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PROBABILISTIC SEISMIC HAZARD ANALYSIS: ISSUES AND CHALLENGES FROM THE GEM PERSPECTIVE

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ABSTRACT

Probabilistic Seismic Hazard Analysis (PSHA) is a practical framework, with a sound theoretical basis, used globally for assessing seismic hazard at different spatial scales to suit many different objectives. Soon after its establishment in the late 1960s, communities involved in PSHA for national seismic hazard mapping and for the siting and design of nuclear facilities led the development of this scientific-technical discipline. In recent years, other scientific and commercial sectors introduced specialised modelling approaches such as the ones shaped by the community serving the financial sector and, most recently, the research groups involved in infrastructure and man-made earthquake hazard and risk analysis.
Notwithstanding the current extensive acceptance and use of PSHA, there remain many challenges in the modelling process owing to the complexity of the underlying natural phenomena, the paucity of the information so far collected and the overall lack of standardisation and consensus on techniques to be used in the construction of hazard models. Projects and activities aiming at building new models, at harmonising and improving methodologies, at building consent on the methods and tools used for various analyses and research, especially on the construction of hazard models are still greatly needed. Since its inception in 2009, the hazard component of the Global Earthquake Model initiative worked at (1) developing open-source datasets and tools for the construction of hazard models and for their calculation and at (2) creating a mosaic of openly accessible hazard models leveraging from the extensive set of products distributed by the global community involved in PSHA at national and regional scale. This set of tools and models is an insightful perspective on the current state-of-practice in PSHA at the global scale that helps in highlighting controversial aspects and possible areas for further improvement. We summarise the experience gained by the GEM hazard team throughout the past few years on hazard modelling and we outline some possible directions toward which GEM aims to advance within the end of the second implementation phase in 2018.

Keywords: Probabilistic Seismic Hazard

INTRODUCTION

Probabilistic Seismic Hazard Analysis (PSHA) is a scientific branch of knowledge that connects and leverage upon fundamental research done in several scientific and technical disciplines such as earthquake geology, tectonics, seismology, engineering seismology and geotechnical earthquake engineering. Improvements, challenges and issues in PSHA derive from a multitude of contributions and influences coming from a wide community of scientists and engineers involved in PSHA studies performed at different spatial resolution and with various characteristics and goals, across the world. Diverse scientific and commercial sectors use seismic hazard results for different purposes using, very often, tailored methodologies. For example, in the catastrophe modelling industry probabilistic seismic hazard analysis is always performed using the so-called event-based or Monte Carlo based approach (Musson, 1999), whereas in the nuclear sector most of the focus is on capturing the set of epistemic uncertainties controlling the overall variability in the computed results at low probabilities of exceedance (Bommer, 2012).

The Global Earthquake Model initiative (GEM herein) is a public-private partnership that promotes open and reproducible seismic hazard and risk models. The hazard component of GEM is presently leading the development of a suite of open-source datasets and tools for the construction of hazard models and for their calculation. It also coordinates the construction of a mosaic of openly accessible hazard models (see Figure 1), leveraging from the set of models distributed by the global community involved in PSHA at national and regional scale. The collection of hazard models so far incorporated into this mosaic is accessible through the web-based OpenQuake platform at the following link http://platform.openquake.org (last accessed on May 23rd 2016). By the end of 2018 GEM will conclude the compilation of this mosaic of hazard models and will return to the community a suite of open PSHA models with a complete global coverage represented following a default data format.

In this paper, using the experiences collected while performing the aforementioned tasks, we discuss some of the most controversial and challenging aspects, which emerged throughout the years and we illustrate some of the datasets and methodologies we would like to incorporate in the future. The paper is organized in a number of sections each one discussing a particular component of the process leading from the basic datasets until the calculation of the final PSHA results starting from basic datasets until the calculation of hazard.

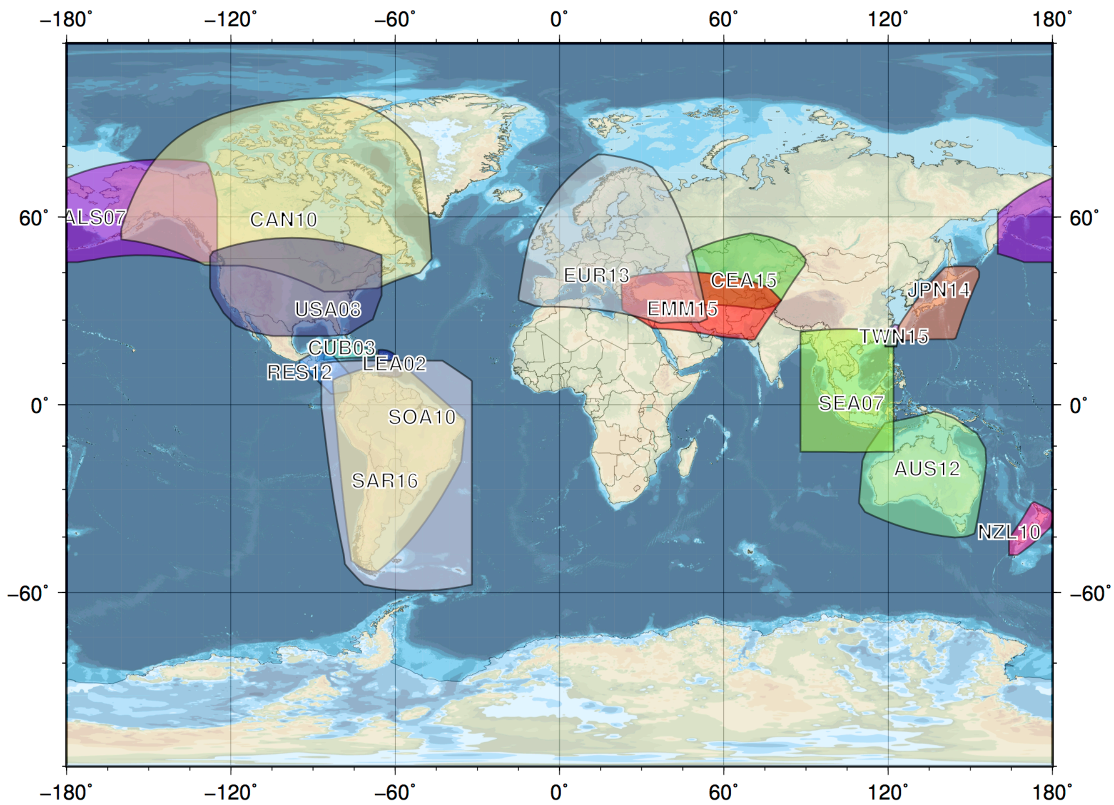

Figure 1 - Current status of the global mosaic of hazard models collected by GEM (model acronyms: ALS07: Alaska; AUS12: Australia; CAN10: Canada; CEA15: Central Asia; CUB02: Cuba; LEA02: Lesser Antilles; EMM15: Middle East; EUR13: Europe; JPN14: Japan; NZL10; New Zealand; RES12: Central America; SAR16: South America; SOA10: South America; TWN15: Taiwan; USA08: United States)

BASIC DATASETS AND DATA PRE-PROCESSING

It is well-established practice that seismic hazard analysis projects must be founded on a solid set of basic and homogenised information. Based on this simple principle, GEM sponsored five international projects aimed at the construction of either a global uniform dataset or of guidelines providing recommendations on the procedures to be used for the construction of a component of a PSHA input model (Pagani et al., 2015). The principal goal of these projects was to provide the global scientific community with uniform datasets to be considered in the construction of new hazard models. If successful, this will promote the creation of more rational hazard models in various areas of the world. All these projects were positively completed within 2014, nonetheless, by the time of their conclusion it emerged clearly the necessity and the importance of complementing these high-quality datasets with new or supplementary information.

Active fault databases

In modern PSHA, Earthquake Source Models (ESMs) must include active fault sources to the largest extent possible. One of the global GEM sponsored projects focused on (a) designing a database structure for collecting the information considered relevant for the description of active fault data and the construction of sources and on (b) the harmonization into this database of the various datasets available across the world. The project – called Faulted Earth (Christophersen et al., 2015) – was able to collate active fault data from many countries (including Japan, United States, New Zealand), but missed the information needed to comprehensively describe vast areas for which national active fault databases were not available or easily accessible (e.g. Latin America, Africa and vast portions of Asia). To fill these gaps, GEM currently faces the challenge of promoting and supporting new activities aiming at the systematic collection of information on active fault data already available in the scientific literature and, in parallel, promoting a common format for storing and exchanging data effortlessly. The need for a community-based data format descends from the recognition that the idea of a centralized database was erroneous and that a decentralized model might be more effective in harmonizing the wealth of information produced in the earthquake geology community.

Earthquake catalogues and associated pre-processing procedures

Past seismicity is a primary source of information for the characterization of earthquake sources yet most of the historical seismicity information is collected in a heterogeneous way. Leveraging on research performed in different areas of the world (e.g. Beauval et al., 2013) the GEM hazard team developed a tool for merging various catalogues into a uniform one using a completely reproducible and customizable methodology (Weatherill et al., 2016). Using this tool is now possible to combine a high quality catalogue like the ISC-GEM (Storchak et al., 2015) covering the mid and high magnitude range with other global and regional catalogues (e.g. the GCMT) and local catalogues containing magnitudes in the mid and low range. The inclusion of the latter is essential for a stable estimation of the parameters characterizing the magnitude-frequency distribution (MFD). This tool was already applied in various regions across the world including South America, Sub-Saharan Africa as well as at the global scale. However, the construction of a homogenous earthquake catalogue is just a first step in the process aiming at the characterization of earthquake sources using past seismicity.

The definition of earthquake recurrence habitually entails the removal of foreshocks-aftershocks i.e. declustering, the definition of a set of time-magnitude windows within which the catalogue can be considered complete, the possible construction of sub-catalogues for the various earthquake sources in a model (e.g. in the case of an area source this can be created by selecting the earthquakes whose epicentre is within the polygon defining the source boundary), and, the calculation of the parameters of the selected MFD for each source. The removal of aftershocks and foreshocks is a practical operation performed in PSHA to guarantee that the earthquakes used for the characterization of sources can be considered independent. Declustering is an operation often prompting discussion since the percentage of earthquakes removed from the original catalogue can vary considerably based on the algorithm used and on the values of the parameters controlling its functioning. For example, in the recently completed Hanford SSHAC level 3 project (Coppersmith et al., 2014) four declustering algorithms were used: the original Gardner and Knopoff (1974; GK herein) algorithm, two modified versions of the GK algorithm (Grünthal, 1985; Uhrhammer, 1986) and the one based on the EPRI/SOG methodology (EPRI, 1986). Considering the magnitude range between 4 and 4.5 and for the "completeness region north" catalogue, the selected algorithms remove a percentage of earthquakes between 13 and 25. On the contrary, the declustering procedure used for the construction of the 2013 European hazard model SHARE (Woessner et al., 2015) was the one proposed by Burkhardt and Grünthal (2009); with this methodology only 26% of the earthquakes in the original catalogue were included in its declustered version and successively used for the characterisation of earthquake sources.

At least two are the key issues related to the declustering of earthquakes catalogues for PSHA. The first one pertains with the possible use of different declustering algorithm (or different declustering parameters) in different tectonic regions. The second one relates with the verification that the computed declustered catalogue fits the original purpose. Yet, despite the overall goal of the declustering procedure in PSHA is to obtain the largest catalogue of independent events, a posteriori verifications (e.g. Luen and Stark, 2012) are rarely performed – or hardly included – in the documentation accompanying a PSHA study.

Strong ground-motion recordings

Ground Motion Prediction Equations are an essential component of a PSHA Input Model used to compute the mean and standard deviation of a Gaussian distribution describing at each site of interest the distribution of the logarithm of the ground-motion generated by a given rupture in a specific tectonic context. Considering the nature of these models and the need to test their validity and performance against observations within specific regions, the availability of large sets of strong motion recording is essential for a reliable calculation of hazard. However, despite the progress made over the last decade in the construction of openly available strong motion databases, their accessibility remains quite limited in wide areas of various continents where often knowledge on the characteristic of ground-motion is inadequate. For example, strong-motion recordings of large events occurred along the East African Rift are quite scarce despite the earthquake potential and the level of risk in the region is considerable.

A second critical point that could help in improving the consistency between the ruptures used in the construction of "flat-files" like the ones released by the Pacific Earthquake Engineering Centre and the modelling of finite ruptures in PSHA would be the regular definition of the geometry of the ruptures used for the calculation of the rupture-station distances during the construction of the strong-motion database. The availability of these ruptures – including their geometry[1] – would be particularly helpful for example in the selection of the magnitude-scaling relationships used for the determination of the geometry of ruptures during the calculation of hazard. At present the selection of these relationships is completed using expert judgement or general criteria defined in the scientific literature (e.g. Stirling et al., 2013).

BUILDING THE EARTHQUAKE SOURCE MODEL

The construction of the Earthquake Source Model is one of the most complex aspects of a Probabilistic Seismic Hazard Analysis. The modeller usually faces several issues during this phase in a majority of cases related with the limited amount of information available. In this the following sections we consider some of the problems, which emerged more prominently in modelling seismic hazard at regional and national level.

Combining faults and distributed seismicity sources

An Earthquake Source Model usually consists of a list of sources belonging to three main categories: distributed seismicity, shallow faults and subduction faults. In the simplest case, when epistemic uncertainties are not considered, the sources belonging to the three categories are developed independently and they are combined into a single model during the final stages of the ESM building process.

At present, the criteria used to combine the various categories of sources vary from model to model. For example, the most recent model for New Zealand (Stirling et al., 2012) contains shallow faults, subduction interface faults and distributed seismicity. The former two have a characteristic magnitude-frequency distribution[2] while the MFD used for the latter source typology is a double

[1] The NGA-WEST2 project released information including some finite fault ruptures used for the construction of the strong-motion database (http://peer.berkeley.edu/ngawest2/databases/; last accessed, June 2016).
[2] In the context here discussed a characteristic MFD is a distribution that associates a single value of magnitude to a rate of occurrence.

truncated Gutenberg-Richter distribution. Stirling et al. combined the three categories of sources under the assumption that double-counting occurrences with this combination of sources is negligible.

As a second example is the SHARE hazard model recently developed for Europe (Woessner et al., 2015). One out of the three ESM developed within SHARE combines large background area sources with shallow faults. In this case the characterisation of fault sources and the background area sources was completed assuming that within each background (BG) area the seismicity occurrence is controlled by the slip rates assigned to the fault sources within the polygon delimiting the background source. Earthquakes of magnitude lower than 6.5 occur uniformly over the area of the BG area and ruptures with magnitude larger than 6.5 are restrained to occur only on the fault sources. The MFD used for the faults and the BG area source is a double-truncated GR distribution; the MFD for the area source is computed by stacking the MFDs obtained for each single fault source in the encompassing polygon. Past seismicity is used to define the value of b of the Gutenberg-Richter relationship used for both the typologies of sources. While consistent in terms of overall moment balancing, this methodology also contains particular assumptions. For example, the database of faults is supposed to be spatially complete above magnitude 6.5 and – since the geologically derived slip rates are used without being scaled – seismic coupling is full and the contribution of aftershocks and foreshocks negligible.

In the hazard models published in 2008 and 2014 by the United States Geological Survey for the Conterminous United States (Petersen et al., 2008; Petersen et al., 2014), inshore seismicity is modelled using a combination of gridded seismicity sources obtained from smoothing past earthquakes and shallow fault sources. The MFD used for the description of earthquake occurrence on gridded seismicity is a double-truncated GR whose maximum magnitude reaches 7.0 for the 2008 model and 7.5 for the 2014. The magnitude-frequency distribution used for faults starts from a magnitude equal to 6.5, hence there is an overlapping between the MFDs assigned to faults and the MFDs describing earthquake occurrence for the distributed seismicity. In California, in order to avoid possible double-counting and to maintain to the extent possible consistency between past seismicity and the one defined by the ESM, the USGS reduced by two thirds the occurrence of earthquakes above magnitude 6.5 for distributed seismicity sources (Petersen et al., 2008; page 21). This scaling factor was obtained from empirical observations, i.e. about two thirds of past seismicity with magnitude larger than 6.5 occurred on known faults. Extrapolating this ratio between on-fault and off-fault seismicity to other regions is clearly not possible since it depends on the characteristics and the completeness of the fault database. In the UCERF3 model (Field et al., 2014) in order to separate the seismicity occurring on faults from the one assigned to the background sources they introduced they concept of fault zone polygon. Each fault zone polygon includes either a fault section or a system of faults. The seismicity included in each polygon is supposed to occur on the fault surface to which the polygon is associated with.

Figure 2 shows an idealised demonstration of the potential impact on hazard results of different approaches for combining faults and distributed seismicity. In this example, the Earthquake Source Model contains one area source and one shallow fault. In Figure 2(a), the boundary of the area source is the blue dashed line while the filled polygon shows the surface projection of the fault surface. Insets from (b) to (d) show different discrete magnitude frequency distributions. Figure 2(b) displays the MFDs assigned to the two sources in a first test case. The MFD for the area source (green squares) has a minimum magnitude equal to 5 and a maximum magnitude of 6.5, while the MFD for the fault is comprised between 6 and 7. Since the two MFD overlaps inside an interval of 0.5 units, the total MFD (i.e. the MFD obtained by summing the MFD for all the sources – see blue crosses in Figure 2(b)) shows between 6.0 and 6.5 an anomalous protuberance. So as to attenuate this effect, one option is to convert the area source into an equivalent grid of points and for all the points within a certain distance from the surface projection of the fault surface (or from the fault surface itself) cut their MFDs at an upper magnitude threshold corresponding to the minimum magnitude of the MFD describing the fault earthquake occurrence. Figure 2(c) displays – for a second test case – the MFDs obtained following the approach just described: the MFD for the fault is represented with green dots, and the MFDs for the point sources are displayed using purple crosses and the grey squares. Note that these MFDs have to maximum magnitude values at 6.0 and 6.5. Figure 2(a) illustrate the grid of points representing the area source; the MFDs indicated with grey crosses have a maximum magnitude equal to 6.5 whereas the MFDs with purple crosses were truncated at 6.0; the buffer distance used in this case is 20km.

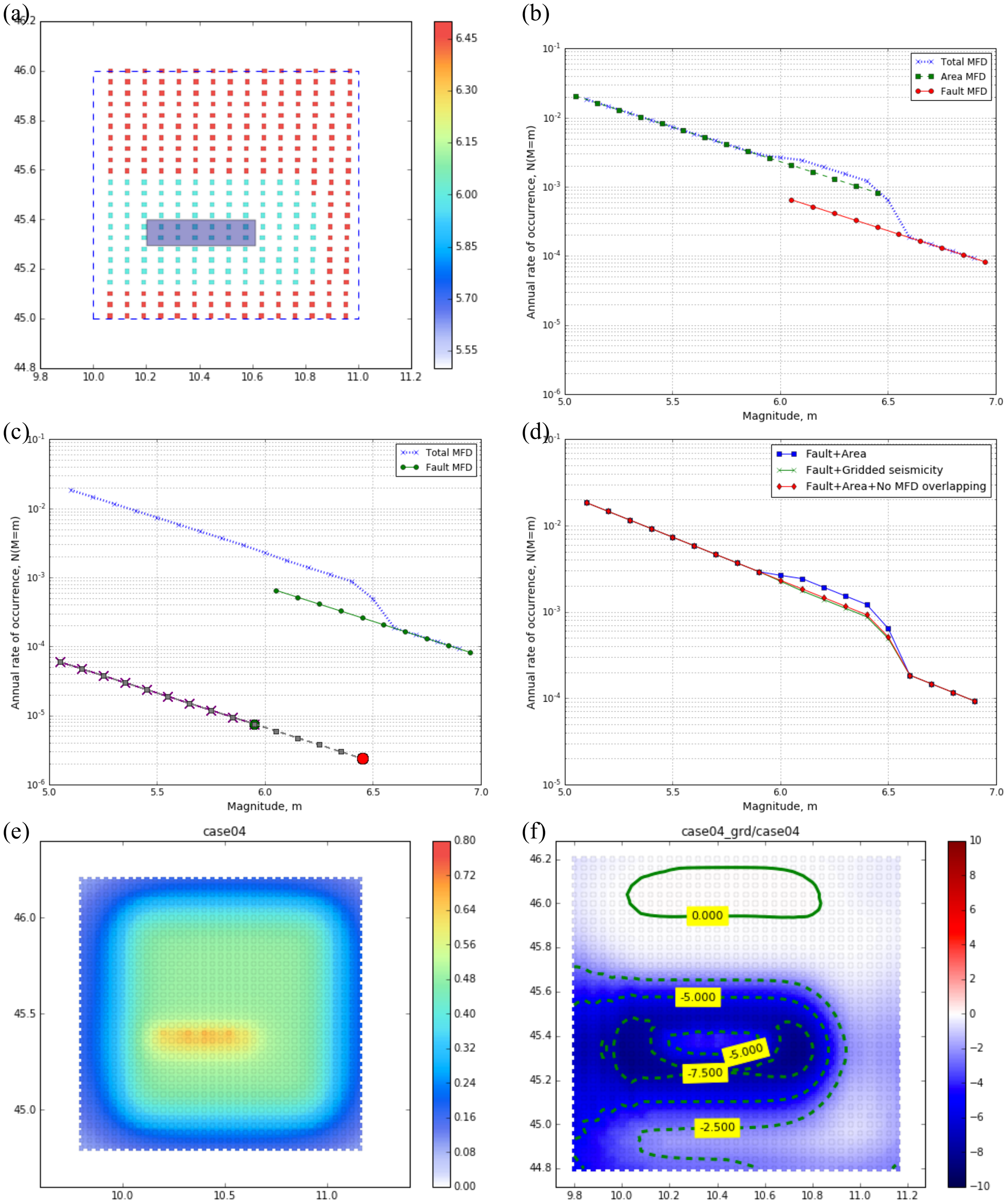

Figure 2 – Idealized example showing the impact on hazard results of different methods for combining faults and distributed seismicity. (a) Geometry of earthquake sources: blue dashed line is the source polygon while filled polygon is the surface projection of the fault surface (b) MFDs assigned to the two sources in the first test case and total MFD (blue crosses) (c) MFDs assigned to sources used in the second test case: fault MFD (green dots) and MFDs for point sources (purple crosses and grey squares) (d) Comparison between the total MFDs computed for test case 1 (blue squares) and test case 2 (green crosses) (e) Example of hazard map – PGA with 2% probability of exceedance in 50 years – computed for test case one (f) Map showing the percentage difference between the maps – PGA with 2% probability of exceedance in 50 years – computed for test case 2 and test case 1, respectively.

As it is clearly demonstrated in Figure 2(d), the protuberance in the total MFD computed using this approach (green crosses) is much less pronounced then the one obtained for the first test case (blue squares see also blue crosses in Figure 2(b)). The overall shape of the total MFD obtained for test case 2 is more in line with common observations. The bottom row of Figure 2 contains on the left one example of hazard map computed using the MFDs depicted in Figure 2(b) for PGA with 2% probability of exceedance in 50 years. The panel on the right shows instead the percentage difference between the hazard map for PGA with 2% probability of exceedance in 50 years computed for test case 2 and the corresponding one computed for test case 1. In the example considered the hazard map obtained with test case two shows values of hazard in proximity of the fault that in some points are more than 7.5% lower than the hazard computed for test case one. This clearly shows that the approach used for combining the distributed seismicity and faults can have a substantial impact on the final results computed.

Modelling of inshore shallow faults

Modern active fault databases are organized following a hierarchical structure that starts from data collected on the field by the earthquake geologists and gets until the definition of the fault source in a format suitable to be used by PSHA software for the calculation of hazard (Haller and Basili, 2011; Christophersen et al., 2015). In most of the cases, the definitions of the geometries of fault surfaces are obtained via "expert judgment" i.e. the traces observed on the field are merged into a broken line that in combination with the dip angle and the upper and lower seismogenic depths set the geometry of the fault source. The process of merging various traces into a single fault structure is often based on empirical evidence (e.g. similarity in the overall geometry between different segments) as well as on rules defining the maximum size of the steps between sections that laterally propagating ruptures can break (e.g. Wesnousky, 2008).

The problem of fault segmentation can be better addressed if analyses focused on the single fault structure are combined with studies that consider an entire fault system as a whole. The OpenQuake Hazard Modeller's Toolkit (oq-hmtk herein; Weatherill et al., 2014) – a suite of tools for the construction of earthquake source models – provide basic methods for the construction of fault sources from information collected on field but lacks of methods capable of analysing the collective behaviour of a set of faults. This ability is of particular importance when different assumptions relating to the behaviour of fault segmentation are explored – as in the case of the recently published UCERF3 model (Field et al., 2014) – but also when analysing the coherence between the deformation patterns admitted by a set of faults and the overall geodynamic evolution of the territory which includes these tectonic features (see for example Petersen et al., 2013). These additional functionalities, which are essential for the development of state-of-the-art earthquake source models, may be added to future releases of the oq-hmtk.

Modelling subduction earthquake sources

Subduction is the geodynamic process controlling the generation of the most energetic earthquakes occurring on Earth. However, the modelling of subduction earthquake sources in PSHA cannot be considered as advanced as the modelling of in-shore seismicity occurring in shallow active crust. Based on our knowledge, the number of hazard models encompassing subduction sources currently openly accessible is limited. Some of the most relevant are: the USGS 2014 model (Petersen et al., 2014), the 2014 hazard model for Japan, the Taiwan model developed by TEM (Wang et al., 2016), the 2010 New Zealand hazard model (Stirling et al., 2012), the SHARE hazard model for Europe (Woessner et al., 2015).

Over the last couple of years GEM coordinated an earthquake hazard and risk project in South America (SARA herein; see Garcia et al., 2017). One of the major objectives of this project was the construction of an open hazard model by incorporating as much as possible contributions from the local community of scientists. GEM's participation to this project helped to emphasize some of the most outstanding issues in modelling hazard in the subduction tectonic environment. A first important aspect was the definition of the overall geometry of the interface surface and of the seismogenic portion of the slab. Various methodologies for the definition of the subduction interface surface based upon the geographic distribution of hypocentral locations of past earthquakes appeared in the recent scientific literature (e.g. Heuret et al., 2011; Hayes et al., 2012). This is also the approach that was implemented in the development of the SARA subduction model although the use of past seismicity proved to be particularly challenging because of the difficulty of assigning earthquakes to the various seismogenic domains (i.e. active shallow crust, subduction interface and subduction inslab). A second extremely challenging problem we faced in the construction of subduction PSHA input models was the definition of segments along the interface. Amongst the various implications of a segmentation model, some of the most relevant with respect to the modelling of hazard are the definition the geometry and position of the modelled ruptures, and the definition of the maximum magnitude admitted along portions of a large subduction structure. A third issue was the modelling on ruptures generated within the slab during the calculation of hazard; a comprehensive discussion of this aspect can be found in Weatherill et al. (2017).

GROUND-MOTION MODELLING

Ground-motion modelling is a scientific discipline, which rapidly progressed over the last decades thank to the expansion of strong-motion networks and the number of recordings available. However, the selection of the most proper Ground Motion Prediction Equations – and their possible adjustment – continue to be a quite delicate and complex phase of the PSHA input model construction. A vast portion of the recent scientific production on this subject focused on methodologies aimed at adjusting the GMPE to single site characteristics (Douglas and Edwards, 2016). However, we neglect this part here since the focus of this paper is mostly on modelling hazard at national and regional level and we briefly illustrate one of the most outstanding aspects of ground-motion modelling in PSHA analysis at national and regional level, which, in our opinion, is the construction of tectonic regionalisation and the methodologies to be adopted for this purpose.

Tectonic Regionalisation

In modern regional or national hazard models the link between the earthquake sources included in a ESM and the corresponding Ground-Motion model is defined, more or less explicitly, through the so called “tectonic regionalisation” (Delavaud et al., 2012; Garcia et al., 2012). A tectonic regionalisation (herein TR) divides a territory in a number of areas each one described in terms of distinctive source characteristics and attenuation properties of the Earth crust. During the model building phase a TR can be applied for the classification of the strong motion recordings to be used for the selection of the best ground-motion prediction equations in each tectonic region.

GEM over the past few years worked at the development of a flexible and reproducible methodology for the construction of a TR applicable at the global scale (Chen et al., 2017). However, this is just a prototypal research and more work is certainly needed at the regional and national scales for testing similar approaches and developing research within this field. In particular, we believe that the modelling of ground-motion and the associated uncertainties - either defined using a classical approach based on a selection of GMPEs or through a backbone approach as recently proposed by Atkinson et al. (2014) – should be guided by an associated TR. This TR is essential for guiding the selection and the characterisation of empirical data to be used (e.g. recordings available in the investigated tectonic region and – eventually – from tectonically similar areas).

CALCULATION OF PROBABILISTIC SEISMIC HAZARD

Modelling of epistemic uncertainty in national and regional hazard models

Over the past decade accounting for epistemic uncertainties - particularly in the case of critical facilities studies - has become standard practice in probabilistic seismic hazard analysis (Bommer and Scherbaum, 2008; Bommer, 2013). However, for studies conducted at national and regional scale the use logic trees with a structure similar to the one used for site-specific studies is not feasible because of the computational demand and the lack of indispensable information. At present, epistemic uncertainties are considered in a small subset of the national and regional hazard models accessible globally. Moreover, uncertainties related to the ground motion model are more frequently considered than the uncertainty affecting the earthquake sources.

For example, in the GEM database of hazard models (additional information available at https://hazardwiki.openquake.org/models; last accessed June 2016) only five out the fifteen hazard models collected incorporate epistemic uncertainties for the earthquake sources while ten models include epistemic uncertainties pertaining the ground motion modelling. It is also worth noticing that epistemic uncertainties relative to the ground motion modelling in the totality of cases considered are defined in terms of a various suites of GMPEs, one suite for each tectonic region included in the source model. Nevertheless, for the models where epistemic uncertainties are considered, the results computed often refer just to the mean hazard.

Douglas et al. (2014) analysed the range of uncertainty in the hazard results computed within various hazard assessment projects. Overall, the uncertainty range reported by Douglas et al. for regional and national hazard studies is lower than the one obtained in site-specific hazard analyses for equivalent tectonic context. This is not an unexpected outcome since the detail that can be feasibly used in the construction of regional and national models is inevitably lower than the one regularly used in the creation of site-specific hazard models. Is it therefore useful and appropriate to model epistemic uncertainties in large scale hazard models given the somewhat intrinsic impracticality of appropriately capturing the range of uncertainty in the results consistently with site-specific hazard models? In our opinion the modelling of epistemic uncertainty in this context is useful for the calculation of more robust mean results. Actually, the inclusion of epistemic uncertainties makes the final results less dependent from the particular modelling decisions that control the characteristics of a PSHA input model which neglects epistemic uncertainties. This is an approach that is used for example by the USGS for the dissemination of national seismic hazard results. In cases where the definition of epistemic uncertainties is part of the requirements clearly a very careful consideration of the results provided is recommended.

Testing and Quality Assurance

Quality assurance (QA) is a practice whose goal is to minimize the possibility of making mistakes or introducing defects during the production process. In hazard analysis, quality assurance is a relatively new concept, which is receiving increasing importance and attention primarily within site-specific hazard analyses (Bommer et al., 2013; International Atomic Energy Agency, 2010; Arvidsson et al., 2012; See also Appendix L of EPRI, 2012). In the PSHA process, QA procedures should be applied: (a) to the procedures adopted for the collection and the pre-processing of basic information (b) to the entire process followed for the construction of the earthquake source model and the ground motion model (c) to the hazard calculation process.

Given the strong societal impact of seismic hazard studies at national scale (e.g. definition of seismic actions for building codes, calculation of losses for the definition of risk reduction strategies) it will be critical to continue the development of QA methods and to promote a wider adoption of QA procedures in probabilistic seismic hazard analysis.

CONCLUSIONS

Despite considerable progress made over the past decades, PSHA still proposes a number of challenging and stimulating problems. We discussed some of the problematic aspects we faced and some of the possible research directions we might explore over the coming years.

Yet, in addition to the several scientific challenges that are still in front of us we believe there are several procedural aspects that it will be important to resolve in the near future particularly regarding the development of regional and national hazard models. Just to mention a few: (1) a more extensive adoption of processes for the construction of hazard models that consider the contributions of the whole scientific community (2) transparent procedures for the construction of PSHA input models and an open distribution of the datasets and the tools used for the preparation of these models and the calculation of the final hazard results (3) procedures for testing the models developed and for proving that the process adopted for the construction of the model matches minimal levels of quality (4) hazard testing procedures and incorporation of their results into the model building process (e.g.

Mak and Schorlemmer, 2016). A wider adoption of these concepts will increase the acceptability and the reliability of the results produced, will increase the exchange of experience amongst the scientists working at the analysis of seismic hazard and will promote the dissemination of more uniform approaches for the development and the calculation of hazard.

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