CONFIDENCE LEVELS IN DETERMINISTIC SEISMIC HAZARD ESTIMATIONS

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ABSTRACT :

Accounting for the inherent uncertainty in the data and models that feed seismic hazard estimates has been an issue for more than 30 years. Probabilistic seismic hazard methods provide so far the only established tools that formally account for uncertainty. In this study, we propose an alternative approach that allows assessing deterministic seismic hazard with associated confidence levels using the French nuclear regulatory guide RFS 2001-01 as an example. The objective of this paper is to propose a methodology that allows integrating uncertainties involved at each step of the determination of an SMHV. The four main steps in the deterministic RFS 2001-01 guidelines entail (1) the definition of a seismotectonic zonation, (2) the selection of most damaging historical or instrumental earthquakes within each zone, and their displacement as close as possible to the site of interest, within their own zone, (3) the evaluation of magnitude-depth characteristics and (4) the estimation of intensity or spectral acceleration at the site. The propagation of inherent uncertainties associated to each step allows proposing different hazard spectrum depending on the confidence level of interest. Finally, deagregation of the hazard spectrum over the entire frequency range allows identifying the earthquake parameters that best fit the seismic hazard spectrum for the chosen confidence level.

KEYWORDS: Seismic hazard, Confidence levels, Deterministic, France

1. INTRODUCTION

The characterization of earthquake sources and of the ground motions that they may produce are necessary steps for seismic hazard assessment. The characterization of earthquake sources requires knowledge of the geometry of the causative faults, of their geological history and, if possible, of their tectonic strain rate accumulation. The definition of the geometry of the sources depends on the available knowledge in the region of study. Regions of high strain rate accumulations are often illuminated by a sufficient number of earthquakes that delineate active faults. Moreover, where such faults leave traces of their past activities, it is possible to propose fault characterizations. In many regions of the world, however, where the strain rate is low or the recording capabilities are insufficient, it is often difficult to identify the active faults, seismicity appears more diffuse and it is thus necessary to propose seismotectonic zones, assumed to have equal seismic potential.
France is a region of moderate to low strain rate accumulation (Nocquet and Calais, 2004) with predominantly diffused seismicity. In such a context, defining the outlines of such zones remains a subject of great debate (Cushing et al., 2003). Once the sources have been defined, it is then necessary to define the earthquake potential of each source zone. Fortunately France has a rather good knowledge of its historical seismicity that covers a thousand years, collected in a relational database visible on-line at www.sisfrance.net (Scotti et al., 2004). The interpretation of intensity database in terms of physical characteristics of the past earthquakes remains a difficult task. Numerous hypothesis can be formulated which can lead to quite different results in terms of magnitude and depth estimates. Thus different catalogues of historical seismicity can be constructed depending on the choices made.

In this paper, we first present the uncertainties involved in the delineation of seismotectonic zones and in the quantification of historical earthquake parameters using the French data as an example. We then propose to integrate these quantified uncertainties in the estimation of the seismic spectral response through an exploration of all plausible parameters. In the final step, we discuss the great interest of this strategy for Deterministic seismic hazard assessments (DSHA) procedures in terms of defining seismic hazard at a specified confidence level.

2. DSHA: THE FRENCH NUCLEAR BASIC SAFETY RULE AS AN EXAMPLE

The Basic Safety Rule (RFS-2001-01) that defines the seismic hazard to be considered for NPP in France is based on a deterministic approach. “It aims to remedy the underlying uncertainties in seismic hazard estimations by taking into account all direct and indirect factors that could play a role in the appearance of earthquakes, as well as all known seismicity data”. The basic approach consists in assuming that earthquakes comparable to historically known earthquakes are liable to occur in the future, with an epicentre position that is most penalising with regard to its effects (in terms of intensity) on the site, while remaining compatible with the geological and seismological data (SMHV). For each SMHV, a "Safe Shutdown Earthquake" (SMS) is defined by adding one-degree in intensity to the SMHV, which corresponds to an increase in magnitude conventionally set at 0.5. The response spectra corresponding to the horizontal and vertical components of the motion are calculated according to the mean ground motion prediction equation as described in Berge et al. (2000).

3. UNCERTAINTY IN SEISMOTECTONIC ZONING

In many countries, there are usually as many seismotectonic zonation schemes (STZS) as there are seismic hazard analysts. Moreover, in DSHA, proposed STZS do not provide uncertainties underlying many of the zone boundary outlines. In this paper, we consider two strategies to quantify uncertainty in STZS. One which explores alternative STZS, and a second strategy that introduces buffer zones for each boundary of a given STSZ. The first strategy may lead to identify different SMHV at a site. In such situations, it is important to estimate the impact of each STZS on the final hazard. In other situations, the boundaries may be similar between STZSs, however, the confidence with which the expert has drawn the boundary line may be quite different. Then buffer zones around each boundary (estimated by expert judgment) can help reflect the degree of uncertainty of the expert.

DSHA is here calculated for a target site located in western France. Two deterministic STZS developed for the French territory are used and the most damaging events for the target site are selected and translated as close as possible to the target site of interest (Figure 1). In our example, three events contribute to the seismic hazard of the target site: the 1775 Caen event, the 1769, Veules-les-Roses event and the 1909 Brest event. For the IRSN-STZS, the Caen event is in a zone where the eastern boundary is very uncertain, mainly defined by the seismic activity and partly defined by the thickness of the sedimentary basin. A 20 km wide buffer zone is thus defined here in order to quantify the impact of this uncertainty in the IRSN- STZS on the final seismic hazard level.

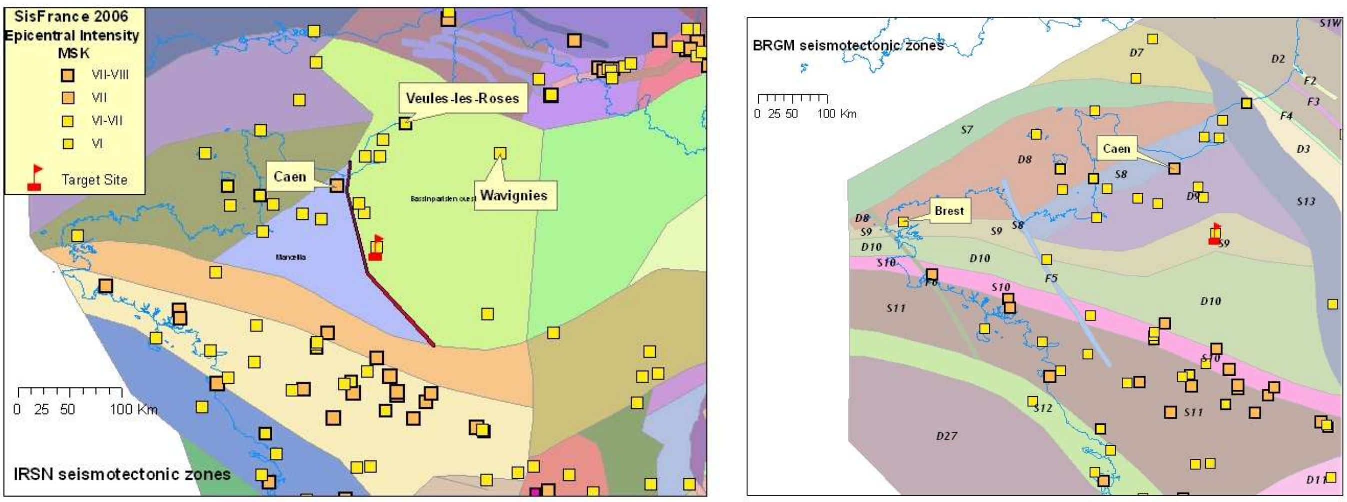

Figure 1 Location of Target site with respect to the IRSN (Cushing et al., 2003) and BRGM (Terrier et al., 2000) seismotectonic zonation schemes (STZS). A buffer zone is also drawn in the IRSN STZS to illustrate an alternative way of including boundary uncertainty when estimating confidence levels in DSHA

4. UNCERTAINTY IN THE MAGNITUDE-DEPTH CHARACTERISTICS OF EARTHQUAKES

Once the SMHVs have been identified, it is necessary to estimate their magnitude and depth. The macroseismic tool proposed in this paragraph aims at quantifying data and modelling uncertainties involved in the estimate of the macroseismic magnitude-depth-I_0 triplet of historical earthquakes (Baumont and Scotti, 2006, 2007, 2008). It involves a two-step procedure: (1) to derive a mean intensity attenuation model and related uncertainty, and (2) to invert for the magnitude terms of the model using various instrumental catalogues.

4.1. Intensity Attenuation with distance and intensity binning strategies

In order to estimate a mean model of intensity attenuation for metropolitan France, we proceeded to a selection of the best documented historical earthquakes of the SisFrance macroseismic database. The data uncertainties that are accounted for in this methodology include those associated with: the intensity evaluation at each locality, the estimation of the epicentral location and the evaluation of the epicentral intensity. In the SISFRANCE database, each one of these parameters is associated with a quality factor (Scotti et al., 2004), which is here converted in a numerical value to be formally included in the uncertainty exploration. Rather than using the intensity data points, most of the published studies are based on intensity binned data (IBD), such as isoseismal, average intensity per distance, etc. However, as discussed in (Baumont and Scotti, 2006, 2007, 2008a) the slope of the intensity attenuation with distance depends on the IBD used. To quantify the impact of the binning strategy on the estimation of the attenuation rate, we assumed that intensity binned data (IBD) decreases with the logarithm of the hypocentral distance (Kövesligethy, 1907; Sponheuer, 1960) and that intrinsic attenuation can be neglected

$$I = I_0 + \beta . Log_{10} \frac{R}{h} + \delta I_{ERR}$$

The intensity attenuation coefficient, β, assumed to be constant over metropolitan France, can be retrieved from a selection of events using an iterative damped least square scheme with inequality constraints (Menke, 1984; Tarantola, 2005). The results obtained depend on a number of parameters such as the set of selected events, the relative event weighting, and the starting model. By exploring each combination of parameters (see Baumont and Scotti, 2006, 2007, 2008a), we can build an empirical probability density function of β for each IBD. As shown in Figure 2, the intensity attenuation strongly depends on the binning strategy and differences are statistically significant.

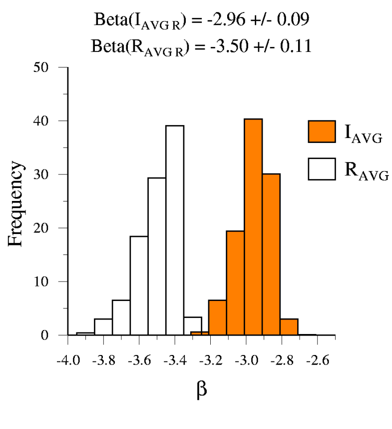

Figure 2 Empirical probability density functions (EPDFs) estimated for metropolitan France for distance (I_{AVG}) and intensity (R_{AVG}) binning strategies.

4.2. Intensity – Magnitude calibration

In the light of these results, it appears necessary to establish an intensity-magnitude attenuation model specific to each binning strategy. The need to consider neighbouring countries stems from the necessity of disposing of the widest magnitude range possible for the calibration. Macroseismic data were thus collected through various

European macroseismic databases (SisFrance2007, DBMI04, ECOS, EMID). Two important assumptions were made: MCS intensity data of the Italian DBMI04 database were converted into MSK using the scheme proposed by Godefroy and Levret (1985) and the β EPDFs established for metropolitan France are applicable to neighbouring countries. (It can be shown that similar β EPDFs results can be obtained using the Italian macroseismic database when MCS values are converted into MSK: $\beta(I_{AVG}) = -3{,}11 \pm 0{,}15$ and $\beta(R_{AVG}) = -3{,}55 \pm 0{,}17$). Two homogeneous catalogues based on a selection of published instrumental magnitudes were constructed in M_S and M_W. The calibration was performed testing various combinations of data and model parameters (Table 1), using the following functional form:

$$I = C_1 + C_2 . M + \beta . \mathrm{Log}_{10} R$$

This exploration resulted in the definition of a family of intensity-magnitude attenuation models for each calibration magnitude (Ms and Mw) and each IDB carrying the empirically derived weight of the β EPDF (Figure 2).

Table 1 : Parameters explored to build intensity-magnitude attenuation relationships (example: Mw/R_{AVG}).

β(RAVG) +weights	Starting depth (km)	Constraints on depth	Homogeneous catalogue in M_W
-3,3 -3,4 -3,5 -3,6 -3,7 -3,8	5	1-25 km (France) ; 1-50 km (other countries)	Europe (#229)
	10	H+/- δH (instrumental); 1-25 km (France) ; 1-50 km (other countries)	FR + NL + CH (#96)
	15		

For each binning strategy, observed magnitudes can be well predicted by a single magnitude-intensity attenuation model over the entire magnitude range ($3 \leq M_W \leq 7$) as shown in Figure 3 for the M_w catalogue based on the R_{AVG} IDB strategy.

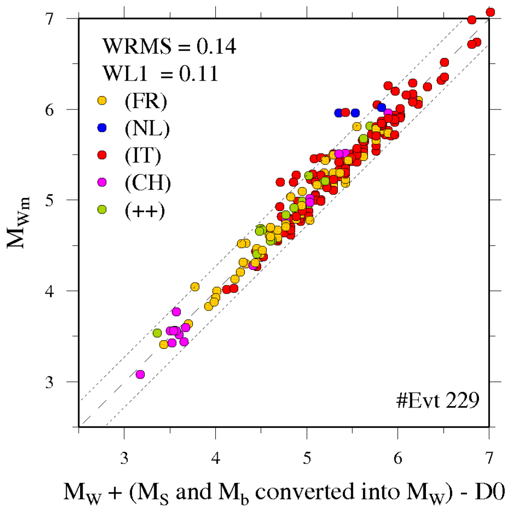

Figure 3 Example of calibration for the R_{AVG} IDB using the median value of β and the selection of events located in Italy, France, Switzerland, Netherlands, and a few cross-boundary events.

4.3. Computing empirical probability density functions to quantify historical earthquake characteristics

The families of empirical intensity-magnitude predictive equations obtained for each IDB and each calibration magnitude sample the epistemic uncertainty associated to the macroseismic evaluation of the magnitude-depth of historical earthquakes. Additional uncertainties may also stem from the functional form used to deduce the intensity-magnitude calibrations. In the following, data and epistemic uncertainties are combined in the macroseismic tool developed here with additional intensity-magnitude schemes available in the literature which may be applicable to France to explore and quantify as far as possible the large range of uncertainties underlining the estimates of magnitude-depth-epicentral intensity of historical earthquakes (Figure 4).

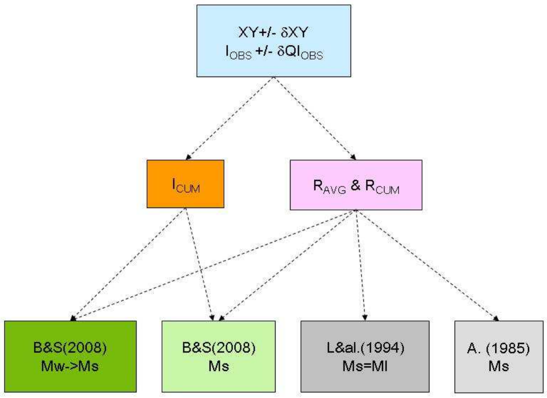

Figure 4: Schematic representation of the epistemic uncertainties explored. For each earthquake, several binning strategies (I_{CUM}, R_{AVG}, R_{CUM}) and intensity-attenuation predictive equations (Baumont and Scotti, 2008; Levret et al., 1994; Ambraseys, 1985) are tested to estimate the magnitude-depth characteristics taking into account the individual observation (I_{OBS}) and epicentral location (XY) uncertainties.

The results of the above exploration is shown for the Veules-les-Roses earthquake (Figure 5) which shows for this case two distinct evaluations that depend on the IDB used.

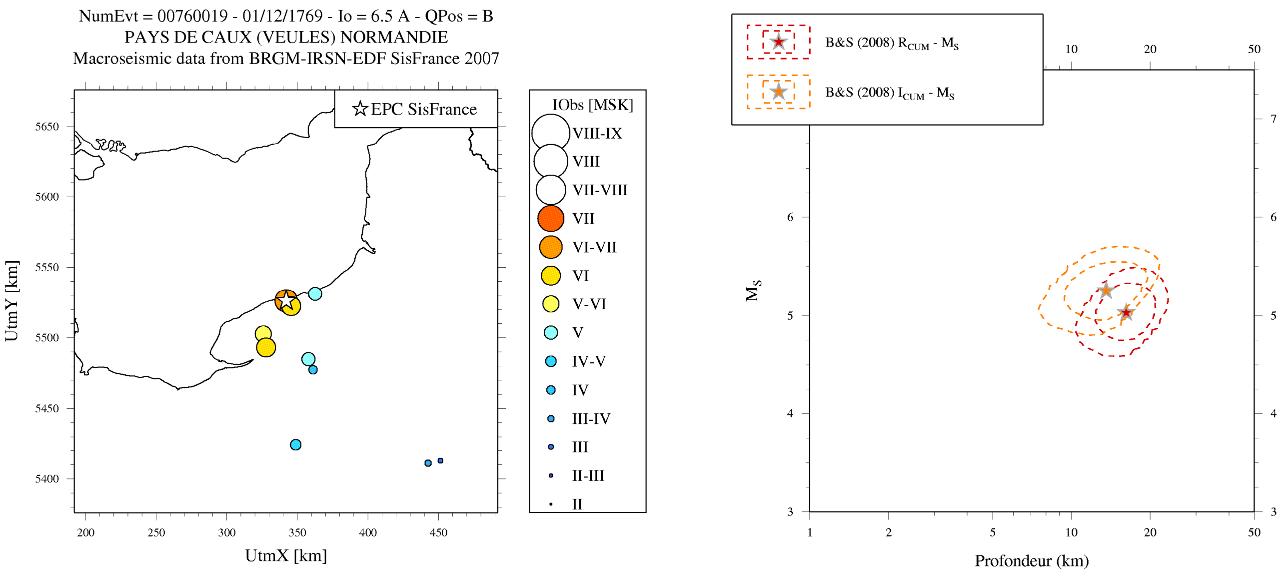

Figure 5: Magnitude-depth estimates of the 1769, Veules-les-Roses earthquake (Iobs shown in the left Figure) described as a probability density function. The great uncertainty underlying the intensity data for this event is well expressed by the wide range of possible values that result. Furthermore, for this event, the individual observations are clearly very sparse and the type of indicator used (R_{CUM} or I_{CUM}) leads to different estimates of the characteristics.

5. ESTIMATING CONFIDENCE LEVELS IN DETERMINISTIC SEISMIC HAZARD ASSESSMENT

In order to compute seismic hazard, it is necessary to choose a ground motion prediction equation (GMPE). It is well known that this choice is critical for defining the final seismic hazard level. Moreover, the treatment of the aleatory variability in GMPE exerts a very pronounced influence on the calculated hazard. These issues have been discussed at length in recent publications (see for example Bommer and Abrahamson, 2006). In this paper, we choose to focus our discussion on the impact of integrating uncertainties in STZS and (M-H-I_0) uncertainties in seismic hazard analysis using a single GMPE (Berge et al., 2003) calibrated in M_S. In accordance with the French regulation RFS-2001-01, we limit our calculations to the median GMPE value. Accounting for different GMPE would lead to different evaluations of the final hazard uncertainty and integrating the aleatory variability would increase the final hazard level.

The objective of this exercise is to estimate confidence levels for seismic hazard spectrums computed according to the French regulatory rule. To illustrate the methodology and appreciate the impact on hazard estimates, results are presented here for the target site by exploring only some of the sources of uncertainties presented in sections 3 and 4. Figure 6a, for example, shows the uncertainty in seismic hazard due to the exploration of various combinations of IBD (e.g. R_{AVG}, I_{AVG}), and intensity-magnitude prediction equations (Baumont and Scotti, 2008; Levret et al., 1994; Ambraseys, 1985). In this case only the 50^{th} percentile spectral level for the SMHV associated to the 1769, Veules-les-Roses event is considered. This epistemic uncertainty alone, can lead to hazard levels that differ by up to 70%. Figure 6b shows, for a given branch (IRSN-STZS, R_{AVG} IDB and M_S, B&S -2008), the integrated uncertainty of magnitude-depth characteristics of all the events that may contribute to the hazard in the IRSN-STZS (Caen, Veules-les-Roses, and Wavignies earthquakes in the IRSN-STZS, see Figure 1). Hazard values estimated at the 50^{th} and the 99^{th} percentiles differ by up to 40 % for this branch. In a more realistic application, the uncertainty would increase if the entire epistemic uncertainty described in Figure 4 were explored. In Figure 6c seismic hazard calculations applied in Figure 6b are extended to include three STZS (the BRGM, IRSN and its alternative with buffer limits were used assuming weights of 0.50, 0.25 and 0.25 respectively). Seismic hazard uncertainty is increased with respect to Figure 6b, even if the hazard values estimated at the 50^{th} percentile remains almost unchanged. It turns out that for this target site, the IRSN and BRGM STZS do not lead to very different seismic hazard spectra in spite of the fact that they lead to different choices of reference events. However, introducing a buffer zone in the IRSN-STZS allows the Caen event to come much closer to the target site, extending the uncertainty to higher spectral levels.

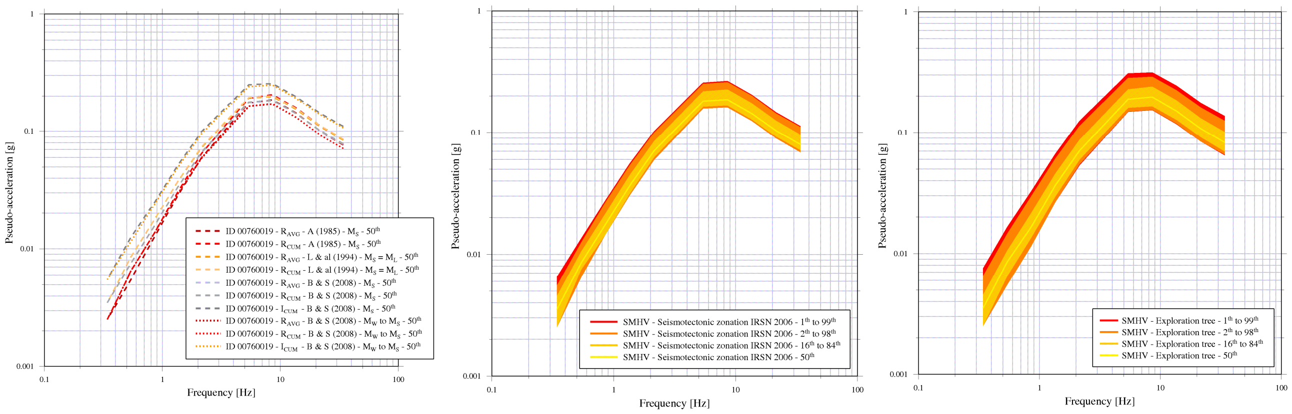

Figure 6: (a) Uncertainty on the 50^{th} spectral level due to the epistemic uncertainty in intensity data modeling (see Figure 4) of the 1769, Veules-les-Roses earthquake in the IRSN-STZS. (b) Confidence levels for seismic hazard spectrums resulting from the propagation of the uncertainty on the magnitude-depth estimates of each event (IRSN-STZS, R_{AVG} IDB and M_S, B&S -2008). (c) Confidence levels for seismic hazard spectrums calculated for three STZS accounting for the uncertainty in the characteristics of each event (see text for weighting scheme).

6. CONCLUSION: ESTIMATING SMHVs AT SPECIFIED CONFIDENCE LEVELS

We have shown that the integration of uncertainty inherent in seismotectonic models and estimations of historical earthquake characteristics is fundamental. Thanks to this methodology it is now possible to estimate confidence levels in DSHA. Finally, in order to identify the (M-R) space that contributes the most to the seismic hazard with a given confidence level, deagregation can also be performed. Rather than presenting a deagregation frequency by frequency, deagragations is shown by integrating over the entire frequency range (0.34 to 34 Hz). Figure 7 shows the magnitude-distance contributions to the hazard at the target site for the 50th and 84th confidence levels shown in Figure 6c. Two main contributions can be clearly identified at the 50th confidence level corresponding to the 1769, Veules-les Roses-earthquake (about M_S 5.0-5.2 at a hypocentral distance of 14-17 km) and to the 1755, Caen earthquake (about M_S 5.3 at a hypocentral distance of about 20 km). At 84th confidence level, the Caen earthquake starts to contribute with (M-R) characteristics similar to the Veules-les-Roses earthquake.

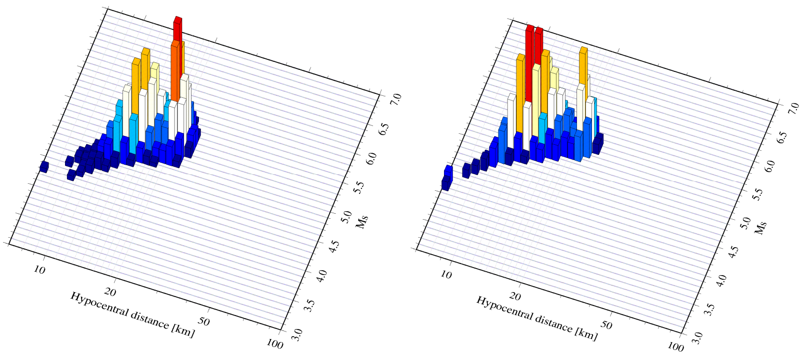

Figure 7: Deagregation of the hazard shown in Figure 6c at the 50th and 84th confidence levels.

ACKNOWLEDGMENTS

The authors would like to thank all the data providers. Data that were used in this study were extracted from the SisFrance 2007, DBMI04, ECOS and EMID macroseismic databases. Source parameters for the instrumental earthquakes were provided by SED, Harvard CMT project, RCMT-MED, ISC, IRSN, RéNaSS, LDG and Karnik catalogue.

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