Insurance-Based Seismic Loss Model for Portugal and Spain

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SUMMARY
This paper presents the methodology and results for a new probabilistic seismic hazard assessment for Portugal and Spain to be used in insurance-based earthquake loss. This model incorporates recent studies on the regional seismotectonic in order to develop a new regional seismotectonic model across southern and western Europe surrounding Portugal and Spain. The geological and tectonic maps of Europe and northern Africa as well as maps with seismic interpretation such as spatial distribution of earthquake epicenters, earthquake ruptures and seismic moment have been prepared as tools to delineate seismic source areas, to study the completeness of the earthquake catalogue, to determine seismic activity, and to define recurrence parameters for each seismic source. The seismicity parameters such as magnitude-frequency relationships and maximum magnitude are determined using past occurrence of earthquakes and expert judgment. A synthetically generated set of potential earthquakes are modelled here which represents temporal and geographical distribution of seismicity in this region. The seismic hazard model developed here in this study in conjunction with built environment inventory and building vulnerabilities are used by the insurance industry to estimate probabilistic seismic losses.

Keywords: Portugal, Spain, Seismic Hazard, Seismic Loss Modelling, Insurance

1. INTRODUCTION

Probabilistic seismic hazard assessment has been used in the last few decades to evaluate potential threat to built environment. Its application in earthquake engineering and development of seismic design codes are well established in the engineering community, however, there have been further applications for such models in other pre- and post-disaster processes. Insurance-based catastrophe loss modelling has been under rapid development in the recent years, helping better understanding of severity and frequencies of economic losses caused by seismic events. Computer risk models today are used to evaluate potential losses from future events and provide facilities for better controlling exposure to potential losses. These computer models provide sound basis for risk pricing for insurance and reinsurance portfolio management. Information obtained from this type of modelling is ideally suited to the regional risk consideration of traditional financial entities as well as to the growing insurance catastrophic market in the region.

The first generation of earthquake loss models for Spain and Portugal were developed in 1998 by EQECAT and have been used by the insurance industry since then. In this paper the methodology and results for a new regional seismic hazard model is presented which is further incorporated in the EQECAT new seismic loss model for Portugal and Spain. The primary objectives of this study are to develop a regional seismic hazard model for the study area. A number of areal seismic sources are delineated for the study area. Regional historical and instrumental earthquakes are used to estimate seismicity parameters. Aleatory uncertainties associated with earthquake locations are modelled using a hybrid approach for seismic source modelling. The approach used in this paper allows implementation of spatial variability of seismological information into the seismic hazard process. This methodology incorporates faulting orientation in to hazard calculation using raster-grid layers.

2. TECTONIC SETTING OF THE STUDY ARAE

The seismicity in the Middle East, western Mediterranean and the Alps region is the result of northward motion of the African and Arabian plates relative to the Eurasian plate. The African and Arabian plates are bounded by several zones of tectonic and seismic activity. In the Central Mediterranean, the oceanic material descends beneath the marginal parts of the continental crust, pushing up mountain chains and island arcs. The development of the Alps and the submarine elevation are the result of this process. The tectonic framework of the Central Mediterranean is the result of complex interaction between the African and Eurasian plates since the Triassic. Here African and Eurasian plates collide, giving origin to some seismically active belts.

The Ibero-Maghreb region is located in the western part of the plate boundary between Eurasia and Africa. The most significant geological features in this region related to interplate processes are the Betic, Rif, and Tell cordilleras, which may link across the Gibraltar Arc. They constitute the westernmost end of the Alpine orogenic belt in southern Europe and limit the Alboran Sea and the Algerian basin. The area of highest fault slip rates corresponds to northern Algeria, the most seismically active area in the Ibero-Maghrebian region. Farther to the west, fault slips are more homogeneously distributed over southern Spain, the Gulf of Cadiz, northern Morocco, and the Alboran Sea. The western part of the basin and the Betic-Rif chain are presently escaping in WNW direction with velocity of about 3 mm/yr with respect to the Eurasia plate. This result indicates that lateral expulsion associated with plate convergence cannot account for much more rapid westward motion of these areas during the Miocene.
Mainland Spain and Portugal are located on the Eurasian plate, close to the southern boundary of the African plate, and exposed to large to very large offshore earthquakes and moderate to large onshore earthquakes in the southern part of the Iberian Peninsula, the western Mediterranean and the northwestern part of Africa (Moreira, 1989). They lie within a region of distributed crustal convergence between the African and the Eurasian tectonic plates that generally trends east-west from the Azores Islands to Tunisia (Figures 1). Structurally, this zone of plate convergence is characterized by distributed right-lateral strike-slip faulting and vertical thrust faulting (Fonseca and Long, 1991; Vegas, 1991; Mezcua *et. al*., 1991). The majority of this plate movement is accommodated on the Gloria fault zone (also termed the Azores-Gibraltar fault). The Azores-Gibraltar section of the boundary is well defined on its western part but becomes diffuse east of 13 W (Grimison and Chen, 1986; Buforn *et al*., 1995), where the two plates converge obliquely in a northwest– southeast direction at a rate of 4 mm/yr (Argus *et al*., 1989). This tectonic setting resulted in significant onshore historical seismicity in western Portugal. The Tagus Abyssal Plain (TAP) is thought to be underlain in part by thinned continental crust and in part by oceanic crust (Pinheiro et al., 1992), whereas the Gorringe Bank (GB), a seamount located southeast of TAP (Figure 1) and traditionally associated with the 1755 Lisbon earthquake (*e.g*., Machado, 1966) is an uplifted fragment of oceanic crust (Feraud *et al*., 1986).

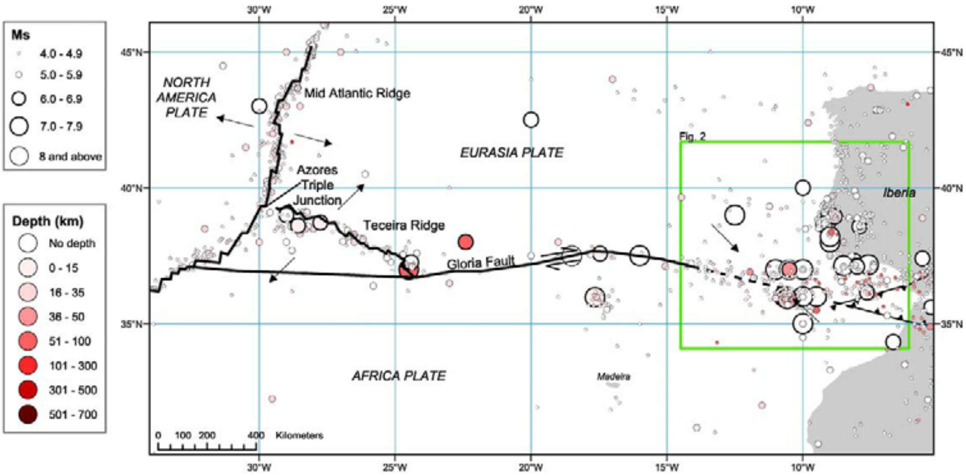

Figure 1. Tectonics of the Azores Gibraltar fracture zone region. Plate boundaries after Jiménez-Munt *et al*. (2001)

3. SEISMICITY OF THE STUDY ARAE

Seismicity in the Ibero-Maghreb region follows the plate boundary zone relatively closely in the oceanic section of the plate boundary zone, from Gibraltar westwards to the Azores (Figure 2). In large part, this is due to the mechanical competency of the relatively strong ocean crust (Mezcua *et. al*., 1991). Seismicity becomes spatially diffuse on the continental margin of the Iberian Peninsula and throughout Portugal where the continental crust is mechanically weaker than the ocean crust and tends to fracture into many small blocks when placed in tectonic compression (Mezcua *et. al*., 1991). Moderate seismicity is associated with convergence between these plates and is distributed over a wide area of deformation, as would be expected in an intercontinental collision. In mainland Portugal, seismicity has been attributed to the reactivation of ancient normal faults that formed during the opening of the North Atlantic Ocean (Fonseca and Long, 1991).

Although the seismic history mentions several important earthquakes distributed in the territory of Spain and Portugal, instrumental magnitudes larger than 5.5 have mostly occurred in the Gulf of Cadiz and north of Africa. The last relevant one is the earthquake of 11 may 2011 of magnitude 5.2 which caused some damages in Locara city and the surrounding area. The largest recent earthquakes were the Gorringe Bank (28 February 1969, Ms = 8.0) and El-Asnam, Algeria (10 October 1980, Ms = 7.3), events. Small and moderate magnitude earthquakes are clustered in the vicinity of Lisbon and are related to secondary faults of the distributed plate boundary zone. Mostly, these earthquakes have moment magnitudes less than Mw 5.0 which generally are strongly felt and causes minor cracks in buildings of ordinary construction.

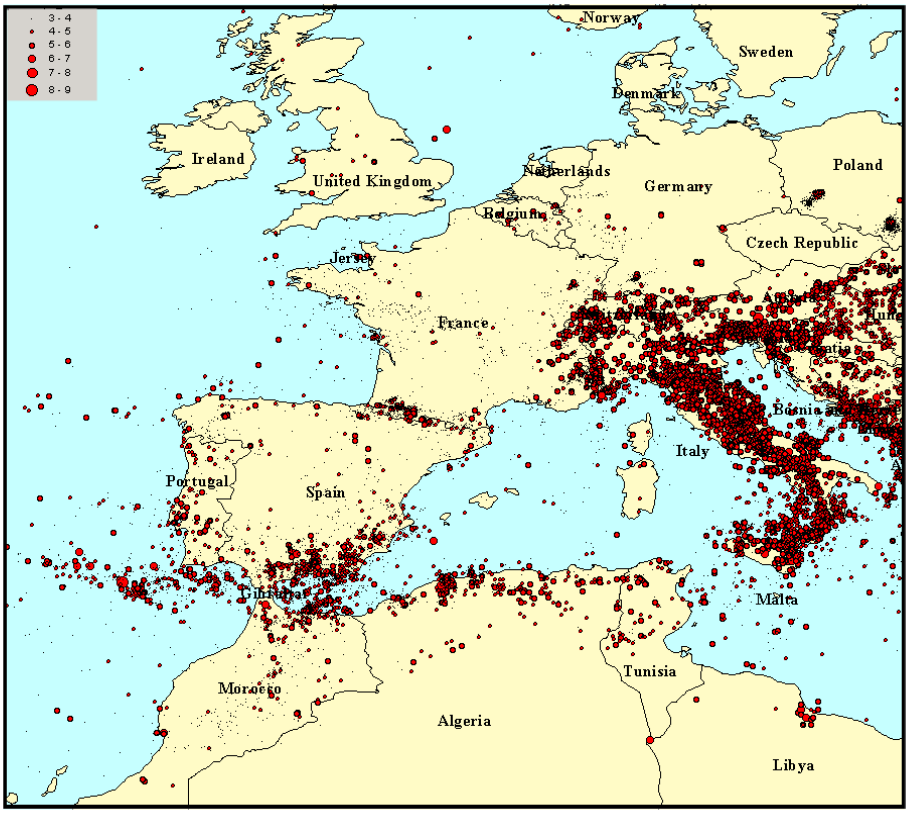

Figure 2. Seismicity map of Central Mediterranean and Adriatic Sea. Historical and instrumental seismicity since 1200 AD.

The great Lisbon earthquake of 1st November 1755 occured oceanward in proximity to the main plate boundary zone at distances beyond approximately 250 km from Lisbon (Mezcua *et. al*., 1991). The earthquake left up to 70,000 casualties in Lisbon and was felt as far away as Great Britain and Finland and the accompanying tsunami caused widespread damage in many coastal cities of the Iberian-

Mahgreb region, including Tangers and Casablanca (Johnston, 1996). This earthquake is the most destructive earthquake to have affected Lisbon historically. Estimates of the magnitude of the 1755 earthquake generally vary between 8.5 and 9.0. It triggered a 5- to 10-m-high tsunami and caused many casualties in Europe and northwestern Morocco. In this study a source magnitude of MW=8.5±0.2 is used, based on the magnitude estimate of Abe (1979). This gives lower and upper estimates of earthquake magnitude of 8.3 and 8.7 MW, respectively. The exact source of the 1755 earthquake remains unknown. This means that a single source model cannot simply be specified. In this study, a thrust fault dipping to the south and located in the north of the Gorringe Bank as suggested by Johnston (1996) is considered as the source of 1755 event, which is related to the tectonic uplift of the Gorringe Bank. Such a fault orientation is favourable to compression in northwest-southeast direction.

4. SEISMOGENIC SOURCE MODEL

The first step in a probabilistic seismic hazard analysis is the definition of earthquake source or sources which will affect the site of interest. This step is often a major part of a seismic hazard assessment. A source model represents distribution of further earthquakes in space, time and size and incorporates geological, seismological and geodetic information. A few national and regional seismic hazard studies have been conducted for Spain and Portugal in the last two decades. Examples for the Iberia local models for Portugal were those of Vilanova and Fonseca (2007) and source zone model proposed by Sousa and Oliveira (1997 and 2008). For Maghreb region, we could address the current model for Algeria (Pelaez *et al.*, 2005, Hamdache *et al.*, 1998) and the SESAME model (Jimenez *et al.*, 2001) for Morocco and Spain. There were also source models proposed for the Ibro-Maghreb region used in the GSHAP program (Jimenez, Garcia-Fernandez, 1999). In the latest efforts by the GEM program and under the SHARE regional project, a new version of the SESAME source zone was adopted for the first generation of hazard analyses for the European-Mediterranean Region. Based on information on the SHARE web site, further efforts are still in process to develop a new set of sources to replace the simple sources in the Ibero-Maghreb region. The only regional published seismic source zones are those used by GSHAP and then later used by SESAME and SHARE projects. All the other published sources are for specific countries and therefore, needed homogenisation to make a uniform source model. Besides the seismogenic parameters for most of these source models are not publicly available or if available, they are based on earthquake catalogue of more than 10 year old and not up to date. In this study, efforts are made to develop a uniform seismic source zone model for the entire region.

A new set of seismic sources are developed in this study based on the relationship between historical seismicity and large scale tectonic processes. Figure 3**Figure 3.** shows the geographical distribution of historical and instrumental earthquakes in the study area. While the records of moderate to larges earthquakes in this region can extend to more than a few centuries, the completeness duration for smaller earthquakes and those with off-shore epicentres are not more than the instrumental era and in some region not more than a few decades.

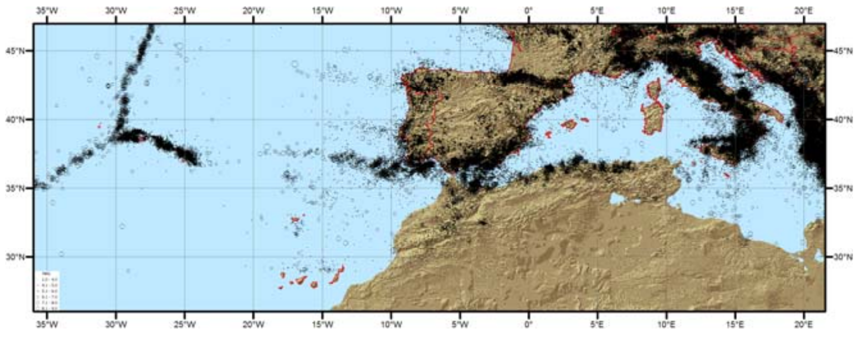

Figure 3. Geographical distribution of historical and instrumental earthquakes in Italy-Ibero Maghreb region

Regional geological and tectonic maps as well as maps with seismic interpretation such as spatial distribution of earthquake epicenters, earthquake rupture and seismic moment have been prepared as tools to delineate seismic source areas, to study the completeness of the earthquake catalogue, to determine seismic activity, and to define recurrence parameters for each seismic source. The seismicity parameters such as magnitude-frequency relationships and maximum magnitude are determined using past occurrence of earthquakes and expert judgment. The earthquake catalogue is examined for completeness within each source and the results are used to calculate the Gutenberg-Richter relationship.

In addition to the epicentral maps usually used in defining source zones, other maps representing spatial and temporal distribution of seismicity are used here. In this study a two-dimensional spatial Gaussian function, as proposed by Zolfaghari (2009) is used to smooth the number of recorded earthquakes. For small earthquakes (Mw<5.5) a symmetric distribution function with the correlation distances of 25 km is used. For larger earthquakes (Mw ≥5.5) faulting orientations is used to implement a non-symmetric smoothing process with correlation distance of 30 km along and 15 km across fault line. The correlation distances used here are based on the error associated with the location of past earthquakes in this region. The faulting orientations for non-symmetric smoothing are based on a combination of seismotectonic information as described by Zolfaghari (2009). Such smoothing process is performed in several grid layers, each representing the number of events for a given magnitude interval. Figure 4 shows boundaries of proposed seismic sources against smoothed seismicity for event with magnitude 4.0< Mw ≤5.0. Similar raster data layers are generated and used for other magnitude intervals. Similar smoothing maps for cumulative seismic moment are developed and used here to better define the boundaries of seismic sources. The cumulative seismic moment along a tectonic feature is representative of either average slip rates on a single fault, or average seismic strain rates over a region. Figure 5 illustrates source boundaries against smoothed seismic moment released over the last 1000 years. As explained earlier the records for off-shore events such those on the mid Atlantic Trench are mostly from instrumental data and only for the last 30 to 50 years. However, in areas such as mainland Italy, historical earthquakes back to 1000 years ago contribute to the patterns and extend of areas of high seismic moment. The shallow-depth source model refers to 75 seismic sources covering all population centres in Italy, Spain and Portugal.**Error! Reference source not found.**

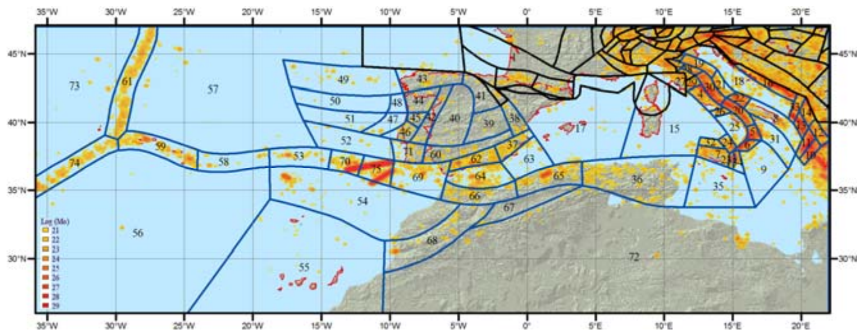

Figure 4. Proposed seismic source for shallow crustal earthquakes and geographical distribution of seismic moment released during 1000-2010

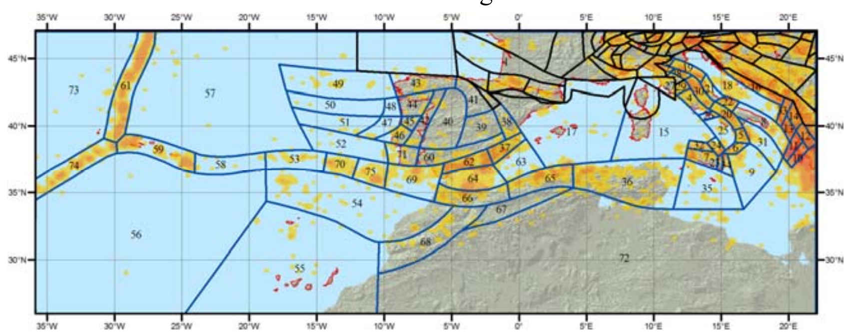

Figure 5. Proposed seismic source for shallow crustal earthquakes and geographically smoothed number of

events with Magnitude 4-5

As an alternative seismic source model, the source boundaries adopted by SHARE project is used. These sources cover the Mediterranean part of these zones, however, they are extended to cover the islands in the Atlantic Ocean, using the sources developed here. Figure 6 shows the boundaries for these sources.

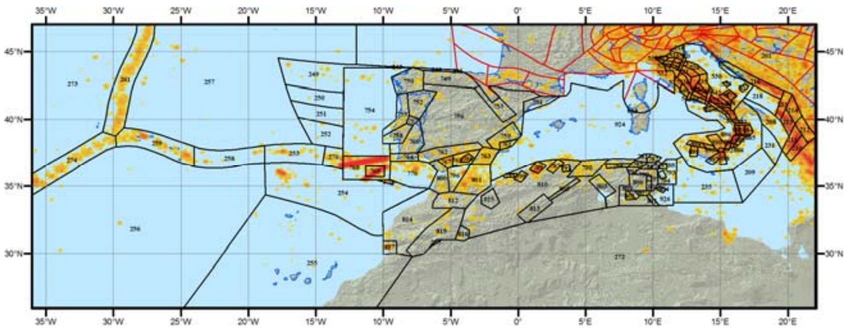

Figure 6. SHARE (SESAME and GSHAP) seismic sources and geographical distribution of seismic moment released during 1000-2010

The statistical method proposed by Stepp (1972) was used for the completeness test which provides estimate of time periods over which earthquakes are recorded completely. Exponential and combined characteristic-exponential relationships were used to model the frequency-magnitude distributions. To account for the epistemic uncertainties associated with the choice of source modeling, recurrence relationships and choice of attenuation functions, logic tree algorithm is used in this study to convolute weighted combination of alternative source models as well as uncertainties on the estimated seismogenic parameters.

Insurance catastrophe modelling tools estimate probabilistic earthquake losses to insurer's portfolio based on ground motions generated from a range of probabilistic events with various magnitudes and frequencies. Every event in this process acts like a scenario with a given frequency, representing the regional seismological severity and frequency. To model this part, the seismotectonic setting introduced for this region has to be converted to a synthetic earthquake set in which each event acts like a real earthquake with size, location and frequency. This event set provides synthetic earthquakes on a regular grid point of a chosen resolution and includes all events produced by seismogenic sources and in the vicinity of the modelled areas. For most moderate to large simulated earthquakes, faulting azimuths are assigned to each event representing the dominant orientation of rupture. A rupture length is also assigned to each event using empirical relationship between rupture length and earthquake magnitude. Based on such relationships and using the faulting azimuth, a virtual fault rupture is assigned to moderate to large earthquakes.

5. CHOICE OF ATTENUATION FUNCTIONS AND TECTONIC TYPE

In order to assign right attenuation function to each event in the eventset, fault mechanism and tectonic type information are required. The latest regionalization map provided by GEM (Figure 7**Figure**), dividing the European region into main tectonic classes are used here. Fault mechanism (Figure 8**Figure**) and tectonic types (Figure 7) are taken from these maps. Some minor modification are made on the original map provided by GEM which includes the modification made in the Alp area to include mixture of reverse and strike-slip and also to capture unique characteristics of events in the vicinity of the 1755 Lisbon Earthquake. Rake values of -90, 90 and 0 are assigned to events of normal, reverse and strike-slip types respectively to be used in the relevant NGA attenuation functions.

6. PROBABILISTIC SEISMIC LOSS ESTIMATION

Using the stochastic earthquake event set and the ground-motion model (attenuation relationships, soil amplification factors and their associated variability), a probabilistic distribution of ground motions for each hazard point is calculated. The monetary damages to each risk or group of risks within the imported portfolio are calculated using mapped vulnerability functions and insurance policy conditions such as deductible and limits. EQECAT's vulnerability functions used for damage calculation are based upon extensive field investigation of over 100 earthquakes and the use of billions of dollars of insurance claim data. Building vulnerability functions are specific to each country and region based upon engineering knowledge of local building codes and practice. Damage functions are sensitive to variables such as building materials and structural systems, building height, age, and occupancy type. The loss model developed for the study region can import users exposure data based on several geographic resolutions such as CRESTA zones, postcode units and site specific location specified by longitude/latitude. Country and CRESTA aggregated data gets further disaggregated into finer resolution based on disaggregation module built into the model. To calibrate the vulnerability functions and also test the validity of the loss results, the model was used to simulate losses from some of the historical earthquakes. Some of the damaging events in the 20th century were used for this purpose.

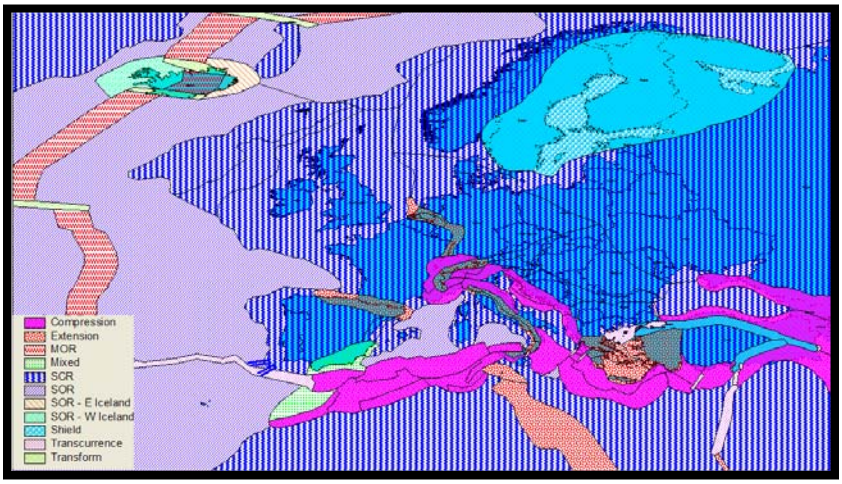

Figure 7. Tectonic regionalization map provided by GEM

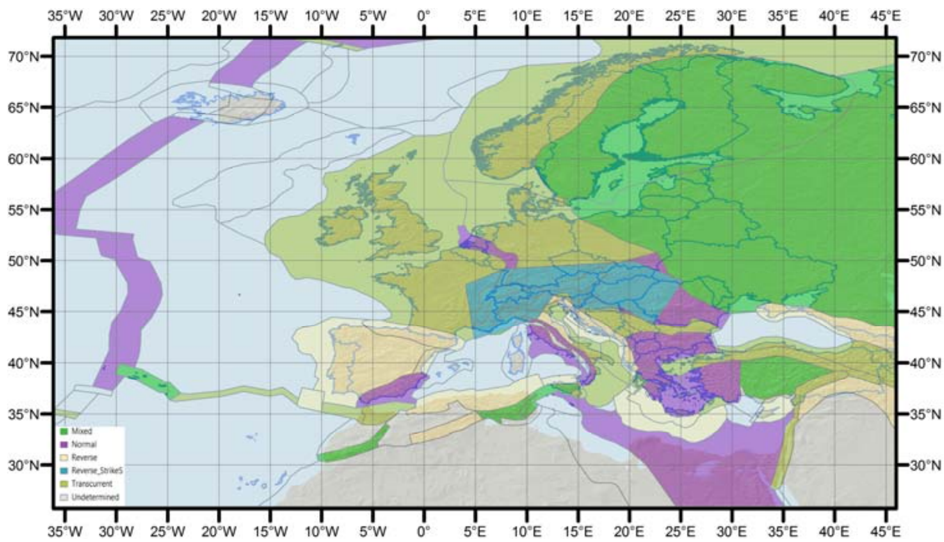

Figure 8. Division of European tectonic environment into fault mechanism types

CONCLUSIONS

This study presents a new regional seismic hazard model for Portugal and Spain. The study incorporates previous findings on the seismotectonic features in the Ibero-Maghreb region in order to define a number of seismic sources and their seismogenic characteristics. The source model is mostly based on recorded seismicity as well as characteristics of major faults in this region. Regionalization of faulting orientation of major faults is used in order to study spatial distribution of seismicity in term of number and seismic moment. Uncertainties associated with the spatial distribution of probabilistic earthquakes are modelled using smoothed seismicity layers. The approach used here also allowed incorporating faulting orientation in seismic hazard computational procedure. The seismic hazard model developed in this study has been implemented in EQECAT's insurance-based computer loss model, capable of estimating seismic losses for different types of buildings by usage, structural types and occupancies. Probabilistic loss curves as well as annual mean losses can be estimated using this model. The model compared to its earlier version, provides much higher geographical resolution both in terms of hazard calculation and loss estimation. Application of this tool on a national scale by domestic insurance companies could help insurance market in these countries to rationally quantify their status with regard to catrisk insurance rate, catrisk policy terms based on risk pricing and homeowner affordability, risk mitigation, healthy insurance penetration, risk-based premium, national awareness, catastrophe insurance law and many other insurance related factors.

REFERENCES

Abe, K. (1979) Size of great earthquakes of 1837–1974 inferred from tsunami data, J. Geophys. Res., 84, 1561–1568,.

Argus, D., R. Gordon, R. DeMets, and C. Stein (1989). Closure of Africa- Eurasia-North America Plate motion circuits and tectonics of the Gloria fault, J. Geophys. Res. 94, 5585–5602.

Buforn, E., C. Sanz de Galdeano, and A. Udias (1995). Seismotectonics of the Ibero-Maghrebian region, Tectonophysics 248, 247–261.

Feraud, G., D. York, C. Mevel, G. Cornen, C. Hall, and J. Auzende (1986). Additional 40Ar 39Ar dating of the basement and alkaline volcanism of Gorringe Bank (Atlantic Ocean), Earth Planet. Sci. Lett. 79, 255–269

Fonseca, J. F. B. D. and R. E. Long (1991). Seismotectonics of SW Iberia: a distributed plate margin?, Monograffa 8, Instituto Geogr~ifico Nacional, Madrid, 227-240.

Jiménez, M. J., M. García, M. Chadi, D. El Foul, A. Izquierdo, J. Martinez- Solares, C. Sousa-Oliveira, and B. Tadili (1999). Seismic hazard assessment in the Ibero-Maghreb region, Ann. Geofis. 42, 1057–1065.

Jimenez, M., D. Giardini, and G. Grunthal, and SESAME Working Group (2001). Unified sesmic hazard modelling throughout the Mediterranean region, Boll. Geofis. 42, 3–18.

Johnston, A. (1996). Seismic moment assessment of earthquakes in stable continental regions—I. Instrumental seismicity, Geophys. J. Int. 124, 381–414.

Jose´ A. Pela´eza,*, Jose´ Delgadob, Carlos Lo´pez Casadoc, (2005) A preliminary probabilistic seismic hazard assessment in terms of Arias intensity in southeastern Spain, Engineering Geology 77 139–151

Machado, F. (1966). Contribuic¸a˜o para o estudo do terramoto de 1 de Novembro de 1755, Rev. Fac. Cien. Lisboa C 14, 19–31.

Mezcua, J., J. Rueda and J.M. Martinez Solares (1991). “Seismicity of the Ibero-Maghregian Region”, seismicity, Seismotectonics and Seismic Risk of the Ibero-Maghrebian Region, Instituto Geografico Nacional-Espana (IGN) Serie Monografia No. 8, p. 17-28.

Moreira, V. (1989). Seismicity of the Portuguese continental margin, in Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound, S. Gregersen and P. Basham (Editors), Kluwer Academic Publishers, 533–545.

Stepp, J. C. (1972). Analysis of completeness in the earthquake sample in the Puget Sound area and its effect on statistical estimates of seismic hazard, in Proceedings of the International Conference on Microzonation for Safer Construction Research and Applications, Vol. 2, Seattle, Washington, 1897–1910.

Susana P. Vilanova and Joao F. B. D. Fonseca Pinheiro, L. M., Whitmarsh, R. B., and Miles, P. R., (1992). Probabilistic Seismic-Hazard Assessment for Portugal by The ocean-continent boundary off the western continental margin of Iberia – II. Crustal structure in the Tagus Abyssal Plain, Geophysical Journal International, Vol. 109, 106-124.

Vegas, R. (1991). “Present-Day Geodynamics of the Ibero-Maghrebian Region”, Seismicity, Seismotectonics and Seismic Risk of the Ibero-Maghrebian Region, Instituto Geografico Nacional-Espana (IGN) Serie Monografia No. 8, p. 193-203.

Zolfaghari MR (2009) Use of raster-based data layer to model uncertainties in probabilistic seismic hazard assessment. Journal of Computer & Geosciences,