Past is the Key of the Present. A Geological Principle as Bayesian Philosophy Applied for Seismic Hazard Analysis.

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ABSTRACT

Current licensing process of the European reactors in operation requires analyzing site seismic hazards. After the Fukushima accident, reviewing the scope of that process has become more essential; especially, to identify and characterize seismogenic structures able to threaten the reactor safety. The most relevant Bayesian approach to constrain the characterization of seismic sources based on historical or recorded seismicity, tries to incorporate new source data preserved in the geological record by surveying primary (surface or near surface displacement) and secondary (liquefaction, subsidence, landslides, rock failing, tsunami…) seismic effects from known and unknown sources. Different methodologies have been developed for identifying past seismogenic activity not represented in seismic catalogues. Incorporating this information following a Bayesian approach for estimating statistical distributions of earthquake sizes and recurrences is the key of the numerical modeling of a Seismic Hazard Analysis (SHA).

Application of a Bayesian approach is rational in any case, but it is especially needed for regions with low to medium seismicity rate as is the Western Europe, crossed from the Valencia Trough to the North Sea by the European Rift which is a very large seismogenic structure, along which a significant number of European reactors are sited. As recommended by the ENSREG at 'European Stress Test Results', methods like the ones proposed in IAEA SSG-9 are good procedures for extending the seismic catalogue backwards or enriching the seismic activity characterization by other means. In the Spanish context, a couple of examples can be cited: a recent reevaluation of the national seismic hazard map was carried out considering paleoseismic information for estimating the maximum magnitude of seismic zones; and secondly, a proved methodology for incorporating paleoearthquakes in zoneless seismic hazard calculations will be briefly described in this paper.

Key words: Seismic Hazard Analysis, seismic source, seismic effects, paleoseismic information, paleoearthquakes.

INTRODUCTION

The world occurrence of earthquakes, even in regions with high seismicity rates like Japan, shows that the time span of historic seismicity is so short to capture seismic source parameters relevant for hazard prediction purposes at any probability levels; examples of these parameters are the maximum magnitude and the seismicity rate. This fact becomes more critical in regions with low to moderate seismicity rates like Western Europe, where its slower behaviour implies a great challenge to identify and characterize existing seismic sources.

Some recent or ongoing EU projects in relation with seismic hazard Analysis (SHA) are GSHAP[1] (1992–1999), PALEOSIS[2] (1997–1999), FAUST[3] (1998–2000), SESAME[4] (1996–2000), ESC–

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1 Giardini, D. Editor 1999; "The Global Seismic Hazard Assessment Program 1992-1999. Spetial Issue. Annali Geofis., 42 (6). UN/IDNDR demonstration program.

SESAME[5] (1996–2002), or more recently TOPO–EUROPE[6] (2006–) or SHARE[7] (2009–2012). A general common objective in these projects has been to improve classical approaches by incorporating new data like past historic and prehistoric strong events, in addition to unifying methodologies at a European scale. To support the SHARE project, two initiatives have appeared in the Iberian Peninsula: the IBERFAULT[8] initiative and the QAFI[9] (Quaternary Active Faults, V. 2.1) database.

The object of these studies is generally to determine the design seismic action of a new structure. Normally more than one level of occurrence probability is to be considered, with different performance requirements. For conventional structures, it is usual to employ a 10% probability of occurrence over 50 years, which corresponds to a return period of 475 years; So the previously dedicated efforts for conventional applications are far from the site specific needs demanded by the safety of critical industries like gas and nuclear installations, where it is common to work with lower return periods (2475, 4975, 10,000, 100,000 years or even more), and considering site-effects and uncertainties analysis performed by technically sophisticated approaches.

A question then arises as to how reasonable it is to produce results for return periods that far exceed the time range covered by the historical catalogue. Instrumental data will span a century at best; the historical catalogue is more variable depending on country, but will never be long enough to contain more than one event with a mean recurrence period on the order of those mentioned in the previous paragraph. The seismic sources characterization obtained out of the catalogue, needs to be supplemented with paleoseismic information.

CURRENT EUROPEAN NPPs FLET STATUS

During past seismic design process of most European NPPs, the knowledge on strong earthquake occurrences was very limited if compared to the current state of the art. In general, almost exclusively historical data were used without carrying out nascent paleoseismic surveys needed to better characterize strong events with low frequency rates. Additionally seismic records available to design at that time were few and of low damage capacity if compared with records available at present.

The European Stress Tests[10] process, carried out in 2011-2012 after the CN Fukushima Daiichi accident, emphasized the relevance of assessing the adequateness of existing NPPs design bases to deal with the worst credible scenario originated by natural phenomena. Their results addressed the necessity to develop guidance on seismic hazard, and the assessment on margin beyond the initially considered design basis of each site, involving the best available expertise. The Western European Nuclear Regulators Association (WENRA) has finished a process to harmonize this

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2 PALEOSIS; ENV4-CT97-0578 (DG12-ESCY: http://ssgfi.geo-guide.de/cgi-bin/ssgfi/anzeige.pl?db=geo&nr=000891&ew=SSGFI

3 FAUST; ENV4-CT97-0528: http://faust.ingv.it/

4 Jiménez M.J., Giardini D., Grünthal G., et al; "Unified Seismic Hazard Modelling Throughout The Mediterranean Region", Boll. Geof. Teor. Appl., 42, 3-18. IGCP (International Geological Correlation Program nº 382), SESAME (Seismotectonics and Seismic Hazard Assessement of The Mediterranean Basin, 1996-2000).

5 ESC–SESAME (European Seismological Commission): http://www.ija.csic.es/gt/earthquakes/

6 TOPO EUROPE: http://www.topo-europe.eu/

7 SHARE, Seismic Hazard Harmonization in Europe; FP7, WP4: http://www.share-eu.org/

8 Iberian meetings on active faults and paleoseismologya, Sigüenza, October 27th-29th, 2010 & Lorca, October 22th-24th 2014: www.iberfault.org

9 http://www.igme.es/infoigme/aplicaciones/QAFI/#

10 ENSREG, 'Post-Fukushima Accident. Stress Test Peer Review Board. Stress Tests Performed on European NPPs', Final Report, v12i, March 25th 2012: http://www.ensreg.eu/node/407

topic by producing Reference Levels[11&12] to new define or revaluate Design Basis Event (DBE) matching a low frequency level resulting from a probabilistic seismic hazard analysis (PSHA). Furthermore, those results encourage the process of Periodic Safety Review (PSR) to develop consistent approaches for assessing seismic margins beyond the DBE. Additionally, to take into account in new reactor designs the lessons learned from this huge accident, the nuclear regulation harmonization process conducted by WENRA, considers a specific section[13] dealing with natural phenomena, including earthquakes. All over these processes, the concern about the correctness or definition of seismic design basis is being of paramount importance in order to assess technical basis which guarantees the safety of European Nuclear Safety Regulators Group (ENSREG) Nuclear fleet[14&15].

An appropriate framework to assess the current seismic design basis and allow estimating margins, is to carry out a PSHA which opens the door to a risk informed decision making, based on the best available science. For this task, it becomes essential to know if there are seismogenic structures threatening reactor sites, by analyzing the geological record from a paleosismic point of view, as addressed in new approaches like the IAEA SSG-9 (August 2010) and was stated by ENSREG[16&17].

From the above statements and after reading all ENSREG country peer review reports, especially those from plants reviewed under IAEA regulations, it is apparent that SHAs performed within the European NPPs licensing processes, should be updated in most cases by considering both, paleoseismic surveys and the current knowledge on active tectonic in Europe.

In the particular case of Spain, the Conclusion 8 of the Final National Report[18] reads: '*The CSN shall introduce a programme to update seismic site characterisation studies, following the IAEA's most recent regulations*'; and the requirement I1 of the National Action Plan[19], includes as a ITC (Complementary Technical Instruction): '*Implementation of the necessary improvements to increase the seismic resistance capacity of equipment relating to the following to 0.3g: a) The two*

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11 WENRA Report on 'Safety Reference Levels for Existing Reactors', 24th September 2014: http://www.wenra.org/media/filer_public/2014/09/19/wenra_safety_reference_level_for_existing_reactors_september_2014.pdf

12 WENRA Statement regarding the revision of the Safety Reference Levels for existing reactors taking into account the lessons learned from the TEPCO Fukushima Dai-ichi Nuclear Accident, October 2014: http://www.wenra.org/media/filer_public/2014/11/13/wenra_statement_on_updated_srl_2014.pdf

13 RHWG Report on 'Safety of new NPP designs', 03.6 Position 6: External hazards, March 2013: http://www.wenra.org/media/filer_public/2013/08/23/rhwg_safety_of_new_npp_designs.pdf

14 69 sites: Belgium (2), Bulgary (1), Czech Republic (2), Germany (12), Finland (2), France (19), Hungary (1), Netherlands (1), Romania (1), Slovakia (4), Slovenia (1), Spain (6), Sweden (3), Switzerland (4), Ukraine (4), United Kingdom (8).

15 156 reactors in operation: Belgium (7), Bulgaria (2), Czech Republic (6), Germany (1)7, Finland (4), France (5)6, Hungary (4), Netherlands (1), Romania (2), Slovakia (4), Slovenia (1), Spain (8), Sweden (10), Switzerland (5), Ukraine (1), United Kingdom (18). Under decommission or new (Finland 1, France 1, Slovakia 2, Ukraine 2, United Kingdom 2) reactors are not included. To see IAEA data base: http://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.

16 4.3... it is therefore recommended that national regulators consider how best to ensure that specific requirements (e.g. IAEA safety standards and WENRA reference levels) for all three topical areas under investigation (Earthquakes, flooding and other extreme weather conditions) are adequately maintained. ENSREG, 'Post-Fukushima Accident. Stress Test Peer Review Board. Stress tests Performed on European NPPs', v12i, 2012: http://www.ensreg.eu/node/407.

17 5.2.3... 'With regard to hazards, particularly seismic, it would appear that techniques and available data are still developing. It is recommended that regulators should consider co-operation with other agencies in order to develop a consistent approach across Europe, taking account of updates in methodology, new findings and any relevant information from continuous research on active and capable faults in the vicinity of NPPs. ENSREG, 'Post-Fukushima Accident. Stress Test Peer Review Board. Stress tests Performed on European NPPs', v12i, 2012.04.25: http://www.ensreg.eu/node/407.

18 'Stress tests carried out by the Spanish nuclear power plantsFinalReport', 30th December 2012: http://www.ensreg.eu/sites/default/files/Spain_Stress-Tests.pdf

19 SPAIN, 'National Action Plan', Attachment 1: 'Requirements included in the CSN Instructions ITC-STS', Table A-1.1: 'Generic Requirements', December 19th, 2012: http://www.ensreg.eu/node/690

"safe shutdown paths" defined in the IPEEE, b) Containment integrity, c) Mitigation of station blackout (SBO) situations, and d) Severe accident management'.

The updated National Action Plan[20], informs that plant responses to the ITC was completed at December 2014 (Table A-1.1), and an action related to the former Conclusion 8 is foreseen for the first quarter of 2015: '*Issuing by the CSN of a new ITC that will require a reassessment by the licensees of the seismic risk of each site. This assessment will take into account geological and palaeo-seismological data characterising relevant active faults*'.

GEOTECTONIC SETTING OF WESTERN EUROPE

According to the IAEA SSG-9 (2010), the first goal in evaluating seismic hazards at any nuclear site, is to build a sound database of geologic, geophysical, geotechnical and seismologic data collected at four distance/detail scales from both, past and surveyed new information, to construct a reliable and coherent seismotectonic model (and alternative models if needed).

Any seismotectonic model consists of two types of seismic sources: a discrete set of identified seismogenic structures, and diffuse seismicity that is not attributable to specific structures. This second type, typically represented as zones, has been the only one used in classical approaches, supported by historic seismicity. In order to minimize this duality, namely to identify seismogenic structures, it is needed to carry out paleoseismic surveys that let us discover known and unknown seismogenic structures. The overall bottom line, is that events of interest for Earthquake Engineering are generated by fault ruptures, and to reduce uncertainty is necessary discover the roll of each fault or faults system, especially if they are close to nuclear sites or located further but representing a potential threat.

Seismogenic structures can consist of isolated faults, or more frequently a particular fault can form part of a master system (a bigger structure or a fault system) which movement is conducted by the master behavior along some geologic stages. In other words, following the Bayesian philosophy, classical approaches constrain the seismicity occurrence, at any scale, as an aleatory phenomenon, but Nature has memory. The challenge to resolve this duality will remain as an unresolved issue in the near future, especially if seismicity rates are low or medium and other bayesian constrains from paleoseismicity surveys and updated knowledge on active tectonic are not considered.

At intraplate domains like Western Europe, according to the IAEA SSG-9 in order to increase the knowledge on geodynamic setting where NPP sites are located, the recommended tasks include: to identify master structures, current/past tectonic regime, the depth/width of the seismogenic layer, as well as to carry out paleoseismic surveys as far as earlier Pliocene (historic seismicity is usually located around towns but actual sources can be located away from towns: in this respect the landscape and other geologic features that may have been affected by past events, can provide fruitfull information).

Most WENRA countries are located on an intraplate domain, where the regional geotectonic setting is driven by two main actors: the Alpine orogene, formed by a belt of ranges (Betic-Alps-Carpathians-Balkanides to the north, and Rift-Appenines-Dinarides-Hellenides to de south) with a high seismicity rate and its passive foreland or intraplate domain with low-moderate seismicity rate (Figure 1). The passive foreland has two main cortical features. One is the Tornquist intracontinental fault zone, that extends from the Skagerrak Sea to the Black Sea, separating the

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20 SPAIN, 'National Action Plan', Rev. 1, Attachment 1: 'Requirements included in the CSN Instructions ITC-STS', Table A-1.1: 'Generic Requirements', and Attachment 2: 'Recommendations and Suggestions of the ENSREG Peer Reviews carried out in Spain', December 17th 2014: http://www.ensreg.eu/sites/default/files/Spain%20-%20NAcP%20rev.1%202014.pdf

Baltic shield and the weaker Western Europe craton with a significant change in the crust thickness (Northeast of Figures 3 and 4). The other is the European Rift, a extensional structure more than 2,000 km long and with variable width, that extends from the North Sea between the United Kingdom and Norway all the way to the Valencia through (even more), through which are drawn some master systems gradationally separated (Yeats 2012): Mediterranean and North Sea basins, Rhenish Massif, Jura transfer zone, and grabens of Bresse-Rhone, and Lower and Upper Rhine (Figures 2 and 3).

The European Rift was introduced by Maurice Mattauer (1973), and is a structure active since the Cenozoic, having today a low deformation rate (Yeats, 2012). Along its onshore trace there was Quaternary and Holocene volcanism (Figures 3, 5), and also strong seismicity has happened along its body highlighting the existence of potentially seismogenic faults (Figure 4). In addition to strong events discovered by paleoseismic surveys (Camelbeeck et al, 2007; Cushing et al, 2000; Masana et al, 2000), from 1356 year until today, more than a dozen historical strong earthquakes with EMS intensities as high as VIII–X took place in Netherlands, Belgium, France, Spain and Switzerland[21]. Along the European Rift there are near located 19 sites with 41 operating reactors in Belgium, Germany, France, The Netherlands, Spain, Switzerland and United Kingdom (afps 1996; BRGM 1979, 1980, 1981, 1985; IGN 2002). Closer in time, a couple of events with intensity VII (EMS) shutdown Biblis (13.04.1992) and Fessenheim (15.07.1980) NPPs, both located on the Lower Rhine graben.

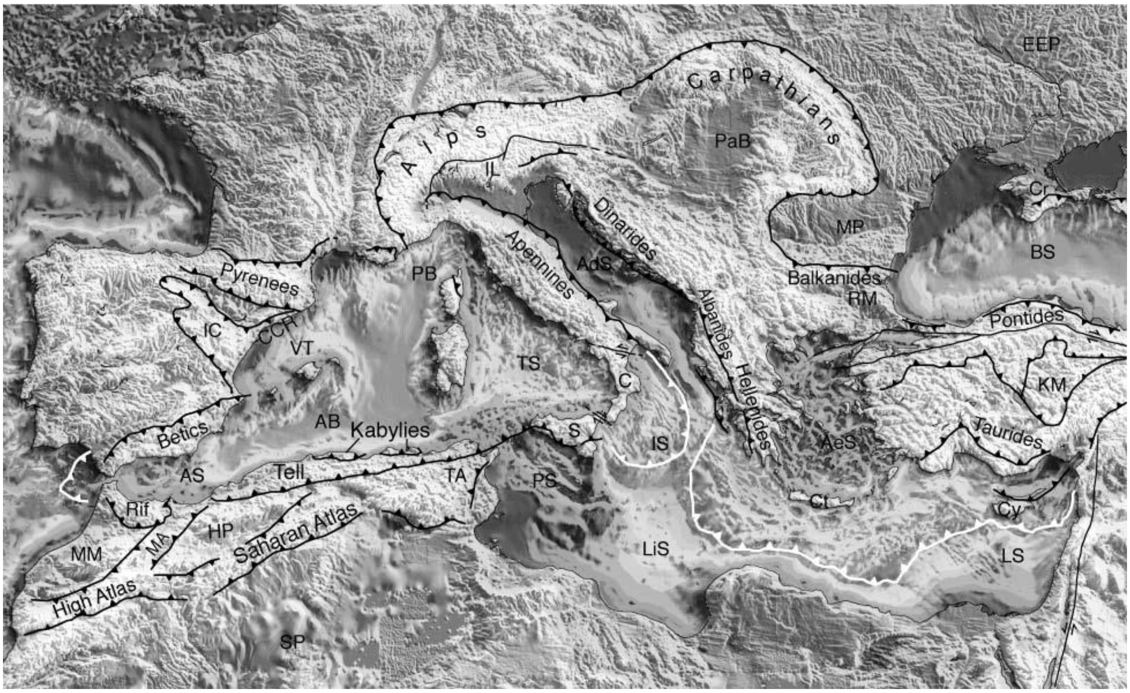

Figure 1. Terrain digital model of the Mediterranean region with simplified mayor geological structures. Quoted from Cavazza and Wezel (1983).

21 North Sea South (VII-VIII, May1382), Basel (IX, October 1356), Remiremont (VIII, May 1682), Buguey-Chautagne (¿??) Bugey (VIII, February 1822), Vercors (VII-VIII, April 1962), Tricastin (VII-VIII, January, February 1773, Agoust 1873), Trevaresse (IX, June 1909), Amer (VIII, March 1427), Olot (VIII-IX, May 1427), Queralbs (IX, February 1428), Enguera (IX-X, March 1748). Xátiva (VIII, November 1519), Tabernes (X, December 1396).

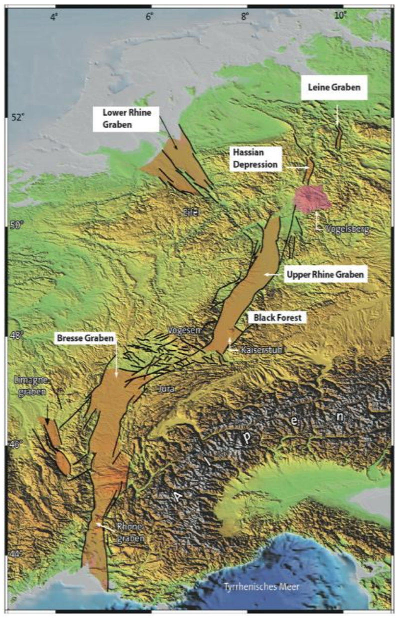

Figure 2. Grabens of Bresse, Lower and Upper Rhine, Limagne, Hassian and Leine. Quoted from Reicherter et al (2013).

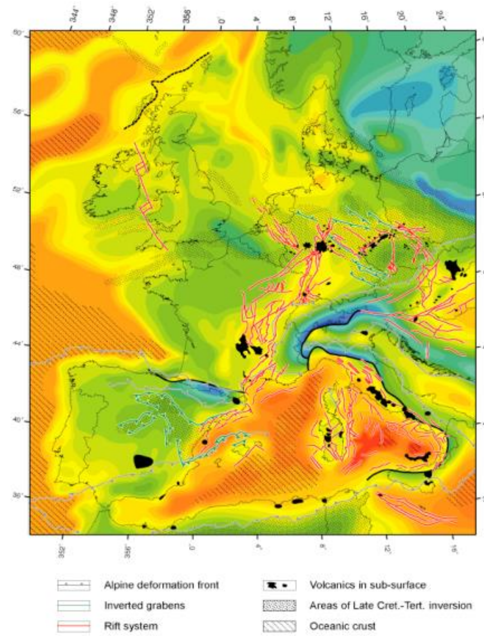

Figure 3. Red lines show the Rift system and black stains Quaternary volcanism. Quoted from Ziegler et al (2005).

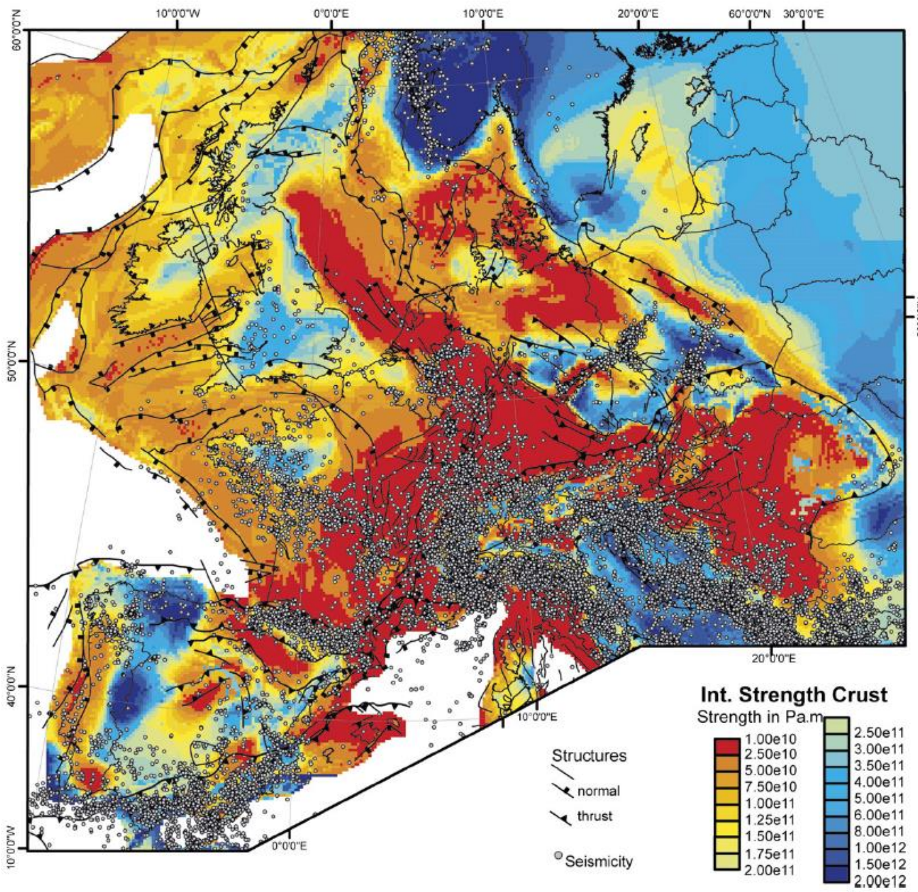

Figure 4. Integrated strength crust for intraplate Europe. Contours represent integrated strength in compression total lithosphere, mantle and crust, with superimposed distribution of current seismicity (green dots); The European Rift is belonged maximum values of strength (red color). Quoted from Tesauro et al (2007).

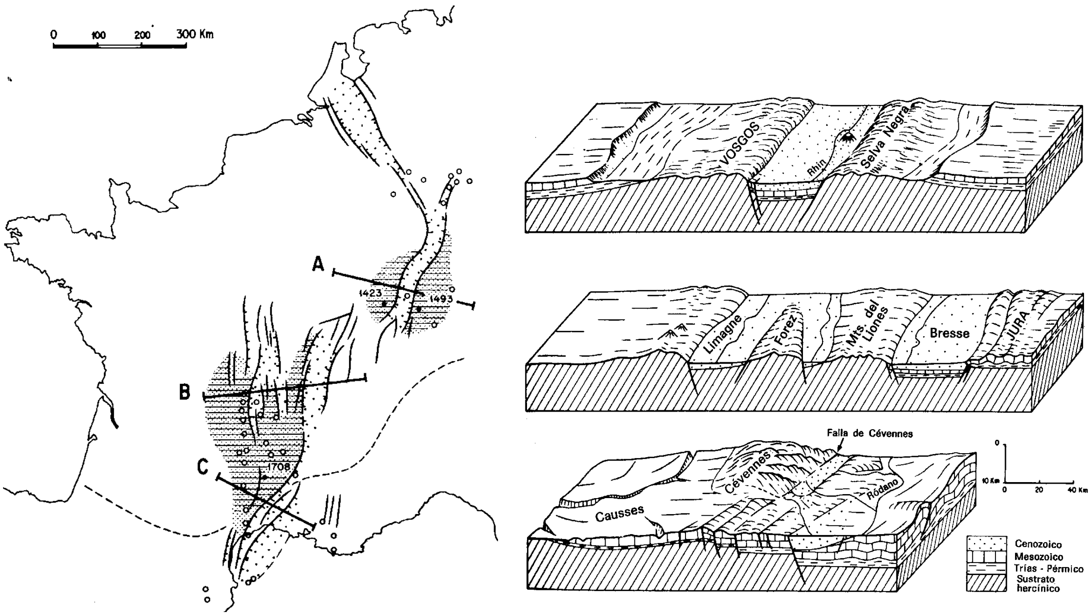

Figure 5. Early description of the European Rift System showing contours of Cenozoic basins, main faults, and volcanic outcrops locations (dots). Quoted from Mattahuer (1973).

From a Bayesian point of view, each master system along the European Rift has a different tectonic style that controls the mechanism of the faults included in each one. The movement rate of a particular fault will be conditioned to the movement of relatives faults. and the maximum magnitude of each master system will be bounded by the seismogenic layer depth/width. This is a huge aim to carry out in next future, but necessary to constrain some PSHA uncertainties.

In the Iberian Peninsula, as result of IBERFAULT initiative was developed the QAFI database, and causative faults of 44 historic strong events were been identified. Also, fault ruptures less than 100Km, maximum M_w between 6 and 7, and occurrences between 15,000 and 20,000 years has been found until today by Spanish geologists. derivation of maximum credible magnitude of zones from paleoseismic information

Seismic hazard map for the new Spanish seismic building code has been developed following the classical zoned model, but assuming as maximum magnitude at each zone or master system the resulting M_w from paleoseismic surveys. Also, a new method to incorporate paleoseismic information in zoneless approach is developing. Both initiatives are showed below.

EXAMPLES OF INCORPORATING PALEOSEISMIC INFORMATION INTO A PSHA

Example 1: incorporation of paleoearthquakes in zoneless methodologies.

A zoned model can be supplemented with faults wherever the information is available. To describe their activity one can make use of the characteristic earthquake (Schwartz and Coppersmith, 1984), assuming that the fault can generate earthquakes over a certain range, with frequencies centred around a given magnitude. A second possibility is the maximum earthquake model (Wesnousky et al, 1993), which assumes that the fault can only produce earthquakes of a certain magnitude.

Still there is continuous research regarding the magnitude beyond which surface ruptures are produced and hence their associated activity rate should be assigned to known faults, indeed this may even depend on location. For Spain, Rivas (2014) has recently presented information in this regard.

In zoneless methodologies such as that proposed by Woo (1996) using kernel functions, the seismic activity rate λ_k depends on magnitude *M* and location **x** and is constructed as:

$$\lambda_k(\mathbf{x}, M) = \frac{1}{H(M)^2} \sum_{i=1}^{n} \frac{K\left(\frac{\mathbf{x}-\mathbf{x}_i}{H(M)}\right)}{T(\mathbf{x}_i)}$$

This adds the kernel functions *K* centred on each catalogue event with location $\mathbf{x}_i$, and weighed with an effective period $T(\mathbf{X}_i)$; the result is a continuous function of location and magnitude that does not have a predefined shape. The bandwidth *H*(*M*) depends on magnitude. Crespo et al (2013) describe this formulation in greater detail.

The kernel function *K* is a probability density function in a two-dimensional space. It is normally symmetric, but it can also be skewed.

Skewed density functions normally have two additional parameters to define an axis and the ratio between radial dimensions in two perpendicular directions. The axially symmetric formulation can be skewed simply by multiplying it by a function. For example, the symmetric bi-quadratic function is:

$$K_{axi}(r) = \frac{n-1}{\pi H^2}\left[1+\left(\frac{r}{H}\right)^2\right]^{-n}$$

where: *n* is a decay exponent
H is the bandwidth

A possible directional version, proposed by Woo, is:

$$K_{dir}(r,\Theta) = K_{axi}(r)\frac{1}{1+\frac{DL}{2}}\left[1+DL(\cos(\Theta))^2\right]$$

where: *DL* describes the degree of anisotropy
T controls the orientation of that anisotropy

This formulation decouples the kernel size from its anisotropy, but is undefined at the origin. Figure 1 shows schematically isotropic and anisotropic versions of the kernel. There is currently ongoing work on an elliptic version of the kernel function that avoids the singularity.

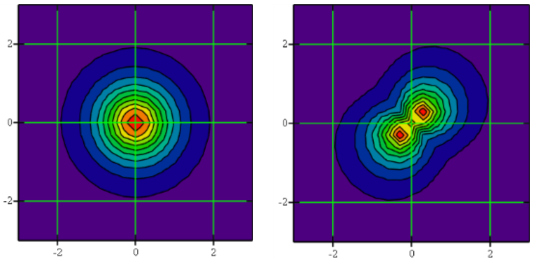

Figure 1 Kernel functions with and without anisotropy

When the kernel function sits on earthquakes without a known fault, axial symmetry is normally assumed. When the fault is known, the activity can be aligned with it. It is worth noting that, even with symmetrical functions, the activity may tend to concentrate along the faults because of the locations of the earthquakes it generates, but this can be enhanced by the use of directional kernel functions.

As explained earlier each earthquake also has its own effective period. These can be assigned simply as a function of magnitude and location, or individually based on its specific characteristics. When the magnitude coincides with that associated to the fault, the effective period should be that estimated for such an earthquake. The effective period should be estimated from paleoseismic considerations and could be longer than the time span covered by the historic catalogue, a period in which not more than one such earthquake may have been experienced. In such cases the activity rate thus represented may correspond to time period longer than the time span of the catalogue.

Moreover, apart from the possibilities afforded by the kernel function and the effective period, new events can be incorporated to the catalogue to represent an activity that it does not reflect but can be transferred from paleoseismicity.

Taking as a reference the two best known models for incorporating faults in hazard studies (Schwartz and Coppersmith,1984; Wesnousky et al, 1993), both would have here natural equivalent formulations. If the fault also produces lower magnitude events, those would be reflected in the catalogue in covered by their corresponding kernel functions. If it only produces events around a given magnitude, its activity would be represented only via some already existing event in the catalogue or via added events.

The chararacteristics of the events added to represent activity deduced from paleoseismicity is given below, using the previous terminology:

- Epicentral location $\mathbf{x}_i$ centred on the fault or, if the fault is very long, via several events along it.

- Characteristic magnitude M of the fault and its uncertainty, which will be incorporated as a random variation when constructing the activity rates for different magnitudes.

- Effective period T equal to the recurrence period of the fault. If several events were placed, the effective period will be the recurrence period time by the number of events, so that the contributions are weighted with the recurrence period.

- The bandwidth H should be on the order of the width of the fault projection of the surface, though this may be influenced by the kernel function employed.

In regions of low to moderate seismicity with scarce neotectonics and few/low associated seismicity, activity rates, represented in this case by M and T, cannot be derived from statistical analysis of historical earthquakes. The combination of the available evidence with the Bayes theorem is a quantitative mean for incorporating evidences, seismicity and geological information into a hazard assessment in a consistent way.

When the fault is made of several segments each can be represented with an event with the proper orientation. The paleoseismic study may lead to more than one possible interpretation: a single fault with a characteristic magnitude or several segments that practically behave as independent faults. Both can be adequately represented with added events.

The zoneless methodology based on non-parametric density estimators (kernel functions were described here) allows an easy and versatile integration of the seismic activity obtained from paleoseismicity, whether it is represented by catalogue events on known faults or by added events. Both alternatives require the fault geometry, its characteristic magnitude, and its recurrence period.

For generating the engineering input sought, it is worth analysing to what extent the alternatives (distributed zone, several independent faults) entail differences in the results. Indeed it may be best to adopt different strategies for different regions, depending on distance to the site, as some guides already suggest; this is for example the case of SSG-9 (IAEA, 2010).

Example 2: derivation of maximum credible magnitude of zones from paleoseismic information.

CONCLUSIONS

The European Stress Tests results have emphasize the relevance of assessing the adequateness of existing NPPs design bases to deal with the worst credible scenario originated by natural phenomena, including earthquakes. Seismic design of most European NPPs were obtained using, almost exclusively historical data, and site seismic characterization should be updated in most cases by considering both, paleoseismic surveys and the current knowledge on active tectonic.

This finding was highlighted years ago by some events took nuclear sites at Japan and the IAEA SSG-9 (2010) was released as approach to conduct necessary geologic surveys to support PSHA analysis. To day five documents (two Safety Reports and three TecDocs) are in press to detail the SSG-9 approach.

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