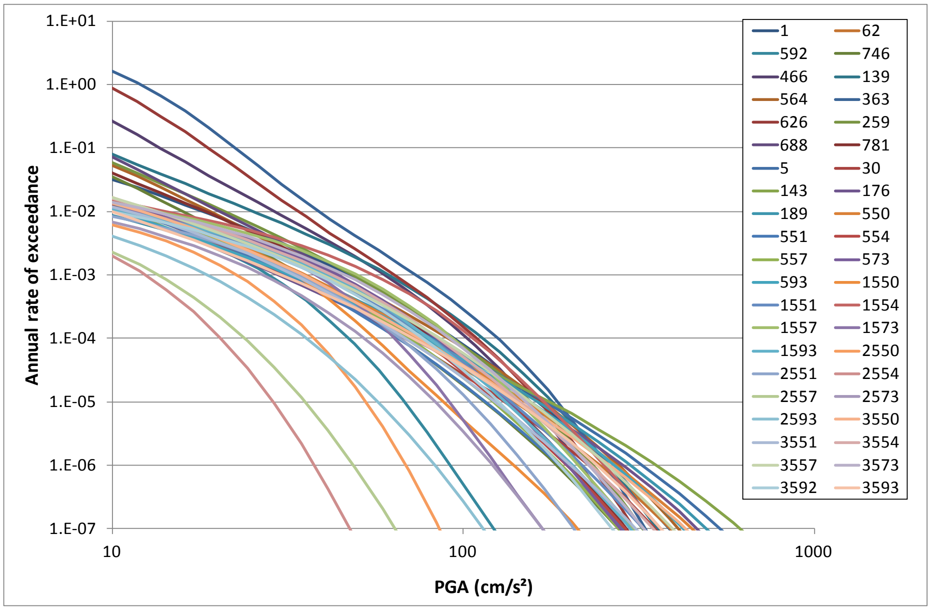

Fig. 4 – Illustration of the 42 hazard curves resulting from the logic tree under consideration at a given site

5.2 PGA-to-Intensity transformation

In order to propagate a large range of uncertainties, different relationships from different authors were used. The only criteria that was used to select PGA-to-Intensity relationships is the domain of validity in term of PGA that should be large enough to allow to estimate Intensities without any bias (especially boundary effects).

These selected PGA-to-Intensity relationships are presented in table 1 and plotted in Fig. 5.

Table. 1 – PGA-to-Intensity relationships used in this study

Author	Domain of application	Relationship (PGA in cm.s^{-2})	σ
Atkinson&Kaka (2006)	Missouri & California I ϵ [II ;IX] PGA ϵ [0.4;260]	I=2.315+1.319*log(PGA)+0.372*log(PGA)²	0.93
Atkinson&Kaka (2007)	Centre US & California I ϵ [II ;IX]	If log(PGA)≤1.69, I=2.65+1.39*log(PGA) If log(PGA)>1.69, I=-1.91+4.09*log(PGA)	1.01
Faenza & Michelini, 2010	Italy I ϵ [I ;VIII]	I=2.58*Log(PGA)+1.68	0.35
Marin, Avouac, Schlupp, & Nicolas, 2004	France	I=2.3*Log(PGA(g))+10	0.3
Worden, Gerstenberger, Rhoades, & Wald, 2011	California I ϵ [II ;VIII-IX] PGA ϵ [0.07;800]	If log(PGA)≤1.57, I=1.78+1.55*log(PGA) If log(PGA)>1.57, I=-1.60+3.70*log(PGA)	0.73
Wald et Atkinson & Sonley (BRGM-2000)	California-France	If I≤V, I=7.58+2.2*log(PGA(g)) If I>V, I=10.18+4.35*log(PGA(g))	1.7

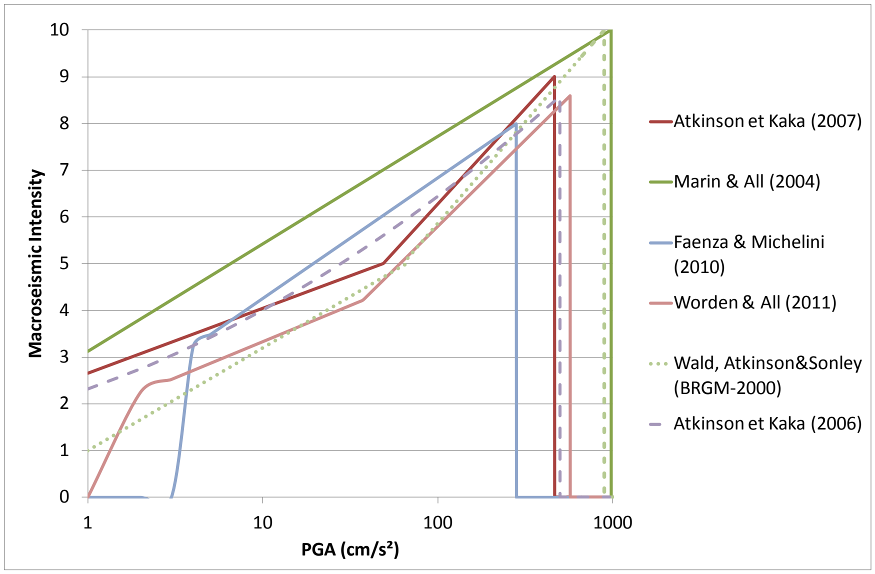

Fig. 5 – PGA-to-Intensity relationships used in this study

5.3 Completeness periods for historical seismicity

Based on SisFrance historical seismicity database [15], the period of completeness of historical seismicity is known for the French Metropolitan territory, as shown in table 2.

Table. 2 – Completeness periods for historical seismicity

Zone	intensités IV et IV-V	intensités V et V-VI	intensités VI et VI-VII	intensités VII et VII-VIII	intensités VIII et VIII-IX	intensités IX et IX-X
France	1920	1880	1850	1750	1500	1300
Alpes	1950	1880	1830	1800	1500	1300
Massif Armoricain	1920	1880	1750	1700	1500	1300
Nord	1920	1880	1850	1750	1500	1300
Provence	1925	1880	1850	1750	1500	1300
Pyrénées	1930	1910	1910	1750	1500	1300
Rhin	1885	1870	1750	1630	1500	1300
Autres régions	1960	1850	1750	1750	1500	1300

This assumption has to be consistent with the one that is made for the prior PSHA, in term of period and uncertainties, if any. This consistency was confirmed in our case.

5.4 Observations: Historical earthquakes felt on sites

Based on SisFrance database and Seismic Hazard Assessment of the EDF's NPP, it is possible to quantify the number of historical events felt on the 19 EDF sites. This number of observed events, quantified per range of magnitude, is presented in table 3.

Table. 3 – Total amount of historical events felt on all EDF NPP sites

Intensity range Completenes period	V 135 y	V-VI 135 y	VI 165 y	VI-VII 165 y	VII 265 y	VII-VIII 265 y	VIII 515 y	VIII-IX 515 y	IX 715 y	IX-X 715 y	X 715 y
Total number of event (whole 19 EDF's sites)	24	12	3	2	0	0	0	0	0	0	0

5.5 Logic tree developed for Bayesian updating

The logic tree developed to update the weight of the 42 hazard curves is described in fig. 6.

This process allows to account for different PGA-to-Intensity relationships and to account for different Intensity ranges (i.e. different return periods).

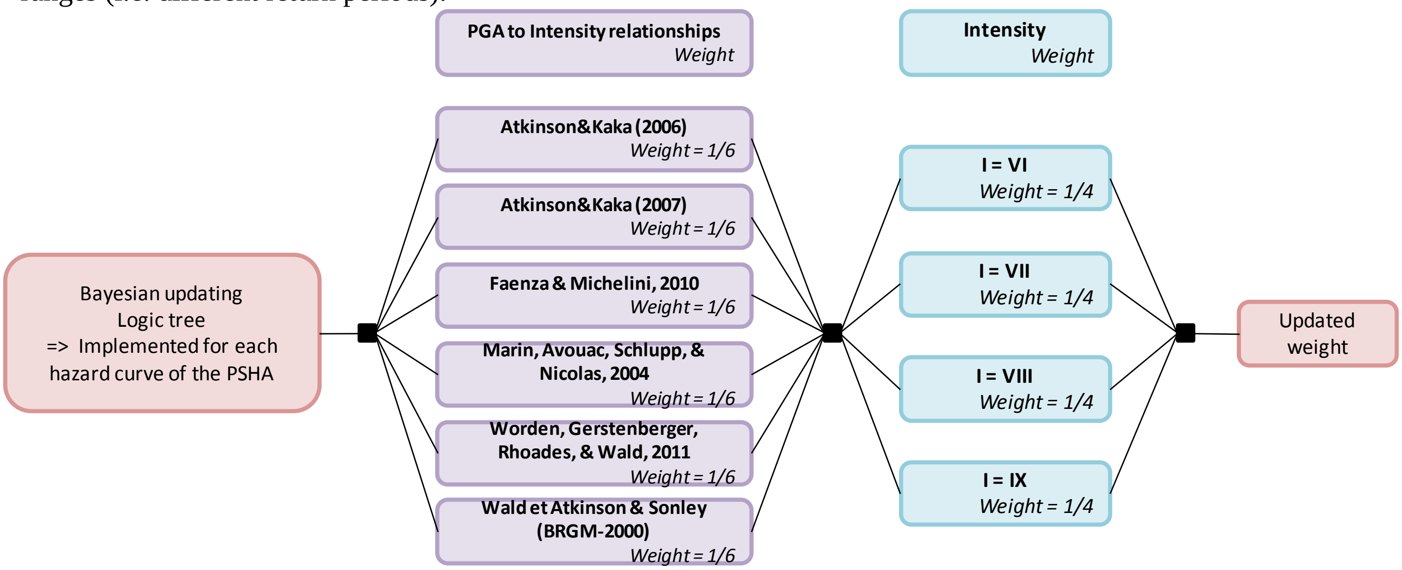

Fig. 6 – The logic tree developed to update the weight of the 42 hazard curves

5.6 Results

The updated weight (Bayesian likelihood function) of the hazard curves are presented in the next figures.

The likelihood function obtained for each PGA-to-Intensity relationship is shown in Fig. 7. In this figure, the height of the colored bar corresponds to the value of the likelihood of the hazard curve under consideration, for the PGA-to-Intensity relationship under consideration.

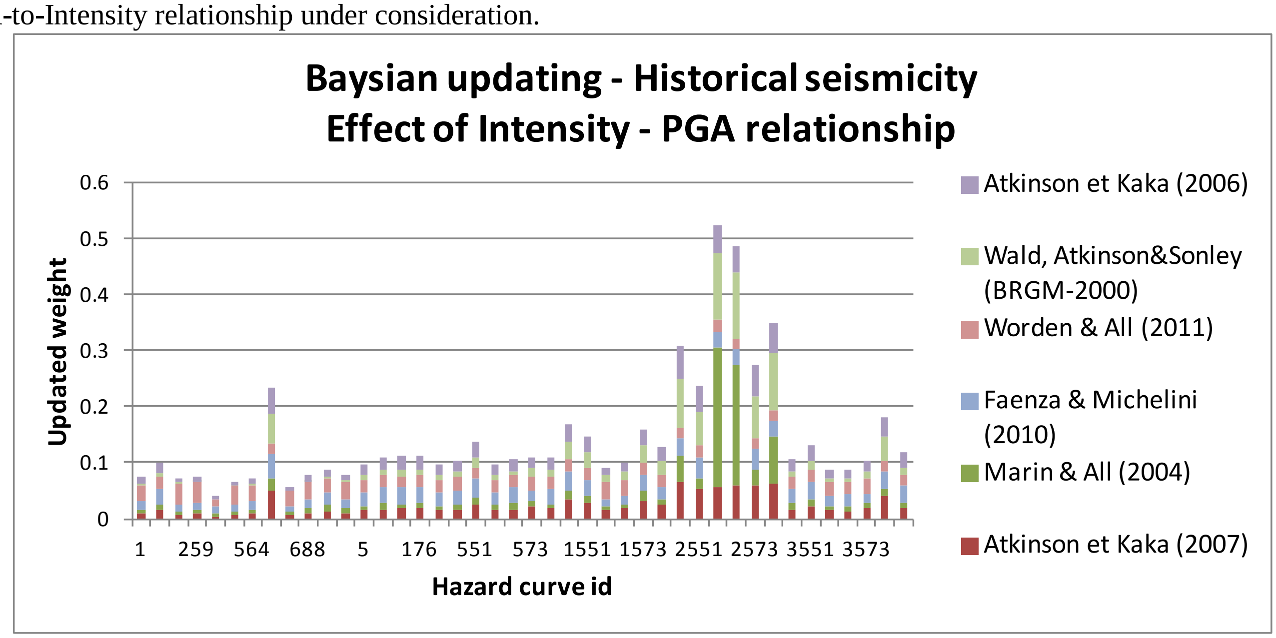

Fig. 7 – Likelihood function depending on PGA-to-Intensity relationships

The likelihood function obtained for each Intensity range included in the logic tree is shown in Fig. 8. In this figure, the height of the colored bar corresponds to the value of the likelihood of the hazard curve under consideration, for the Intensity range under consideration.

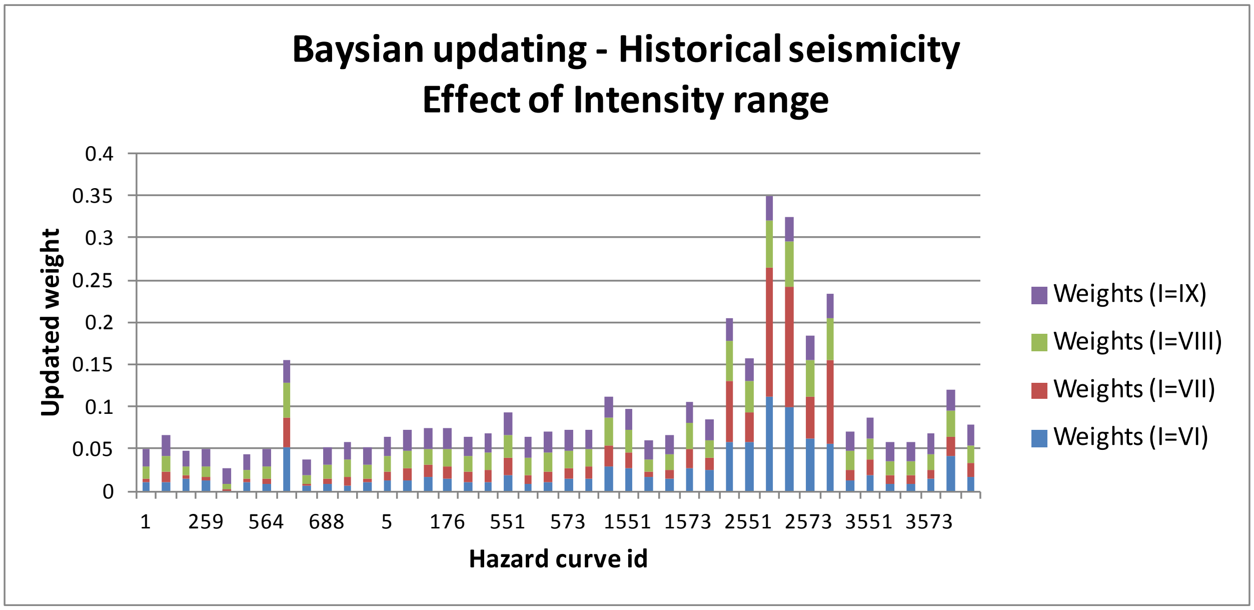

Fig. 8 – Likelihood function depending on range of Macroseismic Intensity used

Fig. 9 “radar view” illustrates how the likelihood evolves with Intensity. This figure shows that for high Intensity (I = IX), the likelihood is quite comparable for all hazard curves. This illustrates that for such high Intensities, the updating process is not able to rank the hazard curves, simply because at this level of Intensity (which corresponds to long return periods), all hazard curves do not predict any observation, as actually observed. When there is not enough observation, the updating process does not modify prior weights, as also observed in [3].

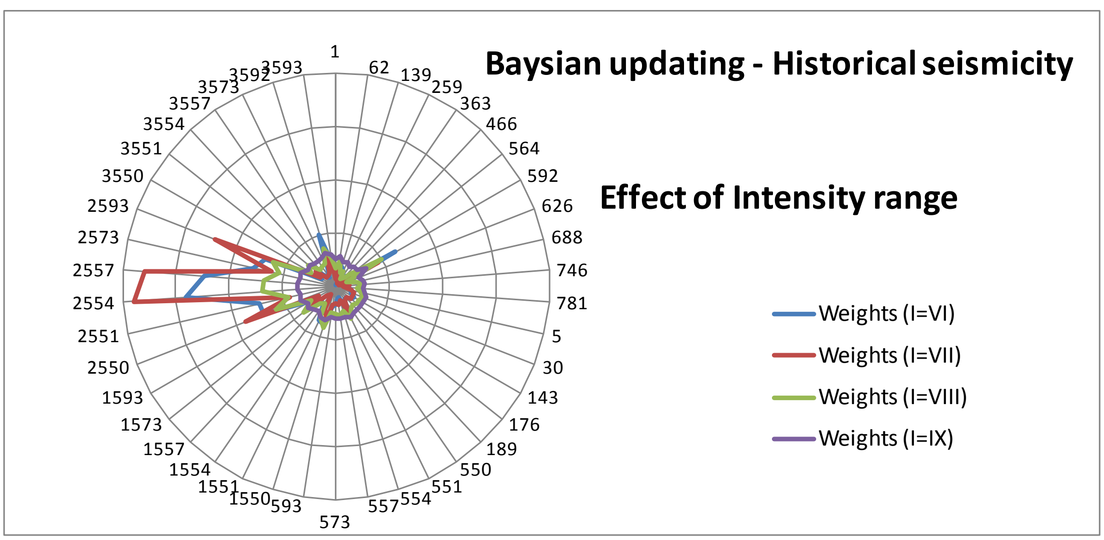

Fig. 9 – Likelihood function depending on range of Macroseismic Intensity used – Radar view

Finally, the updated weight of the hazard curves resulting from the whole logic tree is shown in Fig. 10. This figure clearly shows the efficiency of the updating process. The updating process, which does not modify any of the parameters of the prior PSHA, only modifies the weight of the hazard curves. One can finally observe that none of the prior hazard curves are completely eliminated. Their weights are reduced according to the likelihood that is calculated through Bayes theorem of conditional probabilities, according to observations.

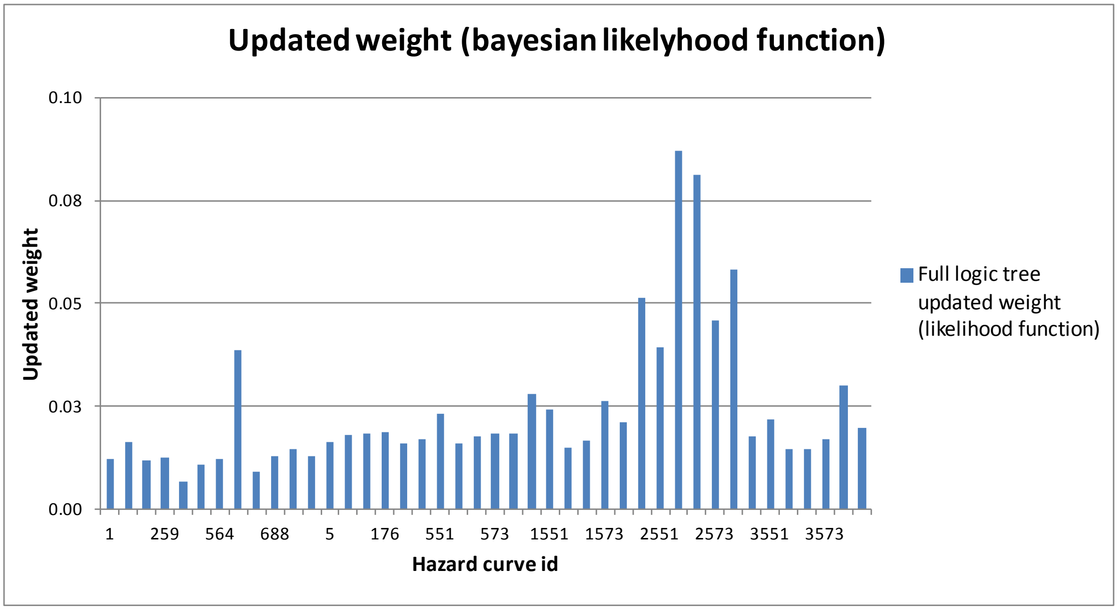

Fig. 10 – Full logic tree (6 PGA-to-Intensity relationship + 4 ranges of Intensity): Final likelihood (updated weight)

6. Discussion

First of all, we can conclude that the Bayesian updating procedure is successfully implemented and allows to update a PSHA based on actual historical seismicity as observed on the sites under consideration.

We also observe that if observations are not sufficient, the updating process does not affect the prior estimation (typically the case for Intensity IX in our study). This means that there is no risk of performing updating: the process is self-reliable. This also means that even with few (even no) observation, Bayesian updating can be implemented.

In addition, it is important to point out that the updating process does not modify any of the assumptions or input data of the prior estimation. It only updates the weight of the hazard curves (output of the PSHA), based on observations. This process allows to reduce the epistemic uncertainties that are contained in the prior model, based on their intrinsic (and objective) likelihood.

Finally, the procedure developed in this paper, based on historical seismicity, takes into consideration all sources of uncertainties (random and epistemic) in the PGA-to-Intensity transformation process and in the random occurrence of events, which avoid any deterministic or inappropriate choices.

7. Conclusion and perspectives

As recommended by the OECD/NEA/CSNI Workshop [11], a state-of-the-art PSHA should include a testing phase against any available local observation (including any kind of observation and any period of observation) and should include testing not only against its median results but also against its whole distribution (percentiles).

This study, by integrating historical intensity through a Bayesian updating technique with the proper propagation of all sources of uncertainties, and performed on every branch of the prior PSHA, allows to fulfill this requirement.

Such approaches are now fully matured and should be systematically used as a final step of any PSHA, using actual observations on the sites under consideration, in order to reduce epistemic uncertainties that could not be addressed through experts' judgments.

In the next stages, we will implement this Bayesian updating process on a full scale PSHA, using both instrumental and historical seismicity in the same manner, in order to take into consideration all available data.

Finally, we strongly recommend that such PSHA testing or Bayesian updating should be included as a final step to SSHAC procedure.

8. References

[1] International Society for Bayesian Analysis, https://bayesian.org/

[2] Runge A, Händel A, Riggelsen C, Scherbaum F, Kühn N, (2013) "A Smart Elicitation Technique for Informative Priors in Ground-Motion Mixture Modeling" M. EGU General Assembly 2013, held 7-12 April, 2013 in Vienna, Austria, id. EGU2013-990

[3] R. Secanell, C. Martin, E. Viallet, G. Senfaute (2015): Bayesian methodology to update the Probabilistic Seismic Hazard Assessment. *OECD/NEA/CSNI Workshop on "Testing PSHA Results and Benefit of Bayesian Techniques for Seismic Hazard Assessment", 4-6 February 2015, Eucentre Foundation, Pavia, Italy*

[4] N. Humbert, and E. Viallet (2008): An evaluation of epistemic and random uncertainties included in attenuation relationship parameters. *14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China*

[5] M. Ordaz, S. Singh, A. Arciniega (2007): Bayesian Attenuation regression: an application to Mexico City.

[6] M. Wang, T. Takada (2009) "A Bayesian Framework for Prediction of Seismic Ground Motion BSSA vol. 99 no. 4 2348-2364

[7] Stirling, M. & Gerstenberger, M. (2010), "Ground Motion-Based Testing of Seismic Hazard Models in New Zealand", BSSA, vol. 100, no. 4, pp. 1407-1414.

[8] Recent Findings and Developments in Probabilistic Seismic Hazards Analysis Methodologies and Applications, *OECD/NEA/CSNI Wokshop proceedings, Lyon, France, 7-9 April 2008*

[9] M. Keller, A. Pasanisi, M. Marcilhac, T. Yalamas, R. Secanell, G. Senfaute (2014): A Bayesian methodology applied to the estimation of earthquake recurrence parameters for seismic hazard assessment. *Quality Relibability and Engineering International, Volume 30, Issue 7*

[10] Tasan H., C. Beauval, A. Helmstetter, A. Sandikkaya, and Ph. Guéguen (2014): Testing Probabilistic Seismic Hazard estimates against accelerometric data in two countries: France and Turkey. *Geophysical Journal International 198, 1554–1571*

[11] Workshop on Testing Probabilistic Seismic Hazard Analysis Results and the Benefits of Bayesian Techniques, *OECD/NEA/CSNI Wokshop proceedings, Pavia, Italy, 4-6 February 2015*

[12] E. Viallet, N. Humbert, C. Martin, R. Secanell (2008): A Bayesian methodology to update the Probabilistic Seismic Hazard Assessment. *14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China*

[13] N. Humbert, E. Viallet (2008): A method for comparison of recent PSHA on the French territory with experimental feedback. *14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China*

[14] N. Humbert (2015): PSHA Updating Technique with a Bayesian Framework: Innovations. *OECD/NEA/CSNI Workshop on "Testing PSHA Results and Benefit of Bayesian Techniques for Seismic Hazard Assessment", 4-6 February 2015, Eucentre Foundation, Pavia, Italy*

[15] http://www.sisfrance.net/