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Sensitivity study on the SHARE PSHA model and exploration of uncertainties on earthquake recurrence – application to France

Étude de sensibilité sur le modèle PSHA de SHARE et exploration des incertitudes liées aux modèles de sismicité – application à la France

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RÉSUMÉ. Le projet SHARE a produit fin 2013 des cartes harmonisées de l'aléa sismique pour l'ensemble de la région euro-méditerranéenne. La présente étude est menée dans le cadre d'un groupe de travail de l'AFPS ayant pour objectif d'analyser les méthodes proposées dans SHARE et les résultats pour la France. Les modèles de SHARE, pour la France, reposent fortement sur des critères d'expert. La sensibilité des résultats au choix des magnitudes minimales et maximales est quantifiée. Le modèle intégrant les failles est analysé et son impact sur l'aléa est quantifié. Des erreurs dans les fichiers d'entrées sont identifiées, et une carte corrigée est produite. Afin de quantifier les incertitudes sur le modèle de source, nous avons repris le catalogue de sismicité de SHARE (SHEEC), et avons établi des courbes de récurrence avec incertitude. En parallèle, le SI-Hex catalogue de sismicité unifié et homogène récemment publié par Cara et al. (2015) a été exploité pour fournir des modèles de récurrence alternatifs. Les estimations d'aléa sismique probabiliste basées sur ces différents modèles de sources montrent que l'impact sur l'aléa est important. Plus d'attention devrait être apportée aux modèles de source et à la quantification des incertitudes qui les caractérisent.

SUMMARY. In 2013, the SHARE project delivered a harmonized model characterizing the seismic hazard in the entire Euro-Mediterranean region. This study is led within the framework of an ad hoc AFPS working group discussing the SHARE assumptions, methodologies and results for France. The SHARE earthquake recurrence models for France rely greatly on expert opinion. A sensitivity study on some input model parameters is performed (minimum and maximum magnitudes contributing to the hazard). The impact of the fault model on the hazard is studied. Some errors in the input files are identified, a corrected hazard map is produced. In an attempt to account for the uncertainties on the source model, new recurrence curves with associated uncertainties are derived based on SHARE's earthquake catalog (SHEEC). The recently published SI-Hex catalog, a new unified instrumental catalog for France (Cara et al., 2015) is also used to derive alternative recurrence curves. Based on these new source models, alternative PSH estimates are obtained for France. The results show that the uncertainty on the recurrence parameters in France is large and that the impact on hazard can be so large that it should not be neglected.

MOTS-CLÉS : PROBABILISTE ; SHARE ; SENSIBILITE ; ALEA SISMIQUE ; FRANCE

KEYWORDS: PSHA ; SHARE ; SI-HEX ; SENSITIVITY ; SEISMIC HAZARD ; FRANCE

1. Introduction

The most commonly used approach to determine seismic-design loads for engineering projects nowadays is probabilistic seismic-hazard analysis (PSHA). The primary output from a PSHA is a hazard curve showing the variation of a selected ground-motion parameter against the annual rate of exceedance. The design value is the ground-motion level that corresponds to a preselected design return period. It is fundamental to understand the mechanics of this PSHA approach thoroughly, in order to clearly define its limitations and uncertainties, and thus the confidence levels of the results it provides. The present study analyses the SHARE calculations and results for France, and proposes new earthquake recurrence models with associated uncertainties, with the ultimate aim to evaluate the impact on hazard results.

2. SHARE project

The SHARE project created a time-independent hazard model for the Euro-Mediterranean region (Giardini et al., 2014). It is intended to serve as reference model of the updated European seismic regulations for building design. The SHARE Deliverables are describing the methodologies followed and some of the decisions taken (www.efehr.org). PSHA is calculated with the software OpenQuake (Silva et al., 2014).

Epistemic uncertainties are addressed within a logic-tree approach. The two main PSHA components, earthquake source and ground shaking, are included in different branching levels. Three mean source models are included in the logic tree; the uncertainty on each model is not explored in the logic tree. SHARE includes a tectonic regionalization to apply the selected Ground Motion Prediction Equations (GMPE, Delavaud et al., 2012), classifying the seismic sources either as Active Shallow Crust (ASC, 4 GMPEs) or as Stable Continental Regions (SCR, 5 GMPEs). All calculations are performed for rock site conditions. The hazard results are available for return periods ranging from 73 to 4975 years and for spectral periods till 4.0 seconds (www.efehr.org).

Some of the decisions and methods mentioned in the Deliverables were revised in the final hazard calculations. These decisions can thus only be understood by analysing the Shapefiles describing the source model, and the OpenQuake input files, available on the www.efehr.org website.

3. Analysis and sensitivity study on SHARE source model for France

3.1 Source model logic tree and area-fault model

SHARE includes in the logic tree three models to forecast earthquake activity. These mean models result from alternative interpretations of the available tectonic, paleoseismic, geological and seismological data:

- AS (weight 0.5) is an area source model, relying on a seismotectonic zoning and past seismicity. The earthquake recurrence is modeled by a Gutenberg-Richter curve.
- FSBG (weight 0.2) combines active faults (Basili et al., 2013) with background seismicity. Where no fault is taken into account, the source zones in the FSBG model are identical to the AS model ones. For source zone including active faults, the earthquake recurrence is modeled by a Gutenberg-Richter curve: the a -value is derived from the geologic slip rate of the fault (Basili et al., 2013), applying the Anderson and Luco (1983) method, using the b -value from the area model and the maximum magnitude attributed to the fault (defined in Basili et al., 2013). Magnitudes below or equal to M_w 6.4 are assigned to the background, magnitudes larger than 6.4 to the fault plane.

Initially, SHARE had planned to include the faults displayed in Fig. 1a, but in the course of the project, only a subset of these faults has been kept, i.e. faults with highest slip rates and $M_{\max} > 6.5$ (L. Danciu personal communication, Fig. 1b).

- SEIFA (weight 0.3) is based on kernel density estimation techniques in space, applied to both past earthquake locations and fault moment release on crustal faults with assigned slip rates (Hiemer et al., 2014). This model is not studied in the present paper.

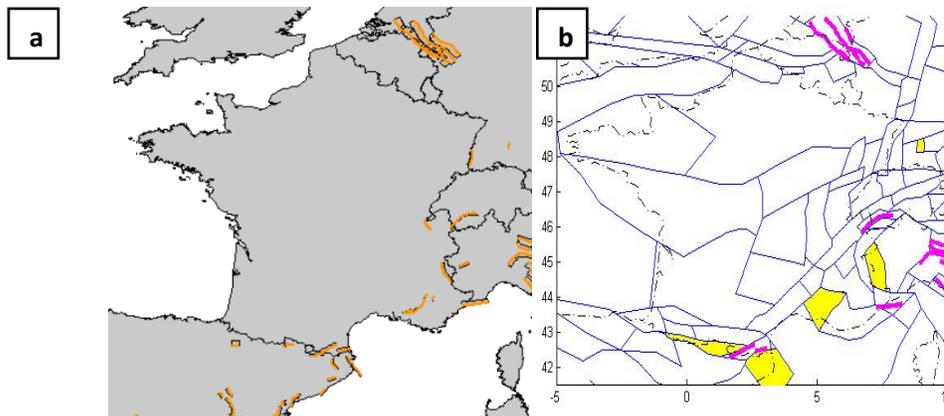


Figure 1. (a) Initially selected faults in SHARE (Deliverable 3.4). (b) Faults (in magenta) included in the final SHARE input files. Yellow polygons: zones with erroneous recurrence model in the FSBG model.

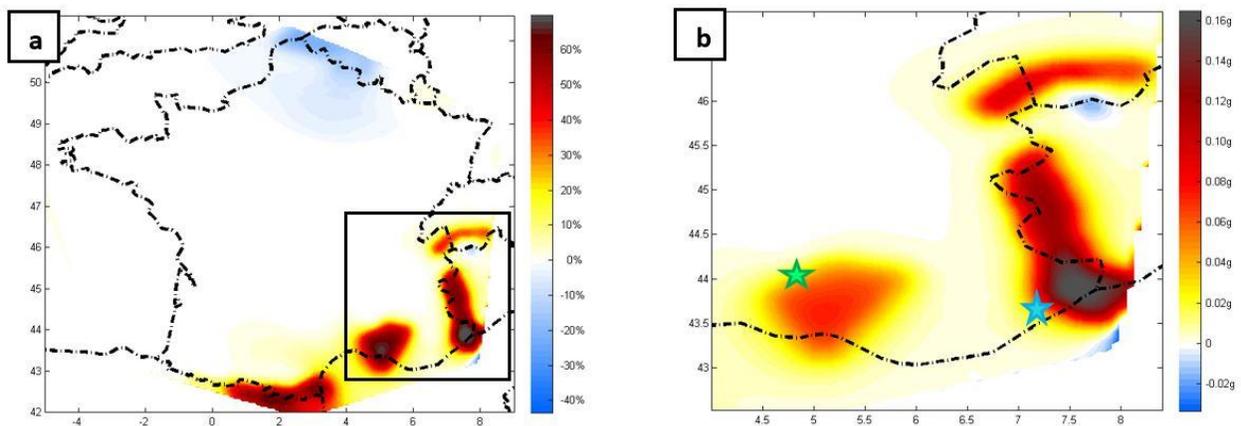


Figure 2. Difference between hazard values relying on the area model (AS) and the area+fault model (FSBG): for the PGA at 475yr. (a) $(A_{AS}-A_{FSBG})/A_{AS}$, in%. (b) $A_{AS}-A_{FSBG}$ (zoom window); green star: Avignon, cyan star: Nice.

To begin with, two hazard maps are calculated at 475 years return period, based on the FSBG model and on the AS model, and the difference in PGA is calculated (Fig. 2). The FSBG model leads up to 65% lower PGA_{475} for sites in south-eastern France and in the Eastern Pyrenees (Fig. 2a). The results for $T=1s$ are similar. The absolute differences in PGA_{475} are large, they reach 0.16g east of Nice (Fig. 2b). In fact, where faults have been included, the

seismicity rates based on the slip rate are around 10 times lower than in the area model (example in Fig. 3). SHARE made the hypothesis that the fault was responsible for all the seismicity in the zone, which might not be the case here given the size of these zones.

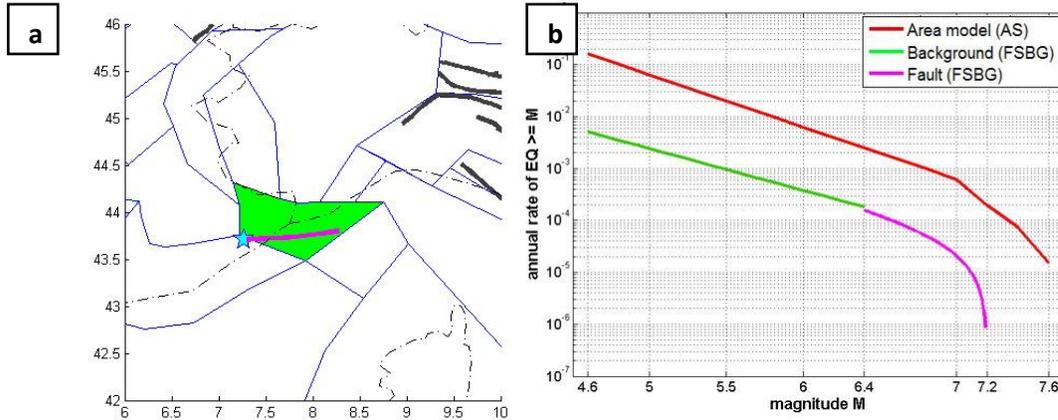


Figure 3. (a) Source zones and faults around Nice (star). (b) Frequency-Magnitude distributions corresponding to the source zone east of Nice. Red: area model; Green+Pink: area+fault model.

The PGA maps in Fig. 2 display significant differences in several regions where no fault is taken into account. In Fig. 1b we highlight these zones presenting an unexpected difference between AS and FSBG model; all these zones were including a fault in the first steps of SHARE (Fig. 1a). An in-depth analysis of the FSBG model shows that these zones have been attributed a wrong recurrence model, the background part of the recurrence curve in the FSBG model, leading to much lower seismicity rates and M_{max} . This type of error has led to an approximate 10% local decrease in hazard in the final SHARE mean hazard map.

3.2 Sensitivity study on the minimum and maximum magnitudes contributing to the hazard (area model AS)

The minimum magnitude that contributes to the hazard (M_{min}) needs to be selected. This should be the minimum magnitude producing ground motions with enough energy and appropriate frequency band to challenge structures. SHARE used $M_{min}=4.6$ for the AS model. A sensitivity analysis on the M_{min} is performed, by reducing it from 4.6 to 4.0 for all areas. All other input parameters are kept unchanged. Using 4.6 or 4.0 implies that the ground-motion prediction models are extrapolated, since most of the GMPEs used in SHARE are valid for $M_w \geq 5$. Reducing the M_{min} by 0.6 can lead up to 60% larger PGA_{475} (not shown). The impact is significant only for spectral periods smaller than 0.5s (low to moderately high buildings). As shown in many previous studies (e.g. Beauval and Scotti, 2004) the impact of M_{min} is decreasing with increasing return period and increasing level of hazard (not shown).

Although four maximum magnitude (M_{max}) values had been proposed for each zone with associated weights (Fig. 4a), SHARE eventually did not include the M_{max} in the logic tree. Instead, a mean recurrence curve was applied, representing the weighted combination of the four recurrence tree curves. The uncertainty related to the M_{max} is not propagated. The value of M_{max} is often a subject of debate. In order to check how important this topic is for 475yr, a sensitivity test is performed using SHARE recurrence curves cut at a magnitude equal to $M_{max}-0.6$. The impact is lower than 7% all over France, and is largest in low-seismicity regions (Fig. 4b). A disaggregation analysis performed for two example sites, Perpignan and Paris, provides the explanation (Fig. 5). For a site located in a low-seismicity

region, sources located at distances up to 200km are contributing ($5 \leq M \leq 7$), whereas in more active regions all contributions comes from a radius of 80 km.

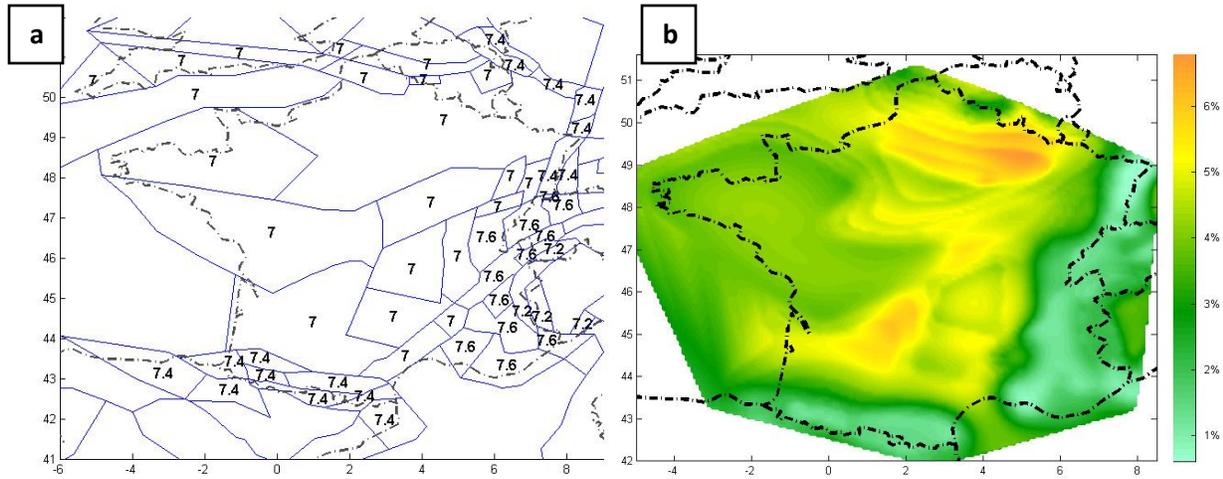


Figure 4. (a) M_{max} values per source zone, inferred from SHARE input files. (b) Impact on hazard of reducing the M_{max} by 0.6: $(A_{SHARE} - A_{test}) / A_{SHARE}$, for PGA at 475yr, AS model.

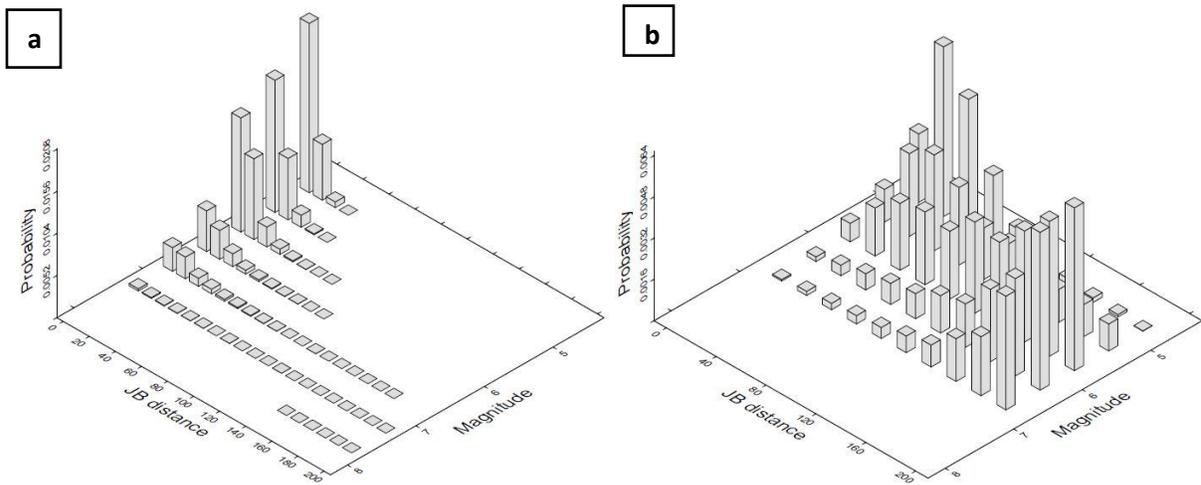


Figure 5. 2D disaggregation in magnitude and distance for PGA at 475yr: Perpignan (a), Paris (b).

3.3 Corrected SHARE results for France

By comparing the Shapefiles and the OpenQuake input files, small input errors have been detected in the input files, mainly plus or minus 0.1 differences in M_{min} , M_{max} and slight shifts on the rates, which cannot be detailed here. After correcting these errors, as well as the error on the area+fault model, a new PGA_{475} map for France is calculated (Fig.

6a) and compared with the official one. These calculations include the complete SHARElogic tree. The corrections lead to lower hazard values (up to 14%) than the official ones, except for three zones where the fault model was erroneous (Fig. 6b). It should be noted that the absolute impact on PGA_{475} does not exceed 0.025g.

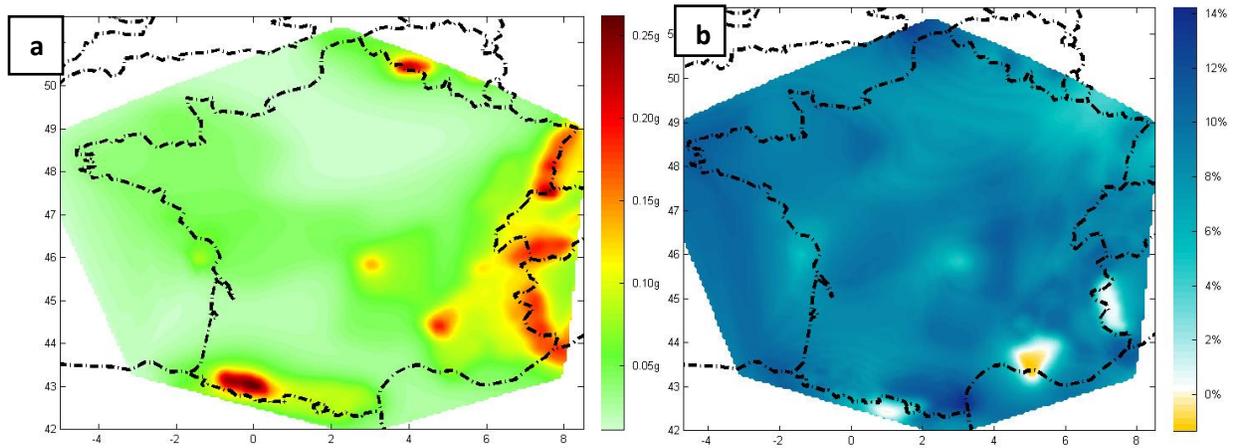


Figure 6. (a) Corrected mean PGA map at 475yr. (b) Normalized difference between PGA_{475} based on the official SHARE source model and PGA_{475} based on the corrected model, $(A_{SHARE} - A_{corrected}) / A_{SHARE}$.

4. Earthquake recurrence uncertainties

Unfortunately the issue of earthquake recurrence uncertainties is not given enough attention in most PSHA studies, due to the difficulty to quantify it, especially when few data are available. The total uncertainty on the seismicity rates is a combination of the uncertainties inherent to the building of a source model: uncertainty on magnitude estimation (recorded, converted or inferred from intensity data) and earthquake location, on the definition of the seismo-tectonic source zoning, on the completeness periods determination, on the fitting of the observed rates to a given recurrence model, and on the maximum magnitude. SHARE used only mean source models, and these models rely greatly on expert judgments. The present study aims at quantifying some uncertainties on the source model but is far from complete.

4.1 Modeling earthquake recurrence based on SHEEC catalog

SHARE used the SHARE European Earthquake Catalogue (SHEEC, Stucchi et al., 2013), covering the period 1000-2007 with moment magnitudes $M_w \geq 3.5$. Completeness periods have been defined for wide geographical areas, but practically, the minimum magnitude that can be used for the calculation of the Gutenberg-Richter parameters (minimum magnitude of completeness, M_c) depends on the source zone. Analysing the observed recurrence rates in each zone in France, we show that M_c is always larger or equal to 3.7. In most zones, few data are available to model earthquake recurrence (a and b values), 19 out of 29 zones have less than 7 events. As a consequence, to our knowledge, SHARE applied the maximum likelihood method in only 3 out of 29 source zones. Elsewhere, expert judgment was applied, fitting the observed rates with a b -value close to 1. Moreover, no uncertainty was associated to the recurrence parameters.

At first we use the SHEEC catalog, taking into account events identified as mainshocks by SHARE and applying the same completeness periods. The widely used Weichert (1980) maximum likelihood method is applied. Analysing the data available in each source zone, we decided to apply Weichert in zones with at least 7 events (within periods of completeness) and to set recurrence parameters to alternative background seismicity floors elsewhere. The σ on the b -value, as calculated by Weichert, is used to quantify the uncertainty on the recurrence curve. The maximum magnitude used is the one defined in SHARE's input files.

In zones with less than 7 events, a background seismicity floor is estimated. Such background always relies on rather arbitrary decisions. In those zones, the uncertainty on the recurrence model is huge, but extremely difficult to be quantified. Two models are defined in an attempt to take into account this uncertainty. The first model provides a seismicity floor separately for SHARE's stable and active regions: it gathers all source zones identified as "stable" (or active) with less than 7 events, and redistributes the rate proportionally to each area. The second model tunes the a -value so that it matches the observed rate relying on the largest number of events for magnitude ≥ 4.1 , applying a b -value equal to 1. The second model proved to be less conservative.

Therefore for each source zone, two recurrence models are defined: an upper and a lower bound. The seismic hazard can now be provided with associated uncertainties. Figure 8a shows an example for Lourdes; the PGA at 475yr return period varies between $0.16g$ and $0.24g$.

4.2 Modeling earthquake recurrence based on SI-Hex

The SI-Hex project produced a new instrumental catalogue of seismicity for metropolitan France that covers the period 1962-2009 (Cara et al., 2015), homogeneous in magnitude ($0.7 \leq M_w \leq 5.5$). The authors dedicated special attention to discriminate natural events from man-induced ones. This catalog is used here to derive alternative earthquake recurrence models. The required hypotheses are strong: earthquake recurrence is derived from the low magnitude range using only 57 years of data. The recurrence parameters are then considered to be valid for the moderate-to-large magnitude range (extrapolation to M_{max}) and representative of long-term seismicity. Note that using the SI-Hex catalog alone ensures certain homogeneity of the dataset.

The three declustering techniques discussed in SHARE are tested (Gruenthal et al., 2007; Gardner & Knopoff 1974; Uhrhammer et al., 1986) all rely on simple magnitude-dependent windows in time and space. This declustering step is a crucial issue given the magnitude range considered. The technique finally selected is Gruenthal et al. 2007 (as in SHARE) providing the strongest declustering and identifying 83% of the events as clustered events. Completeness periods are determined using cumulated number of events versus time, and Gutenberg-Richter plots (Table 1). The number of complete events to derive G-R parameters is much larger than in SHARE (most of them have 35 to 200 events) and the magnitude range is wider. The b -values are therefore much better constrained. The b -values are mostly between 0.9 and 1.3 (Fig. 7). In the Pyrenees all b -values are around 0.8-1.0. The Alps present larger values (1 to 1.3). In a few zones, the b -value is much larger than expected (1.4-1.7), probably due to the inclusion of very small magnitudes. These high b -values cannot be representative of long-term seismicity. More work is required on the declustering issue (testing other declustering algorithms more adapted to low-magnitude events) and also on the identification of artificial seismicity.

New recurrence curves are proposed, with the same M_{max} as in SHARE. The hazard is re-calculated, considering this new earthquake recurrence model and keeping all other parameters identical to SHARE.

Table 1. Completeness Periods determined on the declustered SI-Hex catalog

Magnitude interval	1.7-1.9	1.9-2.1	2.1-2.3	2.3-2.5	2.5-2.7	2.7-5.5
After (year)	2000	1994	1977	1974	1970	1962

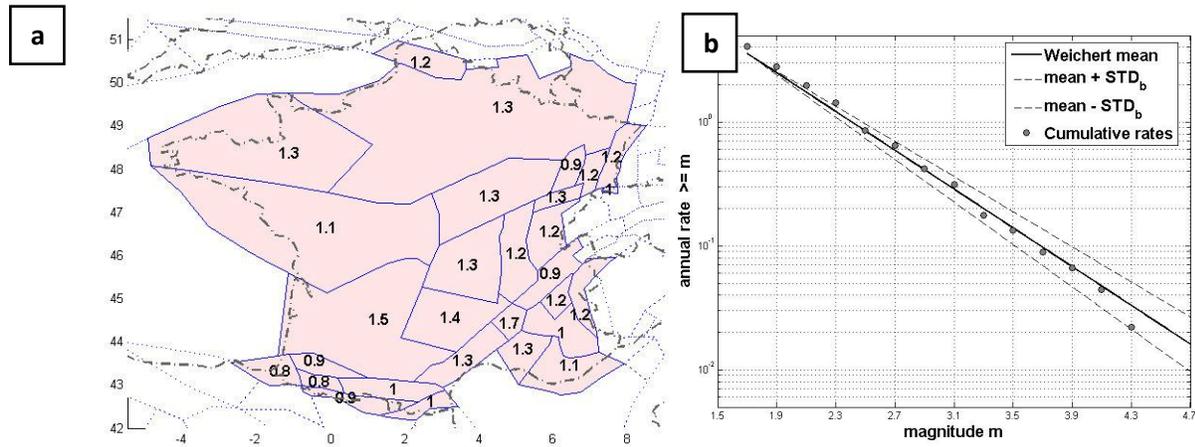


Figure 7. (a) *b*-values for each source zone, based on SI-Hex catalog. (b) Earthquake recurrence modeling, example for a source zone in the Pyrenees with 92 events (within completeness periods).

4.3 Hazard results

The earthquake recurrence parameters derived from the SHEEC and SI-Hex catalogs are used here to calculate probabilistic seismic hazard. An example is displayed for Lourdes (full Uniform Hazard Spectra, Fig. 8a) and for different cities with low seismic hazard in France (PGA, Fig. 8b). At PGA₄₇₅ the variability is huge. Earthquake parameters based on SI-Hex lead to much lower accelerations in almost the entire country. This might be largely due to the *b*-values larger than 1. More work is required on the earthquake parameters derived from SI-Hex. Nevertheless, these results show that the uncertainty on the earthquake recurrence curve can impact significantly the hazard.

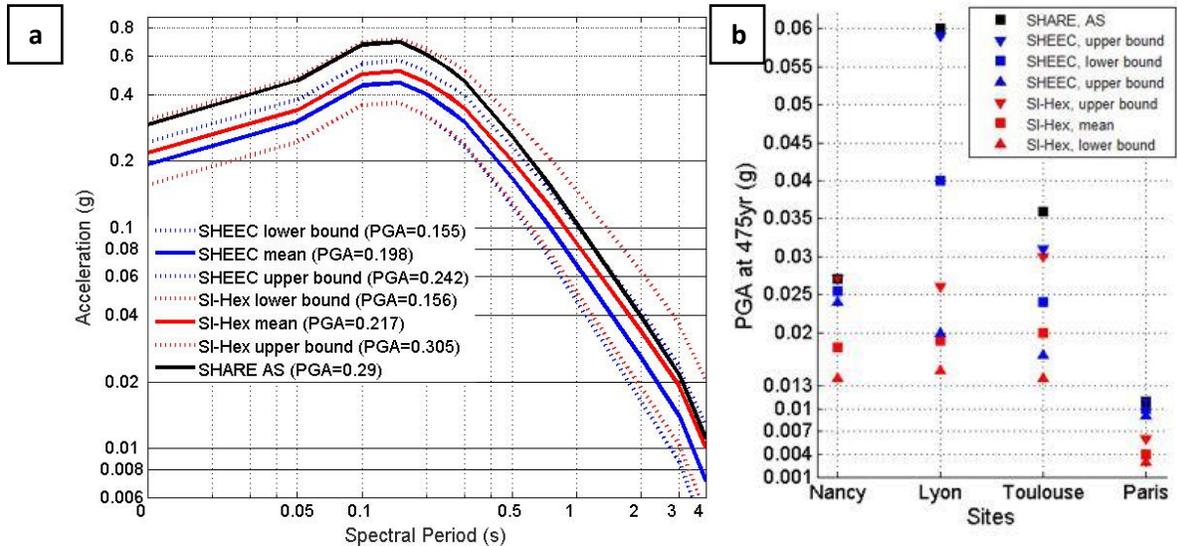


Figure 8. (a) UHS for Lourdes at 475yr. (b) PGA at 475yr for 4 cities. Black, SHARE mean area model; Blue: earthquake recurrence models relying on SHEEC (§4.1), Red: earthquake recurrence models based on SI-Hex catalog (§4.2). Solid line (a) and square (b): mean; dashed line (a) and triangles (b): upper and lower bounds.

5. Conclusions

In the present work, the SHARE source model for France is analyzed in depth and alternative recurrence models are derived. We focus on the area and area+fault models, whereas the smoothed seismicity model is left for future work. Main findings are:

- Area+Fault model: only four faults are considered over the French territory. Including the faults leads to 65% lower PGA_{475} in their vicinity, when compared with the Area model. Investigating the SHARE input files we show that the seismicity rates based on the slip rates are much lower than those inferred from past seismicity. SHARE's assumption that all seismicity in the source zone is occurring on the fault might be questioned. Moreover, we identify four source zones where the fault model is erroneous, producing a 10% decrease on hazard. Input files are corrected and a new hazard map is produced.

- Uncertainties on earthquake recurrence have been partially ignored in SHARE. Moreover the earthquake model is relying strongly on expert decisions. In a low-to-moderate seismicity country like France, where data can be scarce, the uncertainty on the earthquake recurrence is significant. It should be quantified and its impact on hazard estimated. To go in that direction, we have used the SHEEC earthquake catalog (Stucchi et al., 2013) to derive recurrence curves with quantified uncertainties. Furthermore, as SHEEC provides few events per zone (high magnitude of completeness), we took advantage of a newly published instrumental catalog for France, SI-Hex (Cara et al., 2015) to derive alternative recurrence curves, well constrained, with associated uncertainties. For several sites, the range of acceleration values obtained, shows that the uncertainty on the source model is significant and its impact on hazard cannot be ignored.

More work is required on the modeling of long-term earthquake recurrence based on the SI-Hex instrumental

catalog. Using this catalog alone ensures some homogeneity in the dataset. Nonetheless it will be mandatory to also append a historical catalog and derive alternative recurrence curves. These different earthquake recurrence models, relying on different datasets and assumptions, should populate branches in a logic tree.

Most PSH studies are under-estimating the uncertainty on the source model. This study addresses the difficult issue of quantifying uncertainties on the source model in a low-to-moderate seismicity country. Where data is scarce, quantifying uncertainties is a challenge. Only some of the uncertainties affecting the earthquake recurrence model are considered here. More work is required to build a complete source model logic tree; only then, the overall impact on hazard can be quantified.

6. Acknowledgments

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