Towards a new seismic hazard assessment in Spain

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ABSTRACT:
Seismic hazard is an evolving science that is fed by geological and seismological studies. As new data and models arise, the revision of hazard maps is compelling. Additionally, understanding the nature and the sources of the uncertainties involved in seismic hazard analyses is essential in order to reduce them. In this context, Spain is not an exception and a move towards a reassessment of the national hazard maps is pertinent. Several hazard-controlling factors needing to be updated and eventually revaluated are identified in this work in progress. The first one concerns the seismic catalogue. It must be homogenised, incorporating data from neighbouring countries and correlating magnitude scales for different regions and recording periods. A second factor refers to seismicity characterization by zoning and zoneless models: Neotectonic, seismological and other geological data that justify the development of a new zoning model for Spain and adjacent areas are disclosed. Revaluation of seismic areas that are traditionally considered as stable but show evidence of seismic activity at present and during Quaternary times needs to be considered. The interest of developing a neotectonic characterization of active faults is advanced. For zoneless models, the different elements that define the continuous spatial variation of the activity rate density have to be examined. For a zoneless model based on kernel functions, these elements would be the specific type of kernel function, the bandwidth and the reference years. A third factor requiring a modern analysis refers to the implementation of different strong motion prediction models. These include models based on local data and developed with data from other regions. Special attention is paid to the application of the next generation attenuation models originally developed for western North America to Spain. Criteria for selecting different models must be clearly and thoughtfully enumerated. The final goal of this work is to assess the variability of seismic hazard results to the new data and models that are becoming available. Such information will be of indubitable interest for forthcoming versions of the seismic code, national annexes of Eurocode 8 and research projects fomented by the Spanish Nuclear Security Council.

Keywords: seismic hazard, Spain, seismic catalogue, active faults, strong motion models, zoneless method

1. INTRODUCTION

The occurrence of recent earthquakes providing new data and insight into seismic processes and the development of new models representing the different phenomena involved in seismic hazard assessment make it reasonable to review and eventually reassess past work in the light of recent data and ideas.

The present work constitutes an evaluation of the situation in Spain, focusing on those aspects that may be relevant for future revisions and updates of countrywide seismic hazard studies (several studies presenting some innovative aspects have addressed particular regions of Spain only, e. g., Peláez et al. 2003, García-Mayordomo et al. 2007, Secanell et al 2008; Benito et al 2010). This is an area of low-to-moderate seismic activity and the availability of data is relatively scarce (Benito and Gaspar-Escribano 2007). Topics such as hazard calculation methods, seismic catalogue, paleoseismic data, seismic source definition, strong motion models and treatment of uncertainty are addressed below.

2. SEISMIC CATALOGUE

The seismic catalogue of the Spanish Instituto Geográfico Nacional (IGN) is the main source of earthquake data for a seismic hazard study to be developed in Spain. It comprises several revisions, updates and reassessment (Mezcua and Martinez Solares 1983; Mártinez Solares and Mezcua 2002). At present, it contains about 56000 earthquake records from year 880 b.C. (first reference) to 2009 within the geographical area limited by geographical coordinates(21° W, 23° N) and (12° E, 49° N).

The IGN catalogue may be subdivided onto three periods, according to the type of information contained: The first period is historic and may be extended to 1923. Despite there were some observatories stations operating before that year (starting in 1901, San Fernando, Cartuja, Ebro, Almería, Alicante, Toledo), the limited network coverage makes still intensity the most appropriate size parameter available for that period. From 1924 onwards, instrumental measurements and cataloguing becomes common practice.

The second period is called pre-instrumental and ranges from 1924 to 1962, when the first world standard seismic network (WSSN) stations were installed. The information contained in the IGN catalogue contains magnitude and intensity data (generally, not both for the same event). In general, magnitude estimates for this period were based on record duration (m_D) in the revision of Mezcua and Martínez-Solares (1983). During this epoch, the catalogue also contains some body-wave magnitudes (m_b) from NEIS (former USCGS) that correspond to records of offshore earthquakes (epicentre in the Alboran Sea or in the Atlantic Ocean) where duration could not be measured.

The third part of the catalogue is called the instrumental catalogue and comprises from 1963 to date. It contains instrumental data. Intensity estimates complement these data. Within the instrumental period, a further subdivision can be established attending to the development of the seismic network and the different formula adopted to calculate magnitude. Between 1963 and 1998, magnitude definition is based on the Lg phase (m_{bLg} magnitude developed by Mezcua and Martínez-Solares 1983). From 1998 onward, a body wave magnitude (m_b,), based on the formulation of Veith and Clawson (1972) is used for regional crustal events (mainly with epicentre in offshore areas and in northern Africa). Since 2002, a new fórmula for m_{bLg} is developed (López, 2008). It is referred to and calibrated to a local magnitud (Richter). During this period the m_b magnitude is still used for regional crustal events. Additionally, it is initiated and systematised the near real time calculation of M_w magnitudes (Rueda y Mezcua 2005) through the inversion of the seismic moment tensor for earthquakes exceeding a magnitude certain threshold (Dreger and Helmberger 1993).

Due to its nature, the catalogue cannot be considered homogeneous through time regarding size parameter used (intensity, different magnitude definitions and their error margins) and precision of epicentral locations. Additionally, it would be pertinent to review and complete the catalogue with information from other seismic catalogues maintained by regional or international agencies, specially for bordering areas where the seismic coverage of the network is limited or may be completed or with extra data from local sources (for instance, for historic events). Figure 1 illustrates the differences between magnitude and intensity estimates provided by the Spanish IGN catalogue and the French LDG catalogue (both based in the Lg phase) for a broad area centred in the Pyrenees. A general overestimation of magnitude by the LDG with respect to the IGN magnitude is appreciated. In turn, IGN intensity estimates are higher than LDG estimates for the same earthquakes. Figure 2 represents the magnitude estimates provided by the IGN and the IAG. Different symbols represent different geographical areas. Note that symbols for some areas (i. e., North Africa) are clearly grouped in a particular area of the graph (relatively large Mw-IAG magnitudes), demonstrating a geographical bias on magnitude distribution. Therefore differences due to different geographical areas or to data providers need to be considered.

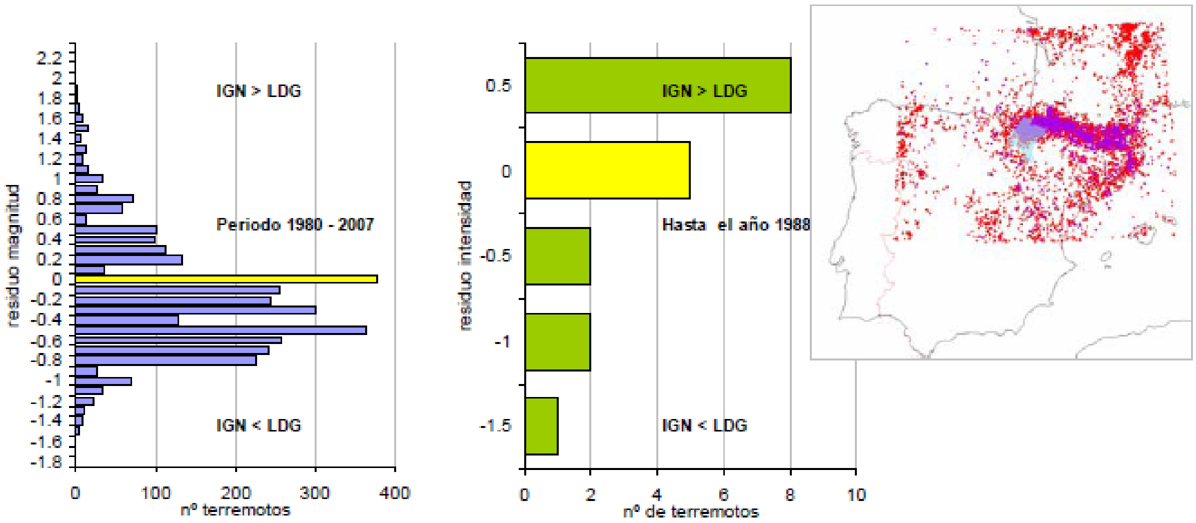

Figure 1. Residuals between IGN and LDG magnitude and intensity estimates for the same events.

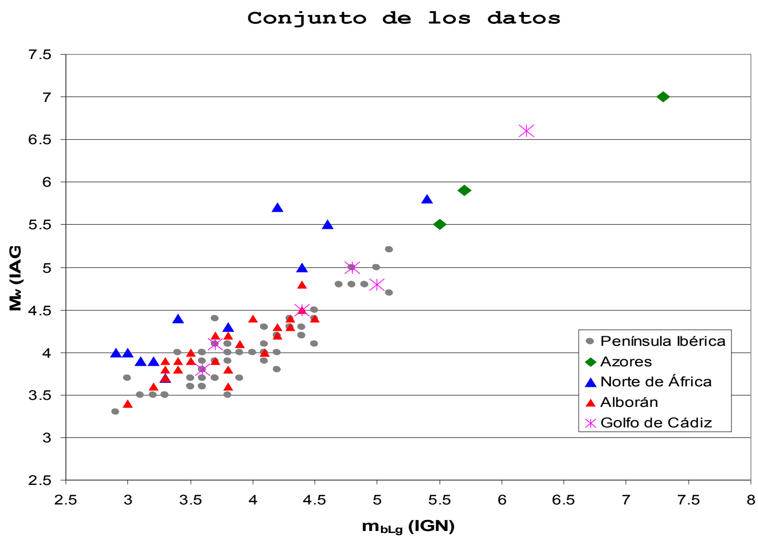

Figure 2. Distribution of IGN and IAG data grouped in different geographical regions.

Consequently, for seismic hazard applications the seismic catalogue must to be modified to make it homogeneous, converting all size measures to a single size definition. The moment magnitude scale M_w (Kanamori 1977) is the preferred option because does not saturate for large events and is directly related to source physics. In this regard it is convenient to complete the M_wIGN catalogue (created in 2002) with other data available from published sources of other agencies. In this work, 155 M_w estimates from the Andalusian Institute of Geophysics (IAG), which M_w catalogue dates back to 1984 and is also based on the inversion of the moment tensor (Stich et al. 2003), were added to the M_wIGN catalogue. A correlation analysis between both catalogues was carried out for the 58 events that appear in both IGN and IAG catalogues, confirming the compatibility between them. Finally, for historic earthquakes, the problem of transforming intensity estimates to M_w magnitudes should be also tackled. This is the most difficult case in the sense that it involves large uncertainties. Results of these analyses are very important for estimating earthquake size for seismic hazard analyses realistically.

3. PALEOSEISMIC DATA AND REDEFINITION OF SOURCE AREAS

The use of fault sources in seismic hazard analyses strongly relies on the assessment of the activity of faults, which admits different definitions depending on the authors consulted. The concept of Neotectonic fault is used to identify those faults that experienced activity during the period embraced by the *current tectonic regime*, i. e., within the period in which the crustal stress field remains coincides with the the Present Day stress field (Muïr-Wood and Mallard, 1992). For the Iberian Peninsula, this period encompasses the last 9 Ma, during which the Eurasian and African plates approached at a roughly constant rate of 4-5 mm/a in NNW-SSE direction. This approach to characterise the activity of a fault, based on mechanical and geological considerations, seems unrealistic for seismic hazard applications. A more refined classification to active faults for hazard applications considers those faults that affect Quaternary rocks (Quaternary fault). This concept is used in intraplate areas or countries with more moderate activity rate (United States).In interplate zones subjected to high seismic activity (such as Japan and New Zealand), it is considered that a fault is active at present if it has shown activity during the Holocene (about 10,000 years).

Traditionally for deterministic seismic hazard analyses, periods for limiting fault activity were related to the time span that dating methods may reach. Accordingly, faults showing activity during the last 50,000 years (time limit obtained with Carbon 14) can be defined as active faults (this period can be extended if thermoluminiscence dating methods are used). This limit is somewhat arbitrary and hardly related with geological or rheological arguments. For these reasons, a criterion with more geological basis is to consider that a fault is active in a low-to-moderate seismic area (intraplate or interplate with low activity) when shows evidence of motion during the Quaternary. The inclusion of such a faults in seismic hazard analyses would depend on the maximum expected damage that can be derived for that fault, the type , quality and availability of data constraints and the expert opinion of the analyst.

Seismic fault activity in Spain is moderate if activity rates during the historic period are considered. This low activity rate is related to the position of the Iberian Peninsula and the regional stress field, which induces a low stress loading rate and makes that the stress accumulation-release cycles in faults exceed hundreds or thousands of years. In this context, paleoseismic data are fundamental to unravel and quantify the actual recurrence interval and maximum expected magnitude of a slow active fault. This explains the scarcity of seismic hazard studies including active faults as seismic sources (Pelaez et al 2003; Perea et al, 2006; García Mayordomo et al 2007). The idea of the need of incorporating active faults in these, studies is increasingly spreading in the scientific community working in Spain.

Several studies contributed to improve the potentially active faults in Spain from geological studies. They provide short slip-rates (Holocene slip rate) and recurrence times of a number of faults, and may be used to estimate medium-term slip rates (Plio-Quaternary slip rates) and maximum expected earthquake derived from the segmentation structure of the fault. Additionally, geological data can be used to provide criteria for defining seismic source zones and hence complete the seismic parameters provided by the historic-instrumental catalogue (Figure 3), which tend to underestimate occurrence rates of large events. In this context, the development of the Iberian Quaternary Active Fault Database will provide a systematic database of geological data and related uncertainties (slip rate, recurrence interval, maximum earthquake, age of last deposits affected, structural segmentation, etc) that can be useful for seismic source definition for seismic hazard analyses.

Finally, an important aspect that should be taken into consideration for seismic hazard studies in Spain relates to the high density of low slip rate, moderate longitude, active faults; as well as some large faults with intermediate slip rates ($0.1 < SR < 1.0$ mm/a). Whereas the group of dense, small faults could be used to define the background seismic activity, the large fault could be defined as singular seismic sources in seismic hazard analyses.

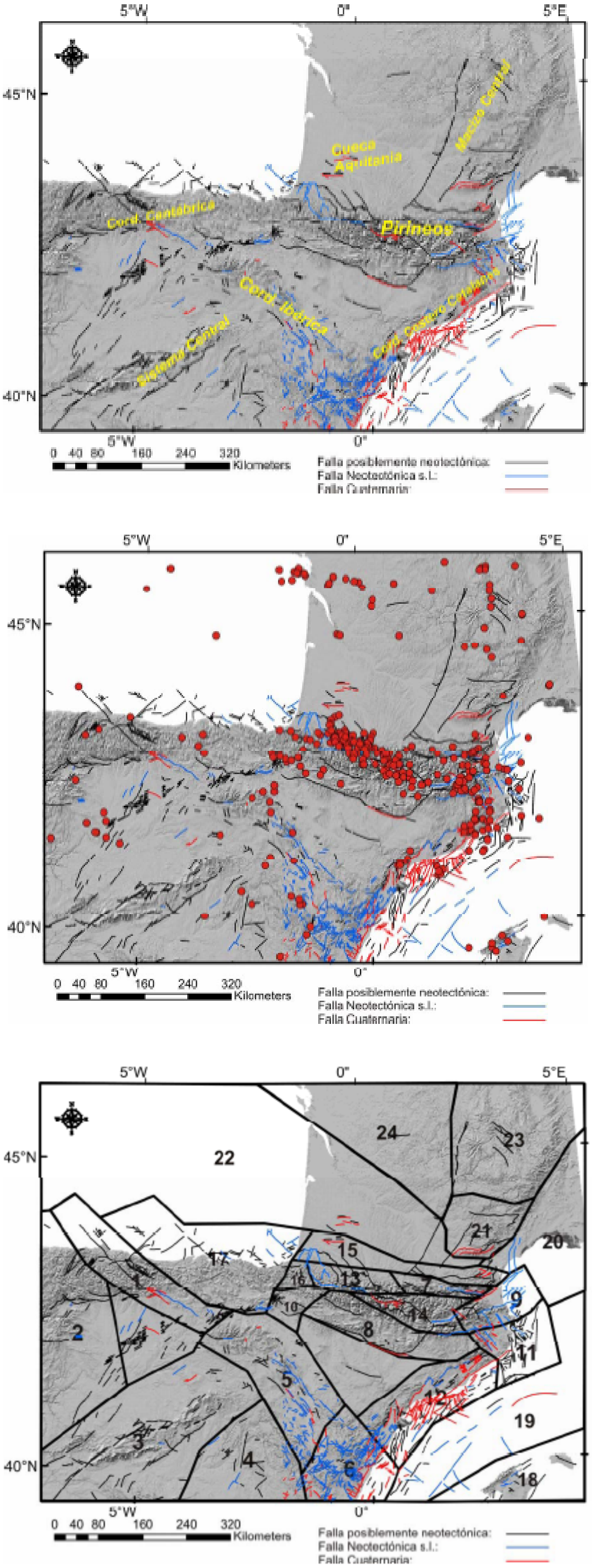

Figure 3. Example of the use of geological data (neotectonic faults in blue, quaternary faults in red and possible neotectonic faults in black) combined with seismic data for the definition of seismic source zones for use in seismic hazard analyses. Top: Map of active faults during Neotectonic and Quaternary periods; Middle: Map of earthquake epicentres; Bottom: Seismic zonification proposed for the seismic hazard study region of Navarre.

4. STRONG MOTION MODELS

Strong motion models represent a key factor for hazard estimation. In areas such as Spain, where strong motion data are scarce, models developed with local data necessarily must use foreign data in order to cover the upper part of the magnitude ranges of interest (Benito and Gaspar-Escribano, 2007). Since no much progress in this aspect can be made with empirical, local data, strong motion models for other areas may be considered. The next generation attenuation models developed for western United States (Power et al., and references therein) may be applied to Europe in combination with other European models (e. g., Ambraseys et al., 2005; Akkar and Bommer 2010) within a logic tree (Stafford et al., 2008) . However, the application of such detailed models to areas where data on fault parameters is scant is not recommendable, at least for countrywide hazard mapping applications.

5. HAZARD ESTIMATION METHODS AND UNCERTAINTY

As in many other areas of the world, approaches to seismic hazard assessment studies in Spain have evolved from purely deterministic to different probabilistic methods, imposing above all the standard zoning method that models seismicity as a poissonian process with a power-law magnitude recurrence (Gutenberg-Richter relation or similar). Attempts to incorporate non-zoning methods of Molina et al. (2001) and Pelaez and Lopez Casado (2002) were based on the approaches of Woo (1996) and Frankel (1995). To date and to our knowledge, no seismic hazard assessment analysis for the entire country has attempted to implement these methods with the new data on active faults available.

Differences between the zoning and non-zoning methods basically concern the shape of the activity rate, which depends in both cases on the spatial distribution and the magnitude. For a given level of magnitude, in the zoning procedure the activity is considered to be constant across each seismogenic zone while in the non-zoning procedure the activity is represented by a continuous spatial variation. Whereas in the zoning method the recurrence of magnitudes is defined with the Gutenberg Richter law (or similar), in the non-zoning this dependence has no predefined shape, it just results naturally from the composition of the different individual event contributions and their associated uncertainties (in hypocentral location and magnitude). In this sense, aleatory uncertainties related to the seismic catalogue are directly integrated in the calculations. The differences between both methods for a single site are apparent in the seismic hazard curves for a given site (Figure 4).

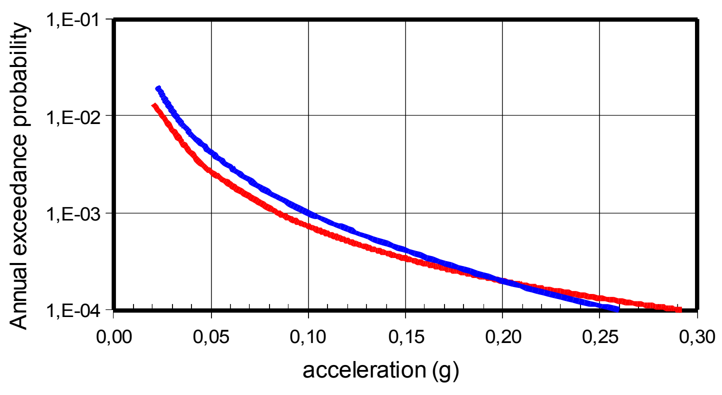

Figure 4. Seismic hazard estimates using the zoning (blue) and non-zoning (red) methods for a specific site.

These basic differences between both methods may be interpreted as different characterizations and modeling of seismic sources. In this sense, the use of one another method may be considered as epistemic uncertainty and their results may be incorporated in a logic-tree framework.

Uncertainties are an important issue in seismic hazard assessment and communication of results. Recent studies in Spain have treated this issue by means of a logic tree (e. g., Benito et al. 2010) or Monte Carlo approaches (Secanell et al., 2008). Such studies covered a limited area of Spain and do not reflect, for instance, the uncertainty related to fault activity. Future seismic hazard studies should reflect the large epistemic uncertainties observed in Spain through a logic tree formalism.

6. CONCLUSIONS

Seismic hazard assessment studies must be updated according to modern trends and using the recently available data. Several aspects relating seismic catalogue homogenisation, seismic source modelling including paleoseismic data and fault characterization, ground motion models available, alternative hazard methods, and identification and quantification of uncertainties have been posted in this presentation. Future projects to be developed in Spain, such as the revision of the hazard map contained in the Spanish seismic code or the site-specific ground motion characterization study that should be developed for the future radioactive waste repository could benefit from these considerations.

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