

## **A Bayesian Updating Technique to Address Uncertainties In Probabilistic Seismic Hazard Assessment**

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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) of nuclear power plants. Such approaches are nowadays considered as well established and come more and more used worldwide.

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, some deterministic choices have to be taken and may lead to strong differences in terms of seismic motion evaluation.

In that context, the objective of this paper is to point out some difficulties that may appear in the development of PSHA studies and to propose an approach that may be used to orient expert judgment and address epistemic uncertainties. The key point, which corresponds to the innovating point of the process, is the use of instrumental experience to update the results of a PSHA using observations that remain consistent with the real regional seismicity, as recorded.

For this purpose, we present first some basic considerations on the current practice in PSHA studies and some resulting difficulties that one may face at different steps of the study. Then we describe an approach that may be used to update the results of the PSHA, which is based on a Bayesian updating technique including real observations as conditional events, with their own probabilistic distribution.

The results presented here point out that a PSHA must be conducted in a real probabilistic spirit that is totally different from a deterministic approach (the choice of “best-estimate” or “median” input data instead of “conservative” ones is one of the key points). In addition, logic tree procedure, which seems to be the most appropriate way to account for epistemic uncertainties, does not quantify the variability on the physical parameter itself but quantify variability on expert opinion. This may also lead to an important bias in a PSHA study.

Finally, the lesson learnt is that results from PSHA may be strongly different from real seismicity, as recorded, especially depending on previous considerations. Then, the comparison to the instrumental experience data appears to be necessary to address such difficulties. In that context, the use of the Bayesian updating technique presented in this paper may become a necessary tool to address epistemic uncertainties in PSHA and its performances could allow to get PSHA more rugged and consistent with observations.

### **CONTEXT AND OBJECTIVES OF THE STUDY**

Since the basic work of Cornell [COR-68], many studies have been conducted in order to evaluate the probabilistic seismic hazard (PSHA) of nuclear power plants. In general, results of such studies are used as inputs for seismic PSA. Such approaches are nowadays considered as well established and come more and more used worldwide, generally in addition to deterministic approaches, typically for risk informed studies, at design stage or for evaluation of existing nuclear power plants.

Nevertheless, some discrepancies have been observed recently in some PSHA [KLÜ-05], especially from studies conducted in areas with low to moderate seismicity. The lessons learned from these results lead to conclude that, due to uncertainties inherent to such a domain, some deterministic choices (concerning input

data for instance) have to be taken and, depending on expert judgment and choices, may lead to strong differences in terms of seismic motion evaluation.

In that context, the objective of this paper is not to describe in detail the PSHA overall approach but its objective is to point out some difficulties that may appear in the development of PSHA studies, and to propose an approach that may be used to orient expert judgment and address epistemic uncertainties. The key point, which corresponds to the innovating point of the process, is the use of instrumental experience to update the results of a PSHA using observations that remain consistent with the real regional seismicity, as recorded.

This paper is divided in two parts. The first part presents some basic considerations on the current practice in PSHA studies and identifies some difficulties that one may face at different steps of the study, especially concerning input data selection. The second part describes an approach that may be used to update the results of the PSHA, which is based on a Bayesian updating technique including real observation as conditional events, with their own probabilistic distribution.

## **PART 1 - BASIC CONSIDERATIONS ON THE CURRENT PRACTICE IN PSHA AND ASSOCIATED DIFFICULTIES**

As the objective of this paper is not to describe in detail the PSHA overall approach, we only focus hereafter on some specific aspects of a PSHA that could lead to difficulties (implying deterministic choices) and we try to quantify their consequences.

### **Seismic Motion Characterization : Random Uncertainty ?**

We would like to discuss first on the characterization of the variability of the seismic motion. In particular, two question may raise related to this factor :

- Q1 : Where does sigma (i.e. standard deviation associated with the attenuation relationship) come from ?
- Q2 : How many sigma around the median value of the attenuation relationship to integrate in the PSHA (1, 2, infinite ... ) ?

#### Elements of answer to Q1

Concerning Q1, it seems to be obvious that sigma comes from the (random) variability of the seismic motion itself. Nevertheless, it is also obvious that in strong motion databases that are used to determine attenuation relationships, the characteristics (magnitude and distance) of the events are determined with an uncertainty which may be significant (typically 0.5 for the magnitude, even more if different types of magnitudes are used ; it may also be the case for the distance, especially for near field events). These uncertainties have a direct impact on the sigma of the attenuation relationship.

To give an order of magnitude, we present the following simple estimation : For an attenuation relationship which would have a coefficient 0.3 on the magnitude dependent term ( $\text{Log PGA} \sim 0.3 M$ ), and a global standard deviation (sigma) of 0.3 (which is a common value), a 0.5 uncertainty on the value of the magnitude given in the database would have a significant contribution on the global standard deviation which should therefore decrease the sigma due to the random variability of the seismic motion itself to 0.25, due to combination of uncertainties :  $0.3 \sim [0.25^2 + (0.3 * 0.5)^2]^{1/2}$ . Of course, this last value of sigma (0.25) should be used in the PSHA instead of the global one.

As this value of sigma has a direct (and important) effect on the PSHA, the "best-estimate" value of the sigma to be used should be carefully assessed. Unfortunately, only a few studies are available on that point.

#### Elements of answer to Q2

In a pure probabilistic spirit, the first answer should be to integrate the sigma to infinite. Nevertheless, the fact that seismic motion distribution follows a lognormal law is only an assumption and should always be checked with real data. Depending on strong motion databases, this verification may not be possible over 2 to 3 sigma (see Figure 1).

This is an important fact to point out. Even if it may be shown that over 3 sigma, the impact may not be so important, the integration should be limited between 2 and 3 times sigma in a PSHA.

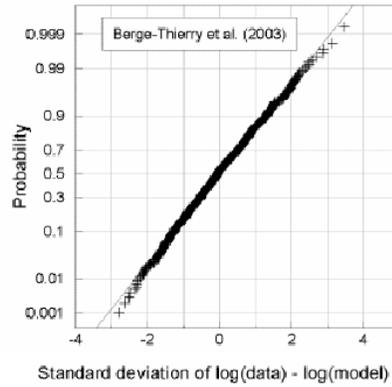


Figure 1 : Comparison between lognormal distribution (records and model)

Another point we would like to discuss now concerns the equivalence of magnitude that may be necessary to use in PSHA, due to historical and instrumental seismicity, and magnitude used in attenuation relationships.

This leads to choices that can be taken in a probabilistic spirit or in a deterministic spirit. For instance, the choice to take a “conservative” relationship between  $M_S$  and  $M_{L(LDG)}$  (see Figure 2), which may be an appropriate choice for a deterministic hazard evaluation for a NPP for instance, may lead to a bias in a probabilistic approach and will directly over-estimate the median value of the ground motion.

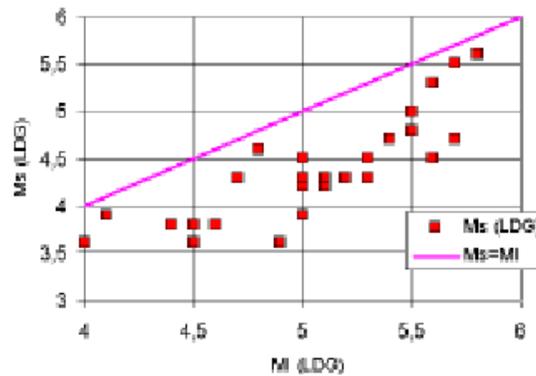


Figure 2 : Equivalence between different types of magnitude : which relationship to use ?

According to the PSHA methodology, best-estimate data should be kept at each stage of the process in order to keep the “median” estimation spirit of the PSHA, as expected.

**Conclusion on the characterization of the seismic motion**

Concerning variability of seismic motion, some choices have to be made (among the possible ones) and may have a strong impact on the results of a PSHA. The most important request is to keep “best estimate” data, to remain consistent with the PSHA philosophy. In that situation, the value of sigma associated with attenuation relationships may be slightly reduced to account for the random variability of the seismic motion only, its range of integration should also be carefully chosen : typically between 2 and 3 sigma but no more, and the potential relationship use to transform different types of magnitudes should be also a best-estimate one.

*This fact should be considered in a PSHA in order to get a “real” median value, as expected.*

**Selection Of Attenuation Relationship For A Given Area : Epistemic Uncertainty ?**

As one can expect, attenuation relationships come from area with moderate to high seismicity (where data are available). However, they may be used for PSHA in area with low to moderate seismicity. In that situation

especially, their applicability (even if there may not be another way to proceed) is to be seriously assessed. In addition, it may be obvious to say that very important differences may be observed from different attenuation relationships (see one illustration in Figure 4).

In a PSHA, this aspect is accounted for based on expert judgment. The knowledge of (i) the real seismicity of the given area and (ii) the construction of attenuation relationships is then a key factor. Practically, this is usually accounted for by mean of logic trees that allow to take into consideration all possible judgments. Nevertheless, one must keep in mind that this logic tree approach allow to quantify variability on experts judgment only but not the variability on the physical parameter itself.

This epistemic uncertainty is expected to be reduced, with increase of knowledge.

#### **Conclusion on the choice of an attenuation relationship**

The choice of attenuation relationships is one of the most important choices in a PSHA and may lead to high differences in the results. In that situation, it is important to point out that the logic trees procedure which seems to be the most appropriate way to account for epistemic uncertainties does not quantify the variability on the physical parameter itself but quantify variability on expert opinion. This may lead to an important bias in a PSHA study.

*The current practice should then be improved in order to reduce the epistemic uncertainty on the physical parameter itself.*

#### **Conclusion Of Part 1**

Although well established, some basic steps of PSHA are still under discussion. But most of the difficulties come from the choice of input data and the way to account for uncertainties, which is different from the way to address them in a deterministic approach.

- *The most important request is to keep “best estimate” data, at each stage, to remain consistent with the PSHA philosophy, and to obtain a “real” median estimation.*
- *It is also important to propagate variability but trying to separate random uncertainty from epistemic ones,*
- *Finally, it must be kept in mind that logic trees allow to quantify the variability on expert judgment but not the variability on the physical parameter itself, this should be improved.*

The next part of this paper is to propose a method to address this last point.

## **PART 2 - AN INNOVATING APPROACH TO ADDRESS EPISTEMIC UNCERTAINTIES USING REAL EARTHQUAKE RECORDS**

### **Context And Available Data**

This paragraph proposes a method to address epistemic uncertainties using real seismicity, as recorded.

This method is based on a preliminary statement that results of a PSHA may not be consistent with real data (as recorded) especially depending on the potential problems discussed previously. This fact is discussed first. Then the method is described and finally, a first application is presented and discussed.

For the illustration of this situation, a case study is used. A PSHA is performed on the French metropolitan territory and records from EDF PWR NPP network and national earthquake network [RAP] are used (see Figure 3).



**Figure 3 : Map of French metropolitan territory and location of earthquake stations**

The comparison is performed for the period of time consistent with the time of available records : 5 to 10 years for RAP stations (about 100 years cumulative time) and 10 to 25 years from EDF NPP stations (about 400 years cumulative time).

To compare results between PSHA prediction and experience events, the number of events with a PGA higher than a selected value are counted or evaluated.

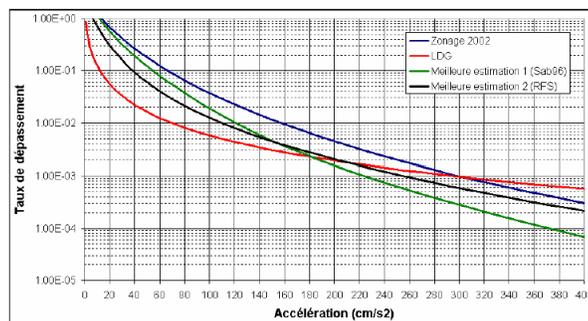
**PSHA Study – Impact Of Uncertainties And Comparison To Available Experience Data**

The PSHA is performed based on usual practice. The input data are selected considering the previous discussion. For this application some attenuation relationships are used and will be considered in a logic tree approach, see table 1.

		Description des modèles historiques				
		H1	H2	H3	H4	H5
Catalogue de sismicité		Catalogue ZPGF de l'étude 2002, sur les 25 dernières années.				
Loi d'atténuation		Ambraseys (1995)	Ambraseys (1995)	Sabetta et Pugliese (1996)	RFS 2001-01	RFS 2001-01
Transformation $M_{LDD}/M_s$		non	Nicolas et al. (2000)	non	non	Nicolas et al. (2000)
Magnitude minimum		4,0				
Grille de calcul		0,3				
Valeur calculée		Médiane				

**Table 1 : Description of model used in the study**

For each attenuation relationship, taken individually, it is possible to perform a PSHA and make an inter-comparison. The results are illustrated in Figure 4.



**Figure 4 : Illustration of the results of a PSHA depending on attenuation relationships**

This shows the potentially large impact of such choices in the probabilistic hazard evaluation (factor of 2 on the PGA or 10 on the return period).

Then it is possible to compare the predictions to the observations, case by case. These results (from 2 among the previous models) are shown in Table 2.

Number of events with PGA > 0.01g			
Network	Model		Observations
	H4	H5	
EDF PWR (total number of events)	85	12	1
RAP stations (total number of events)	87	27	14

**Table 2 : Comparison of number of events higher than 0.01 g (model and observation)**

This comparison shows that, depending on choices, the differences between prediction and observation may be very important.

**Conclusion on the impact of uncertainties and comparison to available experience data**  
 The lesson learnt from this part is that results from PSHA may be strongly different from real seismicity, as recorded, especially depending on choices on input data that always depend on expert judgment.  
*Then, the use of instrumental experience data appears to be necessary to address such difficulties.*

**A Way To Address Uncertainties : The Use Of A Bayesian Updating Technique**

Based on previous results, the objective here is to use records to update the prediction in order to get results more consistent with observation.

The method used is based on a classical Bayesian updating technique, used for many years in reliability field, especially in mechanics.

The basic consideration is simple :

*“based on a probabilistic evaluation of a given parameter, what is the most probable values that this parameter could take (associated with a given confidence level) considering the available observations (including their uncertainties) as conditional events ?”*

The technique used here was developed by Madsen [MAD-85] and its performance and pertinence have been already confirmed [HEI-99].

It uses the Bayesian theorem of conditional probability :

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

In our case, the “realistic” range of the PGA is defined by the 15% - 85% confidence level of the predicted PGA. The probability that reaches both limits may be calculated for each selected return period. The observed data are then taken into account as conditional events, with their own probabilistic distribution.

The updated probabilities are obtained from a classical FORM method within the Bayesian updating framework developed in [MAD-85] and solved for each selected fractile (15 – 85% in our case) by a dichotomy method.

**First Application : Feasibility Exercise**

As a first application of this method, the updating technique is carried out using the results of the complete logic tree from the study described previously. The results obtained are shown in Figure 5.

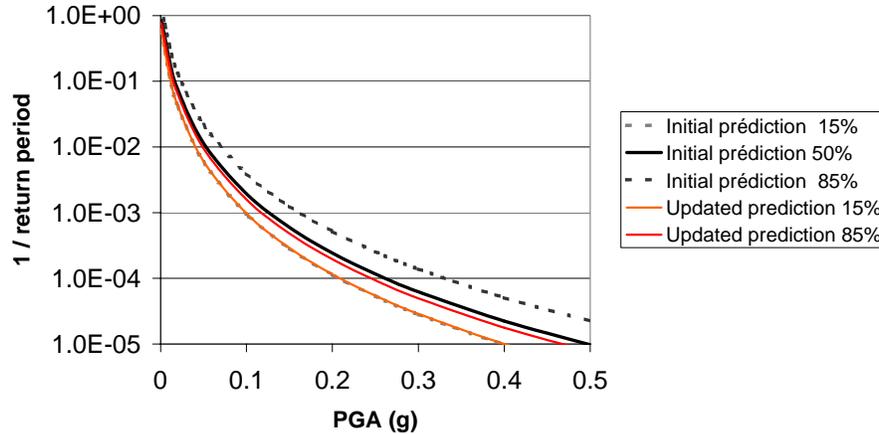


Figure 5 : Comparison between initial prediction and updated one

One can observe the potential effectiveness of the updating process which reduces significantly the scattering of the initial prediction and also “re-center” the prediction around fractiles which are not the median value of the initial prediction. These results are discussed in the next paragraph.

### Discussion Around The Updating Technique

First of all, it is important to indicate that the updating technique does not modify any of the input data or assumption of the initial prediction. The technique only accounts for observations in order to identify the most probable results among the initial ones.

Then, one can notice that the techniques accounts for random uncertainties as far as these random uncertainties are included in the observations (this is the case by considering different stations in different areas and different time of observation). This is one of the reasons that lead to an updated prediction with still variability (in other mechanical studies dealing with other parameters with a low random uncertainty, such as delayed strain in PWR RC containment for instance [HEI-05], the updated technique leads to results with a low variability).

Nevertheless, it must be told that a potential limitation of the current exercise could come from the relatively low period of observations (due to low seismicity in France and relatively “young” seismic network). But some previous studies [HEI-05] have shown that the performance of this technique was really good, even with a low number of observations. In addition, for our case, the time of observation is continuously increasing (for instance, the available data should double within 5 next years !) and it is obviously possible to “update” the updating including new data.

However, low number of data is better than no data at all !

#### Conclusion on the use of the Bayesian updating technique

Our conclusion concerning the use of the Bayesian updating technique is that it may become a real interesting tool to address epistemic uncertainties in PSHA and its performances could allow to get PSHA more rugged and consistent with observation.

*Then, updating technique may become one necessary step in PSHA methodologies.*

### CONCLUSIONS AND PERSPECTIVES

The objective of this study was to point out some difficulties in PSHA studies and to propose an approach that may be used to orient expert judgment and address epistemic uncertainties.

The most important conclusions that we would like to point out are the following :

- First of all, it may be important to keep “best estimate” data, to remain consistent with the PSHA philosophy. In that situation, the value of the standard deviation associated with attenuation relationships may be slightly reduced to account for random uncertainty only, its range of integration should also be carefully chosen : typically between 2 and 3 times sigma but no more, and the potential relationship used to transform different types of magnitudes should also be a best-estimate one.
- The choice of attenuation relationships is one of the most important choices in a PSHA and may lead to high differences in the results. In that situation, it is important to point out that the logic trees procedure which seems to be the most appropriate way do account for epistemic variability does not quantify the variability on the physical parameter itself but quantify variability on expert opinion. This may lead to an important bias in a PSHA study and this should be improved.
- Then, the lesson learnt is that results from PSHA may be strongly different from real seismicity, as recorded, especially depending on choices on input data that always depend on expert judgment. In that situation, the comparison to the instrumental experience data appears to be necessary to address such difficulties.
- In that context, the use of the Bayesian updating technique may be an excellent tool to address such uncertainties and could become necessary to address epistemic uncertainties in PSHA in order to obtain results more rugged and consistent with observations.

One other conclusion of this study is the effectiveness of sharing experience between seismologists and structural engineers which should be systematized in future for PSHA but also for other fields such as characterization of seismic motion and its damaging potential for instance.

In term of perspectives, and based on the results presented here, we plan to perform the following actions :

- performing a large scale PSHA (typically French metropolitan territory) including the updating technique using a more systematic process including observed data from EDF nuclear PWR and national accelerometric network and accounting for potential soil effect that could modify observation and / or prediction (soil effects for seismic hazard and SSI effects for network),
- using historical seismicity and vulnerability to obtain some additional data especially in the range of 500 to 1000 year of return period in order to use all the available observations in the updating process.

As a final opinion, we are convinced that such updating techniques may become one necessary step in PSHA methodologies and could be a real opportunity to share experience between seismologists and engineers.

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