Application of Two Different Vulnerability Methodologies to Assess Seismic Scenarios in Lisbon

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ABSTRACT

An earthquake *simulator* was developed for Lisbon in late 1990 by the Municipality of Lisbon. This *simulator* was constructed making use of: a) historical data was analysed in order to determine the occurrence mechanisms and attenuation laws; b) soil influence was included through the analysis of upper soil layers classified into several categories; and c) vulnerability of the building stock was obtained through the analysis of different classes of construction types, 5 in total, essentially based on the epoch of construction (Tiedemann, 1992 and Coburn and Spence, 1992). This *simulator* contains detailed information on the geological surface layers, on the building inventory and on population data of the Census 1991, using the statistical sub-section as work unit. Scenarios developed within a GIS environment were, though, available for the Lisbon City Council for different magnitudes and epicentral distances, producing the damage inflicted to the building stock as well as the affected population (victims, injures and homeless).

Recently, another vulnerability method making use of the EMS-98 concepts was developed (Giovinazzi and Lagomarsino, 2003). A detailed classification of building typologies existing in Lisbon is now available, considering the age, construction material, and existence of earthquake code provisions, height, state of preservation and lateral discontinuity of adjacent buildings. Vulnerability was assigned to each typology using the approach of EMS-98 scale for the first three parameters.

In this paper, a comparison of the two methods for estimating earthquake vulnerability of the building stock at an urban area is presented. Results from the two methods (keeping all other variables and parameters the same) for the City of Lisbon, in terms of severely damage and collapsed buildings, are very similar in the overall. A few light differences were found only when a detailed analysis is made. Under these circumstances the validity of the old *simulator* can be accepted within certain limits.

INTRODUCTION

This study is intended to characterise with a certain detail the vulnerability of the built stock of the City of Lisbon using two different methods, and to estimate the impact of earthquakes in the City (to buildings and population).

The first vulnerability methodology – Model 1 – developed in the 1990´s to analyse earthquake scenarios in the City of Lisbon was based on the work developed by Tiedemann (1992) and Coburn and Spence (1992), adequately adapted to the Portuguese situation. They used a data-base on damage from world wide statistics of earthquakes occurred essentially in the period 1960-1990.

After that period, many important and damaging earthquakes took place producing better data (more in quantity and more with accurate information). Also, in this later period a new intensity scale, the EMS-98, was developed considering the type of construction, the percent of damage buildings, and the existence of some kind of code enforcement, among other topics related to the seismic performance of buildings.

Giovinazzi and Lagomarsino (2002 and 2003) used the concepts described in the EMS-98 scale [Grunthal, 1998], and data from recent events to develop an alternative method for assessing the vulnerability of the building stock. We used those concepts to develop and implemented a – Model 2 – vulnerability of a variety of construction types representing the different situations existing in Lisbon.

Models 1 and 2 were applied to the City of Lisbon in order to compare the results produced. The seismic input used in the analysis was the same for both situations and corresponds to the studies developed in early 1990.

DEFINITION OF INPUT GROUND MOTION

The topic of impact studies in a metropolitan area has been thoroughly analysed in the past, essentially for the city of Lisbon [Oliveira and Pais, 1993, Pais et al. 1996]. A simulation model was developed obtaining the damage scenario in terms of victims, casualties, destroyed facilities and any other structures. Given an earthquake defined by an epicentral location and depth, and by a magnitude, it is possible to determine the ground motion in terms of Mercalli Modified intensity for the region of Lisbon. The model developed in the 1990´s, considers: (i) an attenuation with one single parameter (affecting the hypocentral distance) which can be changed according to the earthquake source area; (ii) soil characterization considering several classes reflecting the impedance contrast.

In both Models (1 and 2) the same input ground motion was used as described above.

VULNERABILITY DEFINITION FOR MODEL 1

Buildings were classified in 5 categories A to E (A being the oldest masonry construction prior to the strong Lisbon earthquake of 1755 and E the recent reinforced concrete structures built according to the updated seismic code of actions), aggregated into a geographical area corresponding to the county. The council of Lisbon is divided into 52 counties, with a population resident of around 0.6 Million. Data on building and population were obtained from the Census 91 at the county level, together with other local indexes.

Vulnerability and fragility functions used to compute damage inflicted were taken from [Coburn et al. 1992] based on limit states D3 (Figure 1) for severe damage and D5 (Figure 2) for collapse. Population present in 5 different periods of the day were obtained from a study on their mobility. The simulator computed the percentage of damage per typology in each county, number of buildings in class D3 and D5, and costs of repair based on average costs for reconstruction per m^2, number of stories and area in plant. Also damage to population (deaths, injuries, homeless) can be computed.

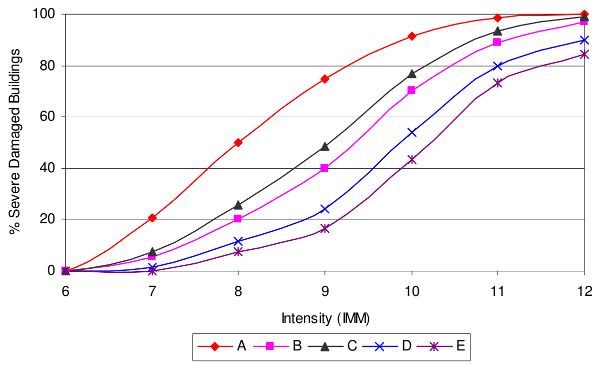


Fig. 1. Vulnerability function for Model 1 (severe damage)

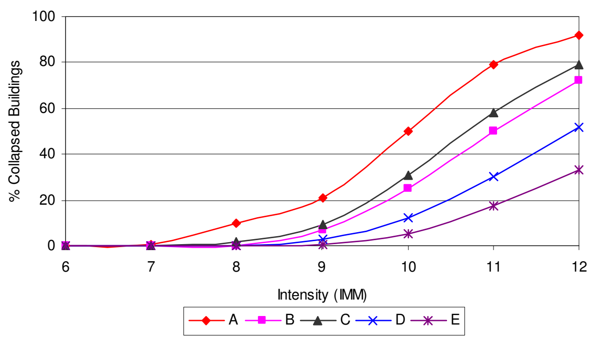


Fig. 2. Vulnerability function for Model 1 (collapse)

VULNERABILITY DEFINITION FOR MODEL 2

CHARACTERIZATION OF IMPORTANT MASONRY TYPOLOGIES VERY COMMON IN PORTUGAL

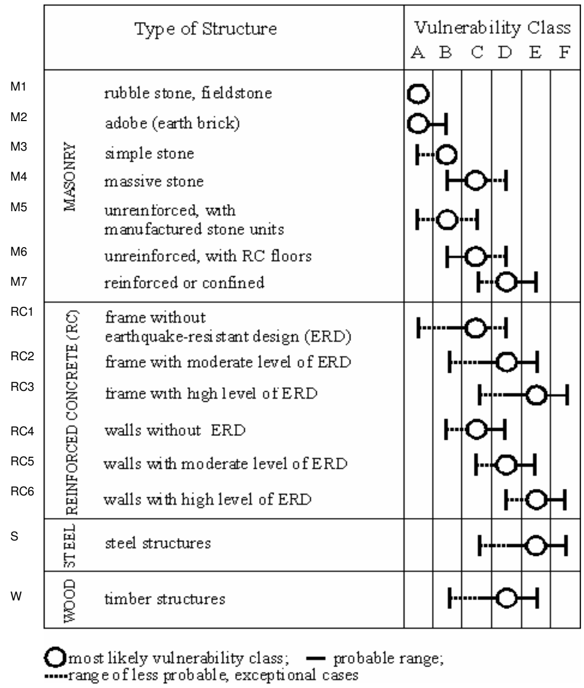
Vulnerability indexes were determined for important masonry typologies common in Portugal. Some cases were taken directly from the EMS-98 scale, but others were derived from their structural properties. This is the case of the *Pombaline* buildings, built in the sequence of the 1755 earthquake, and *Gaioleiro* buildings the last phase of masonry buildings, exhibiting the worse seismic vulnerability, and built in the transition period to the reinforced concrete structures [Oliveira et al. 2004].

The *Pombaline* buildings were the new buildings erected during the first decades of reconstruction after the 1755 earthquake and are characterized by a set of features intended to provide them adequate seismic behaviour, which means enabling them to resist horizontal loads and to dissipate substantial amounts of energy. The "gaiola" or "cage" system existing in the *Pombaline*, consists of a set of timber members embedded along the inner face of the main stone masonry façade walls. Several studies, indicates that, if the state of conservation of the masonries is kept, the timber members are still in "good" shape, and no removable of walls or addition of stories took place, then the overall behaviour is still good.

In the 1850-1940 period was built the *Gaioleiro* typology which corresponds to the time of avoiding the "gaiola" and the initiation of the reinforced concrete (RC) period. This is a very critical typology due to its poor vulnerability and to the large number of buildings still existing in regions of moderate to large seismic hazard. These buildings are essentially masonry of poor quality with wooden floors and partitions. There are few elements connecting exterior walls and many are not well maintained.

In EMS-98 some typologies are considered for masonry (M1 to M7), reinforced concrete (RC1 to RC6), steel (S) and timber buildings (W). The seismic behaviour of buildings, in terms of apparent damage, may be subdivided in six vulnerability classes, A to F (Table 1). (Note: do not mix the designations A to E of Model 1 with vulnerability classes A to F of EMS-98 in Model 2)

TABLE 1: Attribution of vulnerability classes to different building typologies



In parallel to the typologies defined in Table 1, the EMS-98 relates intensity values with Damage grades through a qualitative description presented in Table 2. The terms "Few", "Many" and "Most" are vague and can be interpreted in different ways, as explained in the following sections. Probability Damage Matrices and Mean Damage Grade are obtained as proposed by Giovinazzi and Lagomarsino (2002, 2003) through the vulnerability index V_I. The final vulnerability μ_D is then obtained through:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V_I - 13.1}{2.3}\right)\right]$$

TABLE 2: EMS-98 damage description for Class A.

Damage grades	1	2	3	4	5
Intensity	V	Few			
	VI	Many	Few		
	VII		Many	Few	
	VIII			Many	Few
	IX				Many
	X				Most
	XI				
	XII				

THE USE OF FUZZY SET THEORY CONSIDERING MACROSEISMIC SCALE DEFINITIONS

The vulnerability classes could be well interpretable in the framework of the Fuzzy Set Theory. It is reasonable to attribute to "most probable", "probable" and "exceptional case" terms the percentage values near to 100%, 60% and 20% (Table 3). It is possible to define the membership function of each building type, as a function of the vulnerability index V_I, through a linear combination of the vulnerability class membership functions. For the membership function of each typology, five representative values V_I have been defined through a defuzzification process. Figures 3 and 4 presents an illustration of the method which has been programmed (®Excel sheet) in order to produce automatically the vulnerability index V_I result given the description of any building category in terms of its percent of classes A to F of the EMS-98 scale [Mota de Sá, 2005]. The two selected typologies for membership functions were the ones referred *pombaline* and *gaioleiro*.

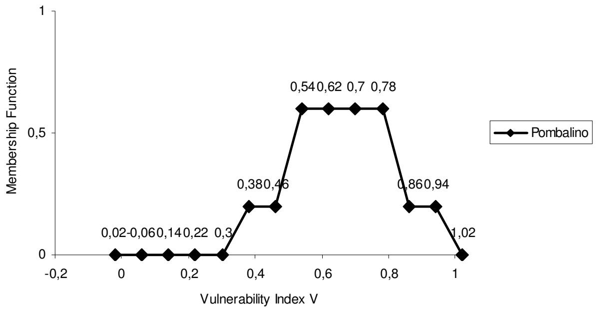


Fig. 3. Membership Function of V_I for *pombaline* typology and its representative values

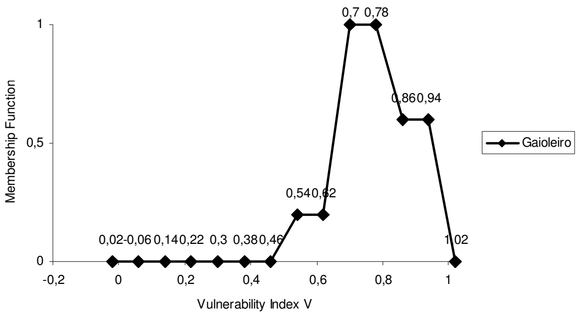


Fig. 4. Membership Function of V_I for *gaioleiro* typology and its representative values

In Table 3 are presented the results for the several types of building categories using the Fuzzi Set theory, grouping the initial EMS-98 typologies into typologies leading to the same vulnerability index V_I and their upper and lower bounds.

The passage from μ_D to damage grades characterized by 6 limit states ("no damage"; "slight damage"; "moderate damage" ; "heavy damage" ; "very heavy damage" ; and "collapse"), we use the beta distribution as recommended by ATC 13 (1985).

TABLE 3: Meaningful values for building typologies

	A	B	C	D	E	F	V--	V-	V*	V+	V++
A	O						0,780	0,820	0,900	0,980	1,020
M1	O						0,780	0,820	0,900	0,980	1,020
M2	O	X					0,620	0,687	0,840	0,980	1,020
Gaioleiro	*X*	*O*	---				0,460	0,650	0,776	0,953	1,020
M3	---	O					0,620	0,660	0,767	0,830	1,020
B		O					0,620	0,660	0,740	0,820	0,860
M5	---	O	---				0,460	0,650	0,740	0,830	1,020
Pombalino	---	X	X	---			0,300	0,520	0,660	0,800	1,020
RC1	---	X	O	---			0,300	0,490	0,644	0,800	1,020
M4,M6		X	O	---			0,300	0,490	0,616	0,793	0,860
C			O				0,460	0,500	0,580	0,660	0,700
Lx4060,F4660		*X*	*O*	*X*	---		0,140	0,360	0,553	0,793	0,860
RC4		---	O	X			0,300	0,367	0,544	0,670	0,860
RC2, W		---	X	O	X		0,140	0,207	0,447	0,640	0,860
D				O			0,300	0,340	0,420	0,500	0,540
M7,RC5			---	O	X		0,140	0,207	0,384	0,510	0,700
RC3			---	X	O		0,140	0,180	0,349	0,480	0,700
S			---	X	O	X	-0,020	0,047	0,287	0,480	0,700
E					O		0,140	0,180	0,260	0,340	0,380
RC6				---	O	X	-0,020	0,047	0,224	0,350	0,540
F						O	-0,020	0,020	0,100	0,180	0,220

Classes de Comportamento

O	Most probable	100%
X	Probable	60%
---	Exceptional cases	20%

The basic vulnerability functions were adapted to the reality of Lisbon (Table 4), and were obtained through the analysis of five different classes of construction types: T1 – Pré-Pombaline (before 1755); T2 – Pombaline (1755-1840); T3 – Gaioleiro (1850-1940); T4 – Unreinforced masonry (1940-1960) and T5 – Reinforced concrete (after 1960).

TABLE 4: Correspondence between EMS-98 typologies, Lisbon typologies and Vulnerability index (Giovinazzi and Lagomarsino, 2002)

EMS-98 Typology	Lisbon Typology	Vulnerability Index
-	Pré-Pombaline Before 1755	0.870
-	Pombaline 1755-1850	0.660
-	Gaioleiro 1850-1940	0.776
-	1940-1960	0.553
RC2	After 1960	0.447

A total of 61032 buildings of Lisbon were characterized using the building inventory and population data of the Census 1991. Figures 5 and 6 and Table 5 present the fragility functions corresponding to Model 1 and Model 2 for the *pombaline* buildings, separating the severe damage from collapse buildings.

Using the proposed methodology by Giovinazzi and Lagomarsino (Model 2), and comparing with the first method we concluded that to the *pombaline* buildings the probability of occurrence of damage grade 3 (severe damage) is higher to model 2 when intensities are between VI-X.

TABLE 5: Percentage of buildings severely damaged and collapsed using the index vulnerability for T2 - Pombaline

Vo 0,66	T2 - Pombaline							
	Model 1		Model 2					
I	m1.dg3	m1.dg5	mdg	mx	p	q	m2.dg3	m2.dg5
6	0,00	0,00	0,35	0,57	0,76	7,24	0,36	0,00
7	1,67	0,00	0,76	1,15	1,53	6,47	2,47	0,00
8	8,13	0,42	1,50	2,02	2,69	5,31	13,52	0,09
9	14,58	5,00	2,53	3,03	4,03	3,97	33,02	1,88
10	24,17	16,66	3,55	4,03	5,37	2,63	30,39	15,99
11	20,84	44,15	4,27	4,89	6,52	1,48	11,31	52,38
12	14,60	66,64	4,66	5,45	7,27	0,73	2,71	82,32

where m1dg3 = damage grade 3 to model 1; m1dg5 = damage grade 5 to model 1; mdg = mean damage grade; mx, p and q are the parameters of the beta distributions; m2dg3 = damage grade 3 to model 2; m2dg5 = damage grade 5 to model 2.

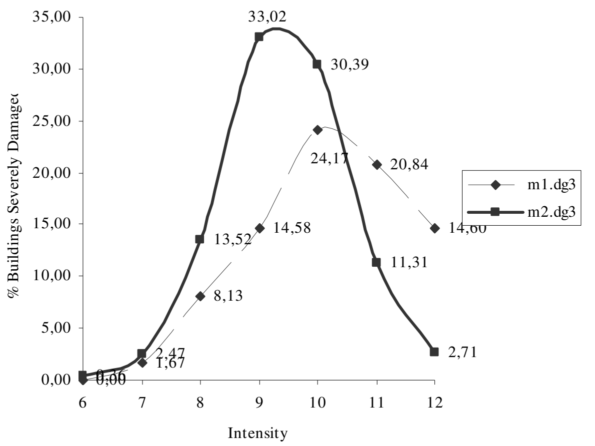


Fig. 5. Fragility curves for buildings of typology T2 – *Pombaline* – Severe damage

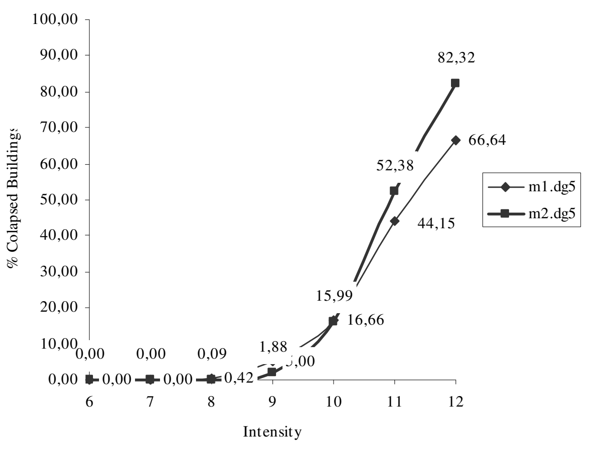


Fig. 6. Fragility curves for buildings of typology T2 – *Pombaline* – Collapsed buildings

TABLE 6: Percentage of buildings severely damaged and collapsed using the index vulnerability for T5 - RC2

Vo 0,447	T5 - RC2							
	Model 1		Model 2					
I	m1.dg3	m1.dg5	mdg	mx	p	q	m2.dg3	m2.dg5
6	0,00	0,00	0,12	0,20	0,26	7,74	0,04	0,00
7	0,00	0,00	0,27	0,44	0,59	7,41	0,20	0,00
8	3,33	0,00	0,59	0,92	1,23	6,77	1,30	0,00
9	8,13	0,40	1,22	1,71	2,28	5,72	8,24	0,03
10	19,17	5,00	2,17	2,69	3,58	4,42	27,32	0,76
11	27,92	17,49	3,23	3,70	4,94	3,06	34,86	8,73
12	25,42	33,32	4,07	4,63	6,17	1,83	16,99	39,13

Figures 7 and 8 and Table 6 present the fragility functions corresponding to Model 1 and Model 2 for the *reinforced concrete T5-RC2* buildings, separating the severe damage from collapse buildings.

Figure 7 shows the percentage of buildings severely damaged considering the methodology 1 and 2. From IX to XI intensity the number of buildings with severe damage increases for Model 2.

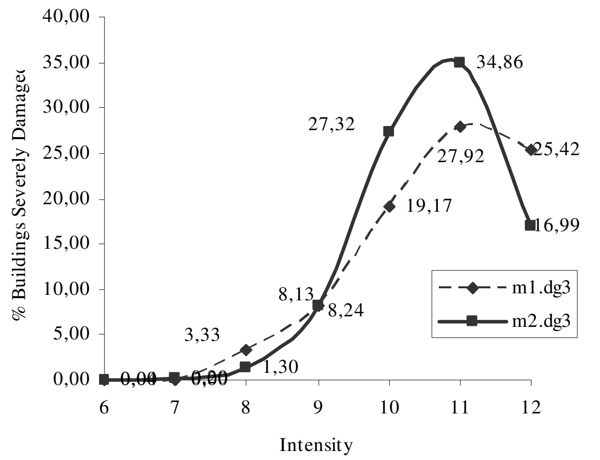


Fig. 7. Fragility curves for buildings of typology T5 – RC2 - Severe damage

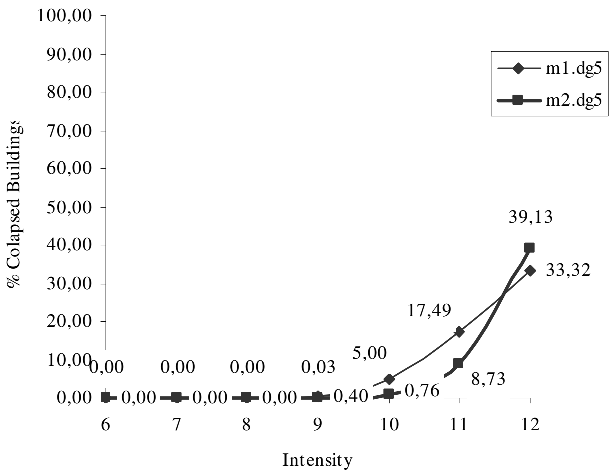


Fig. 8. Fragility curves for buildings of typology T5 – RC2 - Collapsed buildings

RESULTS FOR LISBON CITY

The deterministic inputs that were chosen for the simulation corresponds to the strongest earthquake that hit the region in the last 250 years (MM intensity IX-X) and the event related to the Lower Tagus River Fault that occurred in 1909 (MM intensity VII-VIII). The scenario of consequential damage to buildings and population comparing the two models (1 and 2) can be seen in Tables 7 and 8 and geographical distribution in Figures 9 and 10 for the 1755 earthquake scenario and Figures 11 and 12 for the 1909 earthquake scenario.

TABLE 7: Estimation of variables to the 1755 earthquake

1755 earthquake; M = 8,5; D = 227 km		
	Model 1	Model 2
Collapses	3289	2389
Severe Damage	8423	13547
Death	10888	11961
Injures	10391	11914

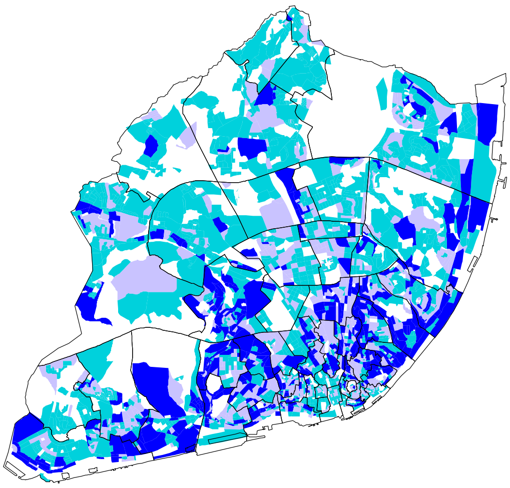


Fig. 9. Collapsed buildings to the 1755 earthquake scenario – Model 1

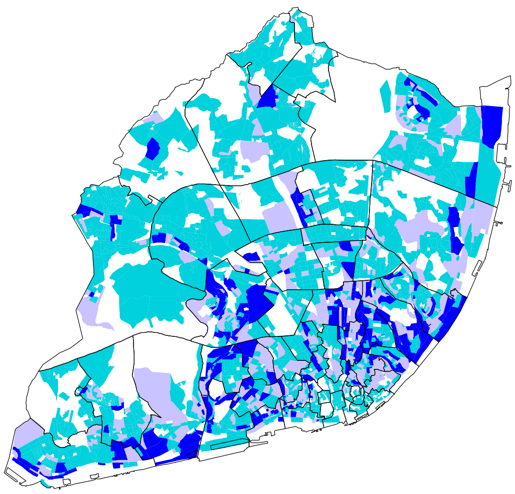


Fig. 10. Collapsed buildings to the 1755 earthquake scenario – Model 2

TABLE 8: Estimation of variables to the 1909 earthquake

1909 earthquake; M = 7,6; D = 38 km		
	Model 1	Model 2
Collapses	217	101
Severe Damage	2337	3659
Death	2407	3067
Injures	2395	3727

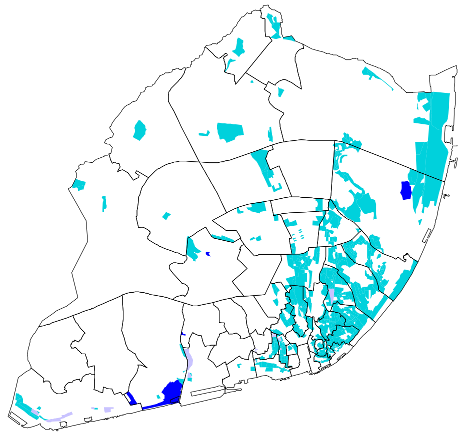


Fig. 11. Collapsed buildings to the 1909 earthquake scenario – Model 1

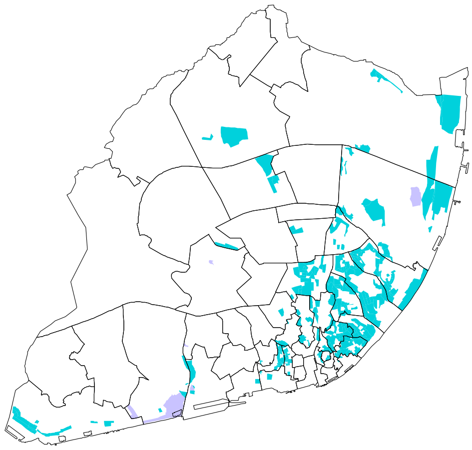


Fig. 12. Collapsed buildings to the 1909 earthquake scenario – Model 2

Comparing the geographic distribution of damage both (Severe and Collapse) for the two models and for two different seismic scenarios, the differences observed are quite negligible, only founded when a detailed analysis is made.

FINAL CONSIDERATIONS

In this paper, a comparison of the two methods for estimating earthquake vulnerability of the building stock at an urban area was presented. Results from the two methods (keeping all other variables and parameters the same) for the City of Lisbon, in terms of severely damage and collapsed buildings, are very similar in the overall. A few light differences were found only when a detailed analysis is made. Under these circumstances the validity of the old simulator (Model 1) can be accepted within certain limits.

Other models of vulnerability have been developed in recent works, bringing the physical modelling of structural analysis into the context. Future work will compare the models presented with the new insights involving this physical modelling.

A final word to emphasize that earthquake *simulators* are important tools that allow the authorities to plan emergency, to help in rapid damage assessment and to inform on the value of any retrofitting programme.

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