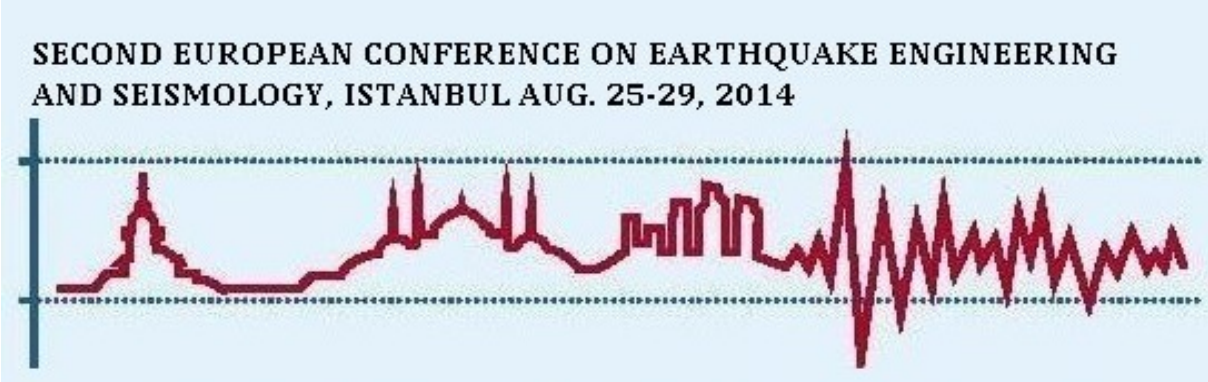

DEVELOPMENT OF A FRAMEWORK FOR REAL TIME EARTHQUAKE LOSS ESTIMATION FOR PORTUGAL

Vitor SILVA[1], Mario MARQUES[2], Helen CROWLEY[3], Humberto VARUM[4], Rui PINHO[5]

ABSTRACT

Portugal has its past marked by the occurrence of very destructive earthquakes. In the well-known 1755 Lisbon earthquake, despite the various estimates proposed by the scientific community it is fair to assume that in Lisbon, more than 50% of the buildings were heavily damaged or destroyed and about 10% of the population perished. In the beginning of the last century, a moderate event of magnitude 6.6 Mw struck the village of Benavente, causing 46 fatalities and damaging more than 3000 dwellings. Besides this moderate seismicity, the Portuguese building stock in highly populated centres is characterized by a large fraction of masonry buildings, which typically have a higher seismic vulnerability. For these reasons, it is clear that a reliable and accurate platform for damage estimation based on deterministic earthquake scenarios is fundamental. This study provides an overview of the initial development of a damage estimation framework for Portugal, as well as a description of the components and input models required for the various calculations. This system has been established at the Faculty of Engineering of the University of Porto, and it will allow not only earthquake engineers and risk modelers to access damage information and launch scenario calculations, but also other experts and decision makers whose needs might have a particular purpose, such as emergency planning.

INTRODUCTION

Emergency rescue reports from several past earthquakes indicate that 85% to 95% of the successful rescues of people trapped under debris occurred within the first 24 to 48 hours (Oliveira *et al*., 2006). The fraction of successful rescue attempts depends on the number of affected people, performance of the rescue operations, and most importantly, the strategic allocation of the limited resources shortly after the seismic event. Thus, the availability of a system capable of estimating the dimension and spatial distribution of damage and loss immediately after the occurrence of an earthquake is of critical importance. Furthermore, the employment of such framework to estimate building damage and economic/human losses due to hypothetical future earthquakes may also provide national authorities and other decision makers with valuable information for the development of risk mitigation actions. These events could be based on past historical earthquakes (Bendimerad, 2001) or be defined through the investigation of seismogenic sources around the region of interest (Ansal *et al.,* 2009).

Seismic risk mitigation measures that may arise from the evaluation of the consequences from single events may include post-disaster emergency planning, strengthening/retrofitting of the building

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typologies contributing the most to the death toll, strategic urban planning, or development of support infrastructures (e.g. shelters) around the affected region.

In the context of loss assessment for earthquake scenarios, Portugal (in particular the Metropolitan Area of Lisbon - MAL) has been the target of extensive studies regarding disaster preparedness (Mendes-Victor *et al*., 1994), influence of microzonation in loss estimation (Oliveira, 2004), site-conditions mapping (Narciso *et al*., 2013), ground motion shaking simulation (Carvalho *et al*., 2008), seismic performance of RC structures (Proença *et al*., 2004; Silva *et al*., 2014a) and damage assessment for a number of seismic events (Spence 2007, Oliveira 2008). Additionally, in the FP7 European project REAKT (Gasparini and Cua, 2012), which addresses real-time earthquake risk mitigation, the profitability of implementing an early warning system in the industrial complex of Sines (southwest of Portugal) is being investigated. Due to the flexibility and modular nature of the framework presented herein, some of the findings and outcomes of these previous studies have been utilized, as described in the following sections.

This study provides an overview of the initial development of the damage estimation framework for Portugal, as well as a description of the components and input models required for the various calculations. This system (herein termed as PORTAL – Portuguese Real-time Assessment of Loss) has been established at the Faculty of Engineering of the University of Porto, located in the north of Portugal.

COMPONENTS OF A REAL-TIME EARTHQUAKE LOSS ESTIMATION SYSTEM

A number of existing systems for rapid estimation of earthquake consequences have been evaluated, in order to understand the critical features that should be covered in the present framework. Some of the systems developed around the world are more focused on earthquake early warning (EEW) systems (e.g. Italy – Zollo et al., 2009; Turkey – Alcik *et al*. 2009; Japan – Hoshiba *et al*. 2011; Taiwan – Hsiao *et al*., 2009), rather than the rapid estimation of the earthquake loss and damage. These initiatives aim to launch alerts seconds before the arrival of the destructive seismic waves, usually through the interpretation of the amplitude of the P waves. This lead-time may be useful to initiate emergency measures, such as the controlled shutdown of high-technological factories, speed reduction of rapid-transit vehicles, orderly shutdown of gas pipelines and advice the population to endorse the necessary precautions (Wu and Kanamori, 2008).

In Portugal, the Portuguese Institute of the Sea and Atmospheres (IPMA [5]) continuously monitors seismic activity, but an EEW system is not yet in place. Nevertheless, once a seismic event occurs, information about its location, magnitude and depth is made available in a matter of minutes, which is an acceptable time range for the proposed system.

The various components that integrate the real-time earthquake loss estimation system (PORTAL) are illustrated in Figure 1.

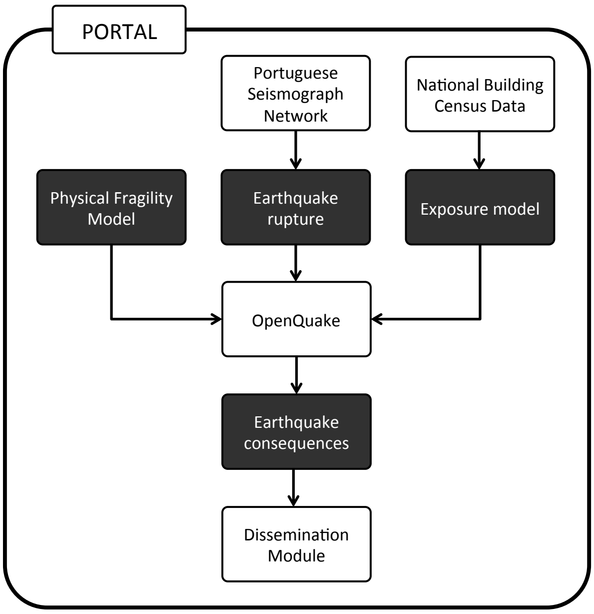

Figure 1 - Structure of the real-time earthquake loss estimation system (PORTAL).

Seismic hazard input

The estimation of the ground motion throughout the region of interest is computed using the scenario-based hazard calculator of the OpenQuake-engine (Pagani *et al*. 2014). In order to properly consider the intra- and inter-event variability, several realizations of the same event are produced, thus leading to several maps of ground shaking, herein termed as ground motion fields. The employment of a large number of ground motion fields, rather than simply considering a single ground motion value at each location, or even a median ground motion and associated standard deviation, enables the consideration of the spatial correlation of the intra-event residuals, which is necessary to robustly model the uncertainty in the associated losses (Weatherill *et al*., 2014). This approach, however, has the disadvantage of potentially becoming considerably time consuming for seismic events affecting a widespread area. Based on several tests conducted in this study, it has been estimated that at least 1000 ground motion fields are necessary to achieve convergence in the spatial distribution of ground shaking, and 2000 to attain the same level of convergence in the respective losses.

The ground motion prediction model (GMPE) is potentially the factor that has a higher impact in the ground shaking distribution (Pelaez and Casado, 2002), and consequently in the associated losses (Crowley *et al*., 2005). The selection of an adequate attenuation model for Portugal represents a challenging task due to the lack of ground motion recordings that could allow the development of a specific ground motion prediction equation, or at least, a reliable verification of existing models (e.g. Delavaud *et al*., 2012). A comprehensive discussion regarding the selection of a set of ground motion prediction equations for mainland Portugal can be found in Silva *et al*. (2014b). This study relied on a number of key factors such as: detailed evaluation of the seismogenic environment in the vicinity of the region of interest; analysis of hazard disaggregation for several highly populated locations; recommendations from ground motion modelling experts (Delavaud *et al*. 2012, Steward *et al*. 2013); and comparison between observations from a limited number of seismic events with estimations from a selection of models carried out by Vilanova *et al*. 2012. The findings from this study recommended the employment of the attenuation models Atkinson and Boore (2006) and Akkar and Bommer (2010) within a logic three structure, with a weight of 0.7 and 0.3, respectively. The same recommendations were followed in the study presented herein.

The estimation of the spatial distribution of ground shaking requires the definition of an earthquake rupture, which is usually defined by a location (pair of coordinates), magnitude and depth, calculated using the typical methodologies (Buland, 1976; Lienert *et al*., 1986). These parameters can usually be acquired shortly after an event occurs, even if limited information is available. Additional characteristics regarding the geometry and fault mechanism of the seismic rupture (strike, dip, rake, rupture area and length) can also be assessed through the analysis of detailed data regarding seismic waves collected at various recording stations. Considering the finite geometry of the earthquake rupture, rather than defining it as a simple rupture point, might influence greatly the ground motion shaking in the affected area, mainly if the event has a strong magnitude. As previously mentioned, the determination of fault complexity can be done through the employment of the so-called finite fault inversion methods (e.g. Hartzell and Heaton, 1983; Ji *et al.*, 2002), which requires the availability of large sets of ground motion signals. The implementation of such methodologies is out of the scope of the initial development of the framework presented herein. Instead, this system is taking advantage of existing datasets comprising fault mechanism and geometry information in the vicinity of mainland Portugal. The fault model and earthquake catalogues from the European Project SHARE (Stuchi *et al.*, 2012; Grunthal and Wahlstrom, 2012) are illustrated in Figure 2.

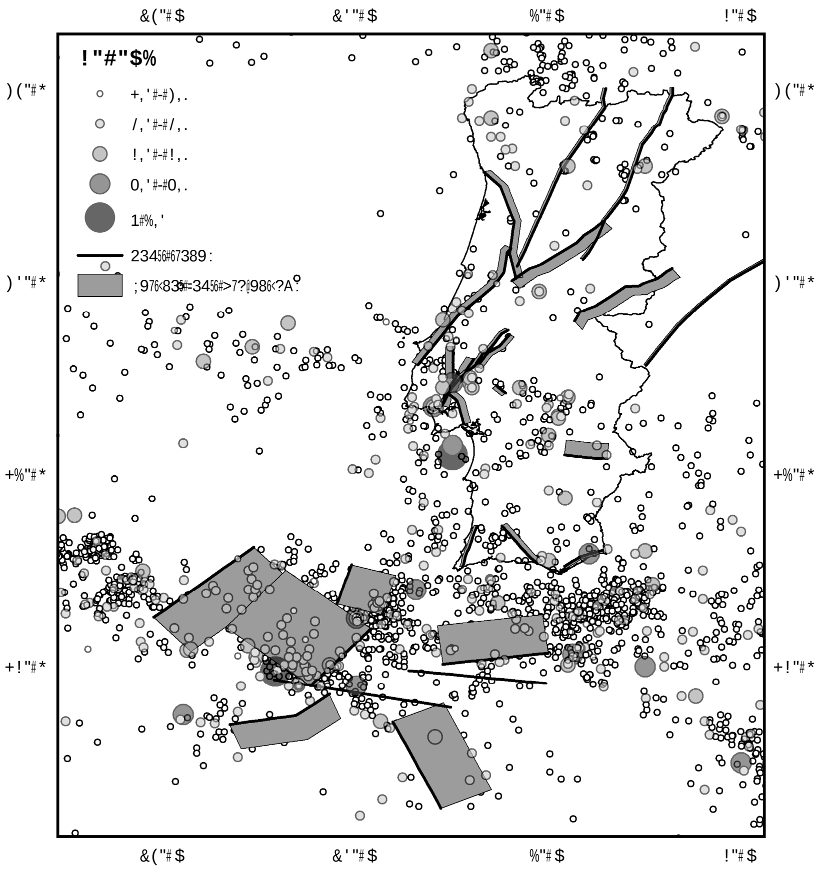

Figure 2 - Representation of the seismic faults in the vicinity of Portugal defined within SHARE, together with the European earthquake catalogue (Stuchi *et al.*, 2012; Grunthal and Wahlstrom, 2012).

The hazard component of the OpenQuake-engine (Pagani *et al.*, 2014) offers two rupture typologies to model single earthquakes: point rupture and simple fault rupture, as illustrated in Figure 3. The former typology is used for earthquakes below magnitude 5 (Mw), whilst the latter is employed for stronger events (i.e. magnitude greater than 5 Mw).

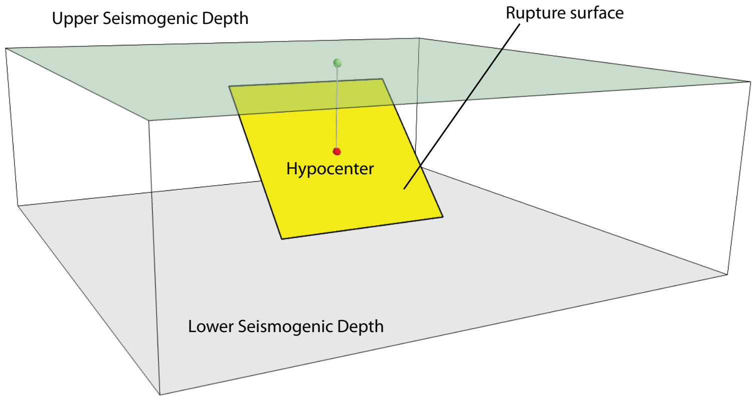

Figure 3 - Representation of a rupture point and rupture surface as defined in the OpenQuake-engine.

For what concerns the consideration of site effects, the measurement of V_{s30} in strategic regions in Portugal has been the target of several projects (SCENE - Narciso *et al.*, 2013; ERSTA - Carvalho *et al.*, 2008a; CAPSA - Carvalho *et al.*, 2009). However, due to the considerable investment that large-scale V_{s30} in-situ measurement requires, there is still a great portion of the territory that lacks coverage. In the work of Silva *et al.* (2014b), in which seismic hazard and risk calculations were performed at the national scale, this issue was handled through the employment of simplified methodologies to derive first-order V_{s30} values. Wills and Claham (2006) established a correlation between a set of geology units and V_{s30} values, whilst Wald and Allen (2007) proposed a methodology that uses 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. A brief comparison between the results provided by these methodologies and field measurements can be found in a study by Narciso *et al.* (2012) which, despite the limited number of data points, indicates that both approaches have a large associated variability and seemed to perform roughly equally. In the work presented herein, it was decided to give priority to field measurements coming from the aforementioned projects, and use the simplified methodologies in the regions where such data does not yet exist.

Exposure model

An exposure model describing the spatial distribution of building count is fundamental for the purposes of estimating earthquake consequences shortly after a seismic event, especially when metric such as building damage and collapse are required. The model implemented in this framework is strongly based on the work of Silva *et al.* (2014b), in which an exposure model for residential buildings was developed based on data from the 2011 Building Census survey. According to this source, in 2011 there were 3,544,389 residential buildings in Portugal, supporting 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 were used to define a set of vulnerability classes.

The construction material follows 5 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), which cover wooden and steel structures. The building stock is comprised of 50.6% masonry buildings (M1, M2 and M3), 48.6% of reinforced concrete buildings (RC), and 0.8% of other typologies (OT).

The year of construction was used to relate each building with a seismic code. The first design codes with simplified recommendations to consider seismic effects were introduced in 1958 (RSCCS) and 1961 (RSEP). Later, in 1983, a more demanding design code (RSA) was released, which is still in force nowadays, along with the Eurocode 2 (CEN, 2004) and Eurocode 8 (CEN, 2005). According to the information from the 2011 Building Census Survey, almost 62% of the building stock has been built before the introduction of the 1983 design code (RSA), representing about 6 million people living in structures that might be inadequately designed. The distribution of the cumulative number of buildings throughout time is presented in Figure 4, as well as the release dates of the aforementioned design regulations.

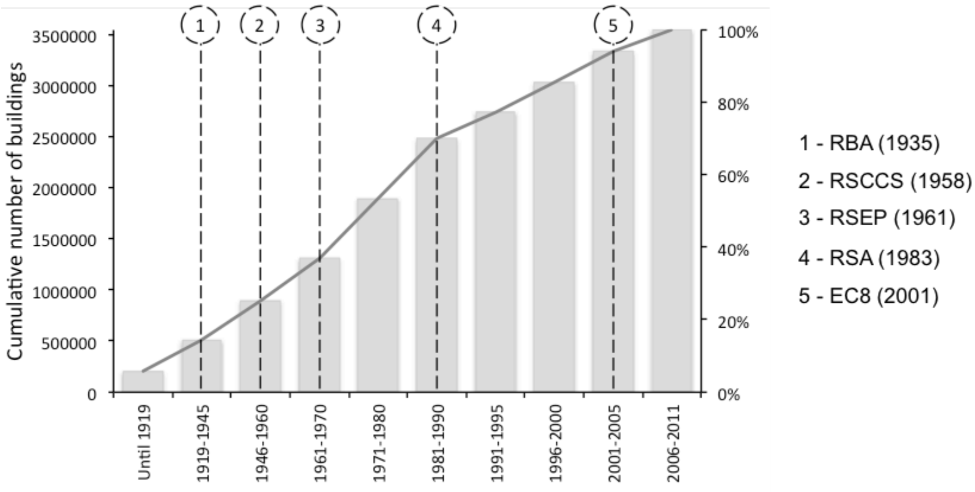

Figure 4 – Cumulative distribution of buildings in Portugal according to the period of construction, at the time of the 2011 Building Census. The dashed vertical lines mark the introduction of a design code.

The spatial distribution of the exposure model represents another reason to strengthen the investigation of the seismic risk in Portugal, as an important portion of the building portfolio is located in the Lower Tagus Valley and Southern regions, which are characterized by a high seismic hazard (e.g. Sousa and Oliveira, 1997; Vilanova and Fonseca, 2007). The distribution of buildings per municipality is illustrated in Figure 5.

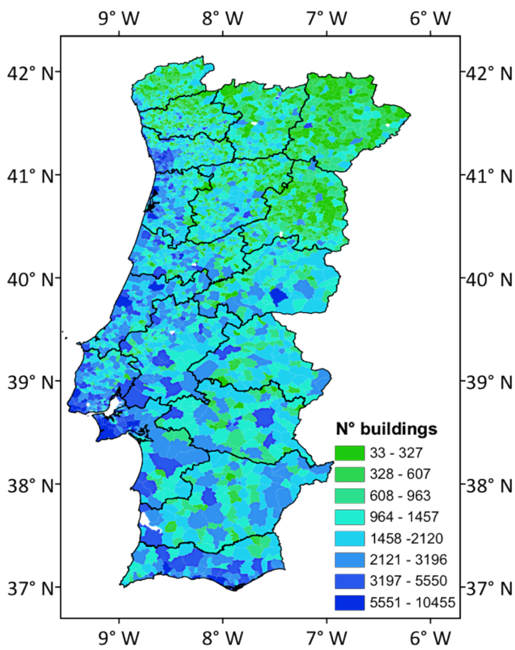

Figure 5 – Number of buildings per municipality according to the building Census Survey of 2011.

Physical fragility model

A fragility model capable of relating the probability of exceeding a number of damage states for a set of intensity measure levels has been developed for moment frame reinforced concrete buildings in Silva *et al*. (2014b). In the latter work, Monte Carlo simulations were employed to capture the geometric and material aleatory variability, and thousands of nonlinear dynamic analyses were performed using a large number of ground motion records, compatible with the tectonic environment in mainland Portugal. A set of fragility functions for 48 building typologies was derived considering two damage criteria (maximum top drift and maximum inter-story drift), and four damage states (slight, moderate, extensive and collapse). In Figure 6, the resulting fragility model for pre-code moment-frame RC buildings with 2 storeys (one of the most common typologies in Portugal) is depicted.

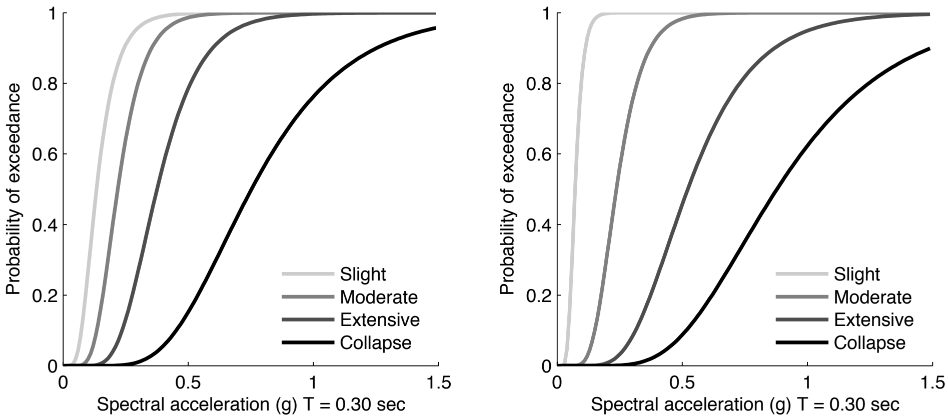

Figure 6 - Fragility model for pre-code 2 stories RC buildings, considering the maximum global drift (left) and maximum inter-story drift (right) damage criteria.

For what concerns the fragility model for the masonry building typologies, the fragility functions derived in the work of Silva *et al*. (2014a) were adopted. These functions were derived through the combination of the set of capacity curves developed by Carvalho *et al*. (2002), with a nonlinear static procedure (Capacity Spectrum Method - Freeman, 2004), resulting in a set of fragility functions for each of the 20 masonry building typologies, following the same number of damage states. Nevertheless, according to the loss estimates presented by Sousa (2006), ANPC (2011) and Silva *et al*. (2014b), this type of construction has the highest contribution to the economic and human losses in Portugal, and thus the development of a more detailed and reliable physical vulnerability model is of critical importance, and is being pursued in an on-going study.

EARTHQUAKE SCENARIOS FOR PORTUGAL

This section serves the purposes of demonstrating the capabilities of the proposed framework, through the presentation of median ground shaking and earthquake loss results from two specific scenario events. These ruptures are composed by a strong magnitude southwest of mainland Portugal (offshore), and a moderate magnitude located in the Lower Tagus Valley (onshore).

Definition of seismic ruptures

The selected earthquake ruptures were defined based on the fault model presented in Figure 2, as well as the findings by Carvalho *et al*. (2008b), in which a comprehensive stochastic model was employed to model ground shaking in the Metropolitan Area of Lisbon. This study included the estimation of peak ground acceleration at bedrock and surface for three earthquake scenarios, from which two were used to assess earthquake consequences in this study.

The first rupture is located southwest of mainland Portugal in the Marques de Pombal thrust fault, which is considered as a possible source of the 1755 Lisbon earthquake. In the aforementioned study, a magnitude of 7.6 (Mw) was considered, whilst in this assessment a larger magnitude closer to the historical Lisbon earthquake was chosen (8.5 Mw). The second rupture has its epicentre in the Lower Tagus Valley, and a magnitude of 5.7 (Mw). The fault mechanisms were defined based on the findings of Carvalho *et al.,* (2008b) and Vilanova and Fonseca (2004). A summary of the earthquake rupture characteristics can be found in Table 1.

Table 1 - Characteristics of the selected earthquake ruptures.

Rupture	Onshore	Offshore
Magnitude (Mw)	5.7	8.5
Epicentre	38.8° N, 8.9° W	36.5° N, 10.0° W
Strike	220°	20°
Dip	55°	24°
Rake	0°	90°

Ground motion fields

The calculation of the ground shaking throughout mainland Portugal was carried out using the scenario hazard calculator from the OpenQuake-engine (Pagani *et al*., 2014). The ground shaking was calculated using the ground motion models from Atkinson and Boore (2006) and Akkar and Bommer (2010), and the spatial correlation of the ground motion residuals was considered using the model by Jayaram and Baker (2010). For each seismic event, 5000 ground motion fields were considered to ensure convergence in the ground shaking and damage results. The spatial distribution of the median peak ground acceleration (PGA in g) at surface for mainland Portugal is depicted in Figure 7 for both earthquake ruptures.

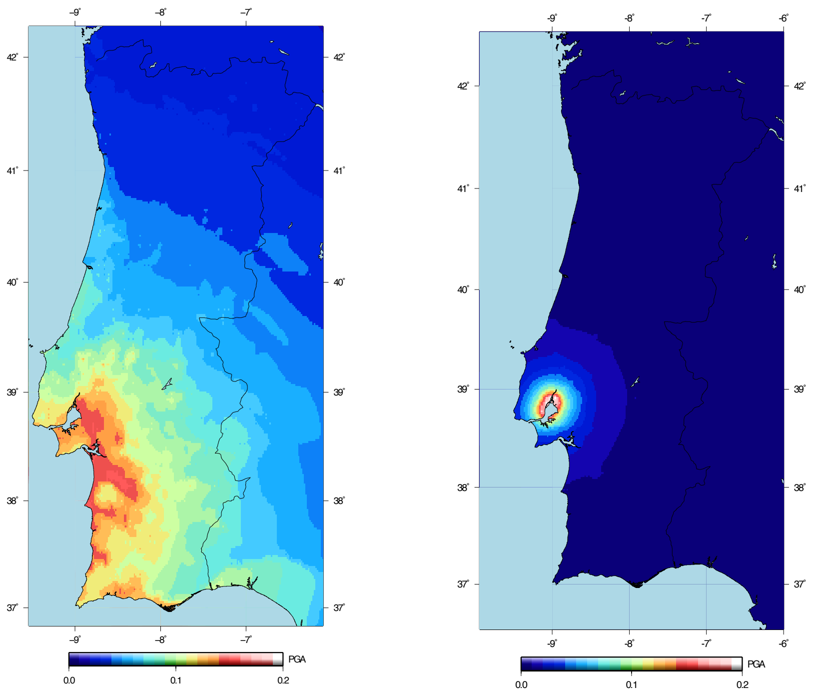

Figure 7 – Median ground motion field for the magnitude 8.5 (Mw) offshore event (left) and magnitude 5.7 (Mw) onshore event (right).

Damage distribution

The distribution of damage has been calculated using the scenario damage calculator from the OpenQuake-engine (Silva *et al.* 2013). Each ground motion field was used to estimate the number of buildings in each damage state, leading to a probabilistic damage distribution per asset. Additional results were also estimated by aggregating the number of buildings in each damage state per building typology. In Figure 8, the mean number of collapses per municipality in mainland Portugal is illustrated for both earthquake scenarios.

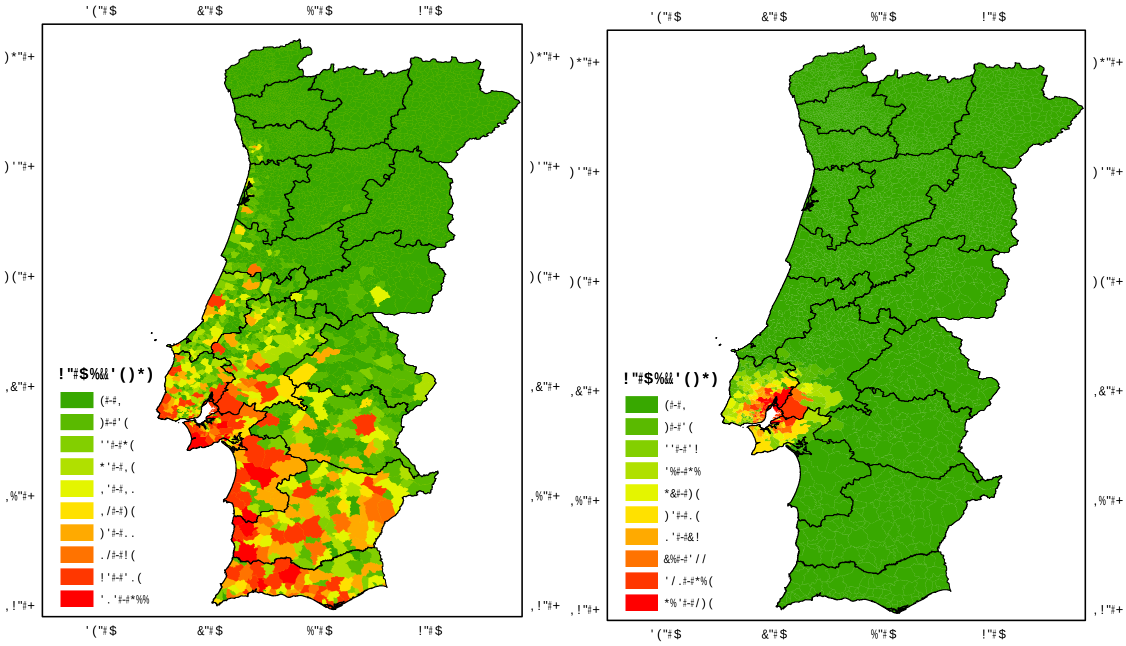

Figure 8 – Mean distribution of collapses for mainland Portugal for the magnitude 8.5 (Mw) offshore event (left) and magnitude 5.7 (Mw) onshore event (right).

The evaluation of the damage distribution across the various building typologies might provide important information regarding which type of construction is contributing the most to the overall collapses, and thus where seismic retrofitting interventions should be prioritized. The damage distribution per building typology is depicted in Figure 9.

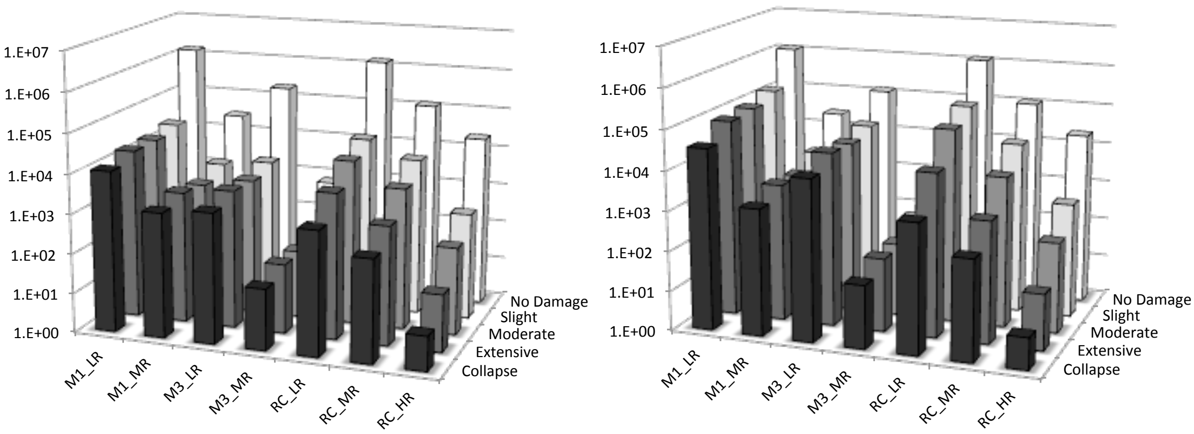

Figure 9 – Mean distribution of building damage for the magnitude 8.5 (Mw) offshore event (left) and magnitude 5.7 (Mw) onshore event (right).

It can be drawn from both scenarios that masonry buildings contribute the most to the total number of collapses, with 78% and 73% of the collapses being allocated to the vulnerability class of masonry with concrete floors (M1/M2), when the onshore and mainland scenarios are assessed, respectively. On the other hand, although comprising roughly half of the Portuguese building stock, only 4% to 10% of the collapses are expected to come from RC buildings. Still, stemming from the fact that RC buildings support the vast majority of dwellings a high impact on human and economic losses is also expected.

CONCLUSIONS

A framework for real-time earthquake loss estimation can be fundamental in the strategic organization of recovery and rescue operations after the occurrence of a strong earthquake. In this work, a platform capable of estimating human and economic losses due to earthquake ground shaking has been described. Besides the capability to estimate earthquake consequence shortly after the occurrence of a damaging earthquake, the system presented herein also offers the possibility of assessing hypothetical earthquake scenarios, which can be useful in risk mitigation actions such as the post-disaster emergency planning or raising risk awareness.

The two earthquake scenarios described above (strong and moderate magnitude) illustrate the real-time performance of PORTAL to date. This performance was assessed through the distribution of building damage, revealing that masonry buildings contribute the most to the total number of collapses.

The loss prediction is highly dependent on the accuracy of the definition of the hazard, exposure and physical fragility models. To this end, particular attention has been devoted to pursue a reliable definition of the real-time loss estimation components, emerging aspects such as the use of field measurements for what concerns the consideration of site effects. Likewise, the density of the Portuguese seismic network (IPMA [5]) may also affect the estimation of loss.

In order to limit false and missed alarms, an appropriate decisional rule and alarm threshold has to be set up, motivated by the uncertain conditions of the loss predictions. Thus, an ongoing research focusing on sensitivity analysis of each model is being conducted, similarly an open discussion with a small group of stakeholders is being undertaken so as to develop both technical and sociological features for providing the real-time earthquake information. Nonetheless, further investigation is required to improve the performance of the loss estimation system, mainly to enhance the ground shaking modelling of large events or the extend the exposure model to non-residential buildings.

Finally, a communication system able to provide warnings to selected communities is planned to integrate the PORTAL framework. Therein, an instant messaging service (email and short message service) will be used to effectively disseminate the earthquake hazard and estimated losses among private and public partners.

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