Seismic Risk Assessment of Lisbon Metropolitan Area under a Recurrence of the 1755 Earthquake with Tsunami Inundation

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LISBOA 2012

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SUMMARY:
The Lisbon Metropolitan Area (AML) has the largest population and property concentration in Portugal. Located near the Eurasia–Africa plate boundary and facing the Atlantic Ocean, the AML is prone to great offshore earthquakes that may trigger tsunami. In history, Lisbon was destroyed by earthquake and tsunami in 1531 and 1755, respectively. Given the growth and expansion of the exposure in last two centuries, a presumed recurrence of the 1755 earthquake would result in a totally different loss scenario in the AML, which is of interest to the disaster preparedness and emergency management. This paper studies the existing building stock in the AML, discusses the vulnerability of built environment to ground shake and tsunami, and conducts loss modelling for the AML subjected to simulated ground motion and tsunami wave of the 1755 Lisbon earthquake. Finally, the loss scenario will be discussed and inferred for disaster mitigation.

Keywords: seismic risk, building vulnerability, tsunami, Lisbon

1. INTRODUCTION

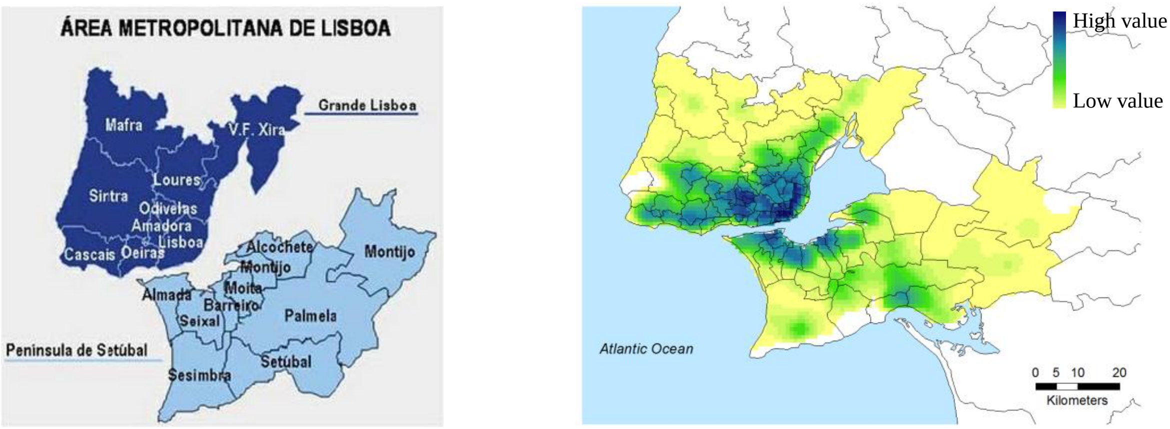
The Lisbon Metropolitan Area (AML) is a territorial zone in Portugal that includes 18 municipalities, nine from Lisbon District north of the Tagus River and the rest from Setúbal District south of the Tagus (see Fig.1.1(a)). The AML has an area of 2,957.4 km^2 and a population of more than 2.8 million today. About one fourth of the Portuguese population lives in the AML. With about 33% of the national employment being located in its territory, the AML contributes with more than 36% to the GDP of the entire country. It is the tenth richest metropolitan area by GDP on the European continent amounting to 98 billion euros and thus €34,850 per capita as of 2008. As the center of the AML, Lisbon City is recognized as a global city because of its importance in finance, commerce, international trade, and tourism. Not only being rich in wealth, Lisbon also has a rich history and ranks as one of the oldest cities in the world. Many peoples have passed here – Iberians, Celts, Greeks, Romans, Moors – before the first king of Portugal conquered the city in 1147. Since then it has been a major political, economic, and cultural center. As a result, historical constructions and monuments can be found all over the city, which are particularly vulnerable to seismic hazard.

Given its location in the western Iberian Peninsula on the Atlantic Ocean, the AML is susceptible to offshore earthquakes occurring on the Africa–Eurasia plate boundary, particularly in the Gorringe Bank region. In this region, the plate boundary becomes a diffusive collision zone between two continents and continental shelves. The collision stress loads up major structures within the collision zone, where great earthquakes including the 1755 Lisbon earthquake originated. The 1755 Lisbon earthquake, with a magnitude estimated at 8.5–9, is the largest known historical earthquake to impact Europe and northern Africa. This megathrust event struck on the morning of November 1st, 1755 and caused an enormous tsunami in the North Atlantic Ocean. Immediately following the tremor, fires quickly broke out in Lisbon that lasted for five days and destroyed most of the city (Pereira, 2009). The death toll in Lisbon was estimated by Pereira (2009) at 30,000–40,000, out of the ~200,000 inhabitants at that time. After the earthquake, Lisbon was gradually rebuilt and witnessed the urban expansion and renewal over time.

Nearly all of Portugal's efforts to bolster disaster preparedness have been linked to the 1755 earthquake. On the occasion of the International Day for Disaster Reduction 2010, a massive door-to-door campaign was launched in Lisbon aimed at increasing the risk perception levels of the citizens, with the distribution of leaflets on seismic risk and self-protection measures against an earthquake. At the same time, it would be definitely informative for policy makers and the insurance industry to assess the seismic risk of today's Lisbon Metropolitan Area under a recurrence scenario of the 1755 event. This is the motivation of the authors to conduct this study.

AIR Worldwide (AIR) is the scientific leader and most respected provider of risk modelling software. The AIR Earthquake Model for the Pan-European Region covers 30 European countries, including Portugal. It is an event-based earthquake model designed for portfolio risk management. The model captures the complex seismicity, calculates the ground motion intensity, and then evaluates the monetary loss for given exposure based on the vulnerability of building and contents. The AIR earthquake model, along with the AIR industry exposure database, is used in this paper to perform a risk assessment for the AML subjected to a simulated scenario of the 1755 Lisbon earthquake. One particular highlight in this paper is the latest research outcome by the AIR team about risk modelling of tsunami events.

As a typical seismic risk analysis, this paper integrates three basic components, i.e. the exposure, the hazard, and the vulnerability of the exposure to the hazard. Firstly, the building stock (i.e. the exposure) in the AML is introduced from an engineering perspective. Then we elaborate on the vulnerability of building and contents to ground shaking and tsunami inundation, respectively. Later a recurrence scenario of the 1755 earthquake and tsunami (i.e. hazard) is generated by sophisticated numerical simulation. Finally, the monetary loss of the exposure in the AML caused by the simulated hazard scenario is calculated and analysed for risk assessment.



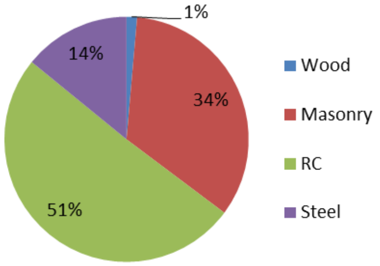
(a) (b)

Figure 1.1. Lisbon Metropolitan Area: (a) map of municipalities (credit to António Costa); (b) distribution of the building exposure.

2. BUILDING STOCK IN LISBON METROPOLITAN AREA

The AML is highly urbanized with an average population density of around 950 hab/km^2. This region has been subject to a constant opening of new areas of urbanization, which caused an increase of 18.6% in housing units between 1991 and 2001, even though the total population grew only 4.3% in the same period (Marques da Costa et al., 2009). In other words, the built-up area had an increase rate much higher than the population growth in the AML. As of 2010, the total number of traditional housing buildings in the AML reached 434,600, which consist of 1,423,654 dwellings, according to the National Institute of Statistics of Portugal. Fig. 1.1(b) shows the spatial distribution of the exposure in the AML in terms of the replacement value of both building and contents, according to AIR industry exposure database. It is seen that the exposure concentrates in the municipalities of Lisbon, Oeiras, Amadora, Odivelas and the waterfront of Almada, where the replacement value can be as high as 2 billion euros per square kilometre.

Typical of many European countries, reinforced concrete (RC) is the predominant type of construction in areas of AML urbanized in the last few decades, accounting for 51% of the current building inventory in terms of value (see Fig. 2.1(a)). Historic districts and city centers, however, contain masonry structures that may be up to several hundred years old. The masonry construction accounts for some 34% of the building stock in the AML. A significantly smaller percentage of the building stock – around 14% – has steel structure, mainly consisting of commercial and industrial buildings. Finally, there remain traces of traditional timber construction, although the fraction of such buildings is very small. The trivial fraction of wood structure implies the region's overall good resistance to fire, and thus fire following earthquake is not modelled in the present study.



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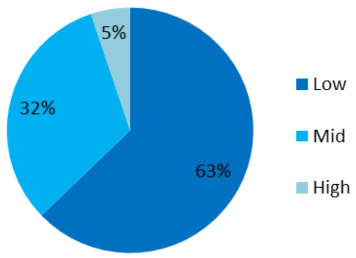


(b)

Figure 2.1. (a) building stock by construction material; (b) breakdown by height for RC construction.

Height is another important attribute of the buildings that affects their seismic vulnerability. For all the RC buildings in the AML, Fig. 2.1(b) illustrates the breakdown of the total replacement value into three height categories, namely low-rise (1–3 stories), mid-rise (4–7 stories), and high-rise (8 stories and above). Very similar height composition is observed for the steel construction. However, nearly all the wood buildings and the majority (~90%) of the masonry construction are low-rise structures. Only a small portion (~10%) of the masonry construction is mid-rise.

Since 1970, a massive process of replacement of the housing stock has taken place in Portugal. Per the 2001 Census, roughly 63% of the country's housing stock was built after 1970 and only 14% was built before 1945 (Federcasa, 2006). From 2001 to 2010, about 130,000 dwellings in new constructions were completed in the AML according to the National Institute of Statistics of Portugal. This sector occupies about 10% of today's housing stock in the AML. The year-built information of the building stock will be used to determine its vulnerability level as discussed in the next section.

3. VULNERABILITY OF BUILDING AND CONTENTS TO GROUND SHAKING

How prepared is Lisbon's building stock against a potential earthquake? Here focus is given to masonry and RC constructions as they are most common in the AML. Masonry buildings there exhibit a variety of typologies, ranging from the traditional rubble-stone double-wythe two- or three-story buildings to the more sophisticated "Pombalino" structures, characterized by a braced timber frame with masonry infill. One study (D'Ayala et al., 1997) found that the poor maintenance of aged masonry structures in Portugal may have a significant impact on their seismic vulnerability. Collapse may be expected due to the overturning of facades or shear failure at the plane of the walls on the ground floor.

While masonry is predominant in Portugal in old times, reinforced concrete structure took off in the

1940s and has become common since 1960. The vulnerability of RC structures is largely influenced by the building code. In Portugal, the first modern seismic design code (i.e. RSCCS 1958) was developed in 1958. Three years later, the Code for Actions on Buildings and Bridges (i.e. RSEP 1961) was published. The RSCCS code comprises three different seismic regions and imposes an increase of the building resistance in accordance with the region seismicity (Campos Costa et al., 1998). In 1983 a new code, RSA 1983, was published, followed by two other important codes for concrete structures (i.e. REBAP 1983) and for steel structures (i.e. REAE 1986). RSA 1983 actually started to take effect in 1985 (Carvalho et al., 2002). According to RSA 1983, the AML is located in the region with the highest level of seismic hazard in Portugal. RSA 1983 remains in effect until the transition to the national implementation of Euro Code 8 takes place in full. Based on the evolution of Portuguese building codes, three age bands are defined for Portuguese buildings to differentiate their vulnerability by year-built: (1) 1961 and earlier, (2) 1962–1985, and (3) 1986 onwards.

The AIR Pan-European Earthquake Model adopts the CRESTA Zones (https://www.cresta.org) as the basic unit to capture the spatial variation of the building vulnerability. The AML region consists of 14 CRESTA Zones. For each CRESTA Zone, the building vulnerability level was determined for every age band based on a comprehensive study on the dominant building codes as summarized above, the construction quality, the damage observations following major historical earthquakes, and relevant references (Campos Costa et al., 1998; Carvalho et al., 2002; Oliveira, 2008 among others). In fact the vulnerability level is determined following a uniform framework of seismic vulnerability assessment (Lai et al., 2012). In this way, both the spatial and the temporal relativities of building vulnerability are measured consistently with a uniform scale across the entire modelled Pan-European region and along the time axis. The building vulnerability level in the AML, a sub-area of Portugal, can be read from the vulnerability maps for the country shown in Fig.3.1 depending on the building age. Clearly the building vulnerability in the AML changes from highest level before 1962 to high for 1962–1985, and finally to moderate level after 1985.

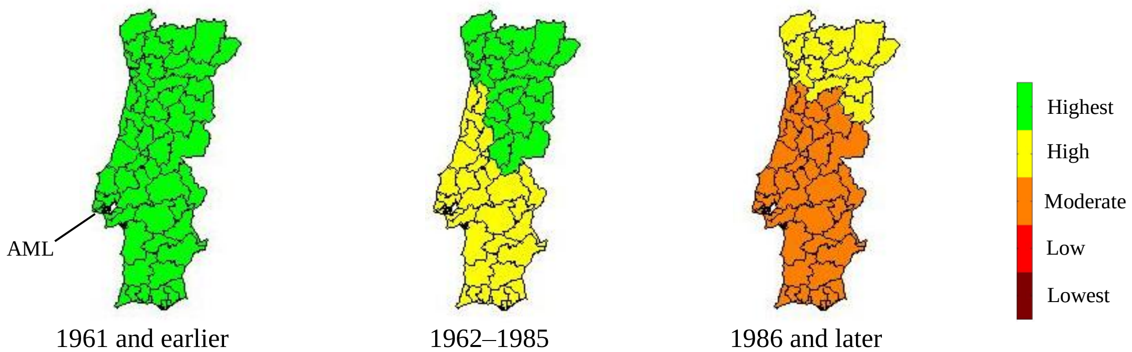


Figure 3.1. Building vulnerability level based on the year-built of the building.

Earthquake-induced damage and the consequent loss are directly related to a building's dynamic response to ground motion, which depends on both the features of the ground motion and the characteristics of the structure itself. In the AIR Pan-European Earthquake Model, the roof drift ratio (RDR), which describes the overall building deformation, is used as the measure of building damage. The RDR is calculated via the capacity spectrum method (ATC 1996; ATC 2005) and then related to the mean damage ratio. The vulnerability components vary not only by the vulnerability level but also depending on the construction type, the height range, and the occupancy class, etc. In addition to the building vulnerability, contents damageability is also modelled explicitly as a function of ground shaking, floor acceleration, and building occupancy. Furthermore, probability distribution around the mean damage ratio was constructed to capture the inherent randomness in seismic response and subtle differences in building characteristics and construction workmanship. Overall the vulnerability module in the AIR Pan-European Earthquake Model has been validated with reported damage and loss information for 70 major historical earthquakes affecting Europe (AIR 2011).

4. VULNERABILITY OF BUILDING AND CONTENTS TO TSUNAMI

Tsunami typically results from the displacement of a large volume of water that is generated by earthquake, volcanic eruption, or other underwater explosion. Although the probability of occurrence is generally lower than other natural hazards, tsunami following earthquake can impose extremely devastating impacts on the economy and the society as demonstrated by the 2004 Indian Ocean and the 2011 Tohoku, Japan disasters, even if early warning system exists. These two catastrophic tsunami events have raised urgent demand from policy makers and insurance companies on risk modelling for tsunami as well as earthquake.

One essential part of tsunami risk modelling is to evaluate various damages (e.g. building damage, contents damage, personal accident) caused by tsunami, which is tightly related to the tsunami intensity. Reese et al. (2007, 2011), Koshimura et al. (2009a, 2009b, 2009c), and Suppasri et al. (2011, 2012) among others developed tsunami fragility curves for buildings or personal casualties. Inundation depth, the maximum water depth above ground, is commonly chosen as the tsunami intensity parameter. In addition, flow velocity and dragging force are also used as the intensity parameters by some researchers. Flow velocity is a critical factor when estimating the tsunami damage. Given inundation depth h, the expected flow velocity v can be estimated by $v = Fr_R\sqrt{gh}$, in which Fr_R is the Froude number ranging from 0.5 to 1.3 (Asai et al., 2012). According to the law of energy conservation, an equivalent inundation depth can be easily derived. This equivalent depth is believed to be a better tsunami intensity measure that integrates the damaging effects of both the physical inundation and the tsunami current. In addition, debris carried by tsunami wave applies impact forces on buildings and can cause substantial damage. In the AIR tsunami vulnerability model, inundation depth, flow velocity, and debris effect are all addressed properly.

Tsunami can damage not only the building structure but also the contents in a building. The tsunami damage function for contents was developed as a function of inundation depth and building damage ratio. In shallow inundation, most buildings suffer non-structural damage. The contents damage is directly related to the ratio of inundation depth to the building height. Building damage increases as inundation goes deeper and, in turn, will cause more contents damage.

5. SIMULATION OF THE LISBON METROPOLITAN AREA UNDER A RECURRENCE OF THE 1755 LISBON EARTHAUQKE AND TSUNAMI

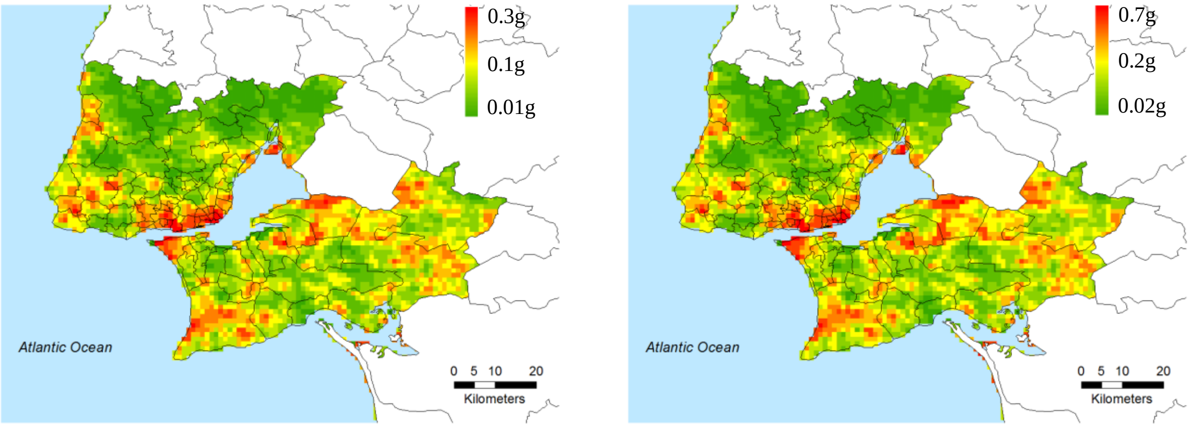
Lisbon was virtually destroyed by a strong earthquake in 1755, the largest ever-recorded natural catastrophe in Europe that had an enormous impact on the economy and culture of the Iberian Peninsula. Dynes (2000) argues that the 1755 Lisbon earthquake can be characterized as the first “modern” disaster, because of the unprecedented coordinated state emergency response, being also a “turning point in human history which moved the consideration of such physical events as supernatural signs toward a more neutral or even secular, proto-scientific causation.” Given its tremendous consequence, the 1755 event has been adopted by the Portuguese disaster professionals to create a collective memory of Portuguese vulnerability designed to fuel contemporary emergency management and disaster preparedness (Worboys, 2006). In this session, a deterministic scenario analysis of the 1755 earthquake and tsunami is conducted aiming to examine the seismic risk of today’s Lisbon Metropolitan Area (AML).

5.1. Simulation of Ground Motion

Happening on November 1st, 1755, the Lisbon earthquake registered a moment magnitude in the range of 8.5–9. There is great uncertainty regarding the exact location of the epicenter. Nevertheless it has been estimated that the epicenter was located approximately 193 km southwest of Cape São Vicente, in the Atlantic Ocean. The event occurred along the Azores–Gibraltar fault in the Gorringe Bank region, which serves as a boundary between the African and Eurasian plates. After an extensive review on the local earthquake catalogs compiled by research groups and government organizations (e.g. Pelaez et al., 2007) as well as recent literature (e.g. Chester, 2001; Gutscher, 2004), the seismologists at AIR proposed the source parameters in Table 5.1 for the 1755 earthquake. Being about 300 km away from the epicenter, Lisbon was shaken by three distinct tremors for several minutes, and ground motion from this event was felt as far away as Finland and Northwestern Africa.

Table 5.1. Source Parameters of the 1755 Lisbon Earthquake used in this Study.

Focal depth (km)	Rupture length (km)	Rupture width (km)	Average slip (m)	Strike (°)	Dip (°)	Rake (°)	M_w
30	105	75	10	235	52	90	8.5



(a) (b)

Figure 5.1. Simulated ground motion intensity of the 1755 earthquake in the AML: (a) PGA; (b) Sa(T=0.3s).

Given the source parameters, it remains a challenge to reconstruct the ground motion field in the AML for this early historical event. To address this challenge, a series of stochastic ground motion fields were simulated using a weighted combination of suitable regional ground motion prediction equations and incorporating local site conditions. These simulations also considered the effects of site-to-site ground motion correlation (Mahdyiar et al., 2010). Finally, one of these stochastic ground motion fields was selected for the subsequent damage and loss calculations according to the available isoseismal maps of this event. The selected ground motion field provides the ground motions intensity at all exposure locations as shown in Fig. 5.1. The peak ground acceleration (PGA) in downtown Lisbon is slightly above 0.2g while the largest PGA, ~0.3g, occurs at Santa Maria de Belém, Lisbon.

5.2. Simulation of Tsunami

The tsunami triggered by the 1755 earthquake affected mainly the coasts of the Iberian Peninsula and Morocco and was observed all over the North Atlantic coasts. Reports indicate that three tsunami waves engulfed the harbor and parts of Lisbon approximately 40 minutes after the earthquake. In the city of Lisbon, the number of casualties due to the tsunami exclusively is estimated around 900, and the penetration of the waters is evaluated to be 250 m (Baptista et al., 1998).
In this study, tsunami propagation and run-up were simulated using the COMCOT code (v1.7) developed by Wang (2009). It utilizes an explicit leap-frog finite difference scheme to solve the shallow water equations and is capable of modelling the entire lifespan of a tsunami (Liu et al., 1998). The earthquake source parameters in Table 5.1 were used to generate this event. The simulation was based on the combined bathymetry and topography data (ETOPO2) released by National Geographical Data Center (NGDC) of the U.S. On land, the ETOPO2 data were replaced by higher resolution SRTM 90m digital elevation data produced by National Aeronautics and Space Administration (NASA) of the U.S.

The model output is presented in Fig. 5.2, where the maximum inundation depth is shown on land while the maximum wave height is plotted in the ocean with respect to the mean sea level. Obviously, the most severe inundation is observed in Estoril, Parede, Carcavelos of Cascais Municipality, where the inundation distance reaches 300–400 m in average and the maximum flow depth ranges from 3 m to 4 m. The coastal area in Setúbal District suffers widespread flood of 1-3 m deep, especially in Northwest Almada and the low lands along a series of streams. The coast of Oeiras Municipality is also inundated hundreds of meters inland at a depth of 1–2 m, locally even 3 m. The simulated tsunami wave propagates into the Tagus River estuary and affected the Lisbon riverfront with an inundation distance of 200–300 m and the maximum water depth ~1 m. These results agree reasonably well with the potential inundation of Lisbon downtown by a 1755-like tsunami estimated by Baptista et al. (2011), considering different earthquake source parameters were used.

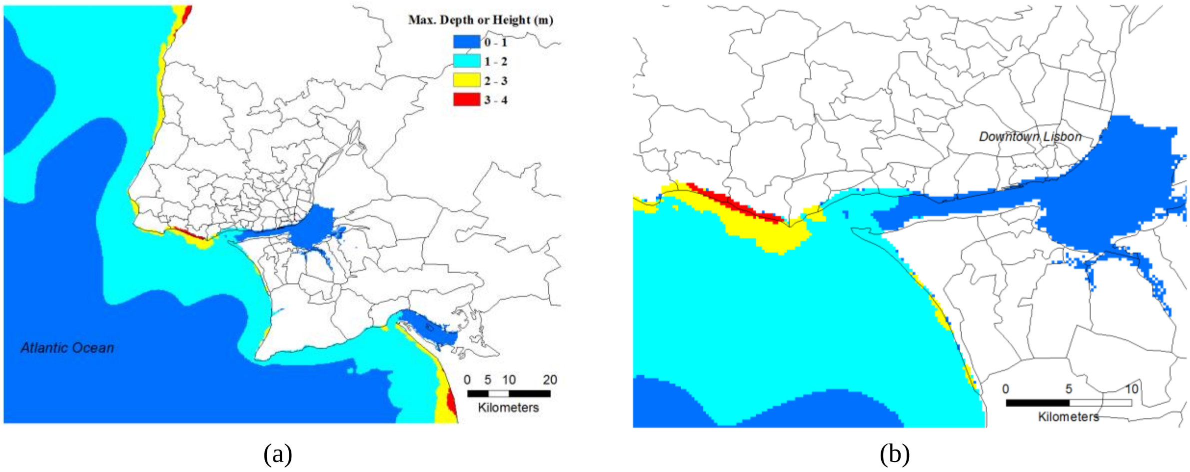


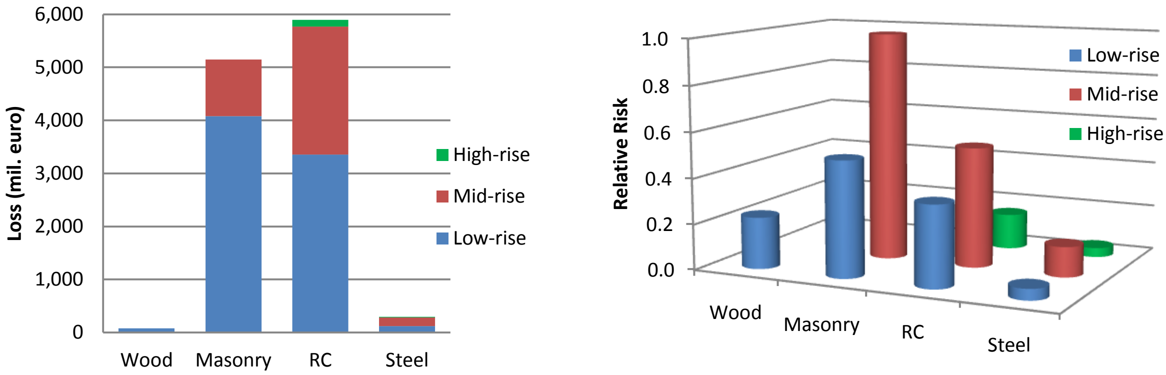
Figure 5.2. Simulated maximum inundation depth on land and maximum wave height offshore: (a) Lisbon Metropolitan Area; (b) Tagus River Estuary.

5.3. Simulation of Damage and Loss

Given the simulated ground motion field and tsunami inundation of the 1755 event, the resultant damage and loss of the exposure in the Lisbon Metropolitan Area (AML) are then computed by the vulnerability module of the AIR Pan-Europe Earthquake Model. The loss amount and its composition are presented next with emphases on the relative risk of different exposure segments and the impact of the tsunami.

The model announced a total loss of 11.4 billion euros for all the exposure, buildings and contents, under ground shaking and tsunami in the AML. This figure is more than 10% of the annual GDP of the studied region in 2008. Roughly 43% of the total loss comes from residential buildings, about 33% comes from commercial buildings, and the rest happens to industrial buildings. The total loss is also broken down by building typology as shown in Fig. 5.3(a), which tells the loss amount attributed to different construction and height classes. It is evident that low-rise masonry and RC buildings are the main contributors toward the total loss. This observation is in line with the fact that low-rise masonry and RC constructions together occupy about 60% of the total exposure in the AML.

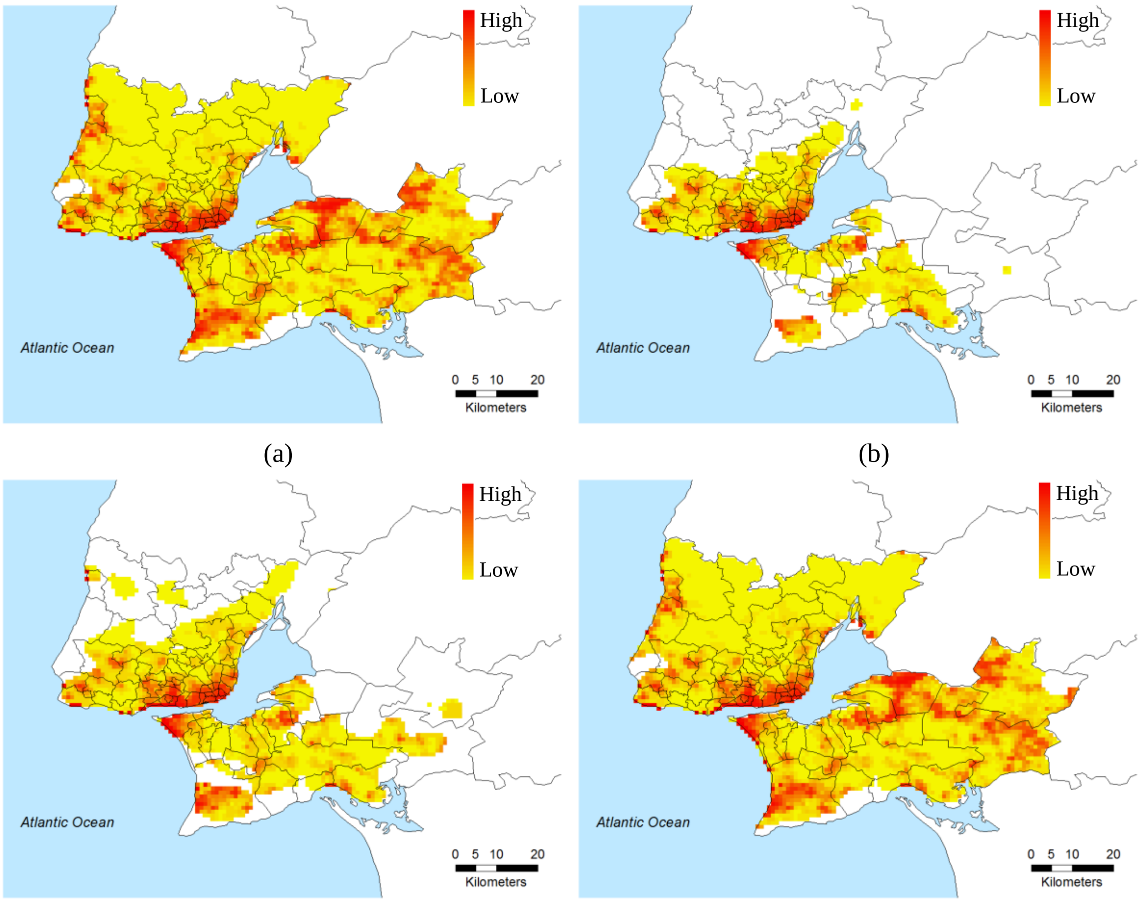
The overall damage ratio in the AML reaches 7.8%, knowing the total exposure value affected by this event is close to 146.1 billion euros. Similarly, the average damage ratio (i.e. loss over affected exposure) is calculated for every building type, respectively. Comparing the average damage ratio among different building types reveals their relative risk under this event. Fig. 5.3(b) exhibits the relative risk of the building types, normalized by mid-rise masonry. In general, mid-rise buildings have higher risk than the low-rise and then the high-rise, which is consistent with the lessons learned from many historical earthquakes. Masonry construction has the highest risk, followed by RC construction. It should be noticed that the relative risk reflects not only the difference in building vulnerability but also the influence of the ground motion.



(a) (b)

Figure 5.3. Loss analysis: (a) loss breakdown by building typology; (b) relative risk among building types.

The spatial distribution of the loss can be illustrated by plotting the loss-cost map that provides the ratio of loss value to exposure value at 1 km by 1 km grids. Fig. 5.4(a)–(d) depict the lost cost maps for residential buildings, commercial buildings, industrial buildings, and all the exposure, respectively. All use the same color scale. Overall, the loss-cost ratio is high in downtown Lisbon, Oeiras, Northwest Almada, Central Sesimbra, and a part of Alcochete. The loss-cost maps in Fig. 5.4 exhibit strong correlation with the ground motion field shown in Fig. 5.1, indicating the dependency of risk on ground motion intensity.



(c) (d)

Figure 5.4. Loss-cost maps: (a) residential; (b) commercial; (c) industrial; (d) all exposure.

The impact of the simulated tsunami on the total event loss is about 5% increase, compared to the situation of ignoring tsunami inundation. This ratio seems not alarming because the simulated tsunami has limited propagation inland in the AML. However, the tsunami is actually very damaging given the fact that only 2% of the total affected exposure is located in the flood area. Considering only the exposure affected by the tsunami, the average damage ratio by the tsunami alone reaches 17%. The influence of the modelled tsunami is considerable for Setúbal District, where the inundation caused 25% increase in the total loss. The increase in loss by the tsunami is 6–7% for the municipalities of Oeiras, Cascais, and Sintra. Particularly, the tsunami has a big impact on the contents in residential buildings, whose loss in the entire AML becomes 10% larger due to the flood.

6. CONCLUSIONS

A presumed recurrence of the 1755 Lisbon earthquake and tsunami was simulated and then used as a worst scenario to assess the seismic risk of the Lisbon Metropolitan Area. The resulted monetary loss was analysed thoroughly from different aspects in order to examine the relative risk with respect to building typology, the variation of the risk in space, and the impact of the tsunami inundation. Not as the ruin by the 1755 event in history, today's built environment in the AML has a significantly improved resistance to a similar disaster. It demonstrates the advancement in structural engineering and seismic building design over the past centuries.

The findings in this paper suggest the following implications for decision makers and risk managers. Seismic retrofit needs to be provided to mid-rise masonry buildings in the AML. Attention should also be paid to mid-rise RC and low-rise masonry structures. Earthquake mitigation measures and emergency plan are crucial for downtown Lisbon, Oeiras, Northwest Almada, Sesimbra, and Alcochete. The coastal areas in Setúbal District and the municipalities of Oeiras, Cascais, and Sintra are facing relatively high tsunami risk. This study focused on the building stock only. If we further consider losses due to business interruption and damage to infrastructure, the total loss in the AML could easily exceed 15 billion euros and, needless to say, have large social and economic impact on the country.

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