Bollettino di Geofisica Teorica ed Applicata Vol. 55, n. 1, pp. 135-148; March 2014
DOI 10.4430/bgta0080

Seismic hazard for design and verification of nuclear installations in France: regulatory context, debated issues and ongoing developments

O. Scotti, C. Clément and D. Baumont

Institute for Radiological Protection and Nuclear Safety, France

(Received: June 29, 2012; accepted: September 7, 2012)

ABSTRACT Deterministic (DSHA) and probabilistic (PSHA) seismic hazard assessments can, and often do, lead to quite different seismic hazard levels. There is a growing need in France for decision makers to understand the origin of these differences. The focus of this paper is to present the current status in the development of a formalized propagation of uncertainties based on the French deterministic seismic nuclear safety rule (RFS 2001-01, 2001). Along the lines of PSHA approaches, the method consists in the construction of a Logic Tree (LT). Preliminary comparisons between DSHA-LT and PSHA-LT averaged over 30 nuclear sites located in metropolitan France show that, if the resulting uncertainty in the hazard spectrum may be comparable, the median hazard spectral values may actually differ. Not surprisingly, the resulting general tendency is that in low seismicity zones, DSHA tends to predict higher median spectral values compared to $PSHA_{RT=1000yr}$. In higher seismicity zones, comparable hazard levels are obtained on average between DSHA_MHPE (Maximum Historically Probable Earthquake) and $PSHA_{RT=1000yr}$, but extrapolation of PSHA results at 10,000-year return periods may have a tendency to exceed DSHA_MHPE+0.5 values. A site-specific analysis including all the constraints imposed by the RFS 2001-01 (2001) (minimal spectral response, paleoseismic spectral response and site-effects) will be necessary for a complete DSHA/PSHA comparison.

Key words: seismic hazard, nuclear power plants, France.

1. Introduction

The seismic hazard methodology (RFS 2001-01, 2001) recommended by the French Nuclear Safety Authority (ASN) for the seismic design of nuclear power plants (NPPs) is deterministic. It is well known that seismic hazard assessment can vary considerably depending on how uncertainties in data and models are taken into account in a seismic hazard study. This point constitutes the main subject of discussion between IRSN (Institute for Radiological Protection and Nuclear Safety) and the nuclear operators. It has been IRSN's practice therefore to confront differences in seismic hazard levels proposed by the operators and IRSN with a quantification of the underlying uncertainties. IRSN has developed a tool specifically for this purpose, which is based on the French deterministic rule. A second tool is also under development, based on the probabilistic approach. Both methods use the logic tree approach to explore the underlying epistemic uncertainties.

After presenting the French regulatory rule that defines the input seismic motion for nuclear installation and the debated issues raised by its application, we provide a brief analysis of the advantages of the present rule and means to tackle its weak points. As the analysis will show, both deterministic and probabilistic methodologies will need to be considered in the near future in order to provide decision-makers with the range of seismic hazard levels that the scientific community at large could estimate.

2. The French nuclear safety rule

Seismic hazard assessment for French nuclear facilities is guided by a regulation based on a deterministic approach (RFS 2001-01, 2001). According to the regulation, seismic hazard assessment at a site requires identifying the characteristics of the "Maximum Historically Probable Earthquake" (MHPE), selected from the historical and instrumental seismic catalogs and considered to be the most penalizing earthquakes liable to occur over a period comparable to the historical period, or about 1,000 years. The methodology can be summarized in 8 main steps:

1. - determine the Seismic Source Zones (SSZs), based on geological and seismological criteria; each zone is considered to have a homogeneous seismic potential;
2. - estimate the characteristics of historical and instrumentally recorded events that occurred in each SSZ;
3. - retain, for the considered site, the events that would produce the most penalizing effects at the site (in terms of macroseismic intensity) if they were to occur at closer distance than they did. In other words, the rule stipulates that the events have equal potential within the SSZ and thus the applicant should retain the closest distance to the site. They constitute the MHPEs;
4. - a "Safe Shutdown Earthquake" (SSE) is associated to each MHPE and is obtained by increasing the MHPE magnitude by 0.5 to account for uncertainties on the characteristics of MHPE (related to knowledge on seismotectonics and seismicity);
5. - evaluate the seismic ground motion (mean acceleration response spectra only) associated with the SSE using the Ground Motion Prediction Equation (GMPE) of Berge-Thierry *et al.* (2003) which predicts, for a magnitude and distance couple, a pseudo-acceleration value for a wide spectral frequency range (0.1 to 34 Hz), accounting for two soil conditions (rock or soil);
6. - for sites located at close distance to faults with evidence of surface rupture, a study is requested to evaluate the vibratory ground motions associated to past events;
7. - site specific studies are required for sites located on very soft soil (V_S < 300 m/s) or associated with a particular geometry (sedimentary basins, topography, etc.) where site effects are anticipated;
8. - finally, the RFS 2001-01 (2001) requires that the spectrum retained by the operator cannot be lower than a minimal response spectrum (defined for the 2 soil conditions) with a *PGA* set at 0.1g.

3. Debated issues

IRSN is the technical support organization for the ASN. When IRSN is asked by ASN to expertise a seismic hazard study of a nuclear operator, IRSN's objective is to evaluate the conformity of the application to the RFS 2001-01 (2001) and evaluate the extent to which uncertainties are integrated in the final seismic hazard level retained by the operators. Indeed, if for a given scenario, the median GMPE is fixed by the RFS 2001-01 (2001), the definition of seismic scenarios (magnitude, depth, distance to site) depends entirely on the definition of the SSZ geometries, the method used to estimate the characteristics of historical earthquakes and most importantly, on the way in which uncertainty is accounted for at each step of the computation.

3.1. Source zone geometries

For the metropolitan territory, several SSZ-schemes have been established (e.g., Terrier *et al.*, 2000; Geoter, 2002; EDF, 2010). Usually the nuclear operator in charge of the seismic hazard assessment proposes its own SSZ-scheme. IRSN continuously updates its own SSZ scheme and active fault database (Baize *et al.*, 2012). The methodology used to produce a SSZ-scheme is based on a synthesis of all geophysical, seismological and geological data constraining the deformation behavior of the studied region. The uncertainty associated with the choice of SSZ is quite variable from one region to another. Quantifying this uncertainty, which depends on the knowledge of the regional seismotectonics, remains a difficult task. Some zone boundaries are located with a good confidence (uncertainty around 10 km), whereas for others, the reliability of the boundary remains expert-dependent. Using the RFS 2001-01 (2001) methodology, the choice of the SSZ scheme has a major consequence and conditions the determination of the reference MHPE event and thus the corresponding level of hazard.

3.2. Predicting macroseismic intensity at a nuclear site

Given that the selection of reference events is made with respect to a macroseismic intensity criterion at the site, uncertainties (distance, magnitude) associated with this predicted intensity should be systematically considered for the definition of the MHPE. However, as this is not codified in the RFS 2001-01 (2001), this point should be improved in the future as it is a major source of expert debate.

3.3. Magnitude, depth and epicentral intensity of earthquakes

A pre-requisite for establishing a seismic scenario in the RFS 2001-01 (2001) methodology is the estimation of the magnitude and location of earthquakes (including depth), considering either macroseismic data or instrumental records. The French catalog of historical earthquakes reports events felt in mainland France dating back to the year 843 A.D. (www.sisfrance.net) while instrumental records cover the last 50 years. Actually, most MHPEs determined for the French nuclear sites are related to earthquakes which occurred in the historical period.

Instrumental earthquake epicenters are in general quite well determined with an uncertainty less than 10 km, compared to their depth. The magnitude estimations are still to this day strongly scattered in France, each institution relying on its own magnitude estimation method. Local magnitude discrepancies can exceed 0.5 degrees depending on the institute providing the estimate (e.g., St Dié 2003 earthquake: $M_{LRénass}$ = 5.4, M_{LLDG} = 5.8, M_{LINGV} = 4.6; moment magnitudes tend to be less scattered $M_{W\ HRVD\text{-}CMT}$ = 4.9, $M_{W\ SED}$ = 4.8).

The robustness of historical earthquake parameters such as magnitude, depth and epicentral intensities is extremely variable. The necessity to account for data and modeling uncertainties in their estimation, has pushed IRSN to develop a macroseismic tool (Baumont and Scotti, 2008a) which allows computing a probability density function of solutions for each historical event which can then be easily compared to the published estimates as well as those proposed by the operator. The tool is based on the development of Empirical Macroseismic Predictive Equations (EMPEs), derived from the analysis of macroseismic intensity data points collected from European databases. The exploration of various combinations of data selections and inversion parameters led to a series of weighted EMPE. The calibration was performed on a homogeneous M_S catalogue (~130 events) based on a selection of published instrumental magnitudes covering the entire magnitude range (3.5 ≤ M_S ≤ 7). For each historical event, magnitude-depth characteristics are described as a probability density function (PDF) (see an example in Fig. 1).

4. Developing a DSHA logic tree to quantify differences in SHA due to different expert opinions

Although the regulation does not impose the use of multiple expert opinions, ASN has imposed that operators verify that the final seismic hazard level retained does cover "reasonably well" other plausible MHPE (ASN, 2003). Given the explicit choices imposed by RFS 2001-01 (2001), the following are the parameters that are subjected to uncertainties and expert opinions:

- differences in the definition of the SSZ (and thus the definition of the MHPE, reflecting the limits of knowledge with respect to the mechanisms that controls seismic activity);
- the estimation of the magnitude and depth of historical and instrumental events is also associated with uncertainties which depend on the spatial coverage, the reliability of macroseismic data or instrumental records and the assumed crustal model;
- the predicted intensity at the site, which is a crucial "filtering" criterion in order to select one or more MHPE for the studied site, can be associated to a large uncertainty which needs to be accounted for in the MHPE selection. (LT) for deterministic seismic hazard assessment, DSHA.

In order to evaluate the extent to which the above uncertainties are integrated in the final seismic hazard level retained by the operators, it has become current practice at IRSN to explore a wide range of plausible MHPE scenarios through the construction of a logic tree (DSHA-LT) that considers various published SSZ-schemes and various magnetic-intensity-depth equations.

Specific developments were made by IRSN to tackle the issue of site effects; however this aspect goes beyond the scope of this paper. The objective here is to limit the expert-debate in DSHA. As it can be seen in Fig. 2, an application of the RFS 2001-01 (2001) based on one expert opinion (IRSN's in this case) allows identifying a suite of MHPEs (lines in the plot) which may be exceeded by alternative choices of MHPEs (distributions shown by the filled colors). In this particular example, the strongest RFS 2001-01 (2001) based scenario computed with IRSN choices falls in the 84^{th} - 98^{th} percentile confidence level band deduced from all alternative scenarios explored in the DSHA-LT (Baumont and Scotti, 2008b). This type of information is

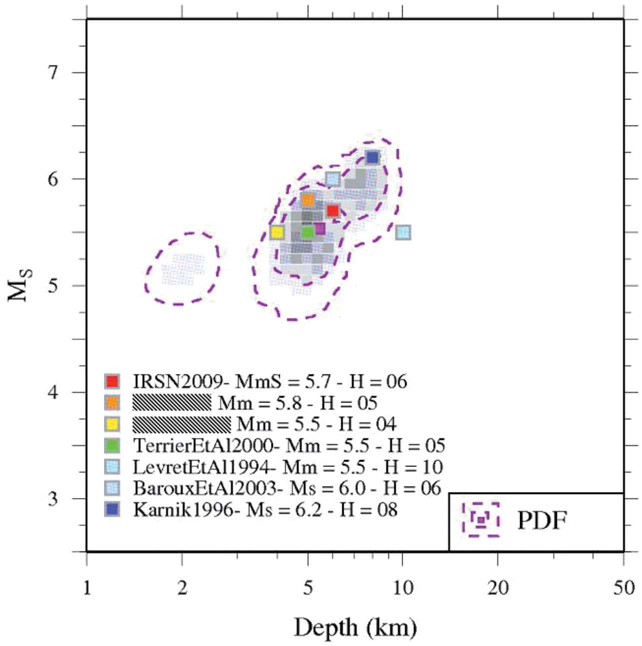

Fig. 1 - Magnitude- depth estimates for the 1909 Lambesc, France, earthquake. The dashed lines define the one and two standard deviation contours of the empirical PDFs computed on the basis of the IRSN macroseismic tool (see text for explanation). The barycentre solution is indicated by the violet square. This primary uncertainty in the data is propagated through in the DSHA-LT. For comparison, previous *M-h* estimates are also shown, including estimates for which the sources cannot be made public.

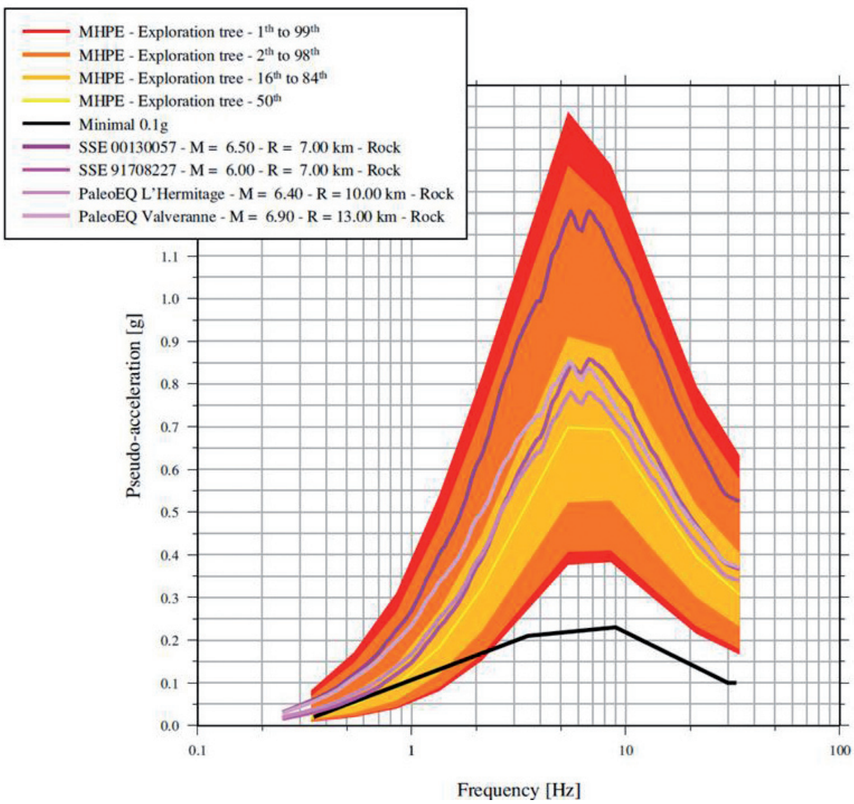

Fig. 2 - In this example, IRSN application of the RFS -2001-01 (2001) leads to the definition of 5 seismic hazard spectra. The strongest hazard level that would be retained by IRSN (the uppermost violet curve) falls between the 84th and 98th percentile of the DSHA-LT. The GMPE used in this example is Berge-Thierry *et al*. (2003). In accordance with the RFS-2001-01 (2001), the aleatory variability of ground motion (σ) is not accounted for.

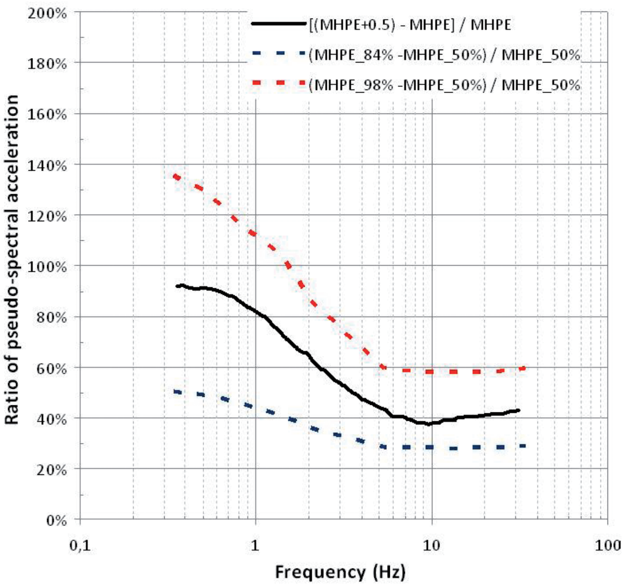

Fig. 3 - Coefficient of variation (COV) resulting from the DSHA-LT uncertainty exploration as proposed by IRSN. For each site-specific DSHA-LT the COVs are computed. Only the median value of all the sites is shown: in red for the COV = (98^{th}-50^{th})/50^{th} percentile and in blue for the COV= (84^{th}-50^{th})/50^{th} percentile. The black line represents the incremental seismic hazard imposed by the French regulation (MHPE+0.5 magnitude units)/MHPE).

necessary to help ASN deciding whether to accept or reject an operator's proposition depending on the safety target that is set in the overall risk-decision making process.

This tool is currently used to establish deterministic uncertainty bounds for the SHA at each nuclear site. The general median DSHA trend evaluated with the IRSN DSHA-LT for 30 French nuclear sites is presented in Fig. 3. Two measures of the dispersion of the hazard results are represented: (i) the coefficient of variation (COV-1) as defined by the ratio between the (84^{th} - 50^{th}) / 50^{th} percentiles, (ii) the COV-2 as defined by the ratio between the (98^{th} - 50^{th}) / 50^{th} percentiles. The overall median COV, that results from the IRSN-DSHA-LT exploration of plausible MHPE, shows values that range for COV1 from 30% to 50% and for COV2 from 60% to 140%. Higher COV values are seen for lower response spectral frequencies.

As can be seen in Fig. 3 (black line), the percentage increase in the MHPE seismic hazard level brought by the addition of 0.5 magnitude units (MHPE+0.5), as imposed by the RFS-2001-01 (2001), introduces a 40% increase in seismic hazard at high response spectral frequencies and reaches up to 90% increase at lower response spectral frequencies. Thus the MHPE+0.5 covers, on average, the COV1 measure but not the COV2 measure on the IRSN-MHPE, especially at lower response spectral frequencies. The higher COV values at lower response spectral frequencies are simply due to the behavior of the GMPE that induces, for a given magnitude increment, a higher increase at lower response spectral frequencies than at higher ones. This difference is exacerbated for the COV2 measure which is based on the 98^{th} percentile.

It should be stressed here that the 98^{th} percentile values are resulting from an automatic procedure that calculates the MHPE response spectral response based on a wide exploration of the parameter space, in particular in the magnitude-depth space. Indeed, Fig. 1 has already shown that a great range of magnitude-depth values may be plausible for a given macroseismic dataset (recall that only the two standard deviation values are actually shown in the PDF of Fig. 1). In the exercise presented in this paper, the entire magnitude-depth space was considered for each macroseismic data set.

Finally, it should be stressed that the exercise is not complete because it was not possible to generalize regulatory requirements concerning the minimal or the paleoseismic spectral response level imposed for the final SSE. These additional constraints contribute to raise the low frequency content of the final SSE response spectrum.

5. Which is the seismic safety target that should be set in DSHA?

In order to overcome the expert-opinion sensitivity of the DSHA results, it has become current practice at IRSN to consider that the 84th percentile seismic hazard of the DSHA-LT is a minimum threshold that the final seismic hazard level proposed by the operator should equal or exceed. If the operator provides final seismic hazard levels (SSE) that lie below this threshold, additional investigations and discussions are recommended by IRSN.

6. Disaggregation of DHSA-LT

To help decision makers understand the range of magnitude-distance MHPE scenarios that are explored in the DSHA-LT methodology proposed by IRSN, a disaggregation is performed. Fig. 4 shows for two different sites two examples: a disaggregation of all the scenarios that contribute up to 100% to the hazard and one for scenarios that contribute only between the 40th and 60th percentile. Concerning the first site (top), two main contributors to the hazard are identified irrespective of the disaggregation strategy. Depending on the relative weight that is attributed to the different scenarios and the percentile target, the resulting hazard may be more or less affected by the distant sources. For the second site (Fig. 4 bottom), on the other hand, the scenarios considered are radically different. The underlying SSZ schemes and thus the reference MHPE events are responsible for this difference. Clearly, depending on the weight attributed to each scenario and the choice of the "reasonable" target percentile, the resulting hazard level will be significantly different. Discussions between IRSN and ASN/operators are today carried out by means of this tool.

7. Beyond the RFS 2001-01: probabilistic seismic hazard assessment

To further appreciate the degree of uncertainty in SHA, in the following section a simple comparison betwen DSHA and probabilistic seismic hazard assessment (PSHA) is presented. IRSN has developed a PSHA approach over the past few years in the perspective of feeding the seismic probabilistic safety analysis studies that are under preparation but also to position the deterministic uncertainty assessments relative to the probabilistic ones. The PSHA methodology developed so far follows a logic tree (PSHA-LT) approach in order to account for various credible SSZ schemes including potentially active fault-SSZ where appropriate. A Monte Carlo approach is coupled to a logic tree, which allows exploring the epistemic uncertainty of the main parameters influencing the final seismic hazard [e.g., Tricastin site-specific PSHA; Clement *et al*. (2004a, 2004b)]. Each hypothesis considered in the logic tree is weighted, proportionally to its credibility.

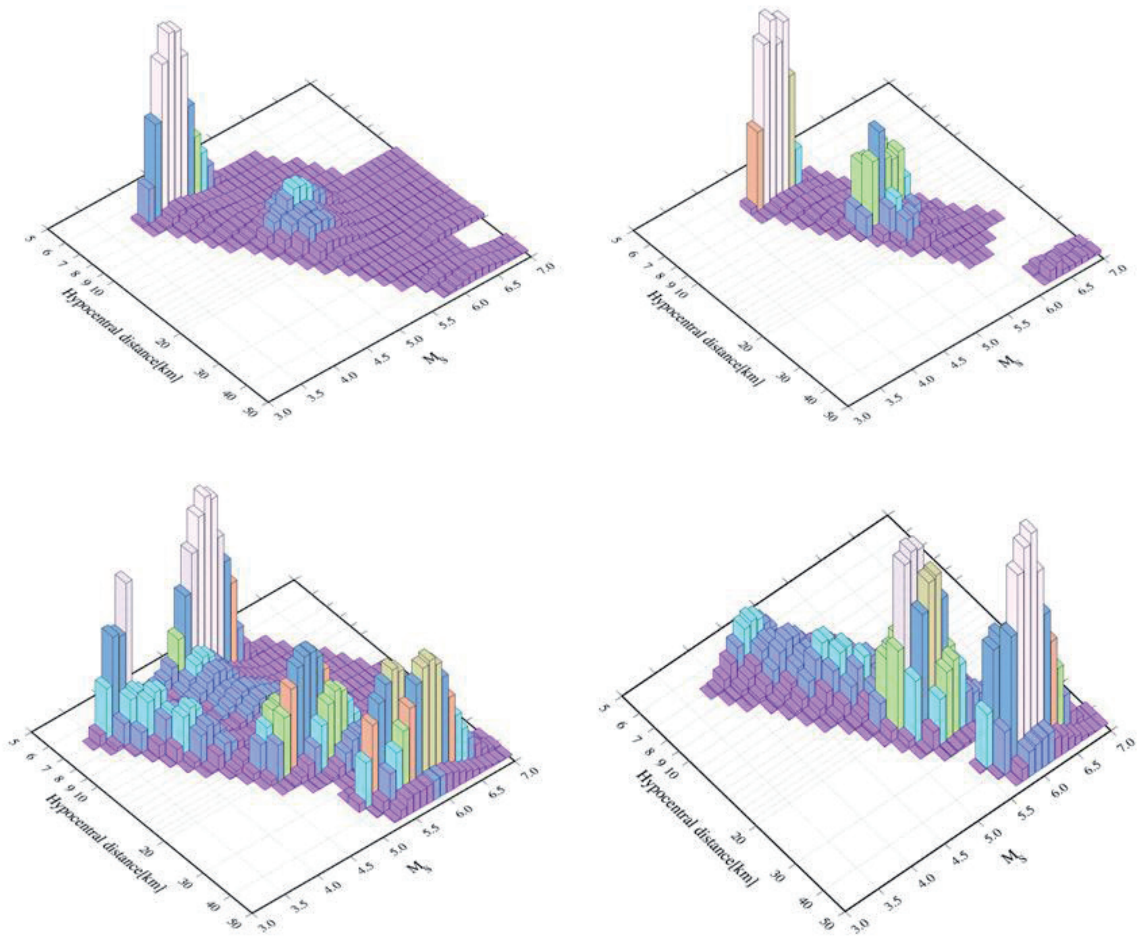

Fig. 4 - Disaggregation of SMHV for two different nuclear installation sites and for two specific percentile targets: (left) MHPE 0-100th, and (right) MHPE 40th-60th.

The PSHA-LT developed for Tricastin, consists of alternative source models (diffuse seismicity/faulting), alternative seismicity models for the faults (Gutenberg - Richter/characteristic earthquakes) and different GMPEs (three different GMPEs were used in this computation integrating across the full aleatory variability). Fig. 5 illustrates the comparison of DSHA-LT and PSHA-LT for the case of the Tricastin nuclear site. The two approaches explore very different hypothesis: on the PSHA side the consideration of alternative GMPEs and the possibility of activity along a nearby potentially active fault (the Cevennes fault), contribute to a wider uncertainty in the seismic hazard levels and to a higher estimate of seismic hazard level at lower response spectral frequencies. On the DSHA side, the range of hazard uncertainties is mainly controlled by the exploration of the uncertainty associated with the characterization (magnitude and depth) of the historical earthquakes. The seismic scenarios are located under the Tricastin site and lead to a higher hazard level in the higher response spectral frequency range.

To further illustrate the importance of developing the PSHA methodology in parallel with the DSHA-LT methodology, Fig. 6 shows results of a simplified PSHA computation at 30 nuclear sites based on a reduced exploration of hypothesis and a regional approach. This calculation

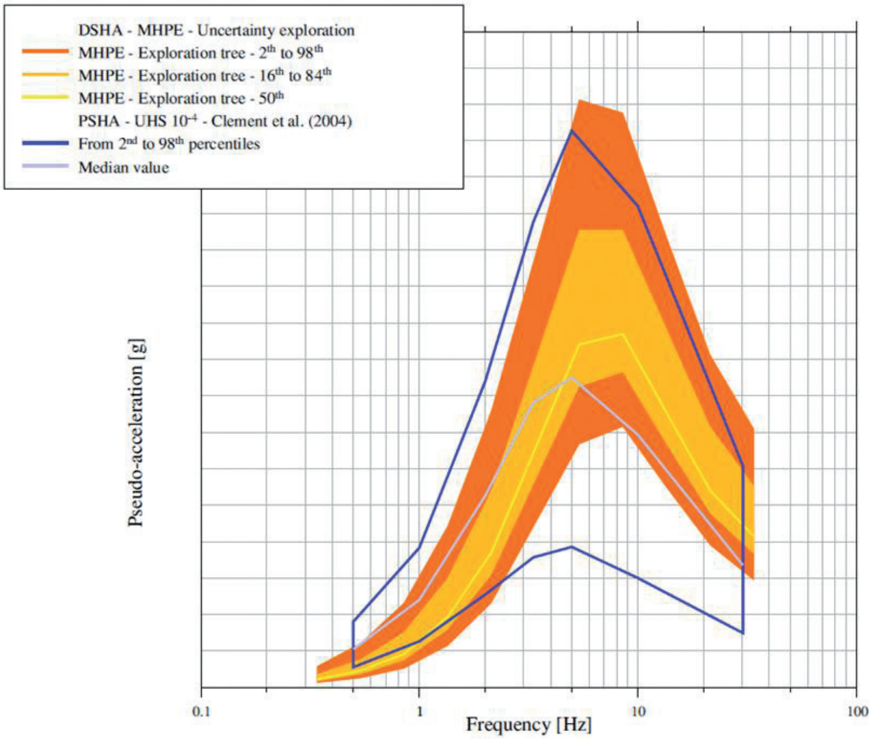

Fig. 5 - Comparison of site-specific DSHA-LT and PSHA-LT seismic hazard spectral uncertainties for the Tricastin NPP site, France (see text for explanation).

does not include faults and is not site-specific. The PSHA-LT used for this purpose is extracted from the model used for the Eurocode 8 (GEOTER, 2002). Namely, only the SSZ branches are considered, one with 52 SSZs and another one with 25 SSZs. For comparison purpose with DSHA calculation, only the GMPE of Berge-Thierry *et al.* (2003) is used with the aleatory variability integrated to infinity. Two calculations were performed, in order to illustrate the PSHA sensitivity to the choice of the minimum magnitude considered for the calculations.

7.1. Results

For the purpose of this paper, DSHA and PSHA results are compared by considering that the target ground motions to be considered have return periods comparable to that of the historical period for the MHPE (about 1,000 years = period covered by the earthquake catalogue) and of about 10,000 years for the SSE.

The PSHA-median predictions are shown in Fig. 6 for a 1,000 years return period. The results are averaged over sites located in seismic zone I, II and III+IV as defined by the Eurocode 8 (CEN, 2002) of the National Annex for seismic zoning. The purpose of the comparison is to show the main tendencies between the IRSN-DSHA-MHPE site-specific approach and a simplified PSHA calculation based on a regional approach. The comparison shows that:

1. - at 1,000 years return period, median PSHA values depend strongly on the minimum magnitude used for the calculations;

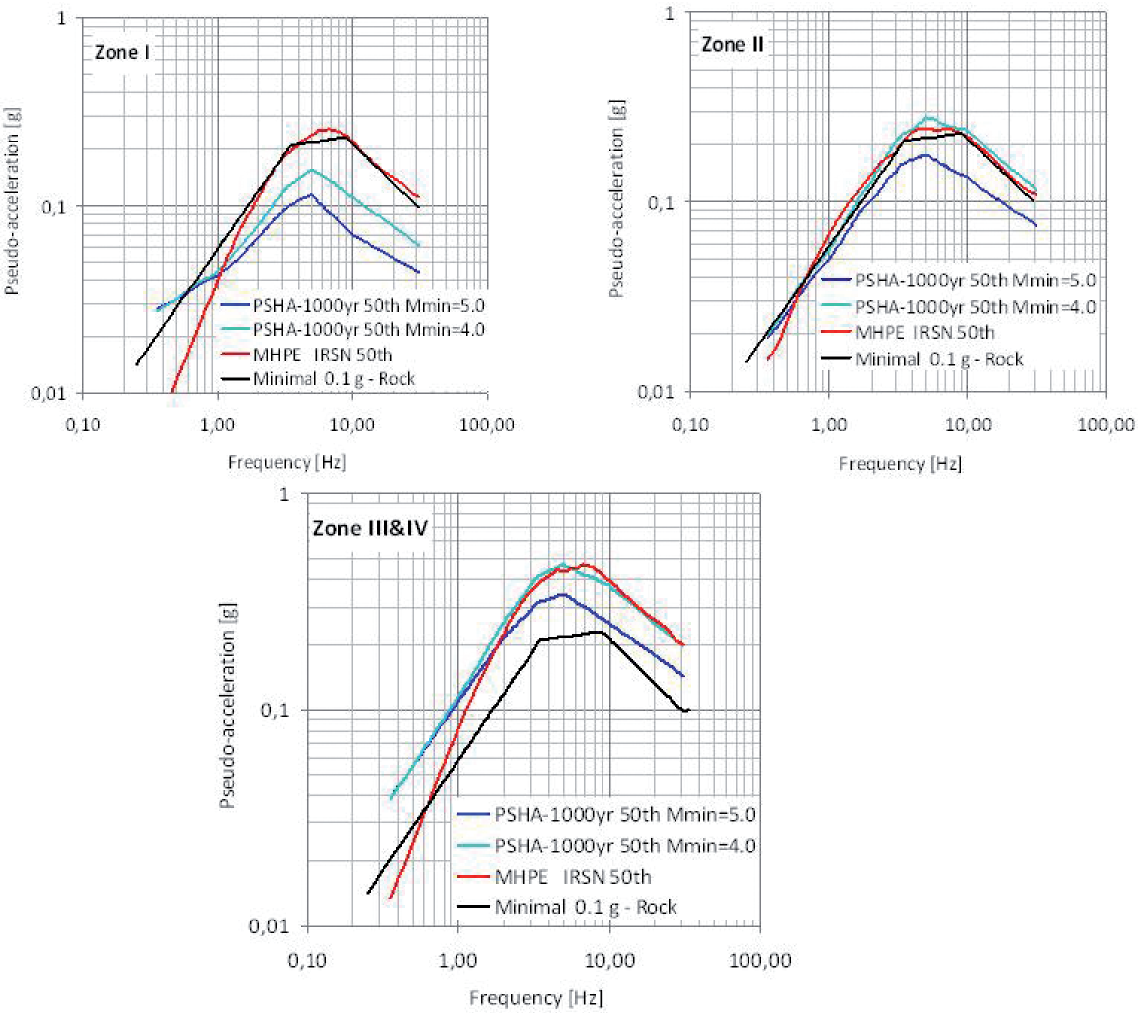

Fig. 6 - Median seismic hazard values of all the sites for each seismic zone (Zone I – very low seismicity; Zone II – low to moderate seismicity; Zone III and IV – moderate to average seismicity). Red curve: IRSN – MPHE DSHA. Blue curves: $PSHA_{RT=1000yr}$ integrating from a minimum magnitude of 4.0 (light blue) and 5.0 (dark blue). Seismic source model extracted from the Eurocode 8 model used for conventional buildings. The minimal regulatory spectral shape anchored at 0.1 g is also shown for reference.

2. - in zone I, where estimated historical earthquake magnitudes are mostly below magnitude 5, the median IRSN-DSHA-MHPE spectral response evaluations lie above the median $PSHA_{RT=1000yr}$ spectral responses, with the exception of the low frequency part of the spectrum;
3. - in higher seismicity zones, where historical magnitudes can be greater than magnitude 5 (zone II) and may exceed magnitude 6.0 (zones III and IV), median site-specific MHPE spectral responses are close (M_{min} = 4.0) or lie above (M_{min} = 5.0) the $PSHA_{RT=1000yr}$ values.

Finally, as Fig. 7 shows, extrapolation of the median PSHA hazard curves from 1,000- to 10,000- year return periods may lead to higher design targets for many nuclear sites compared to the deterministic increase of 0.5 magnitude units, especially for sites located in zones II, III

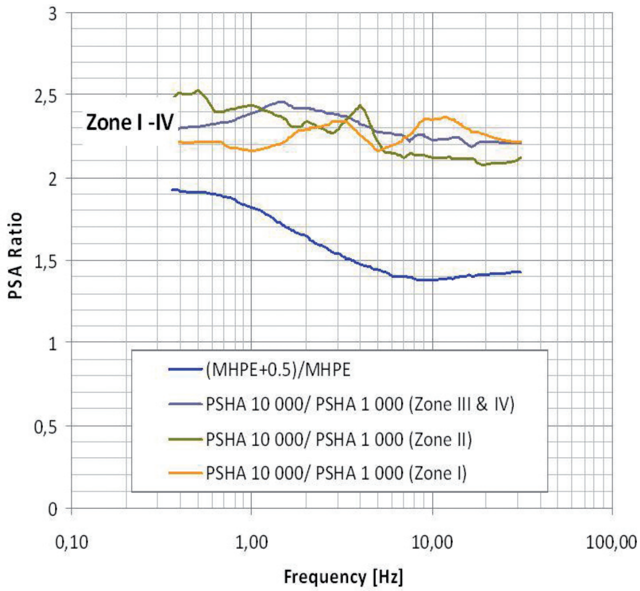

Fig. 7 - Comparison of the incremental seismic hazard imposed by the deterministic regulation (MHPE +0.5)/MHPE and the ratio of the median $PSHA_{RT=1000yr}$ to median $PSHA_{RT=10000yr}$ for the three groups of nuclear sites classed according to the Eurocode 8 seismic zonation scheme.

and IV (60% of the French nuclear park). A site-specific analysis including all the constraints imposed by the RFS 2001-01 (2001) (minimal spectral response, paleoseismic spectral response and site-effects) will be necessary for a complete DSHA/PSHA comparison, including site-specific PSHA issues developed hereafter.

8. PSHA – Some of the debated issues

The purpose here is not so much to provide an exhaustive list of debated issues that affect PSHA calculations but to remind the reader that PSHA is also affected by uncertainties in the basic data, in the models and in the chosen computational options.

The PSHA community has dedicated a lot of effort recently to account for the variability in GMPEs. However, the primary source of uncertainty encountered thus far in France stems from the lack of a robust homogeneous earthquake magnitude in the earthquake catalogues (> 50% uncertainty in the computed activity rates). For the time being M_S is computed from $M_{L\ LDG}$ (M_L as defined by the Laboratory for Detection and Geophysics of the Atomic Energy Commission) assuming equality [as imposed by the RFS 2001-01 (2001)]. Thus the M_S of the Berge-Thierry *et al*. (2003) GMPE has been considered equal to $M_{L\ LDG}$. This equality is source of debate in the scientific community. The computation of earthquake activity rates depends completely on the reference magnitude used and thus conditions the probabilistic calculations.

Similarly to DSHA, an important parameter that controls the level of hazard in the PSHA results presented here is the assumed depth of seismic sources [Berge-Thierry *et al*. (2003), GMPE is based on hypocentral depth].

Moreover, as illustrated in Fig. 6, the sensitivity of PSHA to the lower bound magnitude is yet another debated issue. According to Abrahamson (2006), for example, this sensitivity could be avoided by applying a smooth transition from not potentially damaging to potentially damaging earthquakes by setting the potentially damaging earthquakes in terms of some additional ground motion parameter.

Last but not least, a major source of debate in France is the extent to which expert uncertainty should be explored in a site-specific PSHA for nuclear installations. Indeed, experience has shown that, in spite of a wider exploration of uncertainty compared to the French deterministic methodology, two PSHA studies can produce radically different results due to the way in which experts are elicited and their opinions aggregated. SSHAC (Senior Seismic Hazard Assessment Committee) guidelines proposed back in 1997 and then revisited in 2012, clearly address this question [interested readers should refer to Kammerer and Ake, (2012) for a detailed discussion]. The SSHAC guidelines are concerned with how to capture, quantify, and communicate both the implicit and explicit uncertainties expressed by multiple experts. A few examples of such studies where such procedures have been applied are: the PEGASOS and the PEGASOS Refinement Project, which have been under way since 2002 to assess the seismic risk of Swiss NPPs. This study is an example of a SSHAC level 4 PSHA study (Abrahamson *et al.*, 2002; NAGRA, 2004). The CEUS-SSC Project, which was launched in 2008 for a duration of 3 years and jointly sponsored by NRC, EPRI, and DOE (EPRI, 2008), is an example of SSHAC Level 3 study. The objective of this study was to develop a stable and long-lived seismic source characterization (SSC) model for the Central and Eastern United States (CEUS); the ongoing EPRI-EUS ground motions project is also a SSHAC level 3 study.

Although these are time consuming and expensive projects, it is hoped that the uncertainties of the resulting estimates for the annual frequencies of exceedance of earthquake-caused ground motions will reflect the state of knowledge of the scientific community at large. The implementation of comparable methodologies in the French practice would provide a beneficial framework for the scientific community and the practitioners to contribute together to the much debated issue of seismic hazard assessment for NPPs.

9. Discussion and conclusion

DSHA and PSHA methodologies have a role in seismic hazard and risk analyses performed for decision-making purposes (McGuire, 2001). Thus strengths and weaknesses of DSHA and PSHA methods need to be openly discussed and compared, in particular in regions of low to moderate seismicity where the data is often lacking and hypothesis are not easily justifiable on scientific grounds alone.

The DSHA methodology, as it is applied by IRSN today, provides a formalism to address the uncertainty issue. This methodology relies on the RFS-2001-01 (2001). However, the RFS 2001-01 (2001) imposes the use of a specific GMPE and consider only the median predicted value of this GMPE. Moreover, in the DSHA methodology the “rare” damaging historical earthquakes that have occurred in the past are considered irrespectively of their probability of occurrence. Given the short length of the earthquake catalogue compared to the seismic cycle, relying strongly on (see special cases, as discussed in the French Nuclear Safety Rule section) on those earthquakes that happen to have occurred by chance in the last few hundred years may be debatable.

In the PSHA methodology a wider range of hypothesis is explored through a complementary approach that accounts for the probability of occurrence of each earthquake scenario, including scenarios that have magnitudes greater than the historically known earthquakes. As for DSHA, the available history of seismicity, however, is often too short to be able to construct robust earthquake occurrence models and therefore different hypothesis need to be formulated. PSHA explicitly accounts for the aleatory variability of ground motion. It is the key parameter that leads to high PSHA seismic levels at longer return periods (> 10,000 years). However, when faced with low seismicity regions, in the PSHA methodology, "rare" but strong and damaging historical events are attributed a low probability of occurrence and hardly contribute to the seismic hazard of a given site when a target return period of 10,000 years is considered.

Should the target return period of PSHA be adapted to the seismic activity rate of each region in order to ensure protection against severe low-probability earthquakes? Should precautionary principles be invoked and "rare" events be considered as key deterministic elements of a site-specific seismic hazard analysis (especially for nuclear installations)? Should PSHA be favored when it exceeds DSHA? That is for the nuclear safety authority to decide. Certainly the recent "rare" but damaging earthquakes that have occurred in low seismicity zones (Christchurch, New Zealand, 2010; Virginia, USA, 2011; Emilia Romagna, Italy, 2012) provide food for thought.

Irrespectively of the approach (or combination of approaches) used, expert driven discussions will be inevitable when it comes to seismic hazard assessment. One approach, as recommended by the SSHAC guidelines is to involve the scientific community in the debate. IRSN believes that an evolution in practice where both deterministic and probabilistic uncertainty-based site-specific seismic hazard studies are conducted and the wider scientific community is involved, may lead to more robust evaluations of seismic risk at nuclear installation sites in France and in other regions of low to moderate seismicity. Such evolution may help ensuring that political decisions concerning engineering solutions (be it for design or for verification) are taken with the best knowledge of quantified uncertainty in seismic hazard assessment in mind.

Acknowledgements. The authors would like to thank Julio Garcia and an anonymous reviewer for their stimulating comments and reviews that helped improve the paper.

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Corresponding author: Oona Scotti
Institute for Radiological Protection and Nuclear Safety, France
Avenue de la Division Leclerc 31, 92860 Fontenay-aux-Roses, France
Phone: +33 1 58358647; fax: + 33 1 58358130; e-mail: oona.scotti@irsn.fr