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AN IMPROVED MODEL FOR SEISMIC RISK ASSESSMENT IN PORTUGAL

Abstract

Purpose – Portugal experienced very destructive earthquakes in the past, such as the well-known "Lisbon Earthquake" in 1755. With such in mind, accurate estimates of human and economic losses can play a significant role in providing various societal key players with objective information for response strategies. The present paper aims to present the contribution of the most recent study in Portugal (PRISE) concerning comprehensive seismic risk assessment, which can be used as good practice and reproduced in different contexts.

Design/Methodology/Approach – PRISE (Earthquake loss assessment of the Portuguese building stock) covered three main lines of research, corresponding to the three components typically considered in any seismic risk assessment study: i) the characterization of the seismic hazard; ii) the identification of the exposure to earthquakes and loss potential; and iii) the vulnerability of the exposed assets. Each of those components was fully characterized through the collection of census and local data (exposure), used to carry out nonlinear analysis (hazard and fragility).

Findings – By involving different research institutions and partners with extensive knowledge and expertise in the earthquake domains, the developed model is capable of producing economic and human earthquake loss estimates in real time (through an innovative web-based platform) or for specific event scenarios, considering exposed population, residential and industrial buildings. The platform uses open-source tools hence it can be reproduced in other countries or contexts.

Social implications – The findings and loss estimates for different earthquake scenarios show that planned interventions are required. Decision-makers and other relevant stakeholders (Civil Protection) can make use of the developed platform to produce specific estimates, to test the effect of different retrofitting interventions or to plan for emergency scenarios.

Research implications – Research wise, the hazard, vulnerability and exposure models can still be significantly improved, by e.g. adding critical infrastructure (hospitals, school buildings, bridges) or updating the nonlinear models, for more accurate loss predictions.

Keywords Seismic risk, Loss estimation, Hazard, Exposure, Vulnerability, Real-time platform

Paper type Research paper

1. Introduction

The occurrence of natural hazards, particularly earthquakes, has been responsible over the years for the most devastating effects on human, environmental and economic losses in societies. Portugal has experienced destructive seismic events in the past, including the well-known "Lisbon earthquake" in 1755, during which it is estimated that about 50% of the existing buildings have collapsed and 10% has perished (Silva et al., 2014). The projections of reinsurer Swiss Re (2011) for Portugal reveal a worrying scenario, estimating that the economic impact of an intense seismic event will exceed 25% of the gross domestic product, which is aggravated by the fact that percentage of assets that are insured against earthquake risk is virtually absent (less than 10%). The recognition of the inevitability of the seismic impact to the societies, even in countries with high level of economic and social development, shows how important it is to estimate the expected share of resources that would be affected in a given region. In this sense, it is manifestly urgent to estimate the human and economic losses. The results of such exercise will be capable of providing the various societal players with real and objective information society that supports the establishment of response strategies and better decision making.

Despite the important past studies on seismic hazard (Vilanova and Fonseca, 2007) and seismic risk assessment that were carried out for Portugal (Campos Costa *et al.*, 2009) there is still a long way towards the mitigation of seismic risk. Moreover, a significant percentage of existing Portuguese buildings were not seismically designed and many of those that were indeed seismically designed are not expected to exhibit adequate seismic performance. In this sense, there are few studies that have sought to characterize as accurately as possible the seismic vulnerability of the Portuguese in-built (Sousa *et al.*, 2010), using models of different complexity levels capable of defining fragility functions for various building typologies (derived empirically, analytical or based on expert opinion). Other studies have also addressed the seismic vulnerability and risk assessment of Portuguese urban areas, focusing particularly on historic centres (Vicente *et al.*, 2010; Ferreira *et al.*, 2013; Maio *et al.*, 2015; Lamego *et al.*, 2016; Ferreira *et al.*, 2016). Furthermore, it is also important to note how the measurement of the resilience of the society to respond to the effects of earthquakes, as well as the corresponding impact on economic and industrial activity and on the interdependencies in various physical systems (road networks, rail, energy, etc.), require a high degree of complexity hence an interdisciplinary approach.

A recent resolution of the Portuguese Parliament on the adoption of measures to reduce seismic risk points, in fact, towards the estimation of the extent of the above-mentioned concerns. Within this context, the research project PRISE defined up-to-date hazard, exposure and vulnerability models that realistically represent the possible consequences of future seismic events in Portugal. This paper focuses on the presentation of the main developments and outcomes of this research project, deemed as good practice for large-scale seismic risk assessment initiatives, the advances in different branches of earthquake engineering that were achieved, as well as providing a scientific contribution to inform society and decision-makers on the impact of earthquakes.

2. The PRISE project

PRISE was funded by the Portuguese Foundation for Science and Technology (FCT), involving a consortium of institutions in Portugal and Italy. The project started in June 2013 and was concluded in September 2015. Research wise, the consortium included the Faculty of Engineering of the University of Porto (FEUP. www.fe.up.pt), the coordinator, the Portuguese National Civil Engineering Laboratory (LNEC, www.lnec.pt), the University of Aveiro (UA, www.ua.pt) and the European Centre for Training and Research in Earthquake Engineering (EUCENTRE, www.eucentre.it), in Italy. Finally, representing a share of the decision-makers, the consortium also featured the Portuguese Insurers Association (APS, www.apseguradores.pt). In order to assure a correct and accurate representation of the national context, partnerships for data collection and operative implementation were also established with the Portuguese Sea and Atmosphere Institute (IPMA, www.ipma.pt), the National Laboratory of Energy and Geology (LNEG, www.lneg.pt), Infrastructure of Portugal (IP, www.infraestruturasdeportugal.pt) and the Directorate General of the Territory (DGT, www.dgterritorio.pt).

2.1 Structure and objectives

The project's main goal was to contribute to a better understanding of the impact of the action of earthquakes. To this end, a series of studies were undertaken towards the establishment of a robust approach to the estimation of economic and human losses, properly correlated with structural damage of the Portuguese in-built. At the same time, detailed attention was paid, through parametric studies, to the spread of the uncertainty related to the different input variables of the risk assessment process: hazard, vulnerability and exposure. The planning of the activities featured the following tasks:

1) Seismic hazard assessment;
2) Definition of population distribution and building inventory;
3) Evaluation of physical and social vulnerability of the exposed;
4) Definition of repair cost and economic impact models;
5) Estimation of economic, human and social losses at different resolutions; and
6) Development of an open source web platform for loss estimation according to different scenarios and dissemination among different stakeholders.

2.2 Calculation Tools

The estimation of seismic losses was accomplished through probabilistic seismic hazard analyses (PSHA) and deterministic analyses, representing specific scenarios (SRA – Scenario Risk Analysis). The software employed, OpenQuake (Silva *et al.*, 2014), was developed by the Global Earthquake Model (GEM) Foundation (www.globalquakemodel.org). The choice was due to its open source nature, the ongoing support and the strong involvement of the scientific community in the development of several analysis modules, catering for versatility, efficiency and accuracy. For what concerns the physical fragility model, the structural analyses were carried out with OpenSees (2016), also open source, which presents the advantage of being easily implemented in automatic procedures. The features of the employed software tools were in line with one of the main concerns of the PRISE project, which was to assure openness and access to the information regarding the developed models and tools.

3. Seismic risk model

Bearing in mind the important advances in seismic risk assessment for Portugal, the project activities started with a thorough conceptual review of the existing approaches, their advantages and limitations, with respect to the different tasks. Concerning past studies with a national coverage, the first comprehensive seismic hazard assessment was carried out with a view to the definition of the seismic hazard maps considered in the Portuguese design code. Subsequently, within the activities of the FP6 project LESSLOSS (2006) a seismic risk assessment study was conducted for the Metropolitan Area of Lisbon, using data from Building Census 2001 (www.censos.ine.pt) and simplified methodologies for the vulnerability component. Recently, Silva *et al.* (2015) performed a probabilistic seismic risk study for mainland Portugal based on an improved set of vulnerability functions for RC buildings derived from detailed numerical models. In the European context, there have been recent and crucial contributions from other EU projects: SHARE, SYNER-G, REAKT and RISK-UE. PRISE has built upon these past works, aiming to provide innovative and realistic seismic risk assessment, controlling the uncertainty in its components and considering the existing variability.

3.1 Seismic hazard model

The hazard model for Portugal was sought with the goal of encompassing the most up-to-date developments driven by the most recent studies. To such extent, some aspects were recovered from past projects, such as source zonation, source geometry and activity parameters or attenuation relationships. Ground motions at bedrock level were simulated over a range of interest of magnitude, distance and frequency, obtained from disaggregation analysis, which was carried out considering the faults parameters (Figure 1 *left*) released from the FP7 SHARE project (Woessner *et al.*, 2015).

For five soil types classified according to EC8, and considering the simulated seismic action as input, a one-dimensional shear wave propagation model was applied, assuming the vertical propagation of shear waves on horizontally stratified ground. Moreover, the linear equivalent method, an interactive process to account for nonlinear behaviour of the soil, was employed. A database of response spectra at the surface, for each EC8 soil type, was then obtained.

Furthermore, the source zonation suggested in the national project ERSTA (Sousa *et al.*, 2008) (Figure 1 *right*), concerning seismic and tsunami risk assessment for the Metropolitan Area of Lisbon and Algarve region, was used and updated with a new catalogue of events.

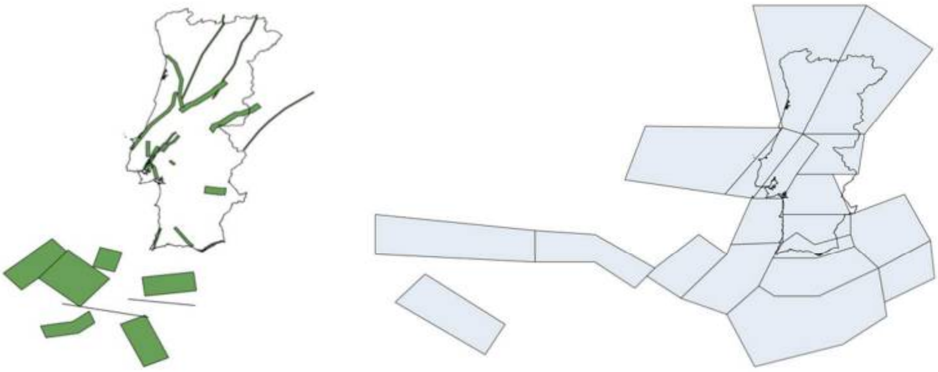

Figure 1. (*left*) Fault and (*right*) area sources used in the hazard model.

Source: Adapted from Sousa *et al.* (2008)

Two ground motion prediction equations (GMPE), for active and stable regions, were derived and applied (Rodrigues *et al.*, 2014), yielding the spectral acceleration (S_a) at the bedrock, as a function of magnitude (M_W), epicentral distance (R_{JB}) and epsilon (σ_ε). From the synthetic database, simple functional forms for those GMPEs were sought, as illustrated in Equation (1), with a minimum required number of predictor variables, including nonlinear scaling of ground motion amplitudes (S_a) with magnitude and epicentral distance dependence. Epsilon (σ_ε) represents the number of standard deviations by which the observed logarithmic S_a differs from the mean logarithmic of the GMPE. A logic tree schema was used to take into account the epistemic uncertainties of the model.

$$log_{10}(S_a) = c_1 + c_2M + c_3M^2 + c_4log_{10}(R) + c_5R + \sigma_\varepsilon \tag{1}$$

Coefficients c_1 to c_5 and σ_ε were determined and calibrated by regression analysis for both active and stable regions, for the bedrock level (Table 1) and also for the five soil categories (A to E) foreseen by Eurocode 8 (CEN, 2005).

Table 1. GMPE coefficients for active and stable regions – bedrock. (Rodrigues *et al.*, 2014)

	Active regions						***Stable regions***					
f (Hz)	C_1	C_2	C_3	C_4	C_5	σ_E	C_1	C_2	C_3	C_4	C_5	σ_E
0.201	4.975	-8.261	2.297	-0.11	-0.657	-0.001	-7.457	2.176	-0.09	-1.298	0.002	0.218
0.240	4.167	-8.178	2.313	-0.114	-0.617	-0.001	-7.765	2.329	-0.106	-1.235	0.002	0.218
0.334	2.994	-7.585	2.23	-0.112	-0.549	-0.001	-8.217	2.589	-0.133	-1.124	0.001	0.219
0.522	1.916	-5.875	1.872	-0.093	-0.465	-0.001	-7.983	2.686	-0.15	-0.991	0	0.221
0.954	1.048	-3.927	1.455	-0.069	-0.401	-0.002	-7.114	2.606	-0.154	-0.906	0	0.226
1.285	0.778	-2.898	1.237	-0.055	-0.41	-0.002	-6.256	2.411	-0.142	-0.879	-0.001	0.228
1.669	0.599	-1.431	0.926	-0.035	-0.478	-0.002	-5.371	2.192	-0.128	-0.866	-0.001	0.23
1.953	0.512	-0.986	0.832	-0.029	-0.489	-0.002	-4.765	2.036	-0.117	-0.867	-0.001	0.233
2.421	0.413	-0.591	0.747	-0.024	-0.494	-0.002	-3.953	1.821	-0.102	-0.875	-0.001	0.236
3.311	0.302	-0.241	0.672	-0.019	-0.492	-0.002	-2.992	1.571	-0.083	-0.893	-0.001	0.24
3.906	0.256	-0.116	0.645	-0.017	-0.489	-0.002	-2.522	1.447	-0.074	-0.91	-0.001	0.242
5.025	0.199	0.022	0.614	-0.015	-0.486	-0.003	-1.98	1.305	-0.064	-0.929	-0.001	0.245
6.25	0.16	0.11	0.595	-0.014	-0.482	-0.003	-1.562	1.202	-0.056	-0.963	-0.002	0.247

7.299	0.137	0.116	0.589	-0.014	-0.496	-0.003	-1.36	1.152	-0.052	-0.982	-0.002	0.249
8.403	0.119	0.12	0.585	-0.014	-0.51	-0.002	-1.211	1.113	-0.049	-0.994	-0.002	0.251
9.901	0.101	0.127	0.58	-0.013	-0.526	-0.002	-1.068	1.076	-0.046	-1.004	-0.002	0.254
12.50	0.08	0.138	0.573	-0.013	-0.548	-0.002	-1.037	1.067	-0.045	-1.036	-0.002	0.256
14.925	0.067	0.149	0.569	-0.012	-0.564	-0.002	-1.016	1.06	-0.045	-1.059	-0.002	0.258
20.00	0.05	0.167	0.562	-0.012	-0.588	-0.002	-0.985	1.05	-0.044	-1.091	-0.002	0.263
22.222	0.045	0.174	0.56	-0.012	-0.597	-0.002	-1.081	1.071	-0.045	-1.098	-0.002	0.261
25.00	0.04	0.183	0.557	-0.012	-0.607	-0.002	-1.21	1.101	-0.047	-1.107	-0.001	0.259
30.303	0.033	0.194	0.554	-0.011	-0.619	-0.002	-1.382	1.142	-0.05	-1.118	-0.001	0.256
40.00	0.025	0.21	0.549	-0.011	-0.636	-0.002	-1.683	1.216	-0.056	-1.136	-0.001	0.252
50.00	0.02	0.135	0.564	-0.012	-0.629	-0.002	-1.722	1.22	-0.056	-1.131	-0.001	0.251

Figure 2 illustrates the GMPE predictions for all the soil types (in addition to bedrock) for both types of regions (active and stable).

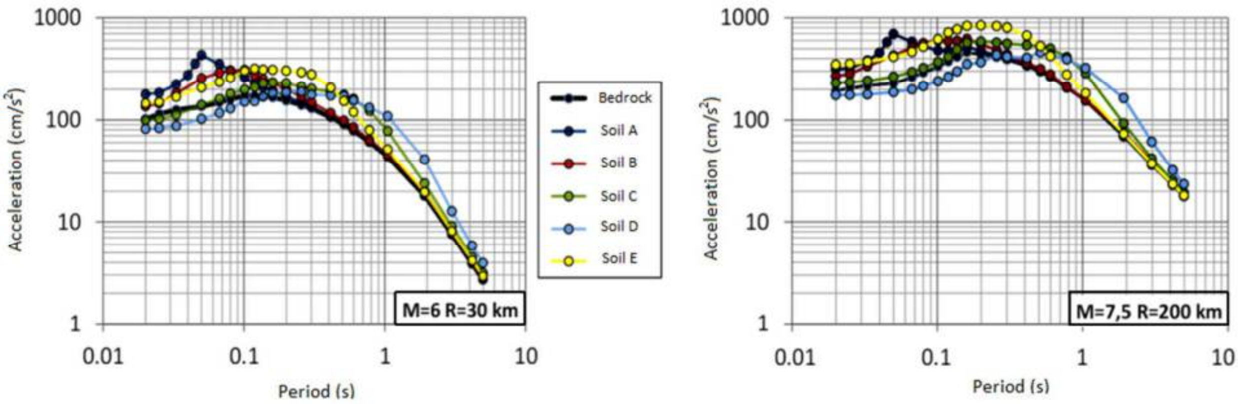

Figure 2. Spectral acceleration for (*left*) active region event (M_W=6, R_{JB}=30km) and (*right*) stable region event (M_W=7.5, R_{JB}=200km). (Rodrigues *et al.*, 2014)

Considering the seismogenic zones identified for Portugal, hazard calculations were thus performed. A parametric study was carried out, considering the fault geometry, tectonic region, source zonation and fault rupture parameters (strike, dip, rake and maximum magnitude) for the Portuguese territory, as well as the importance of each GMPE to the computation of the hazard map. Several branches were considered, to account for epistemic uncertainty. Figure 3 shows the distribution of PGA values (bedrock) obtained for three scenarios: (i) probability of exceedance of 10% in 50 years; (ii) the 1909 Benavente's earthquake scenario; and (iii) the 1755 Lisbon's earthquake scenario.

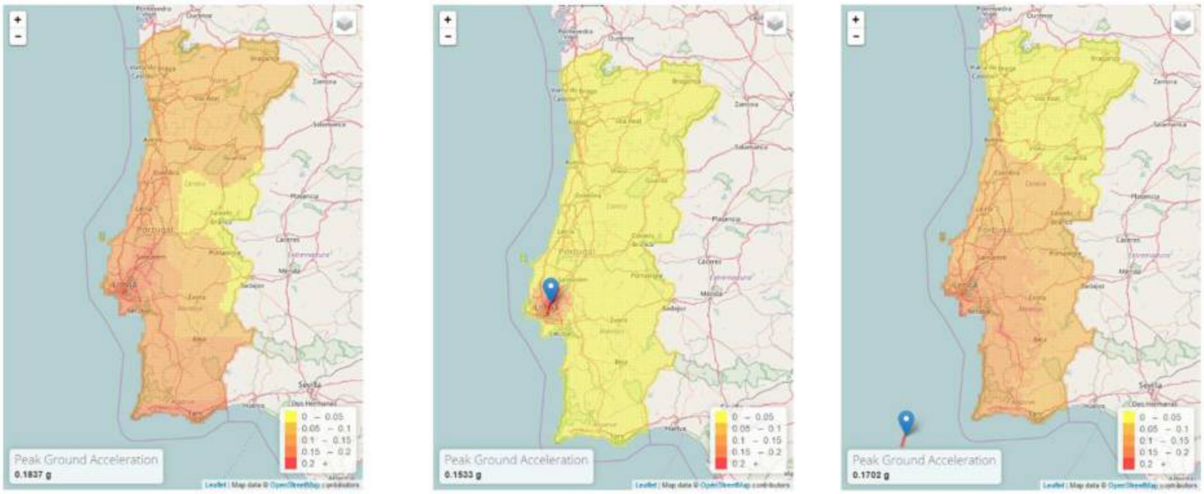

Figure 3. Hazard maps (PGA): (*left*) probability of exceedance of 10% in 50 years; (*centre*) the 1909 Benavente's earthquake scenario; and (*right*) the 1755 Lisbon's earthquake scenario. [from EQlogger (Silva et al. 2015)]

To perform the hazard disaggregation, the hazard contributions were assessed in a bi-dimensional space: the relative contribution to the hazard is studied in terms of elementary bins of magnitude M_W, and source-to-site distance R_{JB}. Disaggregation was achieved in two steps: (i) accumulate in each bin its contribution to the global hazard and (ii) divide the total contribution accumulated in each bin by the total annual frequency of exceedance. The pairs of mean magnitude and distance that contribute to hazard were identified from the disaggregation results (Figure 4) considering the Portuguese counties for three exceedance probabilities in 50 years (10%, 5% and 2%).

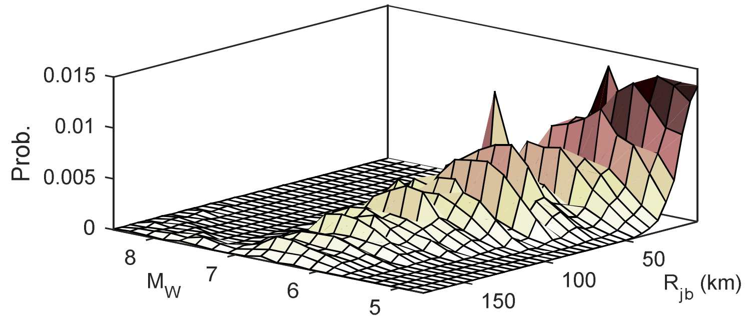

Figure 4. Rupture-by-rupture disaggregation for $S_a(T1)$=0.5g for the city of Lisbon. Ruptures are grouped with $\Delta M_W = 0.2$ ΔR_{JB} =5 km, for visual clarity.

3.2 Exposure model

The exposure model was tackled by assessing the characteristics and spatial distribution of the residential and industrial buildings and population. The Building Census 2011 providing data at a parish level was analysed in detail, reporting 3,544,389 residential buildings. Several attributes were considered from the building census data:

i. *type of construction* (RC – reinforced concrete; M1 – masonry with concrete floors; M2 –

masonry with timber floors; M3 – weak masonry; OT – others);

ii. *year of construction* (Pre-code – design with no code provisions; Low-code – first seismic design codes, corresponding to the period from 1958 to 1961; Mid-code – for buildings constructed between 1961 and 1983; High-code – for buildings that comply with the current seismic design code provisions);
iii. *seismic zones* (low-code structures have three zones, A, B, C; while four zones are considered in mid-code structures, A, B, C, D); and
iv. *number of storeys* (1, 2, 3, 4, 5-7, >8 storeys).

A total of 102 typologies for RC buildings came out of the four considered variables. In order to identify the Portuguese building stock in terms of its geometric and material properties, a survey was conducted in design offices, city halls and practitioners throughout the country with the purpose of capturing the variability in the structural design and construction practice adopted in different regions. This endeavour was an extension of the work initiated by Silva *et al.* (2014), in which more than 200 blueprints and design specifications were analysed, and statistical distributions were fitted to its properties (e.g. storey height, columns and beams cross sections, concrete and steel strength), with the purpose of capturing the variability in the structural design and construction practice in the different regions.

Furthermore, a similar approach was followed for the analysis of industrial buildings, also motivated by the recent poor performance of this sort of buildings during the 2012 Emilia-Romagna earthquake in Italy (Belleri *et al.*, 2014). A total of 200 blueprints and drawings of buildings constructed between 1995 and 2014 were collected in steelwork companies and specialized design offices to fit probabilistic distributions to a set of geometric parameters. These distributions were then employed in the random generation of industrial building portfolios using simulation techniques, such as crude Monte Carlo Sampling or Latin Hypercube Sampling, which have been successfully implemented in other studies related to the seismic assessment of RC structures (Monteiro, 2016). Such portfolios followed a taxonomy comprising six industrial portal frame steel building typologies that was defined by putting together altitude and building height attributes:

1. low wind design (LWD), i.e. altitudes lower that 100m;
2. average wind design (MWD), i.e. altitudes between 100m and 800m;
3. high wind design (HWD), i.e. altitudes higher than 800m; and

i. low buildings (LH), i.e. lower than 5.5m;
ii. high buildings (HH), i.e. higher than 5.5m.

The information on the existing Portuguese industrial assets at risk was taken from the Portuguese National Institute of Statistics (INE), which provides economic statistical data with a maximum resolution at the county level. The assets were distributed spatially (Figure 5) over the same evenly spaced grid of 30 arc sec resolution, based on additional information from the geographical distribution of industrial assets collected from OpenStreet Maps (www.openstreetmap.org), the European Environment Agency Land Cover inventory (CORINE, www.eea.europa.eu) and the AICEP Global Find platform (www.globalparques.pt). The distribution of the assets within each county was carried out considering the inverse distance weighting criterion.

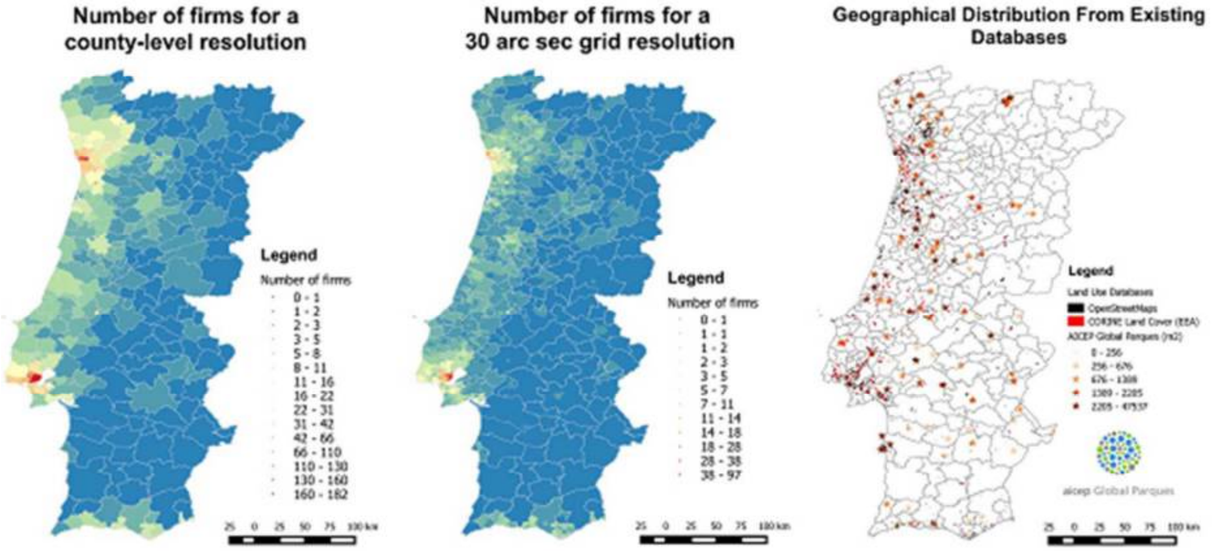

Figure 5. Exposure model for industrial buildings.

A parish-based exposure model containing the number of buildings from each taxonomy branch was created for residential and industrial buildings, and a more detailed resolution was used for the distribution of buildings throughout the Portuguese territory using the population distribution dataset LandScanTM (Dobson *et al.*, 2000) as proxy. This dataset uses an algorithm to allocate population count in an evenly spaced grid with a 30 arc sec spatial resolution (which in Portugal represents approximately 0.75km^2), based on parameters such as proximity to roads and train lanes, terrain slope, land cover and night-time lights. In addition to the Census data, the population distribution scheme was defined taking into account the dynamic mapping along the day (transit, day and night periods), following the approach and using the data from Deville *et al.* (2009).

Regarding site effects, field measurements obtained at several locations in the central and south regions of Portugal by the National Laboratory of Energy and Geology (LNEG) were used to validate the employment of simplified methodologies (based on the slope topography or a set of geology units) to obtain proxy $V_{s,30}$ values. First-order $V_{s,30}$ values were derived from the correlation between a set of geology units and $V_{s,30}$ values whereas the use of slope topography to obtain proxy $V_{s,30}$ values was 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.

3.3 Vulnerability model

In countries such as Portugal, where post-earthquake damage data is very scarce or non-existent, the use of analytical procedures for the definition of vulnerability models is crucial. However, these analytical or numerical models must be used with care in order not to produce erroneous results hence residential and industrial vulnerability functions using accurate nonlinear time-history analyses were derived. Several techniques were assessed for the selection of records consistent with the developed hazard scenario, including state-of-the-art methods. A large dependency of losses and vulnerability functions was found with respect to: (i) the record selection method, (ii) number of records, (iii) intensity measure (IM) types and levels. An innovative methodology for the derivation of conditional fragility functions was proposed (Sousa *et al.*, 2016), according to which multiple ground motion IMs are included in the characterization of building fragility through probabilistic distributions of the damage exceedance probability for each level of spectral acceleration at the building's fundamental period, $S_a(T_1)$ – Figure 6.

The relevance of such novel approach has been demonstrated within the context of loss estimation of building portfolios, where the spatial correlation of ground motion residuals plays a significant role. The importance of the introduced conditional fragility functions is illustrated by demonstrating its capability of consistently taking into account record-to-record variability in the evaluation of fragility. The variability of structural capacity and seismic demand have been considered in an analytical framework based on the random generation of the building classes defined within the exposure model, by considering the statistical distributions of the geometric and material properties. Each structure was modelled in a 2D framework using the open-source software OpenSees, with force-based distributed plasticity beam-column elements. Regarding industrial buildings, in line with the findings of the exposure model in Section 3.2, a moment-resisting portal frame system and a bracing system constituted the in-plane and out-of-plane structural systems of the buildings, respectively, in accordance with the current construction practice in Portugal. Due to very different performance in x and y directions, 3D models were instead used, in this case. Thousands of nonlinear time-history analyses were then performed to take into consideration the record-to-record and building-to-building variabilities.

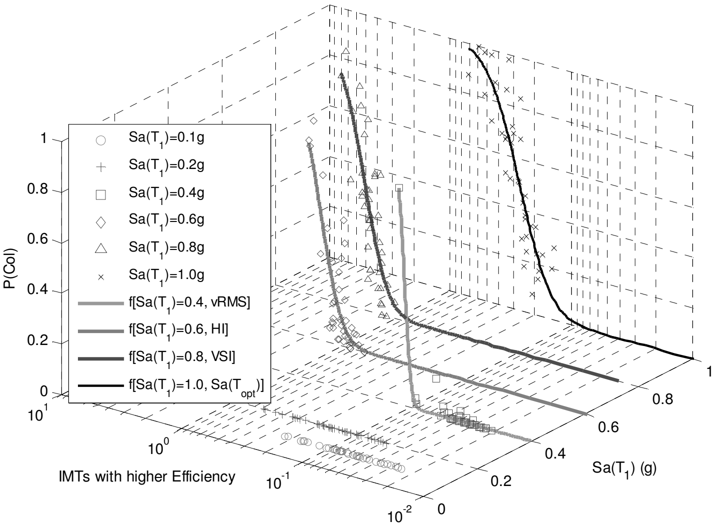

Figure 6. Conditional fragility functions.

Special attention was paid to the assessment of the soil-structure-interaction (SSI) effects in building structures subjected to the seismic action and settled in different soil conditions. A simplified model to include the SSI in time domain analyses was proposed and used for the derivation of fragility and vulnerability functions, leading to promising results, when compared to complex models that present time constraints hence cannot be applied in large-scale vulnerability assessment studies. The same framework was adopted for the industrial buildings, taking into account property (structural and non-structural components), contents, relocation and business interruption, in the vulnerability assessment. Figure 7 shows the 95% quantile of the average loss ratios in 50 years (i.e. ratio between the repair and the replacement costs of the building), obtained for the six building taxonomies with respect to altitude and height, considering a totally fixed support condition (FBPC) and the buildings to be located in the city of Lisbon. The importance of the input dependency, i.e. higher equipment and labour intensity and degree of labour specialization, to the seismic vulnerability of the food and pharmacy activity sectors is also revealed in Figure 7.

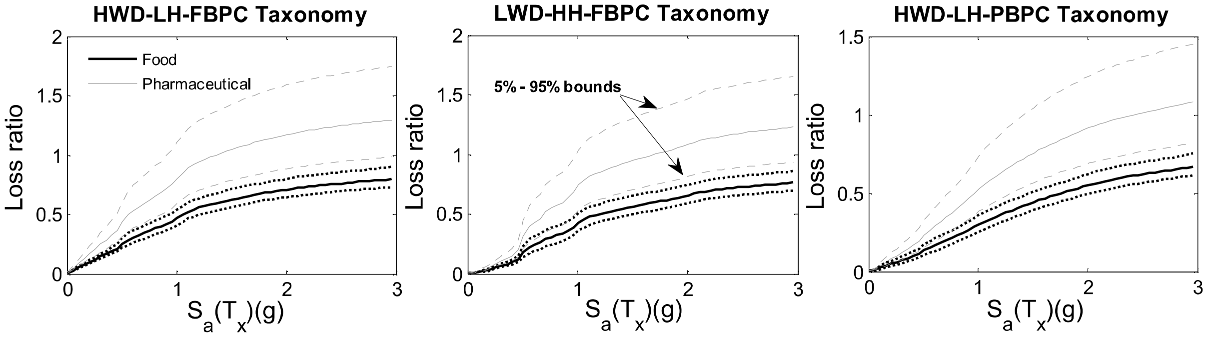

Figure 7. Industrial property vulnerability functions for different building categories: (*left*) HWD-LH with FBPC connection, (*centre*) LWD-HH with FBPC connection and (*right*) HWD-LH with PBPC connection.

Finally, a framework was developed to assess earthquake risk beyond the estimation of direct physical impacts and loss of life. This methodology was built via the integration of estimates of physical risk with estimates of human or economic loss, defined through quantified metrics that represent social and economic characteristics of the Portuguese population. A wide spectrum of social and economic indices (95 variables from the 278 counties in Portugal) were analysed and categorized by geographic location, leading to a total risk index that was used to amplify the physical losses.

3.4 Damage to cost estimation

A major drawback in current seismic risk methodologies is associated with the use of models to convert a certain level of damage to a percentage of economic loss. These models, usually known as consequence functions, relate the fraction of cost of repair to cost of replacement for each limit state of damage, and can be obtained from empirical data, expert judgment or analytical procedures. Only a few models exist, mostly for countries with high seismicity and for limited building classes. Therefore, although the HAZUS (FEMA, 2006) model was applied in previous seismic risk assessments for Portugal, its use is expected to lead to unrealistic estimates of losses due to the differences in the Portuguese and US housing stock, construction techniques, costs, etc. The need to compute a damage-to-loss model for Portugal was tackled by performing a wide review of experimental data on structural and non-structural (infill walls) elements, carried out in the laboratory facilities of the partners of the project. Moreover, for each type of element and level of physical damage, suitable repair techniques and their unit repair costs were associated. A real case study was used, representing the typical high-code RC class (built in the 1990's) in Portugal. The information regarding structural design and structure of costs was analysed in detail, in order to have a deep knowledge about the economic impact of each building component in the overall budget.

Nonlinear time-history analyses of the 3D model of the building (including non-structural elements) were carried out and the seismic performance of each element was assessed. The evolution with the intensity level of the repair costs of each element and the building was estimated (Martins *et al.*, 2015). The referred loss estimation was defined taking into consideration conditional fragility performance between structural and non-structural components defined in terms of expert opinion and empirical data – Figure 8 *left*. Through a modified version of the Park and Ang damage index (DDI) and a comprehensive study of the repair costs, it was possible to estimate element loss ratios, expressed as cost of repair to cost of replacement. The expected losses from the non-structural components have also been considered. This study allowed not only to accurate predict the expected economic losses in buildings, but also to define an adequate consequence model compatible with the Portuguese building stock, Figure 8 *right*.

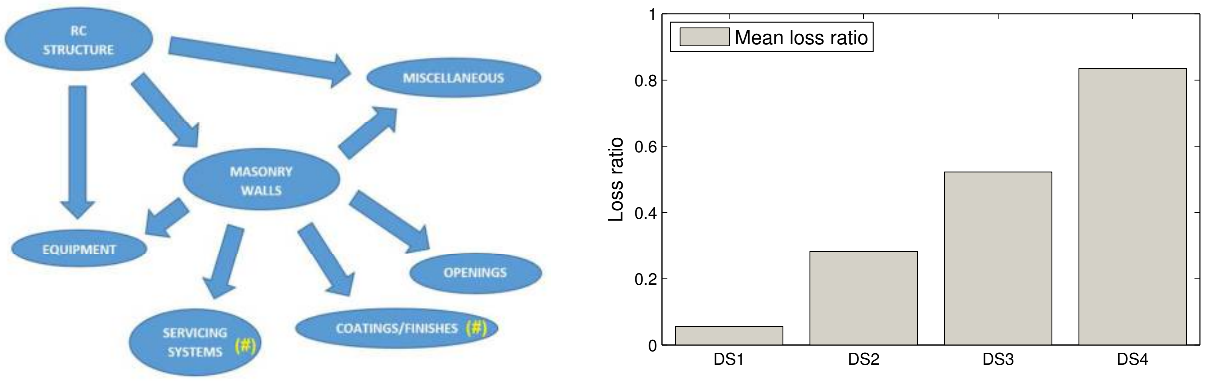

Figure 8. (*left*) Dependency between structural and non-structural components; (*right*) consequence model for RC buildings in Portugal.

3.5 *Dissemination – open source web-based platform*

The components described in the previous sections were integrated to perform both probabilistic and scenario-based risk assessments for Portugal and to estimate the corresponding human and economic losses. For the scenario-based analyses, tree historical earthquake events were selected, which are currently used by the national authorities for emergency plans: the well-known Lisbon offshore earthquake of 1755 (M_W≈8.5); the Benavente earthquake of 1909 (M_W≈6.0); and an event that occurred in 1531 located north of Lisbon (M_W ≈7.0). A probabilistic seismic hazard analysis and a stochastic event-based analysis were performed using the refined hazard model, as described in Section 3.1. The calculations, carried out using OpenQuake, identified the regions at higher seismic risk and the building typologies contributing most to the human and economic losses.

In addition to physical vulnerability, attention was also paid to the social behaviour and the ability of the Portuguese population to recover from an earthquake event. Hence, a simplified approach was applied (Carreño *et al.*, 2012) to integrate the resilience of the society into the direct risk, which was defined from the analysis of several social indices presented in Census data, United Nations and World Bank databases. In addition to the development of the risk model, the PRISE project also guaranteed and effective integration of its outcomes (i.e. tools, models and results) in a transparent, reliable and graphical interface to be used by the public authorities and seismic risk stakeholders. To this extent, EQlogger, an open-source real-time seismic loss estimation GIS web-based platform was developed (Silva *et al.*, 2015). EQlogger is capable of rapidly performing earthquake loss estimations for any earthquake event triggered by the Portuguese Seismographic Network and to alert the registered users by email, with a report of the estimated consequences. A module for earthquake scenario loss estimation is also implemented. The Portuguese Institute of the Sea and Atmosphere (IPMA) continuously monitors the seismic activity and releases information to the server of PRISE regarding the location, magnitude and depth in a matter of minutes, which is an acceptable time range for the framework proposed herein. Once an event is received by the platform, a process to calculate the ground shaking and associated losses is triggered and its potential impact is assessed. In case the event goes beyond a certain damage criterion, the OpenQuake is triggered and the Scenario Damage Calculator is used to estimate the number of collapsed buildings and fatalities for each municipality, making use of the hazard, exposure and vulnerability models that were described. The outputs are available in terms of spatial mapping and graphical representation of the damages and losses – Figure 9.

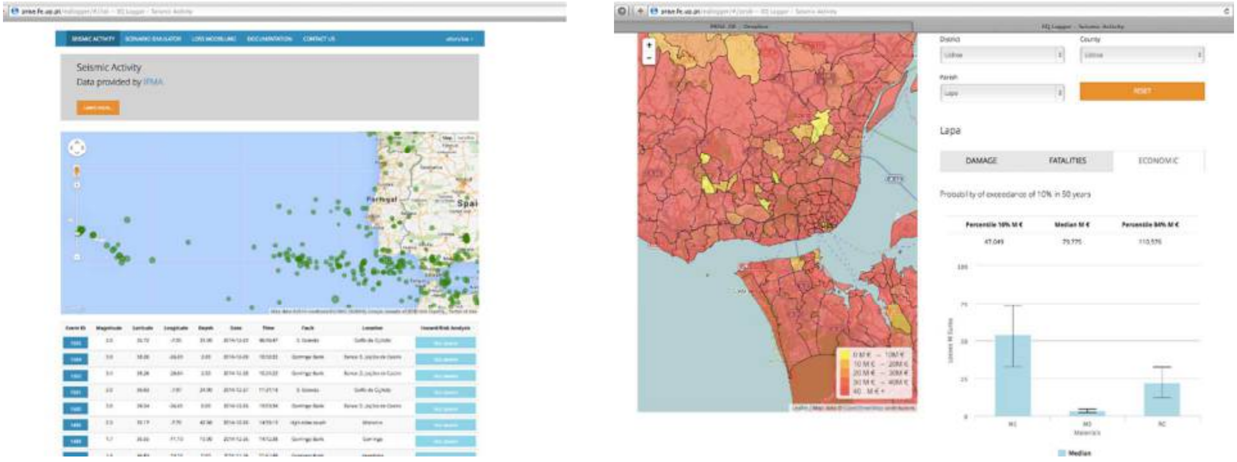

Figure 9. Examples of outputs from EQlogger.

4. Concluding remarks

This paper described an extensive seismic risk assessment study for Portugal, developed within a recent research project – PRISE – covering thoroughly the hazard, vulnerability and exposure components. The most recently available hazard model for the Portuguese territory was presented and used to select and scale ground motion records through PSHA and advanced spectral matching procedures for reduced aleatory uncertainty. Extensive nonlinear dynamic analyses were then carried out for different building typologies in order to produce improved fragility and consequence models for RC and industrial buildings. Further improvement was also obtained for the exposure model by extending the collection of data of the most recent census survey, as well as local/regional databases for increase of accuracy on the loss estimates.

The presented loss assessment framework led to results that differ with respect to state-of-the-art vulnerability assessment methods in a consistent manner across different building typologies and damage state definition criteria. More specifically, it has been verified that state-of-the-art methodologies tend to overestimate the annual rate of exceedance of lower (i.e. more frequent) loss values, with respect to the framework developed in the PRISE initiative. On the other hand, the opposite trend is verified for higher aggregated losses. The latter is shown to be related with the presented methodology's more robust representation of the impact of record-to-record variability in loss estimations, highlighting its strengths and contribution to the improvement of fragility, vulnerability and loss assessment of building portfolios.

As detailed throughout the paper, there were several advances in scientific knowledge and methodologies for risk analysis and loss estimation arising from the project tasks. Particularly, this work provided a significant contribution to the understanding and reduction of the different uncertainties surrounding all models and analysis processes towards seismic risk (e.g. hazard and ground motion selection, fragility curves, damage/consequence functions). Still, other sources of uncertainty require further addressing and improved approaches. Some of these include the characterization of the population dynamics, the 3D behaviour of the buildings of the different taxonomy branches and irregularities in plan, as well as the effects of soil-structure interaction and structural correlation. Furthermore, several additional assets and infrastructure should be included for completeness of the model.

Finally, involving different stakeholders confirmed their continued interest in research openness and collaboration, as well as the need for integrative seismic risk assessment approaches.

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