Damage scenarios in Lisbon using RISK-UE approach

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SUMMARY:
The city of Lisbon has been affected by strong earthquakes in the past. The well-known December 1st 1755 earthquake (M≈9) was the biggest one, but other important earthquakes, with epicentre offshore and inland, have also affected this city. Since several years, the seismic response of Lisbon has been a concern for all scientific, technological and political communities. This study presents the seismic behaviour of current buildings for two different seismic scenarios, in terms of estimated damage. The applied methodology, which was developed during the RISK-UE project, attributes a vulnerability index for each typology that will be used for damage grade estimation using the European Macroseismic Scale (EMS98). An empirical factor was introduced in order to take into account the influence of the topography and the surface geology. Results are present in terms of damage scenarios computed for each census track and for each parish.

Keywords: Lisbon, damage scenarios, vulnerability index

1. INTRODUCTION

The city of Lisbon has been struck, during historical times, by strong and devastating earthquakes. The main seismic events occurred during the XVI and XVIII centuries: the November 1st 1755 earthquake (M≈9), with epicentre offshore SW Cape St Vicent and the January 26th 1531 earthquake (M ≈ 7), with epicentre inland in the Lower Tagus valley seismogenic region (Moreira 1991). The large 1755 earthquake caused destruction not only in Portugal but also in Spain and Morocco (Martínez-Solares, 2001; Levret, 1991). Together with the associated tsunami, it was responsible for the death of about 12,000 people in Portugal, more than 10,000 persons in Morocco and about 1,000 people in Spain (Martínez-Solares, 2001). Its source, located offshore SW of Portugal mainland (150 to 250 km away from Lisbon) is still under discussion by several researchers (Ribeiro et al., 2009). The 1531 earthquake was located in the southern part of the valley, about 30 km far from Lisbon. Mercalli modified (MM) intensities of VIII and IX were reported in Lisbon and it caused serious damage in the town: several churches and palaces suffered strong or heavy damages, about 25% of the houses were damaged with 10% suffering total collapse and 2% of the population was killed (Henriques et al., 1988). During the XXth century no strong earthquake caused serious damage in Lisbon, but the April 23rd 1909 earthquake (M ≈ 6) with epicentre in the Lower Tagus Valley region (at approximately 40 km far from Lisbon) caused large destruction in several villages close the epicentral area, and the February 28th 1969 earthquake (M≈7.5), with epicentre offshore SW of Portugal mainland, caused severe damage in some villages in the south of the country. These two main seismic sources (inland and offshore) correspond to the two different seismic actions mentioned in Eurocode 8 (EC8) for Portugal (IPQ, 2010) and can produce different damage scenarios due to the ground motion and building seismic behaviour. These scenarios, corresponding to the near and far scenarios, will be presented in this paper.

Since the early 1990's earthquake scenarios for the city of Lisbon have been developed by different teams (Oliveira, 2008). In 1993, an earthquake simulator able to produce earthquake scenarios was developed and implemented in the Lisbon Council (Pais et al., 2001). In 2001, in the aim of a project promoted by the Portuguese National Civil Protection another simulator was developed for the

Metropolitan Area of Lisbon (MAL) (Anderson et al., 2004) with data from Census 1991. These simulators are under permanent upgrading, reflecting the new scientific and technological advancements as well as the most recent population and building data (Oliveira, 2008).

Taking into account that in Portugal the Census (statistical information about population and building stock) is performed each 10 years (the most recent was performed in 2011) the elaboration of damage scenarios must be updated, at least, each 10 years. The study presented in this paper address to the seismic response of current buildings. It was performed applying the methodology developed for European cities during the RISK-UE project (EVK4-CT-2000-00014) and used updated data (from 2001 to 2009). The methodology consists on the estimation of vulnerability index for each typology enabling the damage estimation depending on the macroseismic intensity. The intensity degrees, damage grades and typology classification were performed according to the definitions presented in the European Macroseismic Scale (EMS98) (Grünthal, 1998).

This paper will present the main results of this study as well as the description of the several steps undertook to develop it: (1) analysis and processing of the available building databases; (2) identification and definition of the building's typology; (3) characterization of the building's typologies and estimation of the vulnerability indexes; (4) estimation of the vulnerability and fragility curves; (5) definition of an empirical factor to take into account the influence of the topography and the surface geology; (6) damage estimation and damage distribution for different seismic scenarios.

2. THE CITY OF LISBON

Lisbon, the capital of Portugal, is one of the oldest cities in the world due to its strategic geographical location in relation to fluvial, estuarine and marine environments. It is located in the southern end of the Lower Tagus Valley, near the mouth of the river (Figure 2.1) and archaeological remains show a Prehistory of early occupation since the mid-first millennium BC. Nowadays the city of Lisbon has an area of approximately 84 km^2 with a resident population of 564657 people (INE, 2011). However, during the day the present population exceeds 1 million people. The city has 53 parishes ("*Freguesia*"), the third boundary level often used as the smaller work unit in several studies involving statistics.

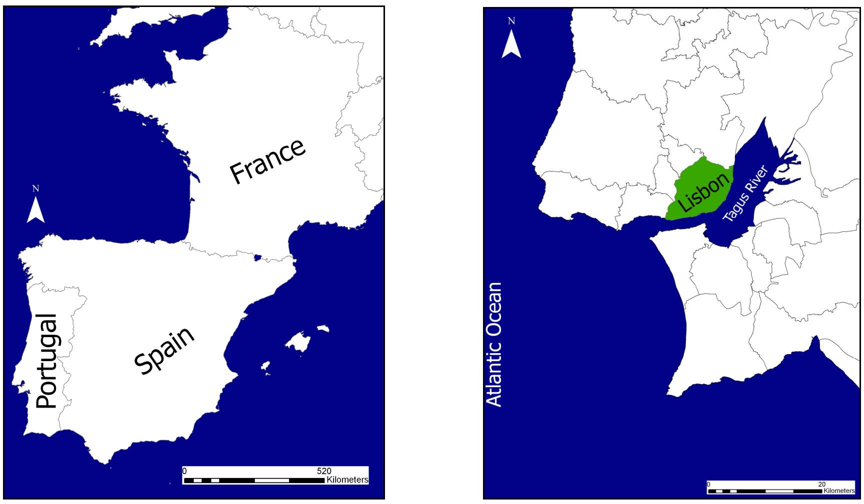

Figure 2.1. Location of Lisbon

Lisbon's residential building stock is composed by approximately 55,000 buildings with large differences between them: several typologies, different numbers of floors, different ages, and heterogeneity is usual in the same block. According to the age and to the material and techniques of construction, Appleton (2008) classifies the current buildings in 7 categories: (1) buildings before the

1755 earthquake ("*pré-pombalinos*"); (2) buildings constructed after the 1755 earthquake ("*pombalinos*"); (3) buildings constructed during the urban extension of the city in the last third of the XIX century ("*gaioleiros*"); (4) buildings constructed during the transition from masonry or hood to concrete; (5) buildings constructed before the first Portuguese earthquake resistance code (before 1960); (6) buildings constructed before the modern earthquake engineering (before 1985); (7) modern reinforced concrete buildings.

The geological setting of Lisbon is characterized by a south-western area, landscaped in Mesozoic formations which include Cretaceous marls and limestones and neo-Cretaceous basalts, and the eastern and northwestern area, with Cenozoic formations, mainly Paleocene and Miocene sedimentary series with alternate marine and continental facies. The total thickness of the complete sequence can be approximately 300 m. As the Miocene forms a monocline dipping east, the sequence is thinner in the west and thicker eastwards. This sequence includes over consolidated sands, clays, marls, limestones and sandstones, with important vertical and lateral facies variations, gently tilted south and southeast with local undulation, giving rise to the geomorphologic setting with incised valleys bounding gentle hills. Several small valleys exist in the city corresponding to old river beds. These valleys are filled by more or less thick deposits of alluvial sediments composed by sands and mud (Almeida, 1986; Almeida et al. 2009). This variety of surface geology and morphology can be important on the seismic response of the city. The soil and topographic effects were taken into consideration on the establishment of the damage scenarios using a simple approach.

3. DATA MANAGEMENT

The information on Lisbon building stock was collected from two main databases on current buildings: INE (Portuguese Official Statistics Institute) and CML (Lisbon Municipality) databases were the sources to create a master database suitable to apply the RISK-UE methodology. Each database has different attributes and different geographical features, but in the whole both have all the information to estimate the seismic risk through the RISK-UE method. The ArcGIS® and Matlab® software were used to create a GIS tool for managing this information, together with other fields and parameters, in order to develop seismic damage scenarios.

In 2001 a survey on the existent population and buildings occurred in Portugal (Census 2001). This provided information on resident and present population, family size, number of buildings and their size, date of construction, etc. This national study allows an actual preview of lifestyle, education level, distribution of people and buildings. The study was performed for the global urban areas and for all the country by districts, councils and parishes. The smaller statistics unit is the census track that corresponds to 1 or a few blocks in the urban areas. INE is the responsible for this national study that is performed with ten year periodicity. In this study only some information concerning buildings were used (Table 3.1).

The database of Lisbon Municipality (CML) has information about all the buildings of the city. The smaller unit cell in this database is the building. Recently this database was updated and we took data up to 2009 for this project. The information on the use of each building enabled the selection of residential buildings. The database was filtered in order to delete the buildings with other use than housing (stadium, theatre, schools, etc.). At the end, the attributes collected from this database were: (i) number of underground floors; (ii) number of floors over the ground; (iii) date of construction.

Table 3.1. Buildings attributes collected from the INE database

BGRI	Identification of each statistical unit
TTEC	Number of residential buildings
E1919	Number of buildings constructed before 1919
E1945	Number of buildings constructed between 1920 and 1945
E1960	Number of buildings constructed between 1946 and 1960
E1970	Number of buildings constructed between 1961 and 1970
E1980	Number of buildings constructed between 1971 and 1980
E1985	Number of buildings constructed between 1981 and 1985
E1990	Number of buildings constructed between 1986 and 1990
E1995	Number of buildings constructed between 1991 and 1995
E2001	Number of buildings constructed between 1996 and 2001
PV2	Number of buildings with 2 or less floors
PV4	Number of buildings with 3 and 4 floors
PV5	Number of buildings with 5 or more floors
EBAR	Number of concrete buildings
EARG	Number of masonry buildings
EPAT	Number of adobe or mud buildings
EORE	Number of buildings with other typologies

3.1. Creation of a Master Database

The information on Lisbon's buildings attributes should be put in a single database. The objective was to join the two former databases. However it was not possible to do it in a simple way because INE uses statistical boundaries (census track units) and CML database use the real position and the contour of each building. For Geographic Information Systems (GIS), INE uses polygons with the number of buildings inside each polygon, while CML uses polygons for each building with individual information. When both databases are joined, buildings and census track units are integrated. This integration allowed a comparison between INE and CML data.

The final information on the buildings was obtained by arranging both databases and establishing some criteria to analyze CML data and update the INE data. The new created database is performed using the census track as work unit cell and the selected building attributes are presented in Table 3.2.

Table 3.2. Buildings attributes included in the master database

Age / Date of construction	Typology	Number of Floors
Before 1919	EBAR	P4 (up to 4 floors)
1920 – 1960	EARG	P5 (between 5 and 7 floors)
1961 – 1985	EPAT	P8 (8 or more floors)
1986 – 1995	EORE	----
After 1996	----	----

3.2. Creation of Intensity Databases

The final purpose of this study is to estimate the damage suffered by each type or class of buildings. The damage will be a function of the assigned intensity produced by an earthquake scenario (an event with a certain magnitude generated at a certain epicentral distance). From the master database, after the vulnerability index calculation, the damage for each typology (as a function of macroseismic intensity) was estimated. Damage data were collected and compiled in a single-intensity database. Figure 3.1 shows the integration process schematically.

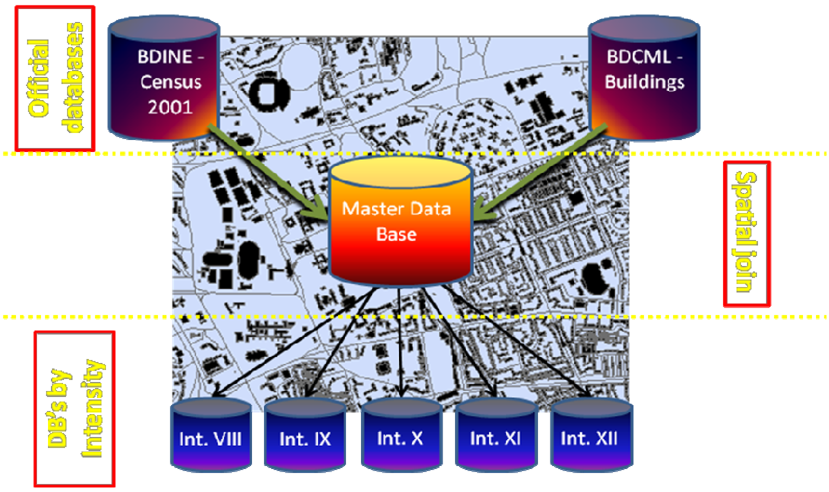

Figure 3.1. Management of the available input databases with the creation of new databases

4. DEFINITION OF THE TYPOLOGICAL CLASSES

One simple way to associate each building to a typological class can be done with the help of the EMS98 (Grünthal, 1998). In this scale the buildings are classified according to their structural type and six classes of vulnerability are defined: from A (the most vulnerable) to F (the most resistant). For each identified building type the most likely vulnerability class is assigned together with a probable variable range. Making the association of the Lisbon current buildings, with their respective attributes (see Table 3.2), to the structure type present in the EMS98 and introducing also the contribution of the number of floors, it is possible present a first vulnerability classification for the Lisbon building stock (Sousa, 2006), Table 4.1.

Table 4.1. Vulnerability class of the different buildings based on the EMS98 (adapted from Sousa,2006)

Date of construction	Number of floors	Concrete (EBAR)	Masonry (EARG)	Adobe/ Mud (EPAT)	Other (EORE)
Before 1919	All	---	B	A	A
1920 – 1960	All	C	C	A	A
1961 – 1985	Up to 7	C	C	A	A
	8 or more	D	D		
1986 – 2009	All	D	D	A	A

The spatial distribution of the vulnerability classes in the city was already presented in Barreira et al. (2010). Summarizing, it is possible to note that the spatial distribution of the building's vulnerability indicates a predominance of the C vulnerability class, but several heterogeneous zones where different vulnerability classes co-exist are also present. In order to understand the distribution of each typology in the city a first map was created to visualize the construction typologies by census track. It was possible to observe that the masonry buildings are mainly concentrated in the old blocks, and that wood/mud and other fragile materials are not relevant in the city. The new buildings, made in concrete, are located in the new blocks of the city (outside the central downtown and adjacent quarters) (Barreira et al., 2010).

With this previous information, the typology classes to use in the RISK-UE method were defined. Construction typology (reinforced concrete or masonry) and age were the two main parameters that defined each typology class. The considered age intervals are the ones presented in Table 3.1: < 1919; 1920-1960; 1961-1985; 1986-1995; > 1996. The distribution of the different typology classes in the city is represented in Figure 4.1. Adobe, mud and other buildings were considered in a single class. In each census track the attributed typology was the predominant one (at least 55%). The heterogeneous census tracks were further homogenised in the next steps of the study. According to RISK-UE methodology the number of floors can be introduced as an aggravation parameter (see next section).

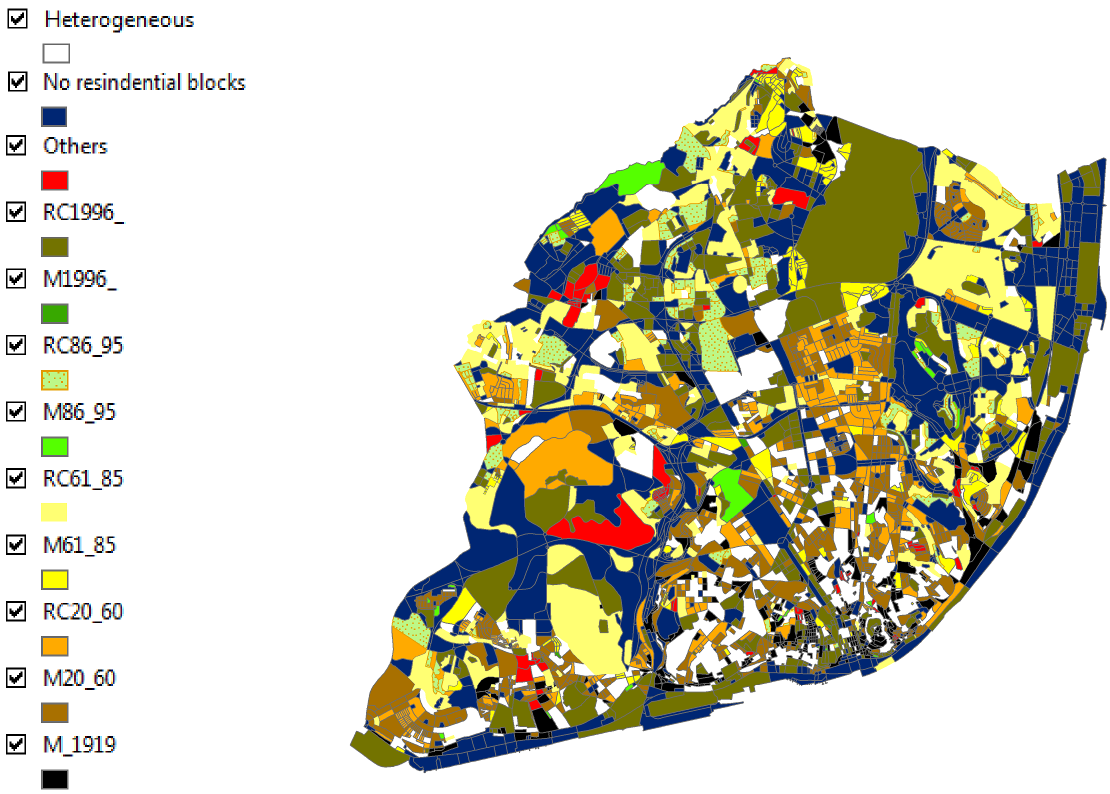

Figure 4.1. Spatial distribution of the considered typology classes

5. RISK-UE METHOD

RISK-UE is considered to be "an advanced approach to earthquake risk scenarios" and was developed to estimate vulnerability and fragility models for the prevailing European built environment. This approach can be implement on two distinct levels depending on the available information: LM1 - suitable for vulnerability, damage and loss assessments in urban environments having not detailed site seismic estimation but adequate information on EMS98 seismic intensity estimation, and LM2 - applicable for urban environments where detailed seismic studies exist, including site specific spectral acceleration, spectral velocities or spectral displacements (Milutinovic and Trendafiloski, 2003).

The method defines some issues to understand its application. Building vulnerability is a measure of the building damages, depending on ground shaking, assuming a specified intensity. A statistical approach allows an acceptable result about building vulnerability. The vulnerability is defined as the degree of damage or loss of the buildings, after a seismic event. These type of studies can be based on past events (LM1 approach), after observing the damages and losses on the physical infrastructures and relating with other parameters like seismic intensity, construction typologies, number of floors, irregularities, etc. This approach involves a statistical correlation between the macroseismic intensity and the damage analysis of the past events. The EMS98 scale is a reference in the damage observation, but it involves a subjective classification. On the other hand, the LM2 approach needs analytical studies of each structure involving detailed seismic studies, in terms of spectral acceleration, spectral velocities or spectral displacements.

Due to the available information for Lisbon, only LM1 approach was used. In spite of this simple approach the results were quite satisfactory and easy to compare former studies performed for Lisbon.

6. APPLICATION TO LISBON CITY

6.1. Estimation of the Mean Vulnerability Index of each typological class

For applying RISK-UE methodology it is necessary to characterize each typological class. This was done by performing some surveys to selected blocks, in order to collect some structural characteristics for completing the database information. The selected blocks were typological homogeneous, taking into consideration the age and the type of construction, and located in different zones of the city: 2,500 buildings of 184 census tracks were analyzed. The attributes collected during the survey were: vertical irregularity, number of floors and conservation state. Besides, the position of the building in the block, differences of height between adjacent buildings and location of the building (in slope or not) were also observed. The collected data were integrated in the database.

Each typological class was associated with a RISK-UE typology in order to assign a mean vulnerability index (Table 6.1). Taking into consideration the attributes collected during the experimental survey, a minimum, mean and maximum vulnerability indices were computed for each identified typological class (Table 6.2)

Table 6.1. Mean Vulnerability indices considered in RISK-UE method

Typology (Masonry)	Mean Vulnerability Index	Typology (Concrete)	Mean Vulnerability Index
M1.1	0.873	**RC1**	0.442
M1.2	0.740	**RC2**	0.386
M3.2	0.776	**RC3.1**	0.402
M3.4	0.616	**RC3.2**	0.522
M4	0.451	**RC4**	0.386

Table 6.2. Vulnerability indices applied for each typological class, at Lisbon

Typological class	Minimum	Mean	Maximum
M>1919	0.531	0.773	1.016
M20_60	0.491	0.745	1.056
M61_85	0.491	0.698	0.956
M86_95	0.451	0.634	0.836
RC20_60	0.522	0.681	0.742
RC61_85	0.482	0.640	0.752
RC86_95	0.462	0.555	0.662
RC<1996	0.426	0.533	0.722

6.2. Vulnerability and Fragility Curves

After de definition of the vulnerability indices, mean damage can be estimated for a certain seismic intensity (I) using this Eqn 6.1:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25\,\overline{V}_I - 13.1}{2.3}\right)\right] \tag{6.1}$$

The vulnerability curves were then computed. Figure 6.1 presents the mean, minimum and maximum vulnerability curves for all the typological classes. Damage grade definition is in accordance to EMS98.

The damage distribution is estimated using a beta-distribution. The fragility curves can be estimated after computing the probability density function. Figure 6.2 presents, as example, the fragility curves for two different typologies. These curves show the probability of a building typology suffer a certain or higher damage grade, depending on the macroseismic intensity.

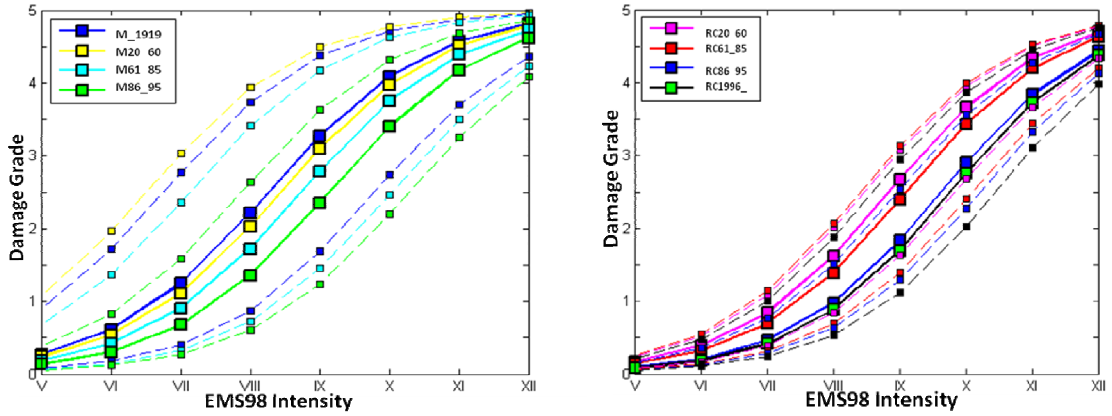

Figure 6.1. Vulnerability curves for the different typological classes: masonry (left) and reinforced concrete (right)

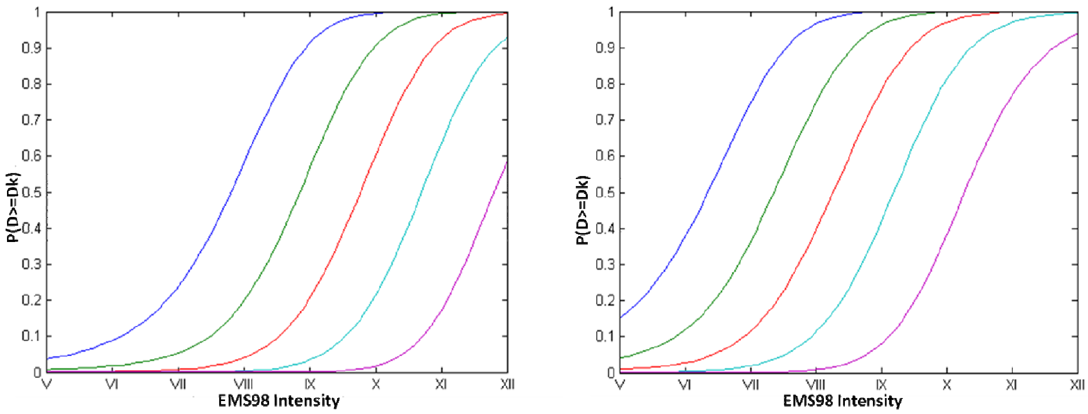

Figure 6.2. Fragility curves for M>1919 (left) and RC<1996 (right) typologies. Each curve represents the probability of the damage grade depending on the seismic intensity: degree 1 (blue), degree 2 (green), degree 3 (red), degree 4 (cyan) and degree 5 (magenta)

7. RESULTS

The damage distribution is present for two different seismic scenarios according to the seismicity pattern for Portugal mainland and to the EC8 (IPQ, 2010): the near scenario, that could correspond to an earthquake generated in the Lower Tagus Valley seismogenic zone (M=6.0), and the far scenario, that could correspond to an earthquake generated offshore SW of Portugal (M=8.5). According to historical records these earthquakes could produce, in Lisbon, a macroseismic intensity of VI and IX respectively.

To take into account the soil conditions where the building is settled, an empirical factor associated to the surface geology was add to increase or decrease the estimated intensity. Different factors were estimated for the two seismic input motions. An additional factor was also introduced when the building is settled on a slope.

The results are presented, for both scenarios, in terms of the number, or percentage, of buildings suffering damage grades 3, 4 and 5. Figure 7.1 presents some damage scenarios considering the census track as unit work, while Figure 7.2 presents the same scenarios in terms of damage in each parish. Both representations are interesting and can be discussed. The use of the census track provides a more detailed visualization of the scenarios while the last presentation is important for comparison and discussion with former studies.

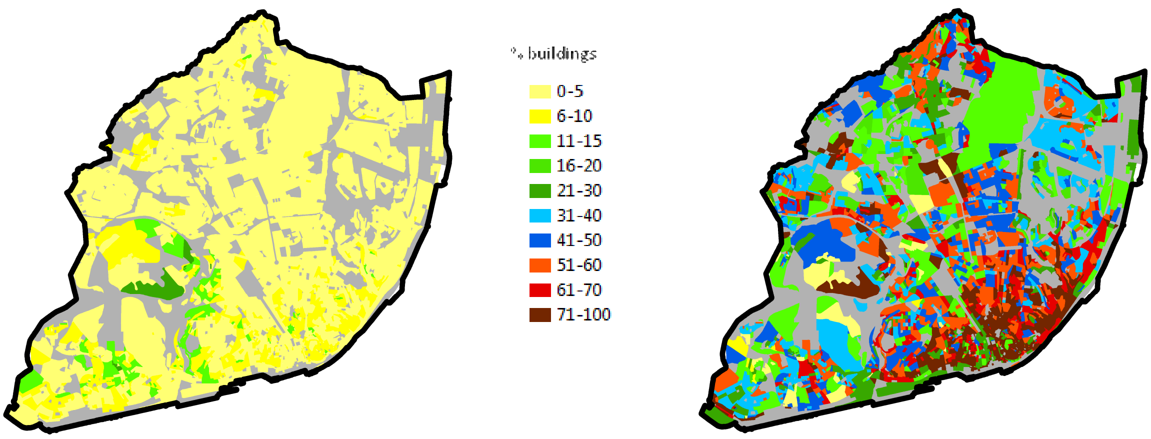

Figure 7.1. Left: percentage of buildings, in each census track, suffering damage grade 3 or higher for a near source event producing intensity VI in Lisbon. Right: percentage of buildings, in each census track, suffering damage grade 4 or higher for a far source event producing intensity IX in Lisbon.

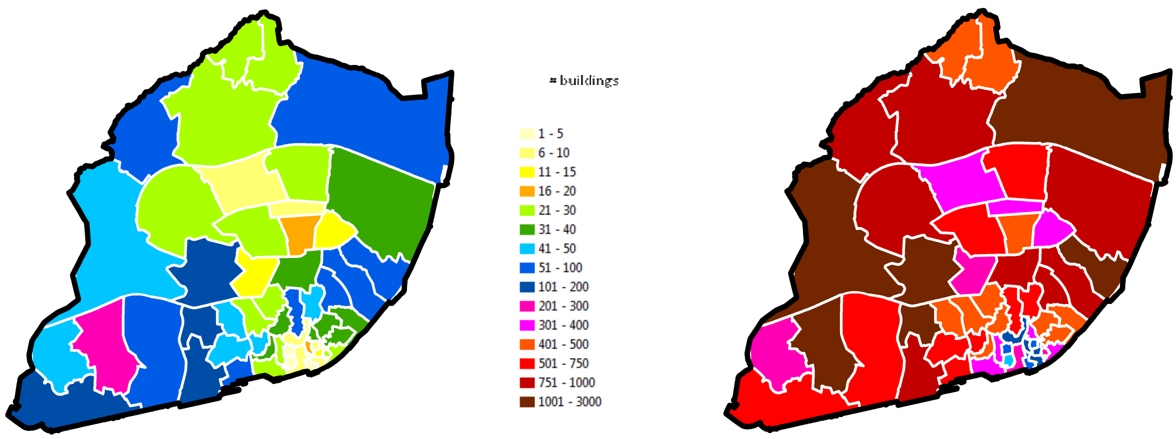

Figure 7.2. Left: number of buildings, in each parish, suffering damage grade 3 or higher for a near source event producing intensity VI in Lisbon. Right: number of buildings, in each parish, suffering damage grade 4 or higher for a far source event producing intensity IX in Lisbon.

8. CONCLUSIONS

Comparing of our results with previous studies, namely the studies performed for the Metropolitan Area of Lisbon (Oliveira, 2008; Carvalho et al., 2008; Campos Costa et al., 2006, 2010), it is possible to see that our approach exhibits similar results. This indicates that the use of the RISK-UE methodology was successfully applied to Lisbon, using census and complementary data. The vulnerability curves shows differences between epochs and construction materials, and the fragility curves follows the trend of past studies. The use of geology and topography data is an improvement from previous models, allowing a better contribution of local soil behaviour for the two different scenarios (far and near). This is not intend to be a complete seismic risk study, for which all structures should be considered (as hospitals, schools, governmental buildings, lifelines, etc.), but it only respects the residential buildings of Lisbon. Nevertheless, the results of this study can (and should) be used for urban planning and for preparing emergency and pre-event measures.

ACKNOWLEDGEMENTS

This study was performed in the aim of the Portuguese project on Evaluation of Risks in Lisbon City (LISBOA-02-3207-FEDER-000044) supported by the Commission of Coordination and Regional Development of Lisbon and Tagus Valley under QREN_PORL Program.

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