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SEISMIC HAZARD AND RISK ASSESSMENT OF PORTUGAL

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ABSTRACT

Seismic hazard and risk assessment can play a fundamental role in the sustainable development of a given region, providing local governments and other decision makers with valuable information necessary to the creation of risk mitigation actions, such as building retrofitting campaigns, creation of insurance pools, strategic urban planning, or post-disaster emergency planning. Portugal is located in the southwest part of the Eurasian plate, near the border of the African and North-American plates, thus is subjected to offshore seismic events with large to very large magnitude and moderate to large onshore earthquakes. Moreover, half of the Portuguese building stock is comprised of masonry structures, which is a type of construction typically more vulnerable to earthquakes. These conditions call for a reliable and comprehensive evaluation of the seismic risk in Portugal, and strategic development of risk mitigation actions. This study provides an overview of the recent developments regarding seismic hazard and risk in Portugal, and present an identification of the regions more vulnerable to earthquakes, together with the expected losses for a probability of exceedance of 10% in 50 years. The results from the present study were obtained through the OpenQuake-engine, the open-source software for seismic risk and hazard assessment developed within the Global Earthquake Model (GEM) initiative.

INTRODUCTION

The evaluation of seismic risk involves the combination of three components: a probabilistic seismic hazard model, a collection of vulnerability functions describing the distribution of fraction of loss for a set of ground motion intensities and an exposure model defining the characteristics of the elements exposed to the hazard. In the present study, a review of the most relevant studies that have contributed to the understanding of seismic hazard and risk in Portugal was carried out. For the first component, an existing seismic source model (Vilanova and Fonseca, 2007) was combined with a set of ground motion prediction equations recently proposed for the tectonic environment in the vicinity of Portugal (Delavaud *et al*., 2012; Vilanova *et al*., 2012). An additional model describing the spatial distribution of V_{s30} values was developed, for the purposes of considering ground motion amplification due to soil conditions. Regarding the structural vulnerability of the building stock, a new set of vulnerability functions for the RC buildings was developed in Silva *et al.* (2014), whilst for the remaining typologies, existing capacity curves (Carvalho *et al.,* 2002) were combined with the Capacity Spectrum Method (ATC-40, 1996) to derive a vulnerability function for each typology. For what concerns the development of the exposure model, information from the Building Census of 2011 [1] was employed, together with building statistics from the Portuguese Statistical Office [2], to create a dataset capable of providing the geographic position, vulnerability class and replacement cost of residential buildings in mainland Portugal.

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For what concerns existing studies that have contributed to the understanding of the seismic hazard and risk in Portugal, various studies with different geographic scales can be found. At a global scale, the Global Seismic Hazard Assessment Program (GSHAP) (Giardini, 1999) was initiated in 1992 and its main objective was the creation of seismic hazard models for the different regions in the world. GSHAP was concluded in 1999 with the publication of the first global hazard map of peak ground acceleration for a return period of 475 years. The activities carried out within GSHAP, with special focus in the Ibero-Maghreb region (Algeria, Portugal, Spain and Tunisia) are described in detail in Jimenez *et al.* (1999, 2001).

At a European scale, three initiatives can be mentioned, each one focusing in different parts of seismic hazard and risk. The SHARE project (2009-2013) had the main objective of creating a homogeneous seismic hazard model for Europe, selecting a set of ground motion prediction equations compatible with the European tectonic environment and producing a European seismic hazard map. In parallel, another project denominated SYNER-G (2009-2013) evaluated the structural fragility of buildings, infrastructures and networks, and a unified methodology for the evaluation of the physical and socio-economic systemic vulnerability was defined. The third initiative (NERA, 2010-2014), facilitates the sharing of information and collaboration of many institutions from the different areas of seismic risk; one of the outputs of this project will be a building exposure model covering all European countries. It is also worth mentioning another two projects, RISK-EU (2001-2004) (Mouroux and Le Brun, 2006) and LESSLOSS (2004-2007) (Calvi and Pinho, 2004), both of which are already completed. In these initiatives, the seismic hazard and structural vulnerability of several European cities (including Lisbon) were evaluated, and the results were employed to calculate the associated seismic risk.

Concerning studies with a national coverage, Oliveira (1977) carried out the first comprehensive seismic hazard assessment for Portugal, whose results served as the foundation for the seismic hazard maps currently endorsed by the Portuguese design code (RSA, 1983). In the scope of the draft of the National Annex for the Eurocode 8 (CEN, 2004), several additional studies were also performed resulting in a seismic hazard map for moderate magnitude events at short distance, and large magnitude events at long distances (Oliveira et al., 1999). In a study by Sousa (2006), a seismic risk assessment was carried out, using the seismic hazard model from Sousa (1996), and several simplified methodologies for the building vulnerability assessment and a detailed exposure model compiled based on data from the Building Census of 2001. Sousa (2006) calculated human and economic loss maps for several return periods, as well as loss maps for two deterministic events equivalent to the historical earthquakes of Lisbon in 1755 and Benavente in 1909. In Vilanova and Fonseca (2007), a seismic hazard model for Portugal is proposed using a logic tree approach to characterize the various epistemic uncertainties such as seismic sources characterization, selection of ground motion prediction equations, earthquake catalogues and methodologies to derive the magnitude-frequency relationship parameters. This effort resulted in the creation of a national hazard map for peak ground acceleration for a probability of exceedance of 10% in 50 years.

Other studies at a regional or local scale are also worth mentioning, such as the studies of Mendes-Victor *et al*. (1994), SNPC (2001), Oliveira *et al*. (2005), Campos Costa *et al.* (2009) for the Metropolitan Area of Lisbon; Oliveira *et al*. (2004) and Sousa *et al*. (2010) for the province of Algarve; Vicente *et al.* (2010) for the downtown of the city of Coimbra; and the vulnerability assessment of the old city of Seixal by Ferreira *et al*. (2013).

Probabilistic Seismic hazard model for Portugal

From the review of the studies presented in the preceding section, it was decided to follow the seismic source model proposed by Vilanova and Fonseca (2007). This model is a recent proposal that addressed in detail the national tectonic characteristics, considered a large spectrum of epistemic and aleatory uncertainties and took into consideration several previous studies in its formulation. Area sources were employed to define the seismicity according to two zonations: one comprising eleven area sources drawn based on the isoseismal configurations from historical events, and a second one adapted from the work of Pelaez and Casado (2002), comprising eight area sources. The authors assumed mainland Portugal as a stable continental region, whilst the areas offshore of south and

southern Spain were defined as active shallow crustal regions. The source zone characterization, tectonic regionalization are illustrated in Figure 1.

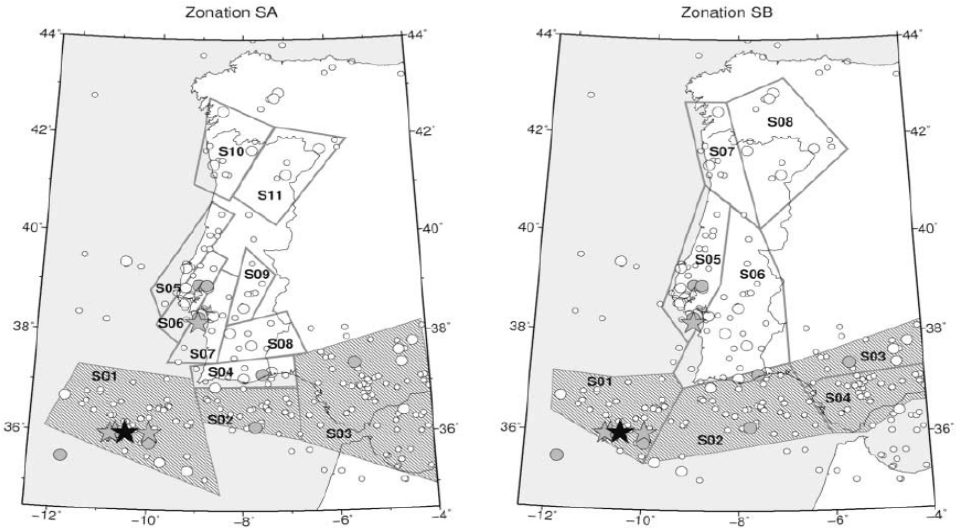

Figure 1 – Zonation and the working earthquake catalogue (adapted from Vilanova and Fonseca, 2007).

Vilanova and Fonseca (2007) proposed the employment of three ground motion prediction equations, Ambraseys *et al*. (1996), Toro *et al*. (1997) and Atkinson and Boore (1997), applied on both tectonic regions with the weights of 20%, 40% and 40%, respectively. A more recent scheme has been proposed as part of the European project SHARE, as described in Delavaud *et al*. (2012), for SCR (Stable Continental Region) and ASCR (Active Shallow Crustal Region). In this effort, the applicability and performance of some existing ground motion prediction equations was evaluated through comparison with empirical data and expert judgement. Table 1 presents the resulting selected ground motion prediction equations and respective weight for each region.

Table 1 - Ground motion prediction scheme for SCR and ASCR proposed by Delavaud *et al.* (2012).

Stable continental region (SCR)		Active shallow crustal region (ASCR)	
GMPE	Weight	GMPE	Weight
Campbell (2003) [1*]	0.20	Akkar and Bommer (2010) [2*]	0.35
Toro (2002) [1]	0.20	Cauzzi and Faccioli (2008) [2]	0.35
Akkar and Bommer (2010) [2*]	0.20	Zhao *et al.* (2006) [3]	0.10
Cauzzi and Faccioli (2008) [2]	0.20	Chiou and Youngs (2008) [2*]	0.20
Chiou and Youngs (2008) [2*]	0.20		

[1] Attenuation model developed for stable continental regions.
[2] Attenuation model developed for active shallow crustal regions.
[3] Attenuation model developed for subjection areas.
[*] Attenuation models that were tested against data for Western Iberia by Vilanova *et al*. (2012).

In addition to the models in Table 1, the models by Atkinson and Boore (2006), Douglas *et al.* (2006) and Atkinson (2008) were also considered as applicable to SCR, and the model by Boore and Atkinson (2008) was considered for ASCR, by the majority of the experts. The ASCR near Portugal proved to be considerably different from other active shallow crustal regions in Europe, due to a very low attenuation which is typically observed in SCR, rather than a high to very high attenuation, frequently reported in other regions of the same regime. Moreover, in a recent study conducted by Vilanova *et al*. (2012) in which the performance of a set of ground motion prediction equations were evaluated against instrumental and historical data from Western Iberia, it was concluded that attenuation models developed for SCR (namely Atkinson and Boore (2006), Campbell (2003) and Atkinson (2008)) tended to provide better results for both onshore and offshore events, whilst attenuation models developed for ASCR (namely Chiou and Youngs (2008) and Boore and Atkinson (2008)) performed poorly, consistently underestimating the ground shaking. The model proposed by

Akkar and Bommer (2010) was also evaluated in this effort and proved to deliver reasonable results, mainly for long period spectral ordinates. In the light of all of these findings, as well as the need to model ground motion amplification, it was decided not to employ the attenuation models from Toro (2002) or Campbell (2003), since both of them provide ground motion for rock only (V_{s30}=2800 m/s). The attenuation models from Chiou and Youngs (2008) and Boore and Atkinson (2008) were also excluded due to a consistent underestimation of the ground motion reported by Vilanova *et al*. (2012). Overall, the models from Boore and Atkinson (2006) and Akkar and Bommer (2010) seemed to fulfil the requirements of the region of interest and to be in agreement with the suggestions from recent state-of-the-art reports, hence, both models were applied to the whole region with a weight of 70% and 30%, respectively.

It is also recognized herein that the use of ground motion prediction equations capable of considering local soil conditions is not the only option to model site effects. Alternatively, the ground motion can be computed for rock, and modified afterwards through the employment of amplification factors based on the type of soils (e.g. Choi and Stewart, 2005), as recommended by many building design codes (e.g. CEN, 2005; BSSC, 2004). However, such approach brings in the additional uncertainty from the estimation of those amplification factors and they are not yet implemented in the OpenQuake-engine, which has been used for the calculations presented herein.

Consideration of side effects

The use of the average velocity of seismic shear waves in the top 30 meters layer (V_{s30}) has become a very common standard to characterize seismic site conditions. Many ground motion prediction models (e.g. Atkinson and Boore (2006); Chiou and Youngs, 2008), which are fundamental for seismic hazard and risk assessment, have been calibrated against seismic station site conditions described with V_{s30} values (Wald and Allen, 2007).

The acquisition of V_{s30} values at a large scale requires a significant investment of economic and human resources, and has only been done nationally or locally in a few regions in the world (e.g. California (USA), Italy, Taiwan, Thessaloniki (Greece), Australia). The recognition of the challenges in carrying out the effort to collect V_{s30} in large areas or in less developed countries, propelled the development of simplified methodologies to derive first-order V_{s30} values, mainly for the purposes of estimating post-earthquake human and economic losses and assessing seismic hazard and risk. Wills and Claham (2006) established a correlation between a set of geology units and V_{s30} values for California. A dataset from the Portuguese Environmental Agency [3] has been used, which provides the type of rock and associated period of genesis. Each geological unit was related to one of the categories described by Wills and Claham (2006) (California) to define the respective V_{s30} value. For the geological units not covered by Wills and Claham (2006), the work of Stewart *et al.* (2008) (Italy) was used.

An additional methodology proposed by Wald and Allen (2007) has also been explored, which uses medium to high resolution slope topography to obtain proxy V_{s30} values, based on the assumption that stiffer materials (high-velocity) are more likely to maintain a steep slope while deep basin sediments are deposited mainly in environments characterized by a lower velocity.

Figure 2 presents the V_{s30} spatial distribution for Portugal obtained with each of the two simplified methodologies followed. A good agreement between these two approaches is observed, mainly in the north, centre and western part of the territory. For the inner-southern region of Portugal instead, significantly lower V_{s30} values are provided by the topographic-based methodology. The discrepancies between these maps highlight the zones where further investigation should be carried out, preferably through field measurements. Both of these methodological approaches were considered within a logic tree structure.

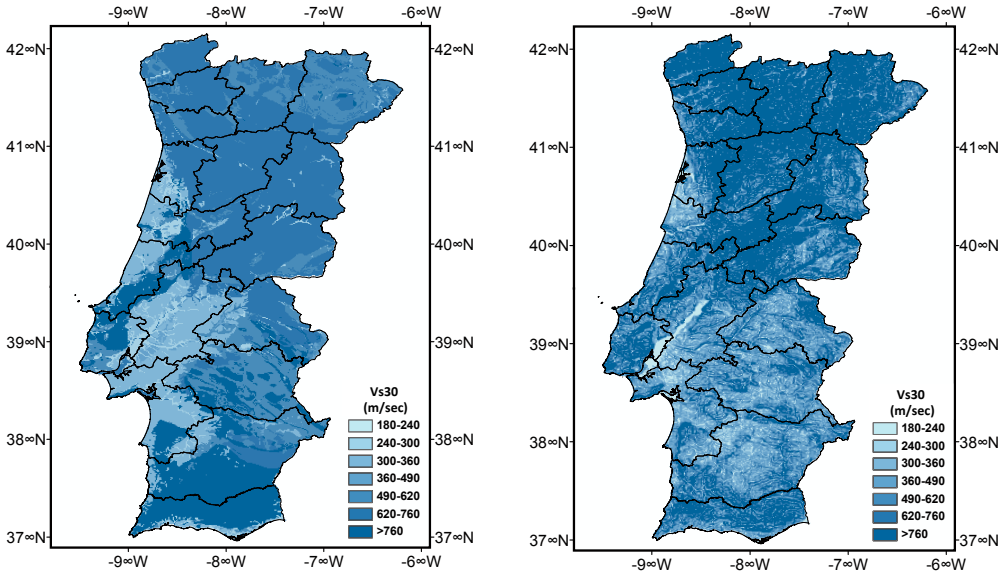

Figure 2 - V_{s30} map based on the methodology proposed by Wills and Claham (2006) (left) and Wald and Allen (2009) (right).

Regarding V_{s30} field measurements in Portugal, it is worth mentioning the on-going project SCENE (Site Conditions Evaluation for National seismic hazard Estimation) (Narciso *et al*., 2012), which aims to create a database of shear wave velocity for mainland Portugal, including also the results from other related projects at a regional scale, such as ERSTA (Carvalho *et al*., 2008), CAPSA (Carvalho *et al*., 2009) for the province of Algarve, NEFITAG [4] (still in progress) for the Lower Tagus Valley. The simplified methodologies employed in this study have been superficially investigated against a set of instrumental measurements by Narciso *et al.*, (2012) who concluded that both approaches seemed to perform roughly equally. For this reason, both V_{s30} maps were given equal weight in the logic tree, for the seismic risk calculations herein.

Exposure model

In this study, the Building Census data from 2011 for residential buildings is considered, thus disregarding public infrastructures and exclusively commercial or industrial buildings. In 2011, 3,544,389 residential buildings were reported, housing 5,878,756 dwellings. Amongst the various attributes considered in the Building Census survey, the type of construction, year of construction and number of storeys have been used herein to define a set of building classes. The first attribute is organized in five categories: reinforced concrete (RC); masonry with concrete floors (M1); masonry with timber floors (M2); weak masonry (M3), comprised of adobe, rubble stone or rammed earthen units; and others (OT), comprised of wooden and steel structures.

The year of construction plays an important role in classifying the building portfolio according to the level of seismic design. In Portugal, the first design codes that contained provisions regarding the consideration of seismic action date from 1958 (RSCCS) and 1961 (RSEP). However, such recommendations were overly simplified and could not impose effectively an adequate seismic performance. Later, in 1983, a new and much more demanding design code (RSA) was introduced, which is still in force nowadays, along with the Eurocode 8 (CEN, 2005). The percentage of buildings from each construction typology according to the number of stories and date of construction is illustrated in Figure 3.

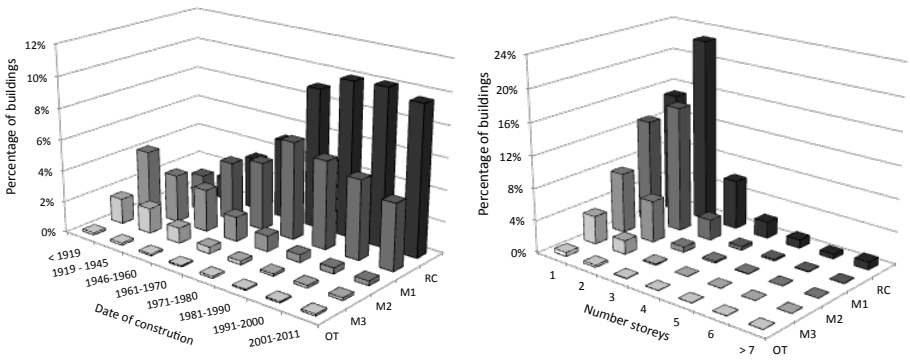

Figure 3 - Distribution of buildings according to type of construction, year of construction and number of storeys.

The building stock is comprised of 50.6% masonry buildings (M1, M2 and M3), 48.6% of reinforced concrete (RC) buildings, and 0.8% of other typologies (OT). Despite this distribution, RC buildings tend to have more storeys (thus containing more dwellings) and therefore it has been estimated that this building typology hosts about 60% of the Portuguese population. For what concerns the date of construction, almost 62% of the building stock has been built before the introduction of the 1983 design code (RSA) and, more specifically regarding the RC buildings, it has been estimated that only 51% were designed while the RSA design code was already in force. For the sake of simplicity, buildings classified as "Other" were added to the M3 category (as they only represent 0.8% of the building stock), and for this class no distinction was made regarding the design level. Moreover, the categories M1 and M2 were merged as one, herein termed as M0 (which is in agreement with the work of Carvalho *et al*., 2002). Buildings that date before 1958 were categorized as pre-code (PC), whilst the buildings constructed between 1958 and 1983 were termed as mid-code (MC), and the ones built after 1983 were defined as post-code (C). Within the latter two categories, it was also possible to consider a number of sub-categories according to the seismic zonation defined by the respective design codes. RSEP (mid-code) establishes three zones (A, B, C), whilst RSA defines four zones (A, B, C, D). Regarding the number of storeys, seven height categories were considered, following the same classes defined by the 2011 Census Survey: 1, 2, 3, 4, 5-7, >8 storeys. The combination between these four factors (construction type, design level, number of storeys and seismic zonation) led to 48 RC and 20 Masonry building classes. In Figure 4, the distribution of building count per parish is presented.

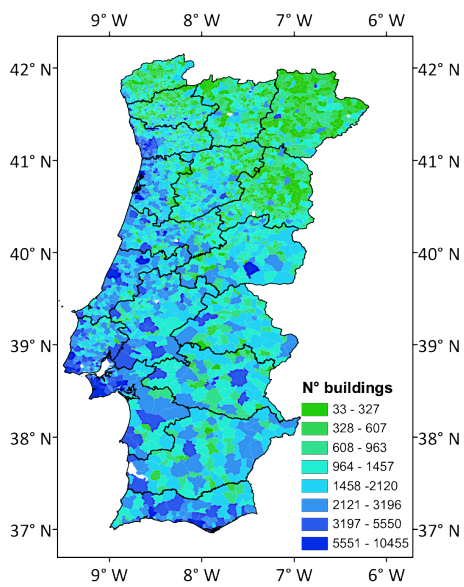

Figure 4 - Exposure model for Portugal at the parish resolution.

For what concerns the estimation of building economic value, the construction costs provided by the Portuguese government (Directive nº 358, 2012) were applied. This value depends on the location of the asset, according to three zones: Type 1, district capitals and other major cities; Type 2, counties located in urban areas; Type 3, counties located in rural areas. Table 2 presents these costs per area.

Table 2 – Construction costs for each zone according to Directive nº 358/2012.

Zone	Type 1	Type 2	Type 3
Cost (€/m²)	793,21	693,38	628,19

The total area per building has been computed by multiplying the average number of dwellings per building by the average area per dwelling, whose values were provided by the National Statistical Office in Portugal.

Physical vulnerability model

The seismic loss calculations were performed through the employment of a vulnerability model, describing the probability distribution of loss ratios for a set of intensity measure levels. For what concerns the reinforced concrete typologies, a new set of vulnerability functions developed by Silva *et al*. (2014) were utilized. Masonry building typologies were not considered in the aforementioned study, and therefore a simplified approach is employed herein to derive a set of masonry vulnerability functions by combining the Capacity Spectrum Method (ATC40, 1996) with the capacity curves proposed by Carvalho *et al*. (2002).

Notwithstanding the recent studies regarding the structural behaviour of masonry buildings in Portugal (e.g. Carvalho *et al.* 2002, Coelho *et al*. 2011; Costa, 2011), a robust vulnerability model covering the most common masonry building typologies does not seem to be currently available in the literature. Carvalho *et al*. (2002) computed a set of capacity curves (*Sa* versus *Sd*) for each masonry building typology, categorized according to the number of storeys and seismic design approach. In the present study, a large number of demand spectra defined according to the spectral shape of Eurocode 8 (CEN, 2004) were combined with the aforementioned capacity curves using the Capacity Spectrum Method (ATC-40, 1996) to assess which demand spectrum intersects the global drift threshold of each limit state. Then, using the peak ground acceleration of the matching demand spectrum at each limit state, the spectral acceleration for the yielding period and 5% viscous damping was computed based on the aforementioned spectral shape, and used as the median of the cumulative lognormal function representative of the associated limit state fragility curve, as defined by the following formula:

$$P_D(D \geq d|Sa) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{Sa}{\overline{Sa}}\right)\right] \tag{2}$$

where Φ stands for the standard normal cumulative distribution function, $\overline{Sa}$ represents the median spectral acceleration for each limit state and β is the logarithmic standard deviation, which was defined according to the recommendations provided in FEMA (1999). Each set of fragility functions was converted into a vulnerability function, through the employment of a consequence model. In this process, the percentage of buildings in each damage state is computed at each intensity measure level, and multiplied by the respective damage ratio (ratio of cost of repair to cost of replacement), obtaining in this manner a loss ratio for each level of spectral acceleration.

Results

Seismic Hazard

The OpenQuake-engine, an open source platform for seismic hazard and risk assessment was used for the calculation of seismic hazard curves and maps. This platform has been developed within the Global Earthquake Model (GEM) initiative and it is currently comprise by several calculators (Silva *et al*., 2013; Pagani *et al*. 2014). For the purposes of these results, the Classical PSHA-based hazard calculator was employed (Pagani *et al*. 2014). This calculator uses the classical PSHA approach (Cornell, 1968; McGuire, 2004) following the methodology presented by Field *et al*. (2003) to compute a hazard curve for a 50 years time span (probability of exceeding a set of intensity measure levels in 50 years) at each site, for each of the possible 128 paths of the previously described logic tree. The employment of a spatial resolution of 0.01x0.01 decimal degrees for the hazard calculations, led to approximately 10 million hazard curves for each intensity measure type. From this set of hazard curves, the mean seismic hazard map for a probability of exceedance of 10% in 50 years is presented in Figure 5.

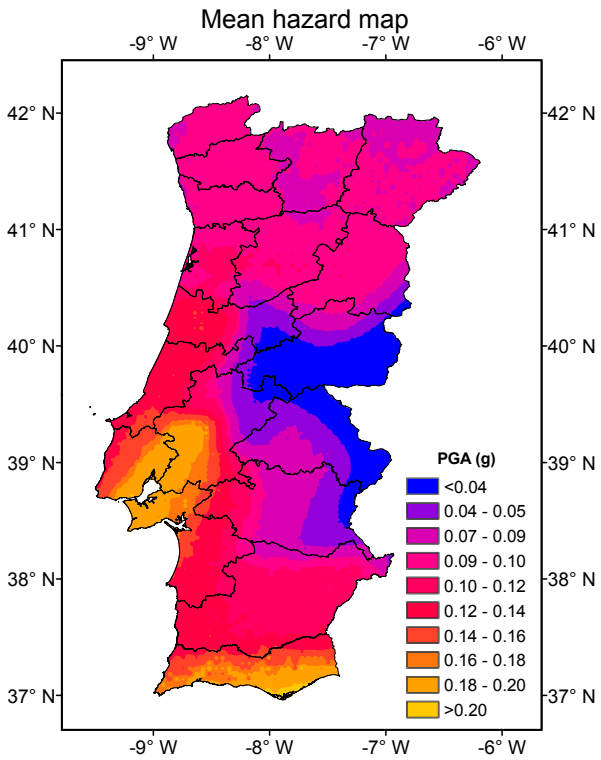

Figure 5 - Mean seismic hazard map in peak ground acceleration (g) for rock, for a probability of exceedance of 10% in 50 years (return period of 475 years).

The spatial distribution of the hazard and range of peak ground acceleration obtained in this study is in agreement with the results proposed by Vilanova and Fonseca (2007) (who originally developed the seismic source model adopted herein), despite the different GMPE scheme considered between these two studies. Vilanova and Fonseca (2007) carried out a comprehensive comparison between hazard assessments for this region, concluding that for the 475 years return period, studies that relied on peak ground acceleration (Oliveira *et al.*, 1999; Jimenez *et al*., 1999) present a pattern with higher hazard in the Lower Tagus Valley and Algarve, whilst for studies based on intensity data (Sousa, 1996; Pelaez and Casado, 2002), a higher hazard is obtained in the southwest of mainland Portugal.

The former trend (higher hazard in the Lower Tagus Valley and Algarve) was also observed in the present study.

Seismic Risk

The seismic risk assessment of mainland Portugal was carried out also using the OpenQuake engine. In order to take into consideration the influence of soil conditions, a new set of hazard curves was derived, considering the two V_{s30} models presented in the previous section as an additional branching level in the logic tree. This set of curves was provided to the Classical PSHA-based Risk calculator (Silva e*t al.*, 2013; Pagani *et al*., 2014), together with the vulnerability and exposure model, in order to calculate a loss exceedance curve (probability of exceeding a set of losses within a given interval of time, taken as 50 years herein) for each asset, considering each possible path of the logic tree. Using the set of loss exceedance curves for each asset, a mean loss map for a 10% probability of exceedance in 50 years was computed, as presented in Figure 6.

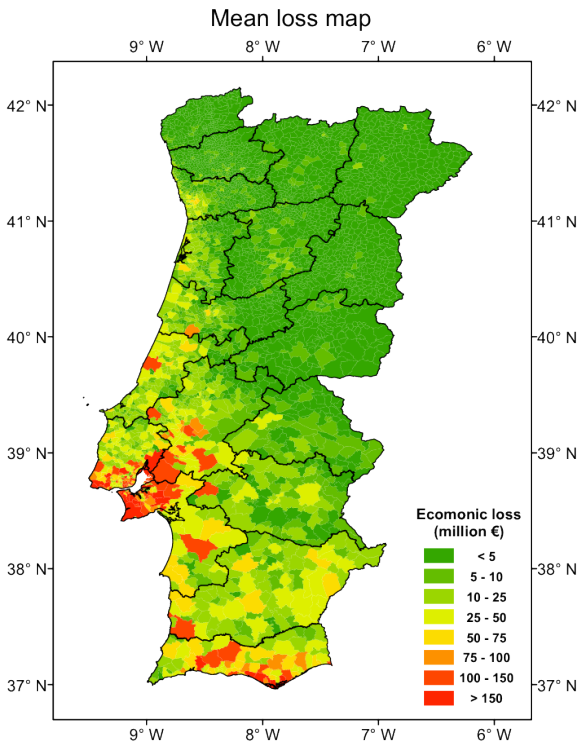

Figure 6 – Economic loss map for a probability of exceedance of 10% in 50 years (475 years return period), considering the parish-based exposure model.

The estimated economic losses in mainland Portugal are mostly concentrated in the western region and the south (Algarve). In the region above the Lower Tagus Valley, despite the decrease in the seismic hazard, significant economic losses are still expected, due to the presence of a large amount of weak masonry buildings (vulnerability class M3) in soft soils, which can amplify the spectral acceleration by a factor of 1.5 for short periods and 2.0 for longer periods (Stewart *et al.*, 2013).

The disaggregation of the economic losses for the return period, according to the building typology indicates that the buildings classified as M0 are responsible for 60% of the losses, whilst typologies belonging to category M3 represent 19%, which is a predictable scenario considering the large proportion of this type of construction in Portugal (51%), associated with its high seismic vulnerability.

CONCLUSIONS

The seismic hazard and risk for mainland Portugal has been investigated herein using up-to-date models, methodologies and datasets. The evaluation of the seismic hazard in mainland Portugal revealed some significant differences regarding the hazard map of the design code (RSA) currently in force. Such differences are more pronounced around the Lower Tagus Valley and in the south (Algarve), which are regions responsible for a great portion of the gross domestic product.

Data from the 2011 Building Census survey was employed to derive an exposure model capable of providing the spatial distribution of building replacement cost for a set of building typologies, categorized based on type of construction, number of storeys and date of construction. The aggregated replacement cost for the Portuguese building stock has been estimated to be approximately 358 billion euro. It is important to mention that a number of simplifications and assumptions had to be followed in order to estimate the replacement cost for each building typology, such as the number of dwellings per building or the average living area per dwelling. Such parameters probably depend on the date and type of construction, however, until such statistics are available, the authors believe that the adoption of a generic set of parameters can still provide an indicative replacement cost. A simple comparison between the exposure models illustrated in Figure 4 and the seismic hazard map depicted in Figure 5 reveals that an important fraction of the building stock is located in zones with high levels of seismic hazard.

The seismic risk map for the probability of exceedance of 10% in 50 years identified the Lower Tagus Valley and the southwest of Portugal as the highest risk-prone regions. The economic losses per building typology indicated that the masonry typologies are the most seismically vulnerable, and therefore the ones for which strengthening/retrofitting should be focused. In the work of Campos Costa *et al.* (2009), it has been shown that applying selective retrofitting interventions in the Metropolitan Area of Lisbon building stock could reduce the economic risk by an amount of 36% for all return periods. A comparison of the results estimated herein with previous studies considering the 2001 building stock indicates similar levels of seismic risk for the Metropolitan Area of Lisbon, and lower levels of risk at a national level, though such differences are within the estimated bounds of epistemic uncertainty.

A number of improvements in the models employed herein have already been initiated in order to reduce or remove some of their limitations. Some of these improvements include the employment of the area and fault source model from the SHARE project, an analytical study to investigate the seismic vulnerability of masonry buildings and a consequence model capable of relating physical damage with percentage of loss, considering the structural characteristics of the Portuguese building stock and reconstruction practices.

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