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A COMPARISON OF RECENT SEISMIC HAZARD MODELS COVERING FRANCE DEVELOPED AT DIFFERENT SCALES

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Abstract: *Several seismic hazard maps covering the French metropolitan territory have been published in recent years by Drouet et al. (2020) and Danciu et al. (2021) [i.e. ESHM20] at national and European scale, respectively. Motivated by recent site-specific seismic hazard assessments performed for several critical facilities in different French regions, we developed regional seismic hazard models relying on (i) a recently developed earthquake catalogue at the scale of Western-Europe (including up-to-date seismicity bulletins, a specific procedure to overcome the border effects, a revised regionalized homogenization scheme in Mw), (ii) a more systematic consideration of active faults, (iii) the variability of activity rates related to the choice of zonings and calculation methods, and (iv) sensitivity studies conducted at return periods of 100 years to 10000 years. In this paper, we present the main features of our model and compare it with existing models. It is observed that moving toward more local/regional model as in this study, the complexity of the logic tree increases as the logic tree is revised and adapted for each specific site based on the local seismological and geological data.*

Introduction

In recent years, several probabilistic seismic hazard models have been developed for metropolitan France, including the latest national model published by Drouet et al. (2020), (called hereafter DR20), and the European Seismic Hazard Model, ESHM20 (Danciu et al. 2021) which will be considered as informative input in the ongoing revision of Eurocode 8. These models are developed at large scales which may lead to a limited representation of epistemic uncertainties at a regional level.

In low-to-moderate seismicity regions such as in France where there is a lack of local data, it is of primary importance to accurately evaluate and treat the uncertainties and therefore to develop hazard models that can capture such uncertainties at more regional and site-specific scale. Seismic hazard studies performed recently for several critical facilities in different regions in France led us to update the seismic hazard assessment model and the methodology based on a regionalized approach considering a recently developed earthquake catalogue and including an updated seismic source characterization (SSC) model, developed at regional scale. The hazard logic tree is adapted for each specific site to account for the seismotectonic and geological data characterizing the seismic sources that control the ground motion hazard at the site. To discuss the hazard variability at regional scale, the hazard results are displayed for 81 sites all around France and compared with existing models developed at larger scale.

Earthquake catalogue

An up-to-date comprehensive and magnitude homogenized catalogue of seismicity (STR22) covering the historical and instrumental periods was built at the scale of Western-Europe with a focus on Metropolitan France. All the relevant information available for earthquakes ($M \geq 1.5$) reported by various local, regional, and global earthquake databases were compiled into a single earthquake parametric database. The assignment of epicentral location information followed a spatially varied priority schemes defined for each domain (based mostly on the administrative/national boundaries) while handling the boundary issues with buffer zones (Baumont et al. 2019). Concerning the magnitude homogenization in Mw*, the methodology of EPRI (NUREG 2115, 2012) which allows to account for multiple magnitude estimates and magnitude types (vector approach) was adopted. A moment magnitude Mw* reference database was established, and it was used to evaluate the magnitude conversion scheme for all other magnitude-type into Mw*. For Metropolitan France, in recent studies e.g. (Bakun and

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Scotti 2006; Laurendeau et al. 2022) concerns were raised for the need of regionalized magnitude homogenization schemes. Thus, we made regionalized regression analysis separating the South-eastern part of France from the rest of the territory.

The obtained unified homogenized catalogue was then de-clustered with spatial-temporal scheme proposed by Gardner and Knopoff (1974). The identification of swarms (which concerns mostly non-tectonic events) was also made through a specifically calibrated scheme including the specific treatments as necessary (for e.g., the Lacq gas field region of France). The de-clustered catalogue was then carefully analysed to define the completeness periods for each completeness domains (defined based principally on seismicity, density of seismic networks and population density) including a range of uncertainty for each magnitude bin. The developed de-clustered catalogue along with completeness scheme was then utilized for the computation of seismicity rates of the source models. The detailed illustration of the work concerning the development of a new seismicity catalogue is in preparation through a journal publication.

The comparison of this earthquake catalogue with the one used in the ESHM20 model, in terms of magnitudes assigned to the events in metropolitan France (Figure 1), shows a fairly good agreement between the two catalogues for the instrumental period (after 1962), even if the dispersion becomes greater for the lowest magnitudes. On the other hand, for the pre-instrumental and historical periods (before 1962), the dispersion is significantly larger, although the differences remain centered on the 1:1 relation. We believe that the main reason of differences comes from the different methods used for magnitude evaluation for historical events in EPICA catalogue (Rovida and Antonucci 2021; Rovida et al. 2022) adopted in SERA project, compared to FCAT17 catalogue (Manchuel et al. 2018) which was used in STR22 catalogue for historical and pre-instrumental period.

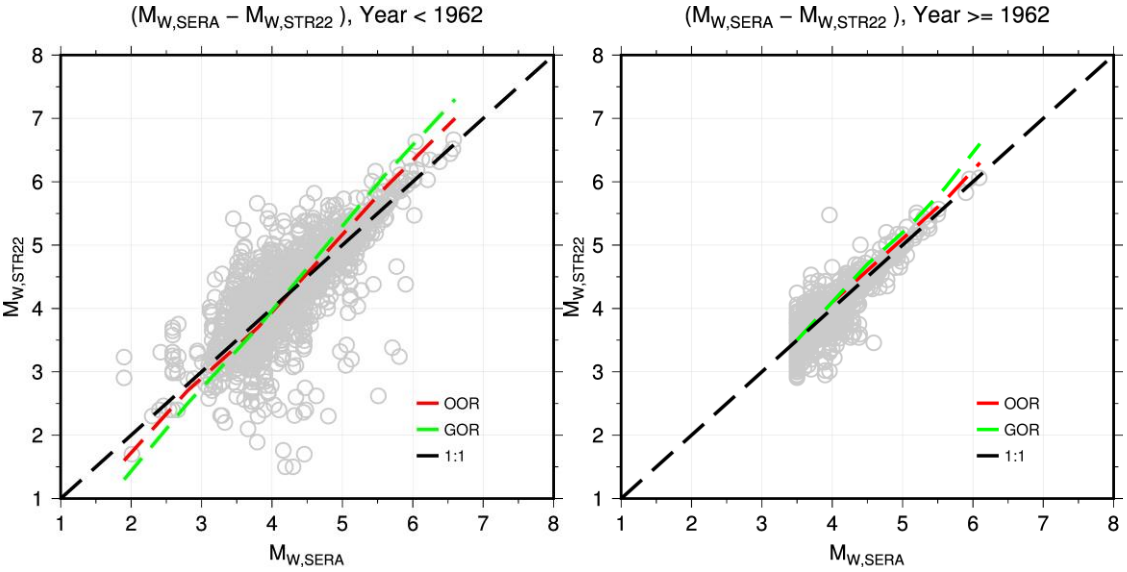

Figure 1. Comparison between the SERA catalogue, and the catalogue developed in this study (STR22) for events in metropolitan France, left (only events before 1962), right (events after 1962 included). Red, green, and black dashed lines are for Ordinary Orthogonal Regression (OOR), General Orthogonal Regression (GOR) and 1:1 bisector, respectively.

Additional verification was performed to check no significant events were missing unexpectedly (i.e., without reasonable explanation) in STR22 catalogue that were accounted for in the SERA catalogue. The result shows that there are much more events in STR22 catalogue indicating that STR22 could be largely more complete that SERA catalogue specially in the lower magnitude range below Mw*< 3.5. Note that for the moderate seismicity region like France, lower magnitude can have significant implications in the evaluation of seismic activity rates and ultimately in the seismic hazard level estimates. The few events that are included in SERA catalogue but not reported in STR22 catalogue were individually analysed to rule out the possibility of any unexplained missing. We confirm that these events should be eventually discarded because the master source for historical seismicity in France (i.e., SisFrance by BRGM/EDF/IRSN) identified these events as fake earthquakes.

Seismic Source Characterization (SSC)

Selected models

Our SSC model includes various seismotectonic interpretations proposed by independent teams for modelling the seismic sources, as well as different conceptual models. Some of the selected seismotectonic models were already included in the DR20 study:

- Our own model called SM1, initially published by Le Dortz et al (2019) and used as GEOTER model in DR20 (Figure 2a),
- SM2, developed by EDF in the framework of the safety assessment of its facilities in the national territory. The reference version of the EDF model dates from 2013 (v1.8),
- SM3, developed by the IRSN (Baize et al. 2013).

Since the study of DR20, the SM1 model is being regularly updated to account for the evolution of available seismological and geological data. In particular, the reappraisal of seismicity and structural geology data for the Paris Basin has led us to introduce a large central zone corresponding to the aseismic core of the Basin, surrounded by transition zones (Figure 2b). In the ESHM20 model, the delimitation of the source zones for France generally follows the IRSN zoning.

For the southern half of France, we also introduced a fourth seismotectonic model (SM4) in our logic-tree:

- In the southeast, we use the model developed in the framework of the SIGMA research program (Martin et al. 2018) ;
- In the rest of the country, we use the model developed by the BRGM (Blès et al. 1998) for the application of the ICPE (Installations Classées Protection de l'Environnement) regulations corresponding to the French decree of 10 May 1993.

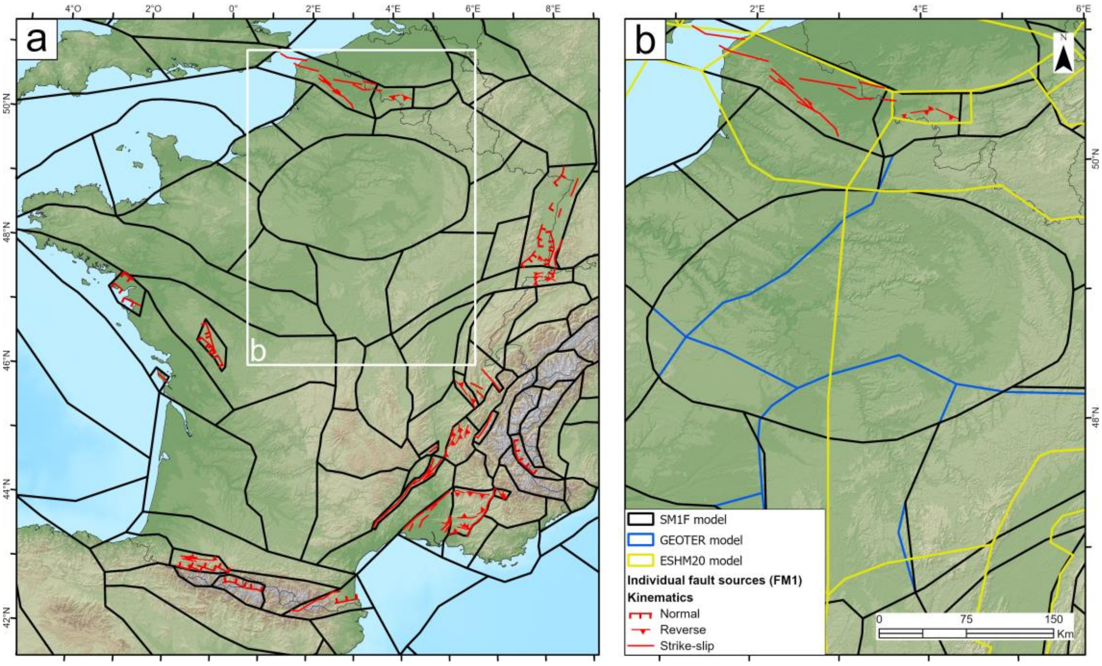

Figure 2. (a) Volume sources and individual fault sources of model SM1 (SEISTER) superimposed over the shaded SRTM relief, (b) comparison between the volume-source models of SM1 (black contour), DR20 (blue contour for the GEOTER model) and ESHM20 (yellow contour) for Paris Basin.

In the last years, there has been significant effort from the scientific community to better identify and characterize the potentially active faults on the French territory. Therefore, our model (and ESHM20 model), in contrary to DR20 model, includes active faults whose individual geometry is specified. The introduction of the faults can have a strong impact on the hazard levels and their variability, especially at long return periods. In our SSC model, SM1 and SM3 are thus introduced in two versions: one in "pure" volume sources; the other combining volume sources and faults (e.g., SM1F in Figure 2). These faults are introduced based on the latest scientific publications which identify the potentially active faults on the French territory (e.g., Bellier et al. 2021; Larroque et al. 2021; Ritz et al. 2021; Jomard et al. 2017). The SM1F model has been developed by our group based on site-specific studies performed for each site in different regions of France and therefore it might not include all potentially active faults at national scale, but it is in continuous evolution. The maximum magnitudes and activity parameters of the faults are defined through a set of alternative scaling laws and recurrence models. The SM3F model on the other hand includes mainly the faults defined in the BDFA database (Jomard et al. 2017).

In the ESHM20 model, the volume source model for metropolitan France follows the geometries of the IRSN model (Baize et al. 2013) while it differs at the border with the other countries. The fault sources were built from a database harmonized at the European scale, which for metropolitan France mainly rely on the BDFA (Jomard et al. 2017). The limited number of fault sources introduced in ESHM20 model are combined with background smoothed seismicity (Danciu et al. 2021). The maximum magnitudes are defined with a single scaling law (Leonard 2014) and the fault activity is modelled with a truncated exponential distribution.

In all hazard models mentioned here, the SSC logic-trees includes a smoothed seismicity approach. It constitutes an alternative approach to seismotectonic volume-source models, where each zone presents a homogeneous activity rate. Smoothing models rely on broad regional areas in which activity rates vary spatially. In our model, the seismicity rates are determined with several kernel functions that smooth the seismicity according to a fixed, magnitude-dependent width (fixed kernel) or to a width estimated from the distance to the n-th neighbour (adaptative kernel). The selection of the kernels for each site is based on sensitivity studies and depends on the regional seismotectonic context. By comparison, DR20 uses a single adaptative kernel function for the whole metropolitan territory. The choice of single kernel function may bias the activity rates considered in the hazard model as its impact on to the ground motion estimates is a function of the seismicity pattern.

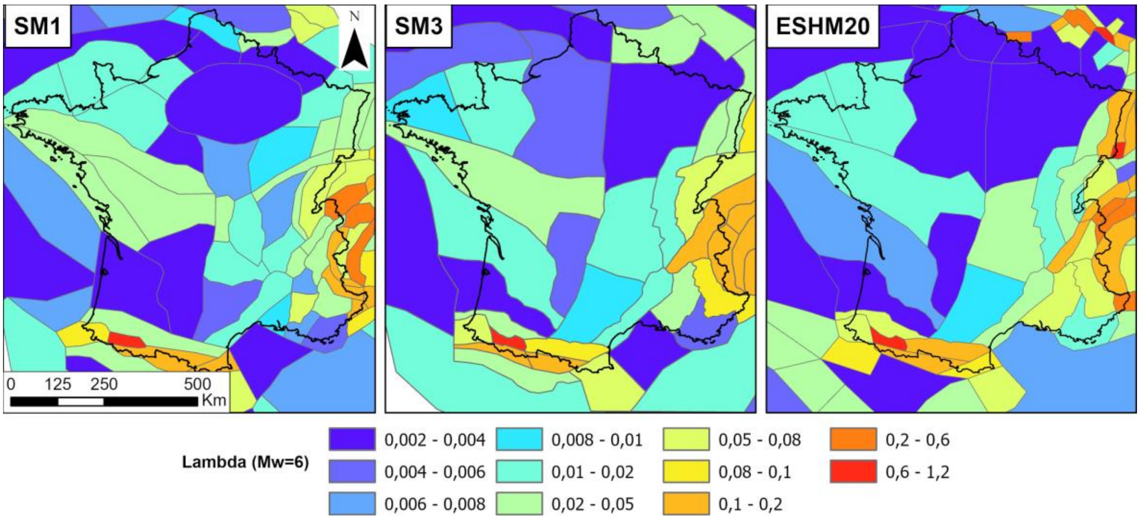

Figure 3. Comparison of activity rates, cumulated by million km², for $M_w \geq 6.0$ between SM1, SM3 (based on IRSN model geometries with additional zones at the borders) and the ESHM20 volume source model.

Predicted activity rates

The comparison of the activity rates predicted using the ESHM20 and our SM1 model highlights significant differences (Figure 3). These differences result, on one hand, from the use of different geometries of source zones. Higher rates are predicted in the ESHM20 model for the Rhine Graben region, where smaller zones tend to concentrate the activity. On the other hand, the difference between the rates computed for the IRSN zones based on our catalogue (SM3, Figure 3) and ESHM20 for similar geometries shows the influence of the different seismicity catalogues used. This effect may be observed in the South of the Armorican Massif, where ESHM20 predicts lower activity rates on average. The predicted rates are closer for the most active zones of the Pyrenees and the Alps.

Ground Motion Characterization (GMC)

The objective of the GMC model is to capture the epistemic uncertainties and aleatory variability in ground-motion estimates for the target site/region.

In DR20, a multi-GMPEs approach was followed and the four models of Ameri et al. (2017), Abrahamson et al. (2014), Cauzzi et al. (2015) and Drouet & Cotton (2015) were used, with equal weights, all over France. In the ESHM20, a scaled backbone approach was followed (Weatherill et al. 2020) and a logic tree was used to account for epistemic uncertainties in distance attenuation and source term (i.e., stress parameter), which were found to vary spatially (Kotha et al. 2020). Five regional clusters (plus one default region) are proposed in order to capture regional variations in large distance attenuation whereas no regionalization of the source term is implemented. The west of France, including the Pyrenees region, is characterized by a “very-slow” attenuation (cluster region 5) whereas the French Alps and Rhine Graben are denoted as “central-fast” and “central-slow” attenuation regions, respectively (cluster region 2 and 1). The rest of France is included in the “default” zone.

In our approach, we first compare for each target site in the regional hazard models the spectral acceleration estimates obtained using the Weatherill et al. (2020) backbone GMM and the multi-GMPEs approach using a large set of GMPEs passing a series of quality and applicability criteria (Cotton et al. 2006). The comparison is done in the hazard space in order to account for the full ground-motion distribution for the relevant sources contributing to the hazard at several return periods. An example of such comparison for a return period of 3000 years is presented in Figure 4 for two different regions in France.

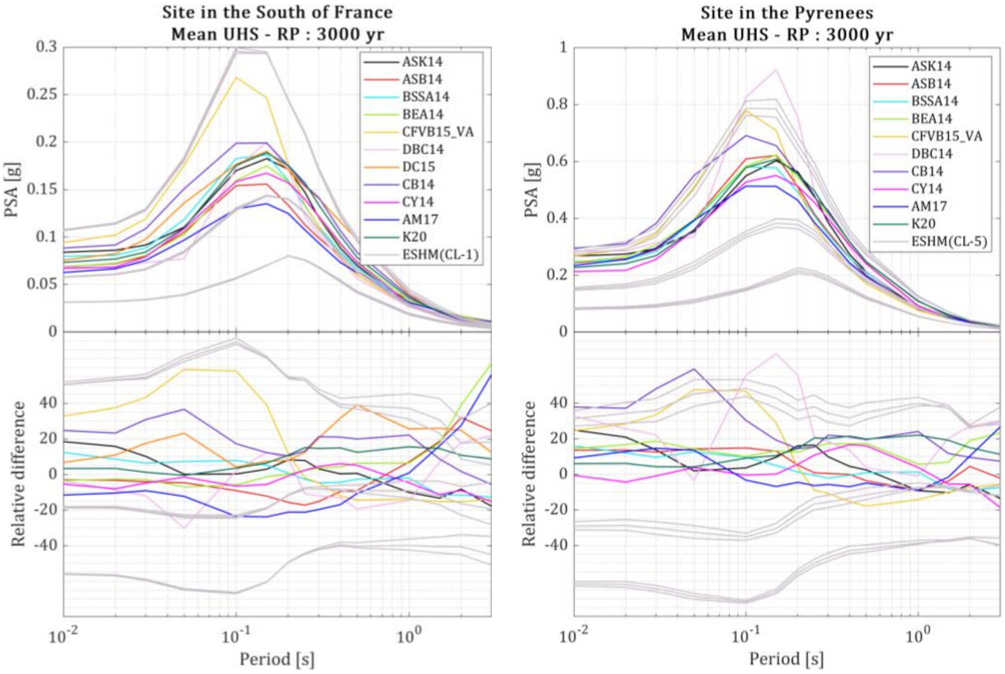

Figure 4. Comparison of the uniform hazard spectra (top) and relative differences with respect to the median UHS (bottom) for two sites in France, calculated using equal weights for different GMPEs^{2}*, with Vs30 = 800 m/s. Return period: 3,000 years.*

As a general trend we observe, for the return periods of interest for critical facilities, that: (1) the attenuation branches of the ESHM20 GMM have small impact on the hazard because most of the contributing sources in France are within at short-to-moderate distances (< 50 km); (2) the source term branches have large impact on the hazard. It is noted however that the source terms are not regionalized in ESHM20, and the epistemic uncertainties are thus controlled by stress parameter variations all over the Pan-European region; (3) the hazard estimates from the multi-GMPEs tend to be included between the central and the upper branches of the source term of the ESHM20 GMM.

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[2] Ameri et al. (2017), AM17, Akkar et al. (2014), ASB14, Bindi et al. (2014), BEA14, Boore et al. (2014), BSSA14, Cauzzi et al. (2015), CFVB15, Campbell & Bozorgnia (2014), CB14, Abrahamson et al. (2014), ASK14, Chiou & Youngs (2014), CY14, Derras et al. (2014), DCB14, Drouet & Cotton (2015), DC15, Kotha et al. (2020), K20.

Based on such results it was decided to adopt the multi-GMPEs approach. For each target site, sensitivity analyses such as the one presented in Figure 4 were used to assess the range of epistemic uncertainties covered. Then a subset of minimum 6 GMPEs was selected to represent central, lower and upper branches of the ground motion distribution in the hazard space over the spectral periods of interest for the target structure.

The currently adopted GMC model for the comparisons presented in this contribution will be further investigated to assess whether the epistemic uncertainties are sufficiently captured. Revisions will certainly be undertaken to move towards non-ergodic models (e.g., Sung et al. 2022).

Building of the Logic-tree

In this study, for building the logic tree, we started from a pilot logic tree that includes all the models mentioned in the previous two sections, and consequently the sensitivity and disaggregation studies are carried out at each specific site to identify the components of the SSC and GMC models that affect the most the hazard estimates at that site and the related uncertainties. Compared to national and European models, the logic tree is revised and adapted for each specific site to account for the seismotectonic and geological context and the available data at the near regional scale, as for most sites the controlling sources are within a radius less than 100 km, except for very low frequencies. As moving toward more local/regional model, the complexity of the logic tree increases leading to larger computational time which is certainly one of reason for the simpler logic trees typically observed for large scale hazard models.

In this study, weights for the SSC logic-tree are assigned to the different branches to value the models relying on the best state of knowledge and/or on the most credible zonings are considered. Concerning the GMC logic-tree, the models far from the mean which show high values of relative differences, are assigned a lower weight, and models near the centre of the distribution, with lower relative differences, are assigned a higher weight.

Comparison of PSHA results

The hazard is computed for spectral periods between 0.01s and 3s at standard rock conditions with Vs,30 = 800 m/s, and for probabilities of exceedance from 0.5% to 40% in 50 years (100 to 10000 years return periods). The PSHA calculations were performed with SEISTER in-house verified and validated software SHEAR and with a minimum magnitude of Mw = 4.5.

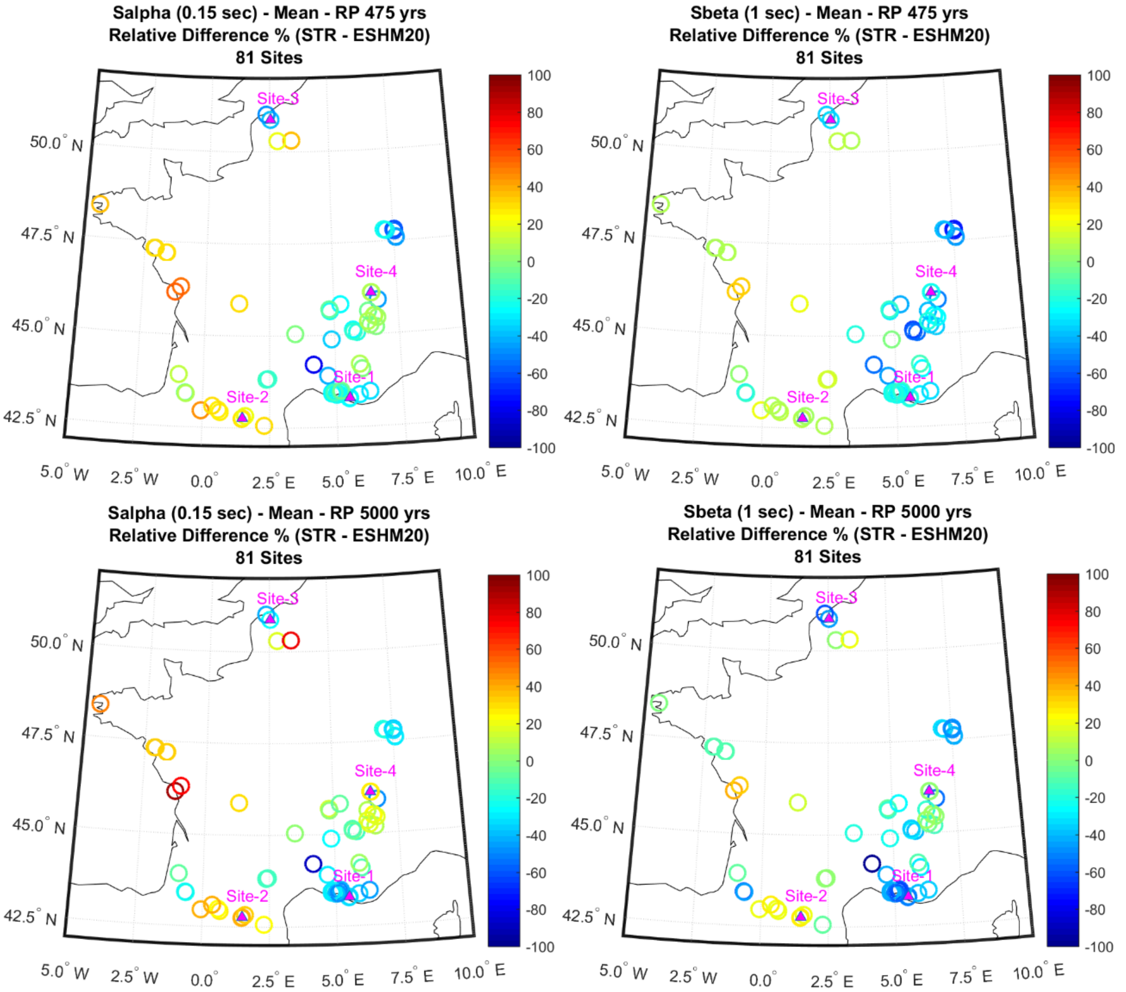
In the first step, the spectral acceleration parameters Sα (T=0.15s) and Sβ (T=1.0s) are compared with the results of the recently published ESHM20 model by plotting the relative difference (%) of the two models for different sites in France. These plots are provided in Figure 5 for return periods of 475 and 5000 years. The positions of four sites for which the calculated hazard curves will be compared with ESHM20 and DR20 models in the next step are shown with magenta triangles.

For the spectral period of 0.15 s and return period of 475 years (Figure 5), the mean spectral acceleration in our model is higher, up to 40% for the sites in the Pyrenees and in the western France. This observation comes mostly from the higher activity rates in our model in this region particularly in western France. For the sites in the Alps, the spectral acceleration is relatively higher in our model up to 10%-20%, while at the sites in the south, the acceleration is up to 35% lower due to higher activity rates in the ESHM20 model in this region. For the sites in the north, there is no clear tendency, for two sites in the extreme northern part, our model leads to lower values while for two other sites, exactly opposite is observed.

Overall, a similar tendency is observed at national scale for return period of 5000 years except for some sites particularly in the west and in the Alps where the difference is more significant. This might be due to a more important contribution of the faults at higher return periods.

At high spectral period (1.0s), the ground motion in our model is higher up to 20% for the sites in the Pyrenees, up to 40% for the sites in the west, and lower up to 50% for the sites in the south. At the Alpine sites, there is a reduction of spectral acceleration up to 60% with respect to the ESHM20 model for the return period of 475 years while for the return period of 5000 years, there is an increase for some sites (up to 5%) and a decrease for the others (up to 50%).

The are many reasons behind the observed differences, from the earthquake catalogue used and the difference in the activity rates computed, to the seismogenic source model and ground motion model logic trees. The ESHM20 model is developed at European scale while our results are the output of a model developed at national scale but revised and adapted for each specific site to account for the seismotectonic and geological context and the available data at the near-regional scale.


Salpha (0.15 sec) - Mean - RP 475 yrs
Relative Difference % (STR - ESHM20)
81 Sites

Sbeta (1 sec) - Mean - RP 475 yrs
Relative Difference % (STR - ESHM20)
81 Sites

Salpha (0.15 sec) - Mean - RP 5000 yrs
Relative Difference % (STR - ESHM20)
81 Sites

Sbeta (1 sec) - Mean - RP 5000 yrs
Relative Difference % (STR - ESHM20)
81 Sites

Figure 5. Relative difference (%) in terms of mean spectral acceleration parameters Sα(T=0.15s) and Sβ(T=1.0s), between the current study (STR) and the European Seismic Hazard Model, ESHM20 (Danciu et al. 2021). Return periods of 475 and 5000 years. Four sites selected for comparison of the hazard curves are shown in magenta triangles.

In a second step, the results of this study in terms of hazard curves are compared with the national model by DR20 and the ESHM20 model. For this purpose, four sites have been selected, each located in different seismotectonic contexts. One is situated in the southeast (Site-1), one in the active region of the Pyrenees (Site-2), one in the low-seismicity zones in the north (Site-3) and one in the active region of the Alps (Site-4). The location of these sites was illustrated in the maps of Figure 5. The comparison is performed for spectral periods of 0.2s and 1.0s as shown in Figure 6. It should be mentioned that the hazard model presented by DR20 was developed with the aim of producing hazard maps for 475 years return period and they present in their paper the hazard curves for only two specific sites up to a return period of 1000 years. Therefore, we should be careful in comparing the results at higher return periods. Furthermore, the ESHM20 model provides hazard maps for return periods of 50, 475, 975, 2500 and 5000 years, even though in their database the hazard curves are provided for higher return periods as well.

For spectral periods of 0.2s and 1.0s, and at return period of 475 years, the mean spectral acceleration at the Site-1 obtained by the ESHM20 model is higher than the DR20 and our study by 20%-30%, mostly because of the higher activity rates computed by the former (as shown in Figure 3). The hazard curves at the site in the north obtained by our model, at spectral periods of 0.2s and 1.0s are showing lower spectral accelerations at return periods between

475 and 10000 years (10%-30%). In the Pyrenees and at a short spectral period of 0.2s, the mean hazard curve obtained by our model is considerably higher than the other two models up to 25% at return period of 475 and 50% at 10000 years. This is also due to the fact that a higher activity rate is computed for this region in our model. However, at a spectral period of 1.0s, the three hazard curves are much closer to each other. In the Alps, the DR20 model provides higher values for the hazard curves at both spectral periods by 30%-50%. At a spectral period of 0.2s, the hazard curves obtained by our model and the ESHM20 are very close at shorter return period of 475 years while they diverge by reducing the annual probability of exceedance (i.e., increasing the return period). This is coming most probably from the specific 3D modelling of the faults in our model which was not taken into account in the DR20 model. In addition, the DR20 model is a model developed at French national scale with one logic tree for every calculation point while our model is more a site specific one with a more complex logic tree adapted and revised for each single site based on the local seismological and geological data.

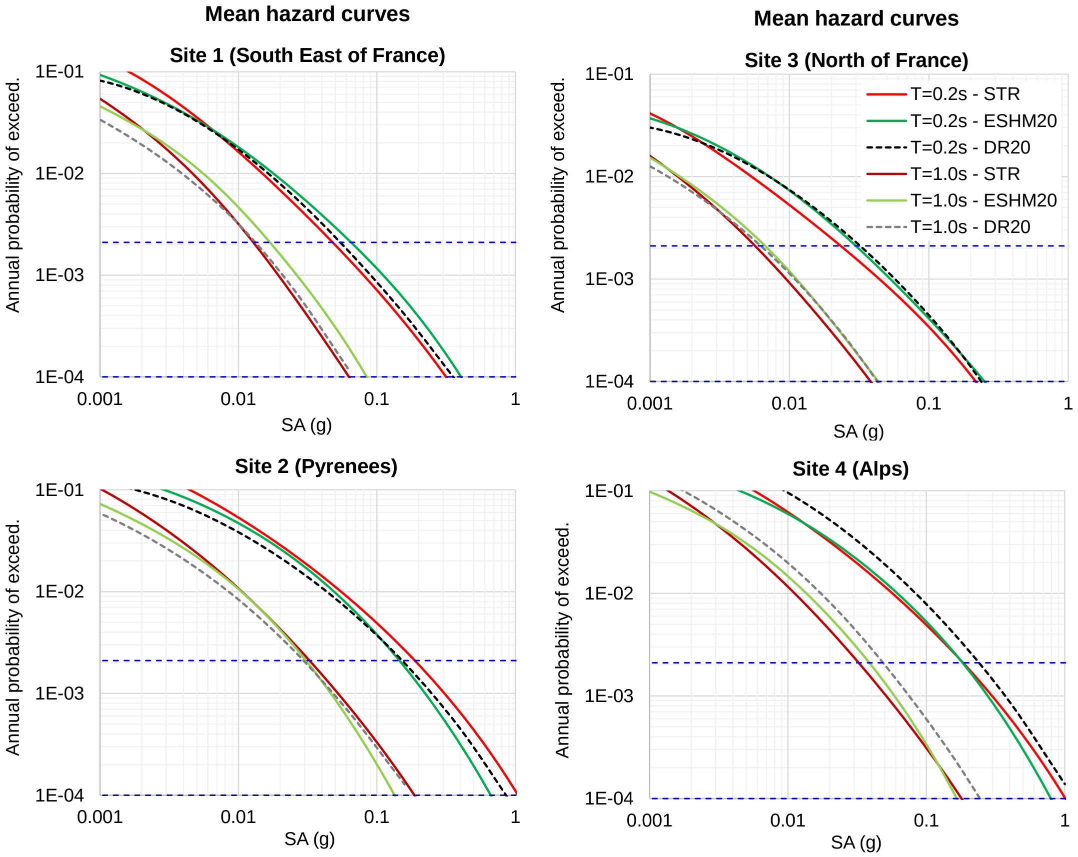


Figure 6. Mean hazard curves obtained in this study (STR), the ESHM20 (Danciu et al. 2021) and the national model by Drouet et al. (2020) for four sites in France and for spectral periods of 0.2s and 1.0s. Return periods of 475 and 10000 years are shown by dashed blue lines.

Conclusion

In this study, the probabilistic seismic hazard assessment model for metropolitan France has been updated by considering a recently developed earthquake catalogue at the scale of Western Europe and an updated SSC model developed at regional scale. This study accounts for both aleatory and epistemic uncertainties and the SSC and GMC logic trees are adapted for each specific site to account for the seismotectonic and geological data at the appropriate scale.

The spectral acceleration and hazard curves are compared with DR20 and ESHM20 models, for several sites in France and in different seismotectonic contexts. The comparison with ESHM20 demonstrates more similar results in the active regions such as the Alps while the difference increases at less active regions such as in the south-east. There might be various reasons for such differences, from the earthquake catalogue and the activity rates computed, to the SSC models used. The ESHM20 model is developed at European scale while our model is developed at regional scale but revised and adapted for each specific site. The same observation can be made when comparing our model to the DR20 model where the same SSC and GMM logic trees are used for every calculation point at national scale. In general, where performing seismic hazard assessment for a specific site, use of regional/local models may be preferred with respect to more large-scale ones.

The current seismic hazard model for France is still in continuous evolution and revisions are ongoing to further asses if the epistemic uncertainties are captured sufficiently for SSC and GMC models. Regarding the former, the improvements may also concern the introduction of all potentially active fault sources at national scale and for GMC model, revisions will certainly be carried out to account more specifically for regional ground motion data, where available. In addition, there will be a significant effort for collecting new local data to establish more reliable site-specific hazard estimates.

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