DETERMINATION OF THE SEISMIC INPUT IN FRANCE FOR THE NUCLEAR POWER PLANTS SAFETY: REGULATORY CONTEXT, HYPOTHESIS AND UNCERTAINTIES TREATMENT

C. Berge-Thierry , E. Cushing, O. Scotti and F. Bonilla
Institute for Radiological Protection and Nuclear Safety, France

Abstract

The French metropolitan territory is characterized by moderate seismicity. Seismic hazard assessment for nuclear facilities is guided by a regulation based on a deterministic approach. This regulation (RFS2001-01) has been recently revised mainly to account for scientific improvements in the field of paleoseismology and site effects. According to the regulation, seismic hazard assessment at a site requires to identify the characteristics of the "Maximum Historically Probable Earthquake" (MHPE), selected from the historical and instrumental seismic catalogs (covering 1000 years). Two safety margins are considered: the first consists in shifting the reference event in the most penalizing position for the site, the second, consists in increasing the magnitude of the MHPE by 0.5 units (defining the Safe Shutdown earthquake SSE). If the latter is homogeneous from one site to the other, the first margin strongly depends on the zonation scheme. The seismic input is represented by an acceleration response spectrum computed using an empirical attenuation relationship (Berge-Thierry et al., 2003 [2]), distinguishing rock and soft soil conditions. Only the mean motion prediction is considered in the RFS2001-01. Depending on how each uncertainty is treated, seismic input prediction at a site can significantly vary from one expert to the other. The probabilistic approach, recently developed and applied at the Tricastin NPP site helps to appreciate the conservative or non-conservative level of such deterministic estimates.

Introduction

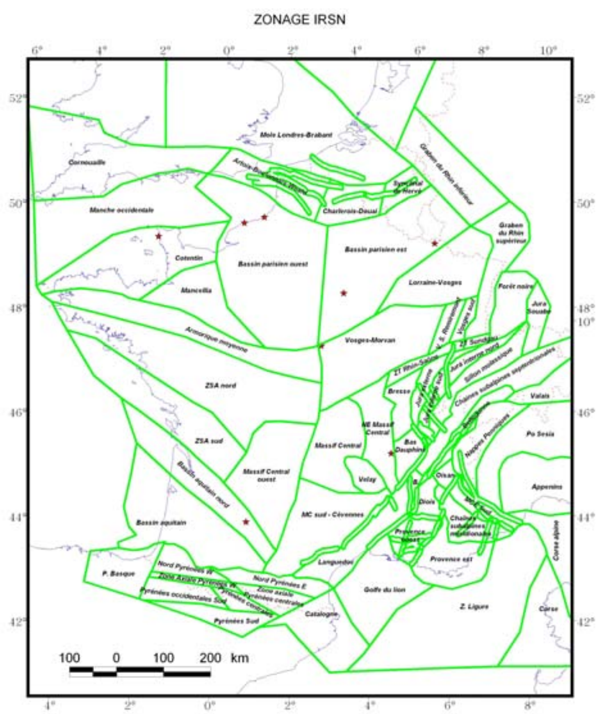
Seismic hazard assessment in France faces two challenges: a moderate to low seismic activity and a poor knowledge of the source zones. Because of the low deformation rate in the country and the long return period of large earthquakes, it often remains difficult to link historical earthquakes to well identified faults. Moreover, despite considerable progress in recent years (using geodetic information for example), it is very hard to clearly identify seismogenic structures and their associated seismic potential. Seismogenic zones are thus defined to partly account for this lack of knowledge. The seismicity knowledge is given by both historical catalogue (SisFrance database) and instrumental records. Nevertheless, the period covered by these two sources (around 1000 years) may not be sufficient with respect to the return period of great earthquakes. Information provided by paleoseismological studies (i.e. Lemeille et al., 1999 [6]) thus increases the observation period of the seismicity record. Irrespective of the applied methodology, seismic hazard assessment requires to identify and model the sources producing the seismic activity, either as diffuse zones or as faults, and to predict the seismic motion at the site of interest. This motion is the input data for the structural engineers for the power plant design or for the resistance tests. This paper presents the methodology proposed in France for determining seismic hazard in the framework of nuclear power plants safety, named the French Safety Rule, hereafter RFS. The purpose of the paper is to present the hypothesis of this deterministic approach and to emphasize the uncertainties associated to each data and step of the method. We illustrate how seismic hazard assessment can vary considerably, even using the same regulation (RFS in this case), depending on how uncertainties on data are or are not taken into account during the study. This point constitutes the main subject of discussion, especially during NPP seismic reassessment, during which the discussion focuses on safety margins. Finally we briefly underline the similarities and differences in the way uncertainties are taken into account between two methodologies: the deterministic one following the approach recommended in the French Safety Rule for the seismic hazard assessment for NPP, and the probabilistic currently under development at IRSN.

Global scheme of the French regulation for assessing the seismic hazard for NPP

The previous (1981) and the current French Safety Rule, recently revised in 2001, propose a deterministic methodology to evaluate the seismic input motion required in the framework of the NPP safety. The revised methodology can be summarized in 5 main steps :

1. Determine the seismotectonic zonation, based on geological and seismological criteria; each zone is considered to have an homogeneous seismic potential.

2.

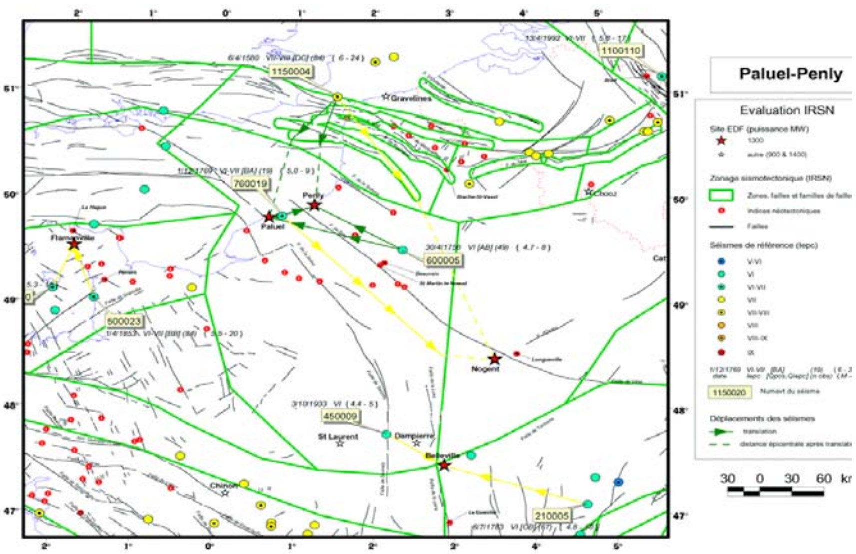


Estimate, in these «seismotectonic zones », the characteristics of the historical and instrumental events that occured in this region. It is assumed that historical earthquakes are likely to occur in the future, with an epicenter in the most penalizing position for the site of interest.

Figure 1: IRSN seismotectonic zonation

3. Retain, for the considered site, one or more events, that produce(s), the most penalizing effect (in term of intensity at the site). In other words, the events are moved inside the zone they belong to as close as possible to the site, and they constitute the "Maximum Historically Probable Earthquake" (MHPE).

4.



A "Safe Shutdown Earthquake" (SSE) is associated to each MHPE and is obtained by increasing the MHPE magnitude by 0.5.

Figure 2: shifting the event to select MPHE

5. Evaluate the seismic movement (mean acceleration response spectra) related to the SSE using the attenuation relationship of Berge-Thierry et al., 2003 [1], which predicts, for a magnitude and distance couple, a pseudo-acceleration value for a wide frequency range (0.1 to 34 Hz), accounting for the soil condition (rock or sediment).

If any credible paleoseismic evidence does exist near the site, the associated seismic motion at the site has to be assessed, and compared to the SSE motion. Finally, the RFS indicates to verify the level of the SSE and paleoevents with respect to a minimal response spectrum (defined for the 2 soil conditions) with a PGA set at 0.1g.

Uncertainties associated with the data

Seismotectonic zonation definition

For the Metropolitan territory, several zonations have been established (i.e. Terrier et al., 2000, [10], Geoter 2002 [6]). Usually the nuclear operator in charge of the seismic hazard assessment proposes its own zonation. IRSN, in the framework of the RFS revision proposed its own seismotectonic zonation (Figure 1). The methodology used to produce a zonation, as detailed in the rule, is based on a synthesis of all geophysical, seismological and geological data constraining the deformation behavior of the studied region. The uncertainty associated to the choice of source zones boundaries is quite variable from a region to another one. Quantifying this uncertainty, which depends on the knowledge of the regional seismotectonic remains a difficult task. Some zone boundaries are located with a good confidence (uncertainty around 10 km), whereas others limits exist for some experts and are not reliable for others. Using the RFS methodology, the choice of the source zones boundaries has a major consequence and conditions the determination of the reference M.H.P.E. event. One or more MHPE are selected, using the criterion based on the intensity produced at the site after shifting the events near the site: the historical or instrumental event, when not located in the site zone, is moved inside the zone it belongs to as close as possible to the site. If the reference event is in the site zone and it is not attached to a fault, it is moved directly under the site. Finally the retained MHPE are the events, after shifting, producing the most important intensity (MSK scale) at the site.

The table below quantifies (in terms of the resulting PGA value associated to a MHPE level) the impact of two published zonations for 3 French NPP sites. These PGA determined using a deterministic method are compared with the PGA proposed by Geoter 2002 [6] probabilistic assessment.

Table 1 : Evaluations for 3 nuclear sites of the hazard using deterministic zonations (IRSN and BRGM (Terrier et al., 2000 [10]): comparison with a probabilistic (Geoter 2002 [6]) assessment.

Site	MHPE characteristics			Translation type		MHPE PGA (g)		Probablistic 975y PGA (g)
	Date	Magnitude	Depth	IRSN zonation	BRGM zonation	IRSN zonation	BRGM zonation	Geoter 2002 study
Bugey	1889	4.7	8	under site	under site	0.14	0.14	0.13
Golfech	1759	5.2	7	under site		0.21		0.05
	1660	6	12		122 km		0.01	
Penly	1769	5.0	9	under site		0.14		0.05
	1756	4.7	8		8 km		0.10	

After Cushing et al., 2003 [4]

Historical and recorded earthquakes characterization

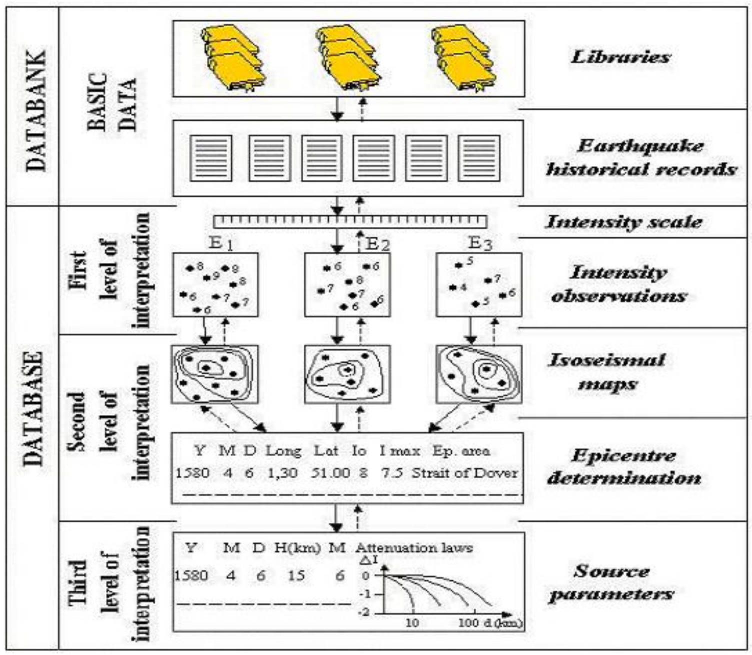
For the French Metropolitan territory, most of the M.P.H.E. correspond to historical events, i.e. events described in the historical archives and texts. The French historical catalog covers the last 1000 years, whereas the earthquakes are recorded with seismometers for the last 50 years. Macroseismic data and epicentral intensity estimation are available through the SisFrance database (www.sisfrance.net).

In the framework of the RFS, the seismic motion is mostly represented by the acceleration response spectrum, evaluated using an attenuation relationship whose parameters are the magnitude of the event, the focal distance between the site and the event, and the geological site condition. One crucial step of the RFS methodology consists in determining the magnitude and the location of the event, considering either macroseismic data or instrumental records.

Uncertainties for recorded events: the epicenter is generally quite well determined with an uncertainty less than 5 km, whereas the depth is not well constrained (uncertainty at least of 5 km). The magnitude estimation is generally strongly scattered. The magnitude uncertainty can reach 0.5 up to 1 degree (confirmed by recent estimation for the French St Dié earthquake, 2003 event, M_L(Rénass) =5,4, M_L(LDG)=5,8, M_L(INGV)=4,6, M_w= 4,8).

Uncertainties for historical events: figure 3 illustrates the steps associated to the evaluation of the location, magnitude and depth of an historical event, from information provided by archives (A), allowing to propose individual intensity values (B). Considering these punctual values, the epicentral zone is estimated using the iso-intensity contours (C). Finally using some attenuation assumptions and correlations between intensity and magnitude, the magnitude and the location of the event is proposed, in agreement, with the intensities distribution (D). Note that the location, the epicentral intensity and the magnitude are associated to uncertainties depending on the number, the quality and the spatial distribution of the data.

Figure 3: Defining event characteristics from historical archives



In the SisFrance database quality codes are indicated for the epicentral location and intensity:

Epicenter location - quality indices:

- **Code A (few km) -** precise location with a maximal intensity area constrained by an isoseist,
- **Code B (around 10 km) -** quite sure location with a maximal intensity area relatively well constrained by an isoseist,
- **Code C (between 10 and 20 km) -** location not precise,
- **Code D (few km up to 50 km) -** location strongly supposed, based on an intensity area not constrained by isoseist.

Epicentral intensity : quality indices:

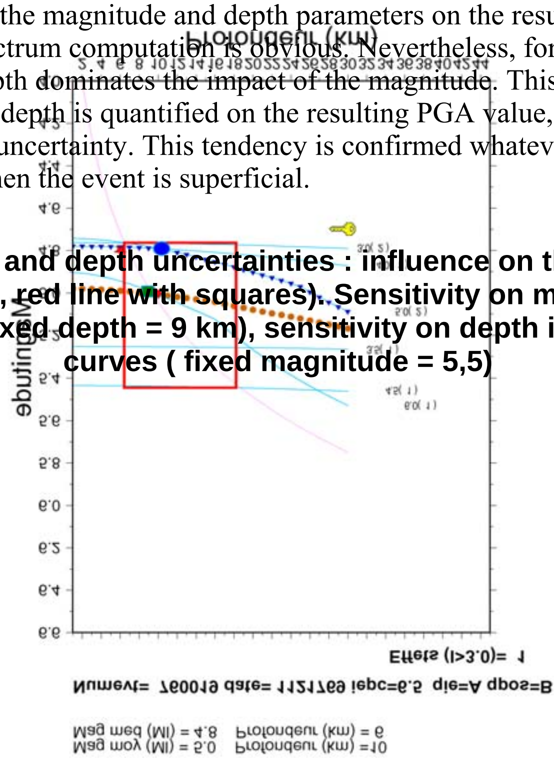
- **Code A :** Epicentral intensity sure, estimated from a dense distribution and maximal intensities well constrained.
- **Code B :** Epicentral intensity quite sure, estimated from a distribution less dense and maximal intensities well constrained.
- **Code C :** Uncertain epicentral intensity, estimated from a scattered distribution and maximal intensities uncertain.
- **Code K :** Epicentral intensity quite sure, estimated from a computation based on an attenuation relationship (Sponheuer).

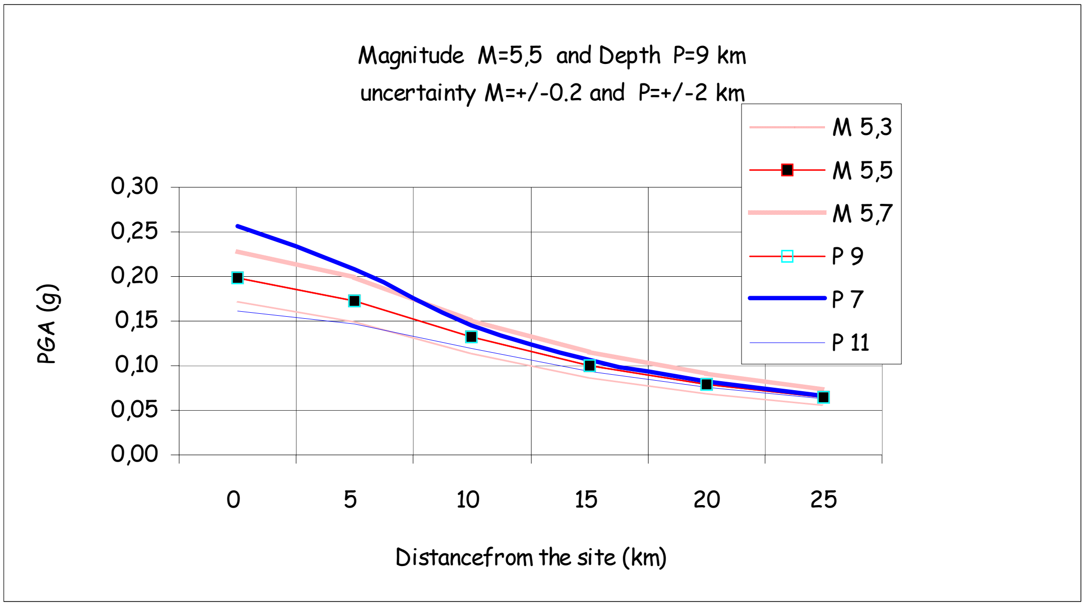
Considering these reliability criteria, it is clear that 0.5 up to 1 degree uncertainty in the epicentral intensity estimate is common for most the historical events.
Evaluating the magnitude and the location of the event from the individual intensity values requires to choose an attenuation modeling of the seismic energy, and to correlate the intensity scale to that of the magnitude. At the IRSN we currently work with the Scotti et al. (1999) [9] method,. Using the Levret et al. (1994) [8] correlation, we get a Magnitude (M) - epicentral Distance relation for each intensity class as a function of the depth. The following relationship exhibits an uncertainty of 0.4 in the magnitude determination. On graph (Figure 4), one can appreciate the dispersion of the (M,h) couple, and the dependance of M as a function of h, computed for each isoseismal radius. In the IRSN approach the preferred (M,h) couple corresponds to the intersection between the epicentral modeling (assuming an epicentral radius equal to the depth) and the mean (or median) of the other curves (green square on Figure 4, whereas blue triangles indicate « minimal magnitude » (Mmin= 4,8, depth=7km) and « maximal magnitude» (Mmax=5,4, depth=18 km) hypothesis). This methodology has the advantage of being coherent with Levret et al. (1994) [8] relationship and its inherent assumptions, and provides an estimation of the uncertainty in the magnitude-depth space (Figure 4).

Figure 4: simultaneous (magnitude , depth) determination for the 1769 event (Scotti et al., 1999 [9] method), and associated uncertainty domain.

The influence of the magnitude and depth parameters on the resulting seismic motion, through the response spectrum computation is obvious. Nevertheless, for events located near the site, the impact of the depth dominates the impact of the magnitude. This is illustrated in figure 5, where the uncertainty on depth is quantified on the resulting PGA value, and compared with the impact of the magnitude uncertainty. This tendency is confirmed whatever the magnitude range, and is more important when the event is superficial.

Figure 5: magnitude and depth uncertainties : influence on the PGA. Reference is (M=5,5 depth=9 km, red line with squares). Sensitivity on magnitude illustrated with pink curves (fixed depth = 9 km), sensitivity on depth illustrated with blue curves (fixed magnitude = 5,5)





Computing the response spectrum for the MPHE and SSE levels

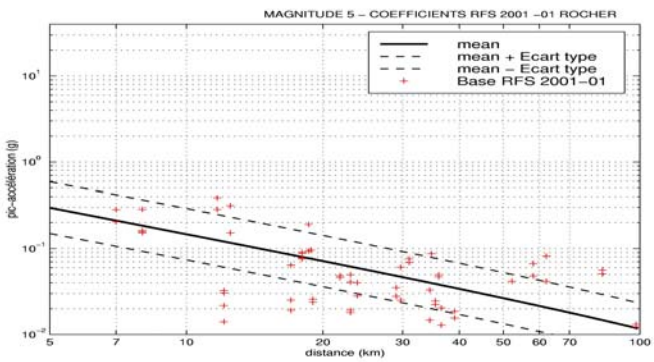
In the framework of the RFS 2001-01 (text available on the safety authority web site http://asn.gouv.fr/data/information/decision12b.asp), the seismic motion at the site is represented by the acceleration response spectra associated with the MPHE, SSE and eventually paleoevents. These response spectra are computed using an attenuation relationship (Berge-Thierry et al., 2003 [2]), which gives, for a magnitude and distance couple, a pseudo-acceleration value on a wide frequency range (0.1 to 34 *Hz*):

$$\log \; PSA(f) = a(f) * \text{magnitude } (Ms) + b(f) * R - \log(R) + c(\text{soil}, f) \qquad + \sigma f \qquad (1)$$

where PSA corresponds to the pseudo acceleration (cm/s^2), f being the frequency, R the focal distance, a, b and c the frequency dependent coefficients, and σ the standard deviation. The coefficients (a(f), b(f) and c_i(f), i=1,2) of the attenuation relationship have been obtained by an inversion procedure using a seismic database of almost 1000 accelerograms. As the French strong motion database is too scattered, the European strong motion database (Ambraseys et al., 2000 [1]) completed with American records has been considered. The coefficients are available for two site categories (rock and alluvium). The final seismic hazard at the site is the mean value of the spectral acceleration. Other important parameters complementary to the response spectra can be considered, such as the time series, Arias Intensity, or duration.

The standard deviation of the relationship reflects the intrinsic seismic motion variability. This variability has many origins, such as the seismic rupture complexities, the seismic radiation, the wave propagation in complex media, the imposed attenuation model chosen (equation 1), and a poor knowledge of the geological site condition of the real strong motion data.

Figure 6: Predicted PGA values for a magnitude 5 event, rock site condition, using the RFS 2001-01 attenuation relationship.



Discussion on the safety margins retained in the French Regulation

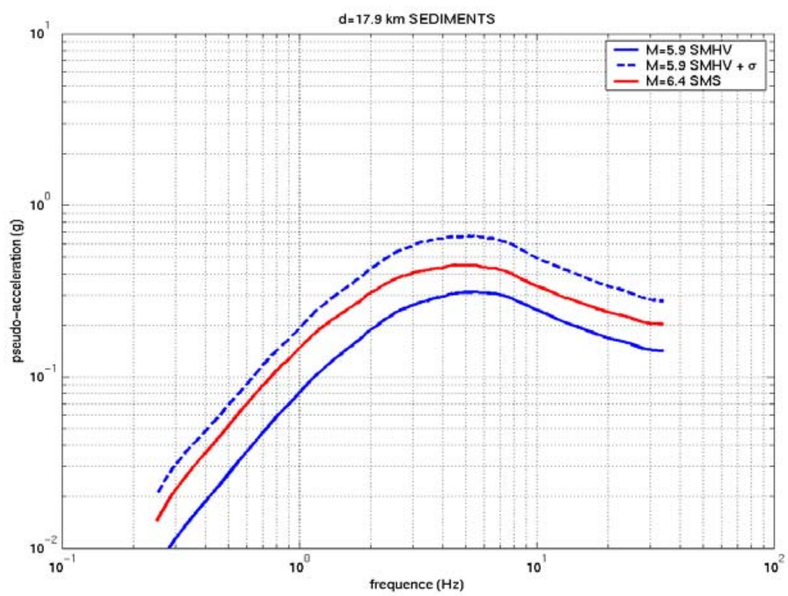
Even if the RFS procedure is deterministic, the seismic hazard assessment coming from its application does not necessarily lead to the worst scenario for the NPP site. Application of the RFS methodology described above, leads to uncertainties that differ tremendously from one site to the next:

- Seismotectonic zonation reflects the limits of knowledge, with respect to the location of active faults and the potentiality of these sources.
- The characterization of the magnitude and the precise location (in depth) of historical and instrumental events is also associated to uncertainties, often linked to the quality of the basic data, that is the number and the reliability of macroseismic data or instrumental records.
- The epicentral intensity of the events, which is a crucial “filtering” criterion in order to select one or more MPHE for the studied site, is by its nature very uncertain.
- The geologic characterization of the site finally conducts to 3 situations, “rock” and “sediment” for which a classical attenuation relation is recommended to compute the strong motion, whereas a specific study is required in case of a site exhibiting shear wave velocities lower than 300m/s, or associated to particular geometries (sedimentary basins, topography, …) where site effects and /or non- linear soil behaviors are anticipated.
- Finally only the mean value of the attenuation relationship is considered. The standard deviation is not considered in the RFS methodology.

Concerning the explicit margins in the RFS, which tend to account for uncertainties described above, the first one is the shift of the M.H.P.E. to the most penalizing location with respect to the site. This margin is clearly inhomogeneous over the national territory and strictly controlled by the seismotectonic zonation. The second margin is the SSE definition from the M.H.P.E by increasing the magnitude of 0.5. Finally the introduction of a minimal spectrum level (PGA at 0.1g) can be associated to another safety margin.

When assessing the seismic hazard for a new building, or during the seismic re-evaluation of existing N.P.P., discussions mainly concerns how conservative or not is the hazard estimation. The major difficulty comes predominantly from the choice of the limits describing the different seismotectonic zoning. This affects directly the choice of the reference M.H.P.E event(s) and thus the corresponding level of hazard. The second difficulty (which is strongly dependent on the previous one) that is encountered is the selection of reference events with respect to the intensity criteria: uncertainties associated to macroseismic data should be systematically considered to define the M.H.P.E., but as it is not codified in the rule, this point remains a major discussion. Finally, at this step, some discussions appear regarding the small earthquakes located close to the site: these events may produce high acceleration values (enriched in high frequencies), supposing that these kind of earthquakes are less damaging than others. These events participate to the seismic hazard of the site and from the IRSN point of view, the demonstration of their potentially less damaging effect should be treated during the structural seismic response study.

Figure 7: illustration of the MPHE to SSE safety margin, with respect to the standard deviation of the spectral attenuation relationship, which is not taken into account in the RFS.



In Figure 7 we illustrate the impact of the RFS choice regarding the mean spectral prediction choice using the attenuation relationship. On this figure it appears that the safety margin consisting in increasing the magnitude of the MPHE event to propose the Safe Shutdown earthquake does not cover a one standard deviation of the spectral acceleration prediction using the RFS attenuation relationship. This conclusion is independent of the magnitude and distance of the MPHE.

Finally, the introduction in the revised RFS of a minimal spectral level (described by the envelope of a moderate near site event and a strong far event), evaluated for the 2 soil site conditions constitutes a complementary safety margin.

What are the fundamental differences between the French Regulation and the IEAE recommendations?

The International Atomic Energy Agency proposes some recommendations in its recent publication « Seismic Hazard Evaluation for Nuclear Power Plants, Safety standards series No. NS-G-3.3. ». This guide strongly recommends probabilistic approaches for assessing seismic hazard, without rejecting deterministic methods. Indeed probabilistic and deterministic methods are complementary in the sense that the data on which the assessments are based are the same, only the treatment of the uncertainties differs.

The probabilistic approach consists in evaluating the hazard accounting for all the seismic sources (i.e. all magnitudes-distances couples). Each modeled source contributes to the hazard in proportion of its annual occurrence rate. The IEAE guide, without giving precise directives, underlines the existence of uncertainties at each step of the assessment, and suggests the logic tree approaches allowing the propagation of these uncertainties, and the integration of different expert opinions. The IAEA guide defines two seismic hazard level, the SL2, characterized by a very low probability of exceedance, and SL1 a lowest level with a more important probability to be exceeded.

The guide very briefly describes the deterministic approach, but does not mention the treatment of the uncertainties. Nevertheless, the guide indicates that some countries working with such deterministic approach adopt a seismic motion evaluated with the median value plus one standard deviation.

Thus the RFS2001-01 is clearly in conformity with the IAEA recommendations, with MPHE and SSE levels comparable to the SL1 and SL2, but without any probability notion.

Combining deterministic and probabilistic approaches

As described above, the deterministic approach consists in expert choices between different hypothesis, that are sometimes all credible. This methodology, in the framework of nuclear safety, frequently results in discussion around expert opinions, especially for the zonation step and historical events characteristics. This bias is illustrated in Figure 8, where, using the same RFS methodology, two groups may provide different seismic hazard assessments. Different zonations may induce, considering the shifting and the I_{max} criterion to different reference events (impact of 0 to 100% on the resulting seismic motion). Considering the same reference event, the evaluation of their characteristics (Magnitude, depth, distance from the site) may impact the seismic motion up to 25%. The difference between soil and rock site results in 20% on the motion (excluding “special site effects”, 2D, 3D). The computation of the mean spectral response using the RFS attenuation relation does not induce any discussion (for the same (M-Distance scenario) since the attenuation coefficients are fixed in the regulation.

The popularity of probabilistic approaches in most of countries motivated the IRSN to develop its own tool, in order to produce such assessment, and particularly to position the deterministic assessments relative to the uncertainty domain. One specific site has been chosen for the first pilot study, the Tricastin site (southeastern France) (Clement et al., 2004 [3]). The logic tree approach has been retained in order to account for various credible seismotectonical models, some of them allowing to model recognized active faults. A Monte Carlo approach has been coupled to the logic tree, which allows exploring the uncertainty domain of the main parameters influencing the final seismic motion.

This approach enables to avoid the deterministic way of choosing a hypothesis ignoring all other possible ones. The detailed of this study is presented in Clement et al., 2004 [3,4]. As an example, the seismic motion prediction is treated considering several attenuation relationships applicable to the French context, accounting for their own uncertainty, instead of providing a mean prediction based on a unique relation, as it is the case for the RFS. Each hypothesis considered in the logic tree is weighted, proportionally to its credibility. Finally such approach enables to compare the seismic hazard evaluated using the deterministic RFS methodology, and the probabilistic one. The logic tree exploration results in a uniform hazard spectrum, related to a return period. On Figure 9 (from Clement et al., 2004 [3,4]), the pseudo acceleration have a 10^4 years return period, in other words, these spectral values have 0,005% of probability to be exceeded over a 50 years observation period. On Figure 9, the comparison between the deterministic SSE spectrum (red curve) and the 10^4 years UHS (with its confidence area) indicates a good agreement for the intermediate and high frequencies, and a slight underestimate for low frequencies; such observation may help the operator or the politician in order to take some decision for its power plant in case of retrofitting for example. In other words such comparison allows to quantify the probability level of a SSE.

Figure 8: Illustration of crucial steps using the RFS methodology providing two different assessments.

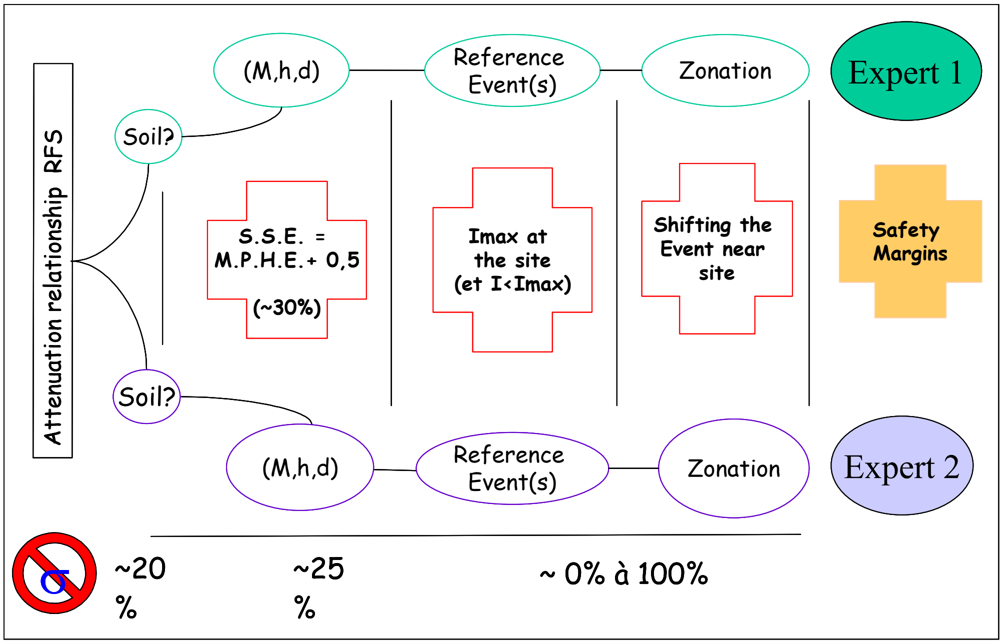
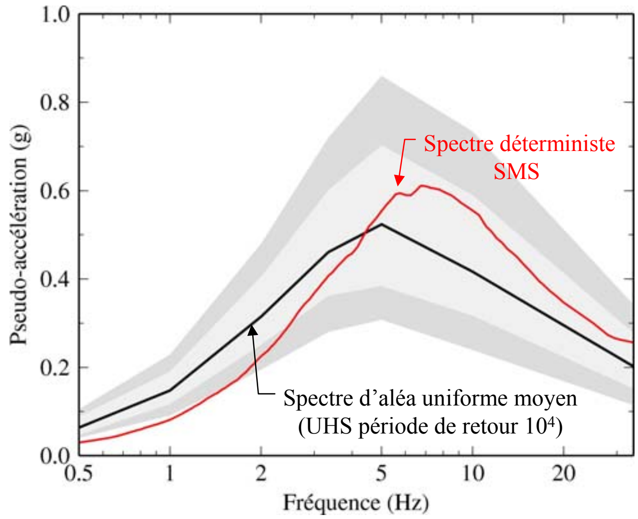


Figure 9 : Comparaison of seismic levels estimated for the Tricastin site using a determinitic approach (SSE, RFS2001-01 - red curve) and a probabilistic one (Uniform Hazard Spectrum - black curve with one σ deviation - grey area, and 2 σ - dark grey area).



Conclusions

The goals of the paper are to present the Safety Rule methodology recommended to assess the seismic hazard for NPP sites in France, and particularly to highlight the uncertainties associated to the geological and seismological data, and to the seismic motion prediction. Finally, although safety margins do exist in the RFS, the final hazard level strongly depends on how the uncertainties are actually taken into account. Probabilistic approaches allow a more exhaustive exploration of the uncertainties on the hazard level due to both model uncertainties and random uncertainties. These probabilistic methods give interesting information on the probability level of seismic assessment compared to deterministic methodologies.

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