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ORIGINAL RESEARCH PAPER

Development and application of a real-time loss estimation framework for Portugal

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Abstract Portugal has its past marked by the occurrence of very destructive earthquakes. In the well-known 1755 Lisbon earthquake, more than 50 % of the building stock was heavily damaged or destroyed and about 10 % of the population in Lisbon perished. In the beginning of the last century, a moderate event of magnitude 6.0 Mw struck the village of Benavente, causing 46 fatalities and damaging more than 3000 dwellings. 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, in order to create adequate post-disaster response plans, or to understand which structure types are contributing to the human and economic losses. This study provides an overview of the initial development of this framework for Portugal, as well as a description of the components and input models required for the generation of the seismic input and estimation of damage. In order to demonstrate the capabilities of the platform, two seismic events were considered to assess structural damage throughout mainland Portugal. This framework has been established at the Faculty of Engineering of the University of Porto. It allows earthquake engineers and seismic risk modelers to access damage information and to launch calculations of losses for scenario events. The products can also be of interest to experts and decision makers, who may wish to consider specific types of outputs such as the distribution of building damage, fatalities and the number of homeless.

Keywords Earthquake losses · Real-time loss assessment · Vulnerability · Exposure

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1 Introduction

Emergency rescue reports from several past earthquakes indicate that 85–95 % of the successful rescues of people trapped under debris occurred within the first 24–48 h (Oliveira et al. 2006). The fraction of successful rescues 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 spatial distribution of damage and losses immediately after the occurrence of an earthquake is of critical importance. Furthermore, the employment of such framework to estimate building damage as well as economic and 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. Scenario 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 and retrofitting the building types contributing the most to the death toll, strategic urban planning, or development of support infrastructures (e.g., shelters) around the affected region.

In the 1755 Lisbon earthquake, despite the various estimates proposed by several authors (França 1989; Oliveira 1988), it is fair to assume that in Lisbon alone, more than 50 % of the buildings were heavily damaged or destroyed, and approximately 10 % of the population around Lisbon perished. In April of 1909, an event of magnitude 6.0 (Mw) (Cabral et al. 2013) struck the small village of Benavente, resulting in 46 fatalities and causing heavy damage in more than 3000 dwellings (Choffat 1912). More recently, a strong offshore event of magnitude 7.3 (Mw) occurred in February of 1969, which despite the measured low ground motion, widespread damage was still observed in southern Portugal, particularly on old masonry structures which still represent an important portion of the Portuguese building stock. The moderate seismic hazard calculated for mainland Portugal by many authors (Sousa 2006; Vilanova and Fonseca 2007), and existence of construction with poor seismic performance (Silva et al. 2014a), motivated the creation of a reliable and accurate platform for rapid estimation of damage shortly after the occurrence of a seismic event.

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-condition mapping (Narciso et al. 2013), ground motion shaking simulation (Carvalho et al. 2008a), seismic performance of RC structures (Proença et al. 2004; Silva et al. 2014b) 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 benefit in implementing an early warning system in the industrial complex of Sines (southwest Portugal) is being investigated.

The National Laboratory of Civil Engineering (LNEC [1]) has developed a Fortran-based software (LNECLoss) capable of calculating deterministic and probabilistic seismic hazard and risk, using different methodologies and incorporating several datasets (e.g. building census data, soil conditions map). Using this software, risk maps in terms of human and economic losses have been derived by Sousa (2006), and the influence of mitigation strategies for the existing building stock in Lisbon has been investigated by Campos-Costa et al. (2010). Despite the usefulness, importance and pioneering character of this software, the Authors recognized that the requirements of the present framework demanded an open-source tool, capable of rapidly performing earthquake loss estimations, while interacting with other applications and sources of information, such as the Portuguese Seismographic Network [2]. Thus, the OpenQuake-engine software developed by the Global Earthquake Model [3] initiative was chosen. This software is platform independent, comprises both hazard and risk calculations, and due to the public availability of the source code [4], and full documentation of the implemented methodologies and formulae (Crowley and Silva 2013), any user has the opportunity of understanding its procedures and verifying its results.

Currently, a framework capable of automatically estimating real-time earthquake losses in Portugal does not exist. There are, however, global initiatives that calculate first-order earthquake losses, such as PAGER or WAPMERR. The PAGER (Prompt Assessment of Global Earthquakes for Response) group, from the United States Geological Survey (USGS), issues a report every time that an event near populated areas and above a certain magnitude threshold occurs. These reports contain not only information about the hypocentre and magnitude of the event, but also estimates of loss. These loss models employ country-based vulnerability models based on empirical data and global datasets with the spatial distribution of population and capital stock. This initiative is able to indicate the order of magnitude of the expected human and economic losses (Jaiswal and Wald 2013). Likewise, the WAPMERR (World Agency of Planetary Monitoring and Earthquake Risk Reduction) initiative provides estimates of fatalities and injuries worldwide (Wyss 2004). This agency uses a global dataset of human settlements and a vulnerability methodology similar to the EMS-98 (Grunthal 1998). In the vast majority of the world these initiatives are the only rapid post-earthquake loss indicator available; however, due to their the vulnerability methodology and uncertainty in the exposure models, they might not be appropriate to provide detailed local information, such as the regions within the affected area where emergency response should be prioritized, or what building types require special attention.

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 framework (herein termed as PORTAL—Portuguese Real-time Assessment of Losses) has been established at the Faculty of Engineering of the University of Porto (located in the north of Portugal) and is connected to a web interface which will allow earthquake engineers, risk modelers and urban planners to access damage information shortly after the occurrence of a seismic event, or to launch scenario calculations for hypothetical events. This platform is not an operational system, but rather a framework for the estimation of the physical consequences considering single earthquakes.

2 Description of the real-time earthquake loss estimation system: PORTAL

In Portugal, the Portuguese Institute of the Sea and Atmosphere (IPMA [5]) continuously monitors the seismic activity, and releases information 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. The various components that integrate the real-time earthquake loss estimation system (PORTAL) are illustrated in Fig. 1.

The earthquake loss estimation procedure followed by PORTAL can be summarized in the following steps:

1. Once an earthquake is detected by the Portuguese Seismographic Network, IPMA issues an alert message containing key information regarding the seismic event, namely the magnitude, the epicentre location, the depth and the time of the event. The message is sent to the PORTAL server using a HTTP protocol. If the epicentre of the earthquake is located offshore, then the platform utilises the information from a global seismograph network to define the rupture model. A process is then triggered that checks for the damage potential of the earthquake. To this end, a criterion using magnitude and minimum distance to any settlement in Portugal was created, with the intention of avoiding unnecessary calculations for events that might be too far or too weak to generate significant losses. Thus, low magnitude events are only considered if located inland or very near the coast, whilst stronger events have a much greater distance threshold. Events with a magnitude below 3 (Mw) were neglected. These limits were evaluated based on the estimation of the minimum distance and magnitude required to generate a peak ground acceleration of at least 0.02 g inland (ground motion that even if amplified due to soil conditions is not likely to cause substantial damage), for a selection of ground motion prediction equations recommended in the

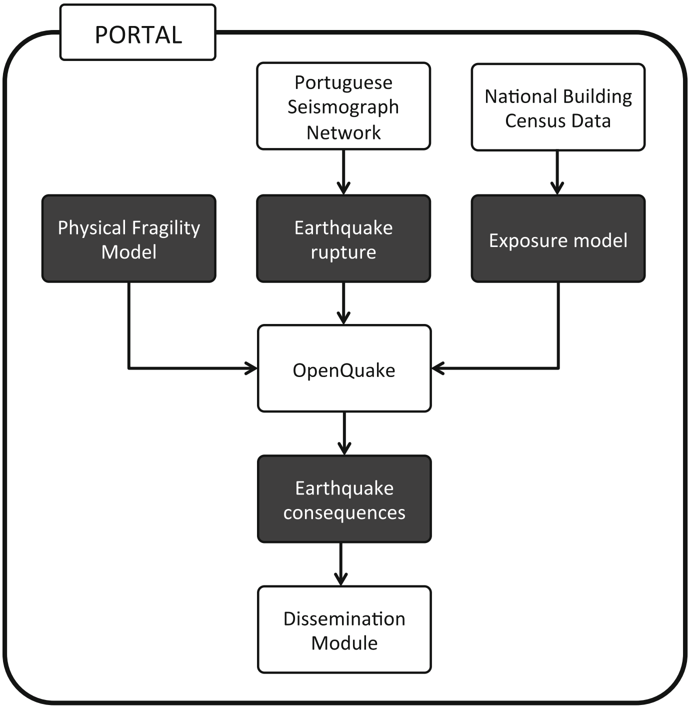


Fig. 1 Structure of the real-time earthquake loss estimation system (PORTAL)

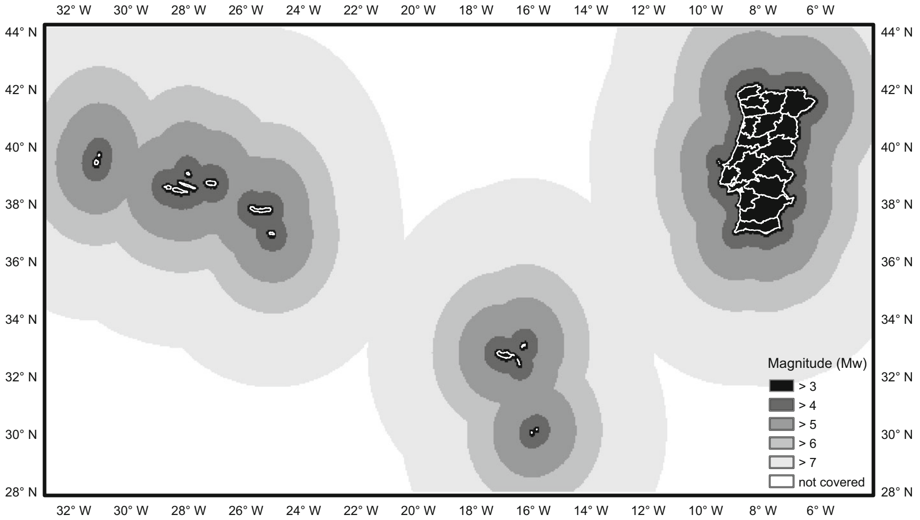


Fig. 2 Definition of the regions and corresponding magnitude (Mw), below which any occurring seismic event is ignored

work of Stewart et al. (2013). The resulting regions and respective maximum magnitude thresholds are illustrated in Fig. 2

2. If an event falls within the criterion defined on step 1, the OpenQuake-engine is triggered, and the Scenario Damage Calculator (Silva et al. 2014c) is used to estimate number of collapsed buildings and fatalities for each municipality. A description of each input model required for the loss calculations is presented in the following sections.
3. Once the earthquake loss estimation is completed, a module is called to analyse the resulting losses and assess if an alert should be issued. In this context, the entire damage distribution is evaluated and a criterion of at least a building in severe damage has been established (the minimum structural damage necessary to possibly cause human casualties).
4. If the resulting losses are substantial, a brief report describing the damage and fatalities distribution per municipally is sent to a number of institutions of relevance for post-disaster emergency response. Additional information regarding the disseminated information is presented in Sect. 2.4.

2.1 Estimation of earthquake ground motion

2.1.1 *Portuguese Seismographic Network*

Currently the Portuguese Seismographic Network has 55 stations, distributed between mainland Portugal, Azores and Madeira, as illustrated in Fig. 3. The information captured by these stations is processed and stored by IPMA, which releases real-time information about the time, location, magnitude and spatial distribution of ground motion and macroseismic intensity through its web-portal [5].

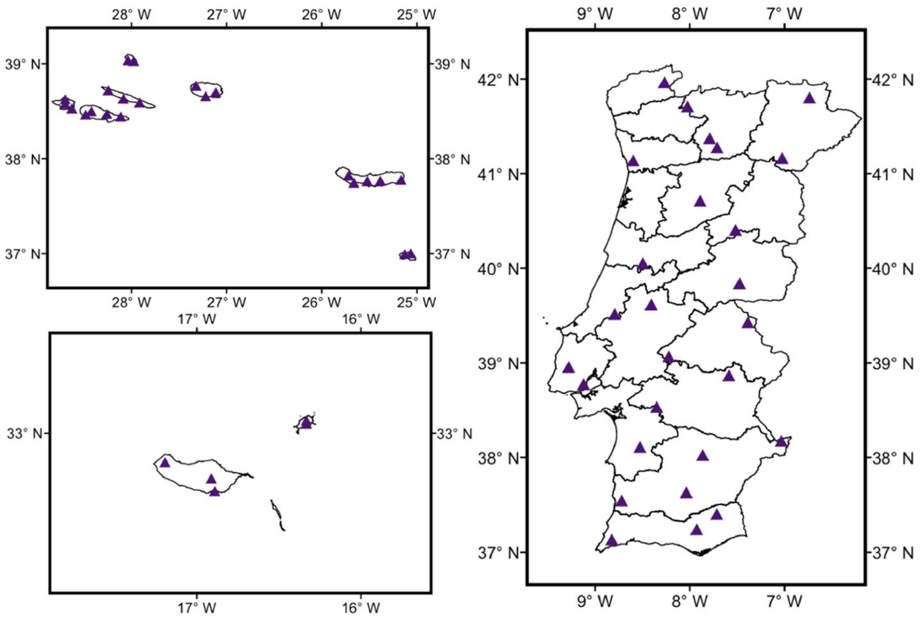


Fig. 3 Distribution of seismographic stations in Azores (*upper left*), Madeira (*lower left*) and mainland Portugal (*right*)

2.1.2 Ground shaking modelling

The selection of ground motion prediction equations (GMPE) has a strong 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. (2014a). This study relied on a number of key factors such as the 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; Stewart et al. 2013); and comparison between observations from a limited number of seismic events with estimations from a number of models (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. Nevertheless, the OpenQuake-engine features a large GMPE library [6], and thus the consideration of additional models can be easily configured. Moreover, it is also important to recognize that often the range of applicability of these ground motion prediction models (in terms of distance and magnitude) might not be respected, simply due to the reason of lack of models capable of covering all the possible combinations of distance and magnitude.

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. These fields are generated considering the spatial correlation of the intra-event residuals, which is a feature that can influence the losses significantly (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 a 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 associated losses. The intensity measure types considered in the generation of the ground motion fields are based on the intensity measures employed in the fragility model (see Sect. 2.3). These include spectral acceleration for a range of periods of vibration varying from 0.20 to 1.10 s. However, for the purposes of presenting to the users of the platform the distribution of ground shaking in the area, a decision was made to utilise peak ground acceleration, and it is an intensity measure type more commonly used for this purpose.

The recognition of ground motion prediction models as one of the main sources of uncertainty in earthquake loss estimation (Crowley et al. 2005), propelled the development of techniques to reduce the uncertainty associated with these functions, when information about the seismic event being analysed becomes available. A typical procedure consists in the estimation of the inter-event variability (also termed as bias), which can represent a reduction in the total variability within the entire region of interest of approximately 30 %. However, in order to ensure a reliable calculation of this parameter, it is critical to have a large number of recordings available (Stafford et al. 2008). Another technique that can also diminish the ground motion variability, involves the treatment of the total variability with strong motion data captured by recording stations. In this context, the total variability at the location of the stations becomes zero, and the uncertainty in the surrounding area varies conditionally on these "anchor points", according to a pre-established spatial correlation model (e.g. Jayaram and Baker 2010).

The ShakeMap system (Wald 2008; Worden et al. 2010) supported by the USGS is certainly one of the most well established efforts to generate ground shaking maps after the occurrence of seismic events. This system employs best available magnitude, location and source mechanism to improve the finite-fault modelling. Furthermore, it uses real-time strong motion data to constrain the ground shaking throughout the affected region, by correcting the ground shaking with the inter-event component (bias), and reducing the total variability in regions in the vicinity of recording stations. In Portugal, an preliminary implementation of this system has been carried by the IPMA, and several maps from previous events (usually in terms of peak ground acceleration and macroseismic intensity) can be found on the respective web-portal [7]. Currently, the raw data of these maps are not released, which hinders their employment in the constraining of the ground shaking. Moreover, only peak ground acceleration (and in a few cases also spectral acceleration at the 0.3 and 1.0 s period of vibration) is considered in the assessment of the ground shaking in the area, whilst the physical fragility model developed for the building stock in Portugal (Silva et al. 2014b) uses spectral acceleration for a wide range of periods of vibration (from 0.20 to 1.10 s). Ideally, for an efficient constraining of the seismic input being used to define the physical fragility, access to the entire ground motion data should be granted. Finally, it is also important to understand that even with a direct access to the strong motion data in real time, the seismographic network in Portugal might not be dense enough to allow for an efficient constraining of the ground shaking (see Fig. 3).

2.1.3 Seismic rupture characteristics

At a minimum, 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. 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 about seismic waves collected at various recording stations (e.g. Hartzell and Heaton 1983; Ji et al. 2002).

There are a few institutions in the world that continuously monitor global seismic activity and release critical seismological information shortly after an earthquake occurs. The GEOFON program of the German Research Centre for Geosciences (GFZ [8]), the European-Mediterranean Seismological Centre (EMSC [9]) and the National Earthquake Information Center (NEIC [10]) of the USGS offer a platform which releases information regarding the hypocentre and magnitude of seismic events in real-time. Due to their global coverage and public availability of seismological data, information from these institutions can be easily employed in post-earthquake loss assessment. Global networks might be able to provide more reliable information, in comparison with national networks (such as the one described in the previous section for Portugal), mainly for offshore events often located outside of the national network perimeter. For this reason, if the epicentre provided by the Portuguese Seismographic Network is located offshore, then the platform uses the data released by the GEOFON program to define the rupture model.

Considering the finiteness of an earthquake rupture, instead of assuming a single rupture point, might influence greatly the ground motion shaking in the affected area. As previously mentioned, the determination of fault dimensions can be done through the employment of the finite-fault inversion methods, which require the availability of large sets of ground motion signals, fault knowledge, distribution of aftershocks and geodesy data. 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 mechanisms and geometry information in the vicinity of mainland Portugal. The fault model and earthquake catalogues (Stucchi et al. 2012; Grunthal and Wahlstrom 2012) from the European Project SHARE are illustrated in Fig. 4.

From the observation of Fig. 4, it is possible to state that an important fraction of the strong seismic events in the past (1000–2006) were located near fault systems, whose characteristics have been the target of investigation by Basili et al. (2013) within the European SHARE project. Thus, for earthquakes above a certain magnitude threshold, the framework verifies if a fault system exists near (within 10 km) its hypocentre. If that is the case, the rupture surface is modelled using the characteristics of the near fault system (strike, rake, dip, upper and lower seismogenic depth), and the surface area is calculated using the formulae proposed by Wells and Coppersmith (1994). This approach assumes a prior knowledge of the location of the faults, which is often associated with large uncertainties. For this reason, the results produced automatically shortly after the occurrence of an event need to be interpreted with due care. Upon the availability of additional data such as source mechanism, geometry, and spatial distribution of the aftershocks, the rupture model can be manually updated, and the associated losses re-calculated.

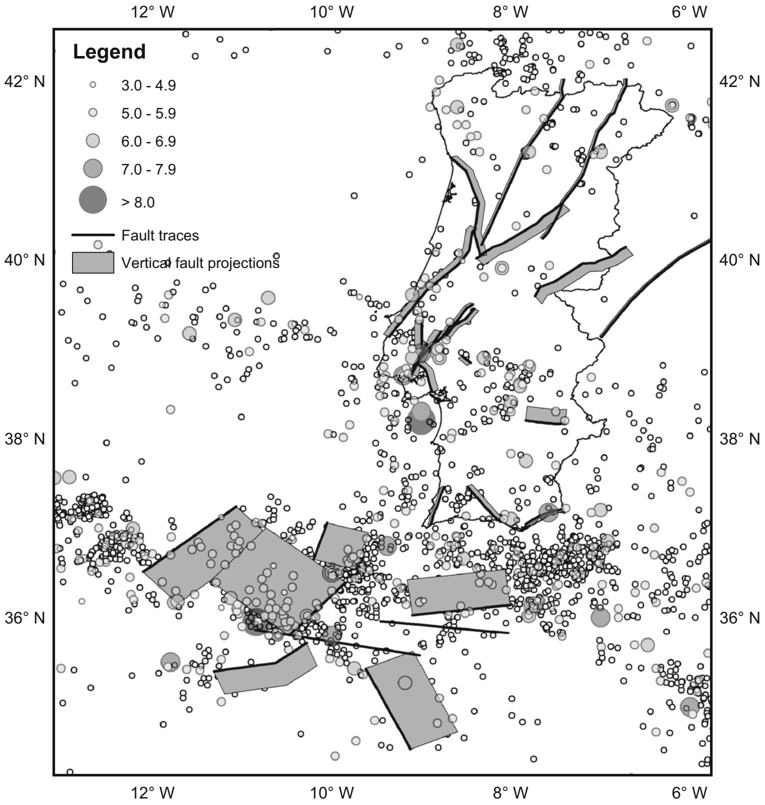


Fig. 4 Representation of the seismic faults in the vicinity of Portugal defined within SHARE, together with the European earthquake catalogue (Stucchi et al. 2012; Grunthal and Wahlstrom 2012)

The hazard component of the OpenQuake-engine (Pagani et al. 2014) offers two rupture types to model single earthquakes: point rupture and simple fault rupture, as illustrated in Fig. 5. The former rupture type is used for earthquakes below magnitude 5 (M_w), whilst the latter is employed for stronger events (magnitude greater than 5 M_w).

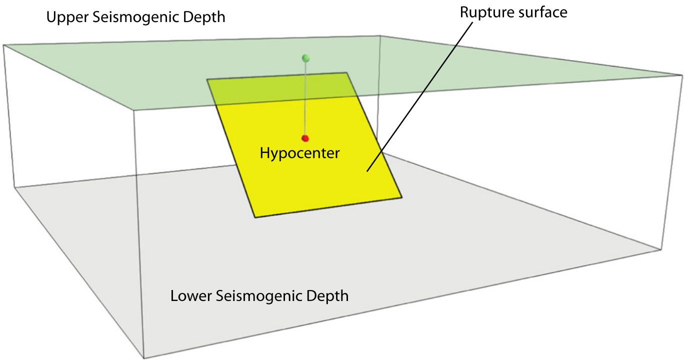


Fig. 5 Representation of a rupture point and rupture surface as defined in the OpenQuake-engine

2.1.4 Influence of site conditions

The existence of soft soils may amplify the spectral acceleration on average by a factor of 1.5 for short periods and 2.0 for longer periods (Stewart et al. 2013) and therefore, the consideration of site conditions is fundamental in loss modelling. Various design codes (United States—BSSC 2004; Europe—CEN 2004a) have adopted the average velocity of seismic shear waves in the top 30 meters layer (V_{s30}) as a standard to characterize site conditions. Furthermore, many ground motion prediction models (including the ones adopted herein) have been calibrated against seismic station site conditions defined with V_{s30} values.

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 a large-scale V_{s30} in situ measurement requires, there is still a great portion of the territory lacking coverage. In the work of Silva et al. (2014a), 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 Clahan (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), in which despite the limited number data points, both approaches are characterized by a large 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. The locations where such information has been collected are illustrated in Fig. 6, together with the average V_{s30} values between the two simplified methodologies.

To this end, when performing the seismic risk calculations, if an asset is located within a radius of 5 km of a location where experimental tests were conduct to measure Vs30, that value is applied to amplify or attenuate the corresponding ground shaking. For the remaining locations, it was decided to use the average Vs30 between the geology-based and topographic-based approaches, as described in Silva et al. (2014a) for mainland Portugal.

Figure 7 presents the spatial distribution of V_{s30} in the Metropolitan Area of Lisbon (MAL) based on the two simplified methodologies, as well as the one created based on field measurements.

2.2 Residential building portfolio

An exposure model describing the spatial distribution of buildings is fundamental for the purposes of estimating earthquake consequences. The model implemented in this framework is based on the work of Silva et al. (2014a), 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, comprised of 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.

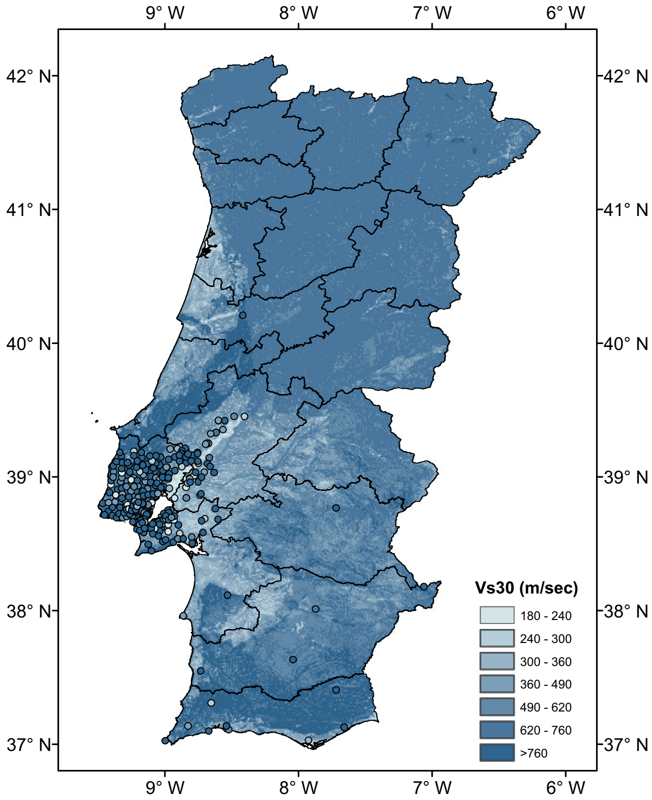


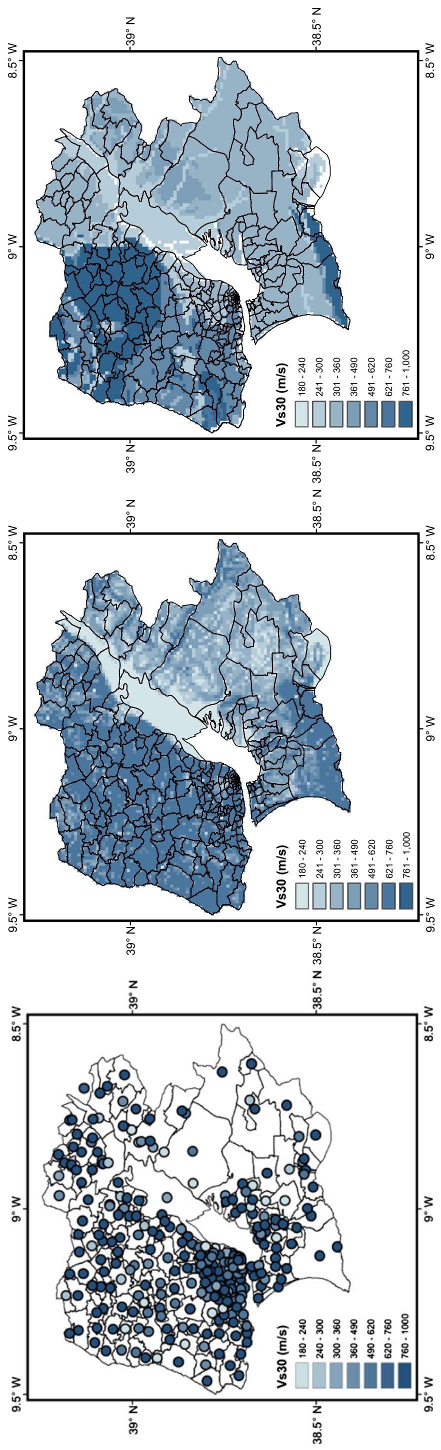
Fig. 6 Average VS30 values between two simplified methodologies, and Vs30 field measurements in mainland Portugal (*circles*)

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 types (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, along with the Eurocode 2 (CEN 2004b) and Eurocode 8 (CEN 2004a). 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 Fig. 8, as well as the release dates of the aforementioned design regulations.

The spatial distribution of the exposure model represents another reason to further investigate the seismic risk in Portugal, as a significant portion of the building portfolio is located in the Lower Tagus Valley and southern regions, which are characterized by

Fig. 7 Vs30 distribution according to: field measurements (left); slope topography (centre), and local geological units (*right*), for the Metropolitan Area of Lisbon



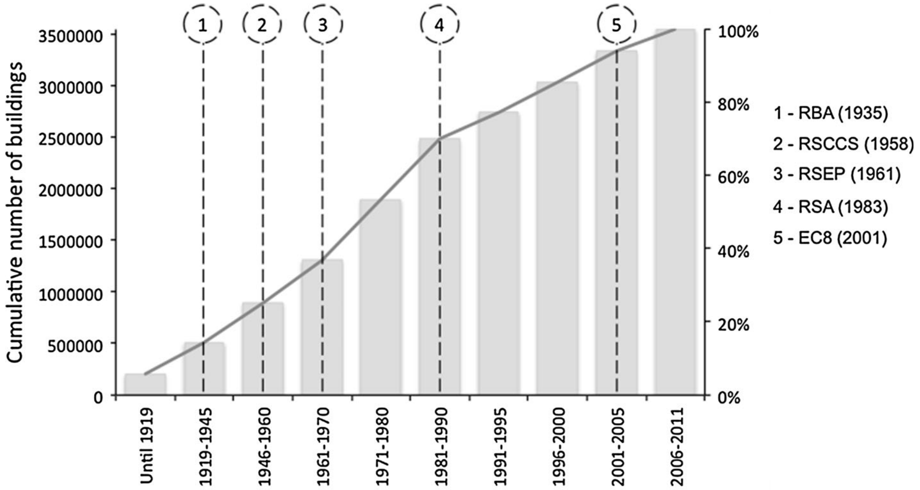


Fig. 8 Cumulative distribution of buildings in Portugal according to the period of construction, at the time of the 2011 Building Census. The *dashed vertical lines* mark the introduction of a design code

moderate seismic hazard (e.g. Sousa and Oliveira 1997; Vilanova and Fonseca 2007). The building distribution per municipality according to the construction category (reinforced concrete—RC; common masonry—M1, M2; and weak masonry—M3) is illustrated in Fig. 9 for mainland Portugal.

For the estimation of injuries and fatalities, conditional on the structural damage distribution, it is necessary to establish the number of occupants per building. These values can vary significantly according to the time of day, and consequently, so will the associated human losses. For example, a seismic event occurring during the night might cause higher losses due to the greater percentage of population indoors, as appose to what would be expected during transit hours, when the outdoor population is higher. Jaiswal and Wald (2010) investigated the population dynamics during different periods of the day, and have proposed a number of formulae capable of estimating the fraction of population inside residential buildings, as a function of the region (urban/rural) and socio-economic factors (work force across the various sectors: primary, secondary and tertiary/services). The expressions implemented in the framework presented herein are described in Table 1.

Information regarding the total population, workforce and distribution of employment across the three sectors was provided at the municipality level by the Statistical Office of Portugal [11], thus allowing a better modelling of the local socio-economic characteristics. The total population and estimated number of occupants within the residential building stock per municipality at the aforementioned periods are depicted in Fig. 10 for mainland Portugal.

From the evaluation of the occupancy fractions across Portugal, it has been estimated an average occupancy of about 24, 95 and 53 % during day, night and transit periods, respectively.

2.3 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

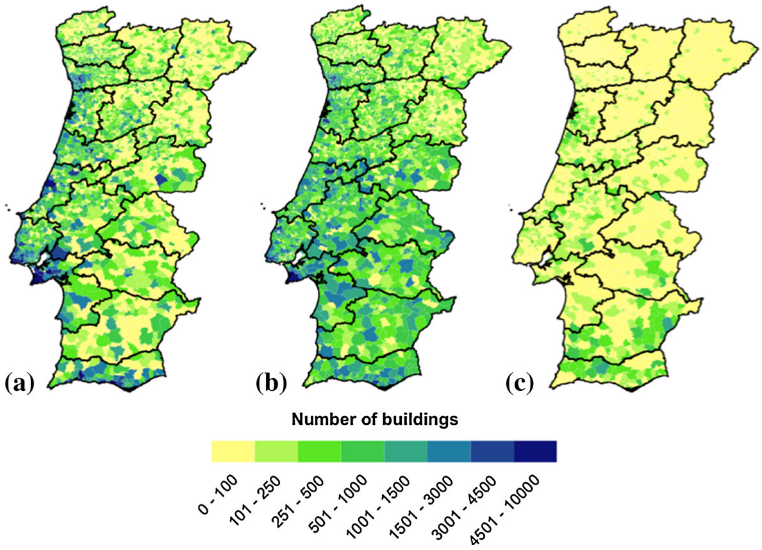


Fig. 9 Number of buildings per type of construction: **a** reinforced concrete (RC); **b** common masonry—(M1, M2), and **c** weak masonry (M3)

Table 1 Formulae providing fraction of population inside residential buildings according to different periods of the day, for urban and rural areas (Jaiswal and Wald 2010)

Period	Urban Area	Rural Area
Day (9 am–5 pm)	$0.4F_{nwf} + 0.01F_{wf}(F_1 + F_2 + F_3)$	$0.4F_{nwf} + F_{wf}(0.05F_1 + 0.01F_2 + 0.05F_3)$
Night (9 pm–5 am)	$0.999F_{nwf} + F_{wf}(0.998F_1 + 0.84F_2 + 0.89F_3)$	$0.999F_{nwf} + F_{wf}(0.998F_1 + 0.89F_2 + 0.89F_3)$
Transit (other times)	$0.75F_{nwf} + F_{wf}(0.45F_1 + 0.20F_2 + 0.25F_3)$	$0.80F_{nwf} + F_{wf}(0.65F_1 + 0.10F_2 + 0.15F_3)$

F_{wf}—fraction of population that is part of the workforce

F_1—fraction of the workforce employed in the primary sector

F_2—fraction of the workforce employed in the secondary sector

F_3—fraction of the workforce employed in the tertiary sector (services)

F_{nwf}—fraction of population that is not part of the workforce

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 time history 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 types was derived considering two damage criteria (maximum top drift and maximum inter-story drift), and four damage states (slight, moderate, extensive and collapse). In Fig. 11, the resulting fragility model for pre-code moment-frame RC buildings with 2 storeys (one of the most common types in Portugal) is depicted.

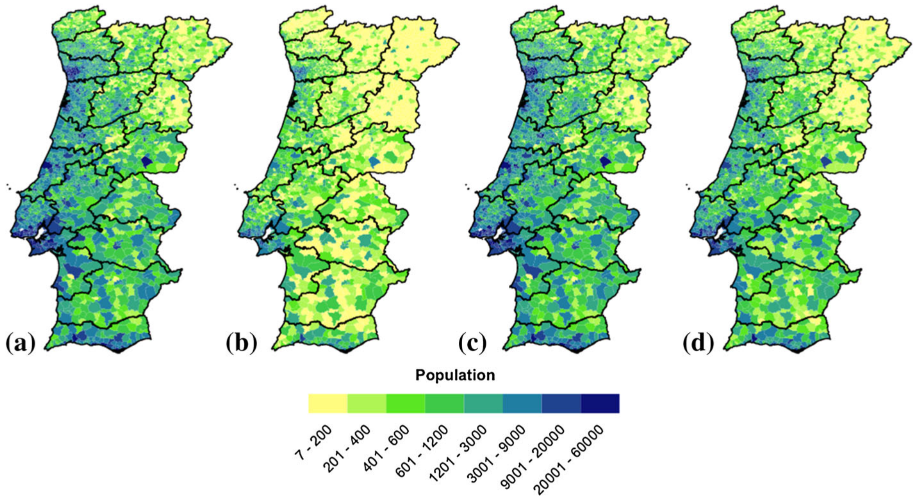


Fig. 10 Population count per municipality according to the 2011 Census Survey (**a**), and estimated number of occupants in residential buildings during 3 periods of time: day (**b**), night (**c**) and transit (**d**)

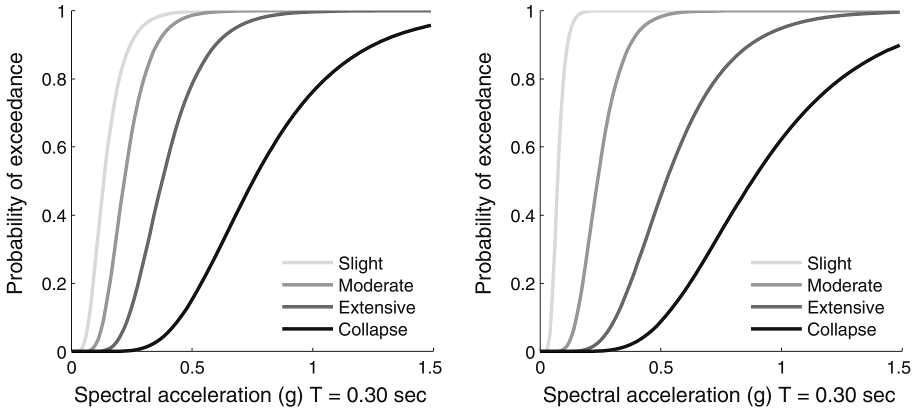


Fig. 11 Fragility model for pre-code 2 stories RC buildings, considering the maximum global drift (left) and maximum inter-story drift (*right*) damage criteria

For the fragility model for the masonry building types, 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 types.

In order to estimate the number of fatalities and injures, it is necessary to establish a relation between the structural damage (as defined in the aforementioned fragility models) and the percentage of injured occupants. Several models for this purpose can be found in the literature, such as the one by FEMA (2003), ATC-13 (1985), Coburn and Spence (2002) or Spence (2007). The FEMA (2003) proposal establishes a fatality rate of either 5 or 10 %, depending on a building classification for the United States, whist the ATC-13 model was developed mostly based on earthquake data from California. Thus, their

Table 2 Injury distributions for specific building types that collapsed according to Spence (2007)

Building type	UI (%)	I_1 (%)	I_2 (%)	I_3 (%)	I_4 (%)	I_5 (%)
RC						
1 storey	32.9	30.0	19.0	3.0	0.2	15.0
2–3 storeys	20.8	30.0	23.0	4.0	0.2	22.0
>4 storeys	9.7	30.0	27.0	5.0	0.3	28.0
Masonry						
1 storey	23.6	50.0	12.0	8.0	0.4	6.0
2–3 storeys	16.5	50.0	15.0	10.0	0.5	8.0
>4 storeys	9.4	50.0	18.0	12.0	0.6	10.0

UI, uninjured; I_1, slight injuries; I_2, moderate injuries; I_3, serious injuries; I_4, critical injuries; I_5, deaths

applicability to the Portuguese building portfolio is questionable. On the other hand, Coburn and Spence (2002) determined a set of fatality rates using empirical data from various past earthquakes, which were later updated in the work of Spence (2007) based on additional information from other events (e.g. Kobe 1995; Kocaeli 1999; Athens 1999; Chi Chi 1999; Bhuj 2001). The consideration of a large dataset of post-earthquake casualty data and the availability of structure-dependent injury/fatality rates, justified the implementation of this model in the loss estimation framework presented herein. The percentage of injuries and fatalities per building type are described in Table 2.

2.4 Public accessibility and dissemination of results

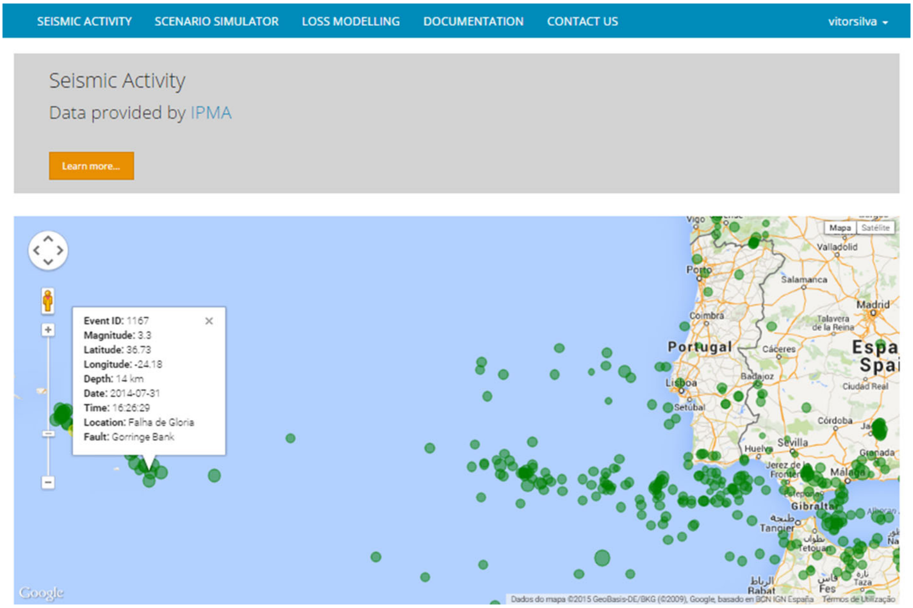
An important component of the PORTAL framework is related with the dissemination of the output data produced by the OpenQuake-engine. As illustrated in Fig. 1, this tool is responsible for processing all the input data and performing the hazard and loss calculations. The output data is then processed and stored in a PostgreSQL relational database. The information regarding the seismic event is also stored in the same database, thus allowing a link between the seismic event and the hazard and loss data.

The results of this process become available to the users of the PORTAL application shortly after the event, through a web interface, as well as a summary report that is sent by email. Due to the sensitivity of the data, the web interface has restricted access in order to prevent unexpected consequences resulting from potential false alarms received by the population. At present, access permission has only been granted to institutions such as the Portuguese Civil Protection and other public authorities.

The web interface consists of two graphical components, one related with the seismic activity communicated by IPMA, and a second one related with the presentation of the seismic input and loss data computed by the OpenQuake-engine. Figure 12 shows a screenshot of the web interface listing a set of recent seismic events provided by IPMA.

The results related with the seismic rupture (median ground motion field) and respective physical consequences (spatial distribution of mean number of collapses and mean number of buildings in each damage state per building type), are presented to in the form of coloured maps and bar plots, as depicted in Fig. 13.

As already mentioned, a summary of all the information is made available in a report that is sent by email to the users of PORTAL, shortly after the OpenQuake-engine finalises the hazard and loss analyses. This information includes maps of the distribution of ground shaking (in terms of peak ground acceleration), number of collapses and fatalities (per administrative region). In addition, the mean and standard deviation of the total loss is also included.

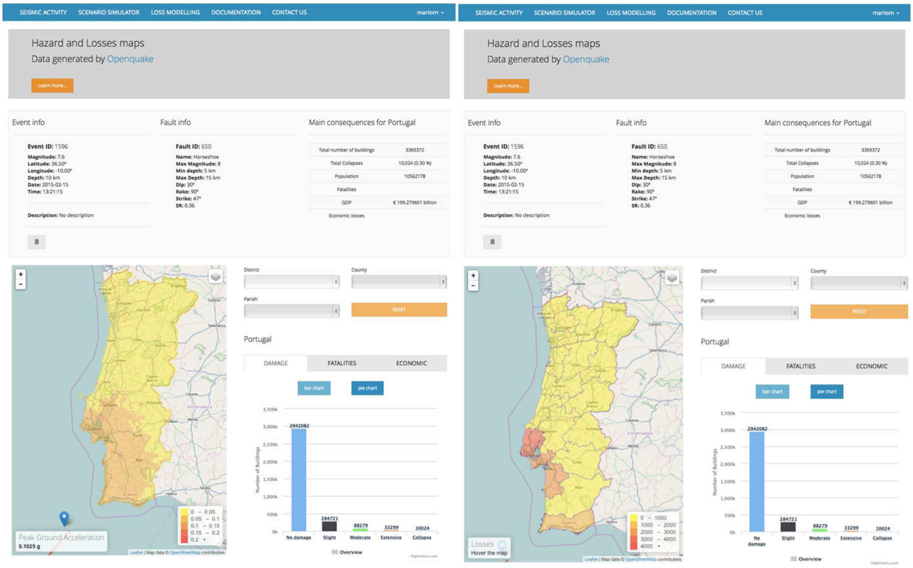


Seismic Activity

Data provided by IPMA

Event ID: 1167
Magnitude: 3.3
Latitude: 36.73
Longitude: -24.18
Depth: 14 km
Date: 2014-07-31
Time: 16:26:29
Location: Falha de Gloria
Fault: Gorringe Bank

Fig. 12 Screenshot of the web interface showing the seismic activity (provided by IPMA)



Hazard and Losses maps

Data generated by Openquake

Event info

Event ID: 1596
Magnitude: 7.6
Latitude: 36.50°
Longitude: -10.00°
Depth: 10 km
Date: 2015-02-15
Time: 13:21:15

Description: No description

Fault info

Fault ID: 650
Name: Horseshoe
Max Magnitude: 8
Min depth: 5 km
Max Depth: 15 km
Dip: 30°
Rake: 90°
Strike: 47°
SR: 0.36

Main consequences for Portugal

Total number of buildings	3369372
Total Collapses	10,024 (0.30 %)
Population	10562178
Fatalities	
GDP	€ 199.279601 billion
Economic losses	

Portugal

Fig. 13 Interface used to display the distribution of the median ground shaking (*left*) and the mean number of collapses per administrative region (*right*)

3 Earthquake scenarios for Portugal

3.1 Selection of seismic ruptures

The various components described in the preceding sections are combined herein to estimate ground shaking and number of collapses for two seismic events. The selected ruptures were defined based on the fault model presented in Fig. 4, 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 the 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. The second rupture has its epicentre in the Lower Tagus Valley, and a magnitude of 5.7 (M_w). The fault mechanisms were defined based on the work of Carvalho et al. (2008a). A summary of the earthquake rupture parameters can be found Table 3, and the vertical projections of the rupture plane are illustrated in Fig. 14.

Table 3 Characteristics of the selected earthquake ruptures

Rupture	Magnitude (M_w)	Strike (°)	Dip (°)	Rake (°)
Onshore	5.7	220	55	0
Offshore	7.6	20	24	90

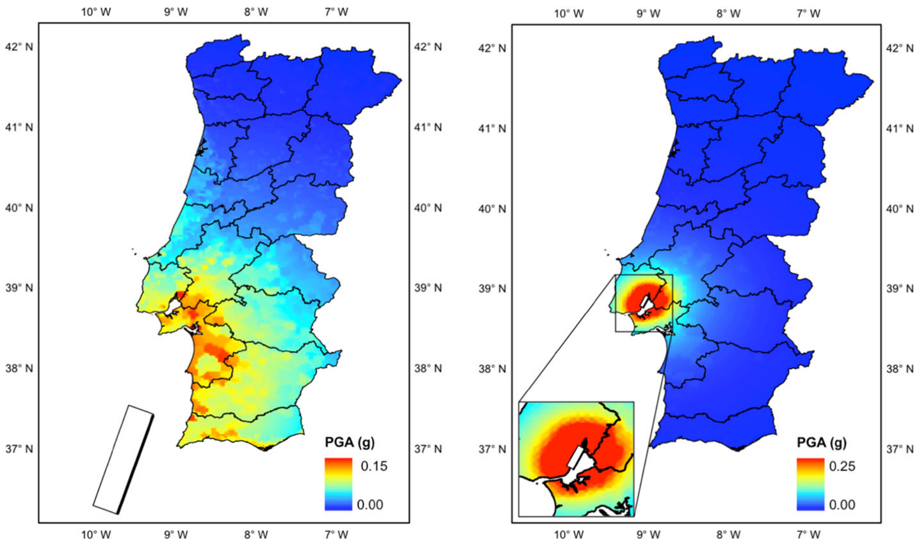


Fig. 14 Median ground motion field for the magnitude 7.6 (Mw) offshore event (*left*) and magnitude 5.7 (Mw) onshore event (*right*)

3.2 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, 2000 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 Fig. 14 for both earthquake ruptures.

3.3 Distribution of building collapses

The distribution of damage has been calculated using the scenario damage calculator from the OpenQuake-engine (Silva et al. 2014c). 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 type. In Fig. 15, the mean number of collapses per parish in mainland Portugal is illustrated for both earthquake scenarios.

The evaluation of the damage distribution across the various building types 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 type is depicted in Fig. 16.

It can be drawn from both scenarios that masonry buildings contribute the most to the total number of collapses, with 71 and 73 % of the collapses being allocated to the

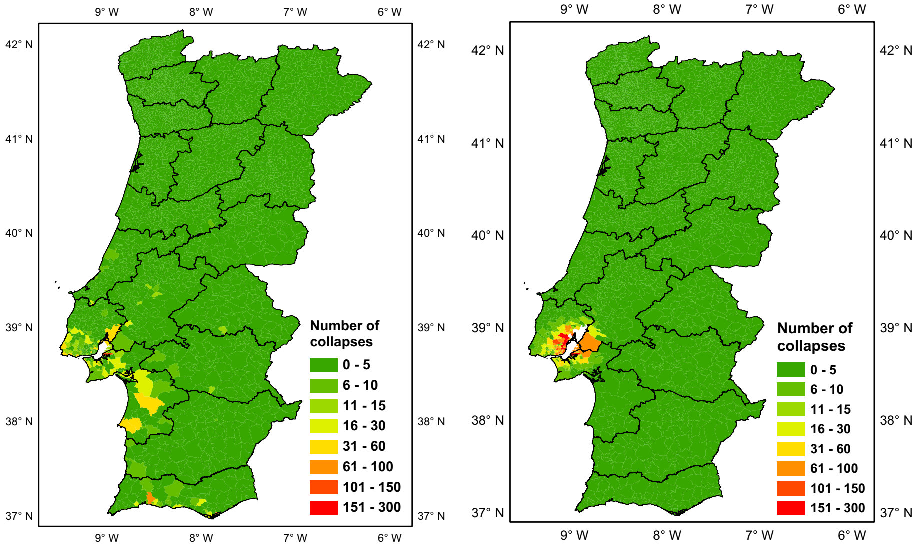


Fig. 15 Mean distribution of collapses for mainland Portugal for the magnitude 8.5 (Mw) offshore event (*left*) and magnitude 5.7 (Mw) onshore event (*right*)

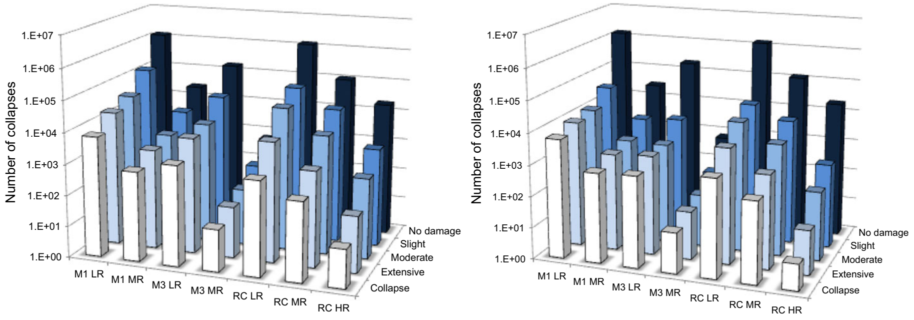


Fig. 16 Mean distribution of building damage for the magnitude 7.6 (Mw) offshore event (*left*) and magnitude 5.7 (Mw) onshore event (*right*)

vulnerability class of common masonry (M1/M2), when the offshore and mainland scenarios are assessed, respectively. On the other hand, although comprising roughly half of the Portuguese building stock, only 13–18 % of the collapses are expected to come from RC buildings. Still, stemming from the fact that RC buildings support a large fraction of the dwellings, a high impact on human and economic losses may be expected.

It is also important to mention that due to the large uncertainty in the estimation of the ground shaking, the resulting estimation of collapses or fatalities is also affected by a large variability in the losses, reflected by the large coefficients of variation (from 20 to 300 %). These levels of variability emphasize the need to develop techniques to reduce the uncertainty in the derivation of the ground shaking (e.g. ShakeMap—Wald 2008; Worden et al. 2010) and fragility models. Nevertheless, such distributions can still provide valuable information within certain confidence intervals, regarding the regions where a higher number of collapses or fatalities are expected.

4 Conclusions

This paper presented the architecture of PORTAL, a real-time seismic loss estimation framework for Portugal. The main scientific components of the framework were described, and the approach adopted for the dissemination, namely the web interface developed for the visualization of the data in a GIS-based system was explained. It is important to clarify that this platform is not an operational system, but rather a framework for the estimation of the physical consequences due to single seismic events.

The prediction of losses or damage is highly dependent on the level of uncertainty and reliability of the seismic input, exposure and physical fragility models. Regarding the first component, the location and magnitude of the events are being derived based on data from the Portuguese Seismographic Network, or the GEOFON program, depending on its location. The necessary ground motion fields are calculated considering the inter- and intra-event variability (e.g. Jayaram and Baker 2010). One of the main limitations of this platform lies on its inability to constrain ground shaking using data from recording stations (e.g. ShakeMap—Wald 2008; Worden et al. 2010). The implementation of this feature would require access in real-time to strong motion data in the vicinity of the affected area, and most importantly, a denser network of stations in Portugal.

Site amplification is accounted through the employment of V_S30 values, either locally measured or assessed through simplified techniques. As for the exposure, information from the last Portuguese Building Census carried out in 2011 was employed to create an exposure model which utilises a large number of vulnerability classes, based on the type of construction, number of storeys and date of construction. Currently, the exposure model utilised by the platform only covers the residential building stock, and thus it does not consider the potential economic and human losses from industrial or commercial buildings. Finally, with respect to the physical vulnerability, a set of analytically derived fragility functions for each vulnerability class was adopted (Silva et al. 2014b).

The PORTAL framework provides access to a rapid estimation of the casualties caused by an earthquake, allowing an optimized allocation of emergency response resources after an earthquake. The estimates of damage and loss can also be useful in the preparation and planning of response measures under using earthquake scenarios, which may contribute to a potential reduction of casualties in affected areas.

Two earthquake scenarios were used as test cases, to demonstrate the efficiency and feasibility of the framework presented herein, and the visualisation capability of the hazard and loss data. The results from these assessments indicated high numbers of collapses for both events, mostly concentrated on the masonry construction.

The open source nature of PORTAL differentiates this application from other existing real-time earthquake loss estimation applications and ensures the possibility to constantly update and verify the various models, as well as the calculation procedures. Although the framework has been developed for Portugal, the vast majority of the modules can be utilized in hazard and loss analysis in other seismic regions.

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