LABORATÓRIO NACIONAL
DE ENGENHARIA CIVIL

DEPARTAMENTO DE ESTRUTURAS
Núcleo de Engenharia Sísmica e Dinâmica
de Estruturas

Proc. 0305/17/17508

EARTHQUAKE RISK SCENARIOS FOR SELECTED EUROPEAN CITIES – LISBON METROPOLITAN AREA

Progress report

Lisboa • Janeiro de 2012

I&D ESTRUTURAS

RELATÓRIO 12/**2012 – NESDE**

Cenários de risco sísmico para cidades Europeias selecionadas – Área Metropolitana de Lisboa. Relatório de progresso

Earthquake risk scenarios for selected European cities – Lisbon Metropolitan Area. Progress report.

Scénarios de risque sismique pour des villes Européennes sélectionnés - Région Métropolitaine de Lisbonne. Rapport de progrès.

Earthquake risk scenarios for selected European cities – Lisbon Metropolitan Area. Progress report.

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Resumo

O Laboratório Nacional de Engenharia Civil (LNEC) participa atualmente numa das sete Tarefas, do projeto Europeu SHARE- *Seismic Hazard Harmonization in Europe*, mais precisamente na tarefa nº 2, intitulada *Requisitos de engenharia e aplicações.*

O presente relatório de progresso descreve a participação do LNEC na sub-tarefa 2.5 - *Cenários de risco sísmico para cidades Europeias selecionadas* – na qual o risco sísmico é avaliado em termos de cenários de perdas para um conjunto de cidades (Istanbul, Lisbon, Messina, Thessaloniki). Os mapas de perigosidade sísmica dos regulamentos mais recentes destas cidades são usados como cenários de ação sísmica para obtenção de níveis de risco de referência nos locais analisados.

O presente trabalho aborda a primeira etapa da sub-tarefa 2.5 apresentando estimativas de perdas para a Área Metropolitana de Lisboa (AML) e para alguns dos seus concelhos limítrofes. Para o efeito, foram tidos em consideração os cenários de perigosidade sísmica preconizados pelo Anexo Nacional Português da EN 1998-1, *Eurocódigo 8: Projeto de estruturas para resistência aos sismos*. Parte 1: Regras gerais, ações sísmicas e regras para edifícios.

As estimativas de perdas foram obtidas utilizando a ferramenta informática LNECloss, que permite avaliar perdas para cenários históricos de ocorrência (selecionados) ou para cenários definidos pelo utilizador. Esta ferramenta integra diversos módulos que avaliam a ação sísmica no substrato rochoso e à superfície, os danos estruturais no edificado e as perdas humanas ocorridas em consequência do cenário sísmico de ocorrência especificado. Neste trabalho, a ação sísmica, em rocha, foi definida pelo espectro de resposta elástico, em aceleração, preconizado no Anexo Nacional da parte 1 do Eurocódigo 8. O efeito das formações superficiais na ação sísmica teve em consideração a caracterização geotécnica da AML realizada em estudos anteriores e modelos estocásticos de propagação unidimensional para representar o comportamento dinâmico não linear dos solos. Os danos em edifícios e as perdas humanas tiveram como informação de base os Censos 2001, que forneceram o número de edifícios residenciais e os seus ocupantes distribuídos por classes de vulnerabilidade adequadas para a região.

As estimativas de perdas agora obtidas serão comparadas, numa fase posterior, com as estimativas obtidas com base no novo modelo de perigosidade sísmica desenvolvido e proposto no âmbito do projeto SHARE, visando analisar o impacto da atualização da perigosidade sísmica nos níveis de risco de cada cidade.

Abstract

In the framework of project SHARE- *Seismic Hazard Harmonization in Europe*, LNEC participates in one of its seven Work Packages, namely the Work Package 2, *Engineering requirements and applications.*

This progress report addresses LNEC's participation in Task 2.5 -*Earthquake risk scenarios for selected European cities* – in which seismic risk is evaluated by means of assessing loss scenarios for selected cities (Istanbul, Lisbon, Messina, Thessaloniki). Seismic hazards maps currently employed in those regions are used as seismic scenarios and a reference risk is evaluated for the analysed city. The influence on risk levels of the new hazard model developed and proposed in SHARE will be studied.

The present work comprises the first step of this study, presenting seismic loss assessments for Lisbon Metropolitan Area, and some neighbouring counties, (MAL), taking into account the hazard scenarios provided by the Portuguese National Annex of EN 1998-1, *Eurocode 8: Design of structures for earthquake resistance - Part 1: General Rules, seismic action and rules for buildings*.

Loss estimations are obtained using LNECloss, a computer tool that evaluates losses as a consequence of a user defined ground motion seismic scenario. This automatic tool comprises several modules that model seismic action at bedrock and at surface level, simulate earthquake damage to buildings and estimate social and economic losses. In this work, the earthquake motion, at a rock sites, is defined by the elastic ground acceleration response spectrum provided in EN 1998-1. Local site effects are considered based on the information about stratified soil profile units for MAL and taking into account an equivalent stochastic nonlinear one-dimensional ground response analysis. Both building damages and social losses are evaluated using the database of 2001 Census for the number of residential buildings and individuals that are classified in vulnerability classes appropriate to the region.

Present loss estimations will be compared, in a future work, with losses estimated with the new hazard model that will be proposed in SHARE, aiming at analysing the risk impact of updating this hazard scenario.

Earthquake risk scenarios for selected European cities – Lisbon Metropolitan Area. Progress report.

1. Introduction

The project SHARE - *Seismic Hazard Harmonization in Europe* - is a Collaborative Project developed within the framework of the Cooperation programme of the Seventh Framework Program of the European Commission.

The project started on June 1, 2009, has duration of 36 months, is coordinated by the Swiss Seismological Service, SED-ETHZ and involves the participation of 18 institutions, most of them European, namely the National Laboratory for Civil Engineering (LNEC) from Portugal.

According to SHARE's Web Page [SHARE, 2011] its "main objective is to provide a community-based seismic hazard model for the Euro-Mediterranean region with update mechanisms. The project aims to establish new standards in Probabilistic Seismic Hazard Assessment (PSHA) practice by a close cooperation of leading European geologists, seismologists and engineers".

LNEC participates in one of its seven Work Packages, namely the Work Package 2, *Engineering requirements and applications,* which, among other objectives, aims to "conduct trial risk assessment applications, at large geographical scales, considering the developed hazard maps, in order to understand what the implication of the introduction of such new hazard definitions may be for the engineering community and also society as a whole (human and economic losses will both be estimated)".

This progress report addresses LNEC's participation in Task 2.5*. Earthquake risk scenarios for selected European cities.* The work comprises seismic loss assessments for Lisbon Metropolitan Area, and some neighbouring counties, (MAL), taking into account seismic hazard scenarios provided by current employed seismic code provisions.

In the final report of this Task 2.5 the new hazard model proposed in SHARE will be considered in order to analyse its risk impact evaluated in terms of losses for a given hazard scenario.

Loss estimations were obtained using LNECloss that is a computer tool that evaluates losses as a consequence of a user defined ground motion seismic scenario. LNECloss was developed and updated in previous projects [LESSLOSS, 2007]. This automatic tool comprises several modules that model seismic action at bedrock and at surface level, simulate earthquake damage to buildings and estimate social and economic losses. The simulation software uses a scientific programming language and was incorporated, as an external application, in a Geographic Information System.

2. Lisbon Metropolitan Area – an overview

Lisbon is the capital city of Portugal and it is the western largest city located in Europe. The Lisbon Metropolitan Area (MAL) is divided in 220 civil parishes [INE, 2011], which represent an administrative division smaller than the municipality level. In fact, a parish represents a fourth-order administrative limit that follow the third-order administrative limit, the county or municipality; MAL is divided in 19 counties [INE, 2011] (see Table 1). About 2,8 millions of people live in MAL administrative region and about 3,1 millions of people live in the broader agglomeration of the MAL (MAL and neighbouring counties), represented in Figure 1.

This is the Portuguese region with the highest demographic and economic concentration of elements exposed to earthquakes. Being a moderate seismic hazard region it has been affected by severe historical earthquakes, like the emblematic 1755 Lisbon earthquake, with Mw = 8.5 - 9.0 [Campos Costa *et al.,* 2010], justifying a recurrent assessment and monitoring of its seismic risk.

Table 1: Statistics for MAL [INE, 2002 and INE, 2011].

Census	Region	Counties / parishes	Buildings	Inhabitants
2001	MAL	19 / 216	397 912	2 563 486
	MAL and neighbouring counties	26 / 277	477 170	2 841 067
2011	MAL	19 / 220	460 060	2 837 627
	MAL and neighbouring counties	26 / 281	548 376	3 059 070

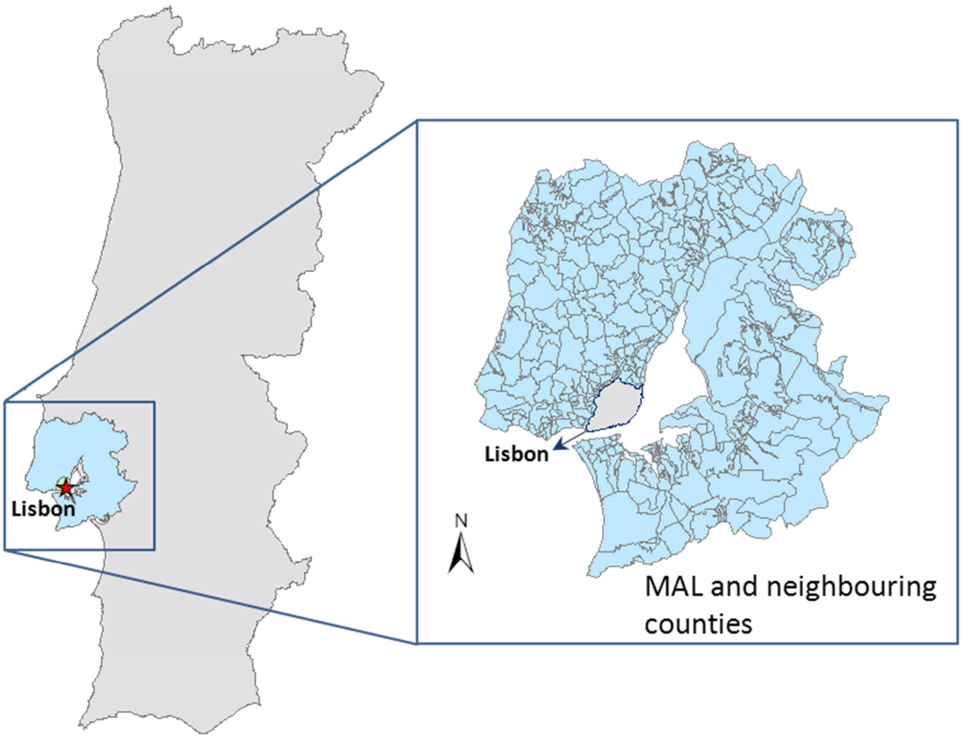

Figure 1: Portugal, Lisbon Metropolitan Area and some neighbouring counties (MAL) and Lisbon municipality.

3. Seismic hazard assessment

As mention in the introduction the seismic risk will be carried out using two different types of hazard: (i) the seismic hazard presently used in the official national standard in Portugal for engineering applications and (ii) the new hazard model developed in SHARE. Herein a description of the current seismic hazard is provided.

Current seismic hazard map

The Structural Eurocode programme comprises 10 standards. The focus of SHARE project is the EN 1998-1, *Eurocode 8: Design of structures for earthquake resistance - Part 1: General Rules, seismic action and rules for buildings*, herein also referred as EC8 [EN 1998-1: 2004]. ENs are translated to each country language and are complemented by each National Annex (NA), whose aim is to indicate how Eurocode standards are implemented in the context of existing national standards, and to provide values for the Nationally Determined Parameters (NDPs).

The EN 1998-1 comprises 56 left open parameters, to be chosen by each country. Key information in this NA comprises the seismic zonation map, the values of peak ground acceleration (PGA) and the corner periods that define the basic seismic actions to be considered in structural design. Seismic zonation should be established for a reference PGA on type A ground (Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface), ag_R, correspondent to a reference return period, T_{NCR}, of seismic action for the no-collapse requirement, recommended as 475 years.

In Portugal there will be soon a transition period in which two codes coexist: the Portuguese code in force till now [RSA, 1983] and the NP EN 1998-1 [NP EN 1998: 1, 2010]; after that period NP EN 1998: 1 will be the official code for seismic design of structures. As in RSA [1983], two scenarios were considered for the seismic zonation of mainland Portugal: (i) a scenario labelled seismic action Type 1, characterizing earthquakes with their epicentres mainly offshore and (ii) a scenario labelled seismic action Type 2, referring to events with their epicentres mainly inland.

Figure 2 illustrates seismic zonation for the Portuguese National Annex of NP EN 1998-1: 2010, in what concerns Mainland Portugal, Table 2 presents the reference peak ground acceleration, ag_R for the considered seismic zones and for the two scenarios (it should be noted that zones 2.1 and 2.2 are for Azores and Madeira Archipelagos and therefore are not illustrated in Figure 2).

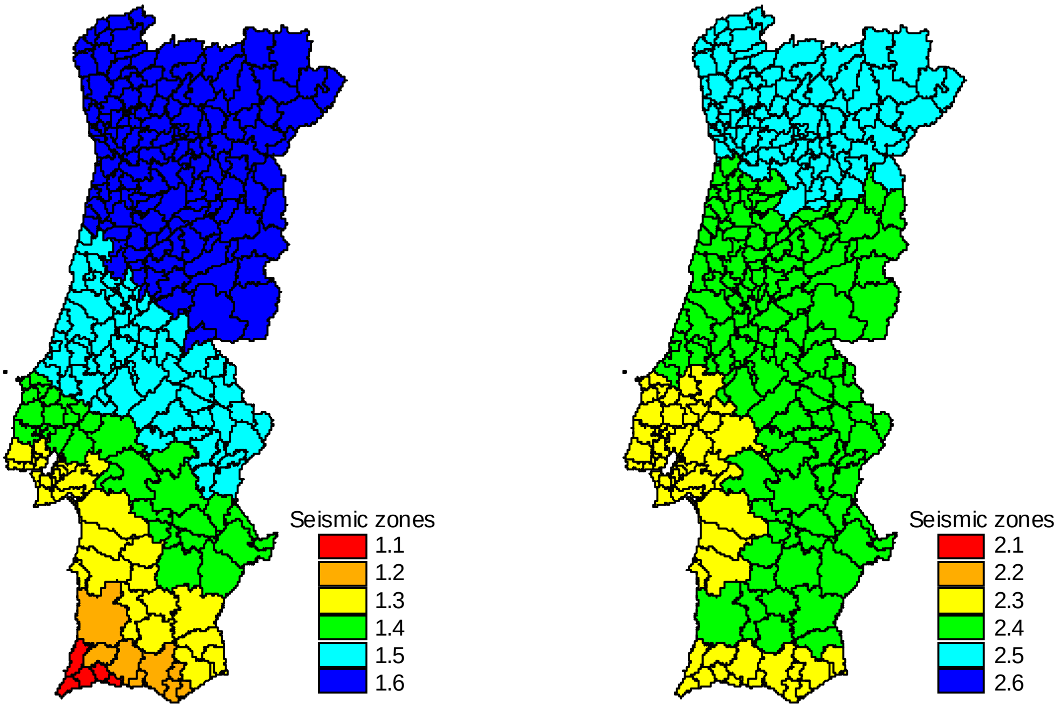

Figure 2: Mainland Portuguese zonation (a) seismic action Type 1 (b) seismic action Type 2 [NP EN 1998-1: 2010].

Table 2: Reference peak ground acceleration [NP EN 1998-1: 2010].

Seismic action Type 1		Seismic action Type 2	
Seismic Zone	a_{gR} (m/s^2)	Seismic Zone	a_{gR} (m/s^2)
1.1	2.5	2.1	2.5
1.2	2.0	2.2	2.0
1.3	1.5	2.3	1.7
1.4	1.0	2.4	1.1
1.5	0.6	2.5	0.8
1.6	0.35	-	-

Within the scope of EN 1998 the earthquake motion at a given point on the surface is represented by an elastic ground acceleration response spectrum, the “elastic response spectrum”, represented in Figure 3. Table 3 presents the values of parameters describing the spectrum, for Portugal, considering soil type A.

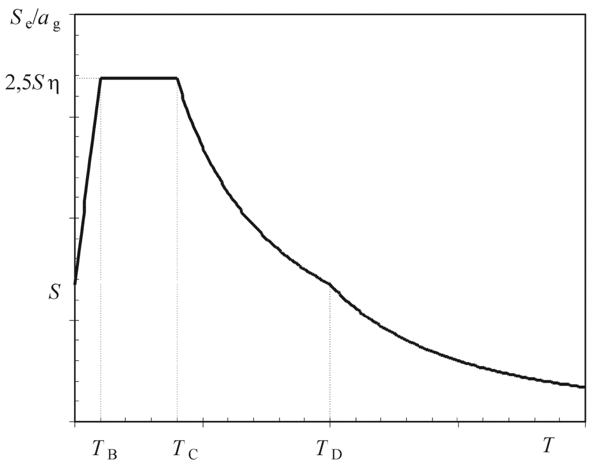

Figure 3: Shape of elastic response spectrum [EN 1998-1:, 2004].

Table 3: values of the parameters describing Type 1 and Type 2 elastic response spectra for Portugal, for soil type A [NP EN 1998-1: 2010].

Action	S_{max}	T_B (s)	T_C (s)	T_D (s)
Type 1	1.0	0.1	0.6	2.0
Type 2	1.0	0.1	0.25	2.0

Figure 4 shows the spectrum shape (seismic action Type 1 and seismic action Type 2) for Lisbon, as they are defined in National Annex of NP EN 1998-1 [2010], and considering a type A ground.

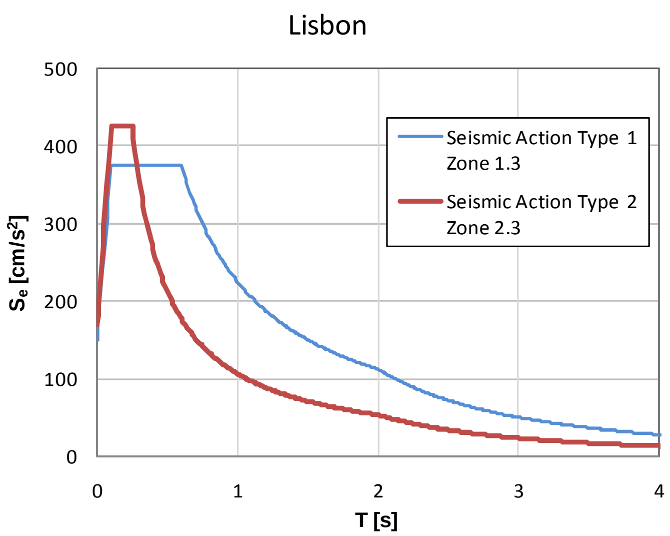

Figure 4: Elastic response spectra for Lisbon.

In the framework of a project conducted by the National Civil Protection Authority, in 2002 [Carvalho *et al.*, 2002] it was carried out a geological - geotechnical inquiry to characterize the soil columns for each parish of MAL (37 soil columns units as shown in Figure 5).

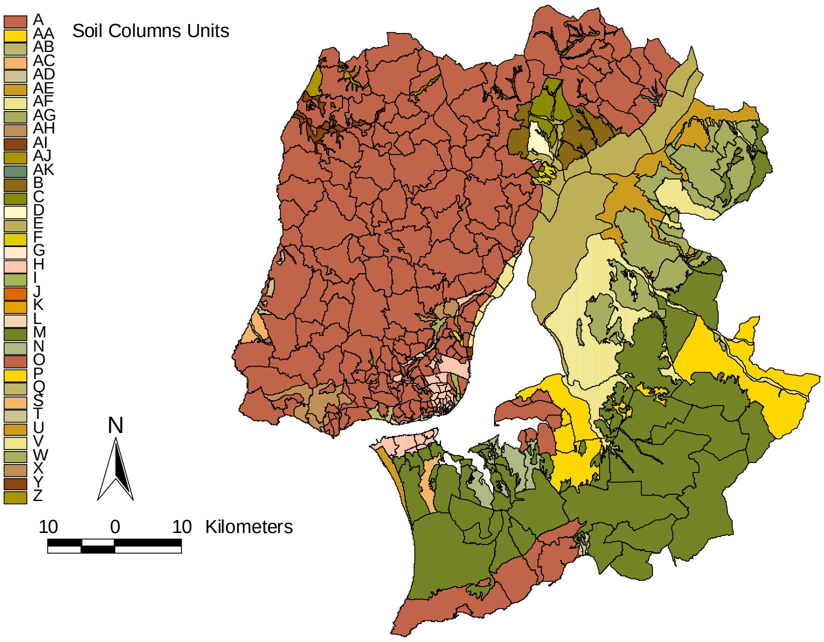

Figure 5: Soil types for each parish [Carvalho et al., 2002]. Soil unit A refers to soil type A, rock.

The computer algorithms developed and implemented in LNECloss introduced some major improvements to take into account site effects due to soil dynamic amplification in rather efficient way. The elastic response spectrum of each parish (the same for all parishes in the present case as we are using the spectrum defined in National Annex of NP EN 1998-1 shown in Figure 4) is transformed into a Power Spectrum Density Function at the bedrock, using the classical theory of stationary random process. Site effects are evaluated by means of an equivalent stochastic nonlinear one-dimensional ground response analysis for each stratified soil profile units designed for the region. Each soil unit is characterized by the thickness of their shallow layers, shear waves velocity, density and plastic index.

Figure 6 presents peak ground acceleration for MAL at surface, i.e., considering the influence of soil conditions, for seismic action Type 1 and Type 2 (as in Figure 4).

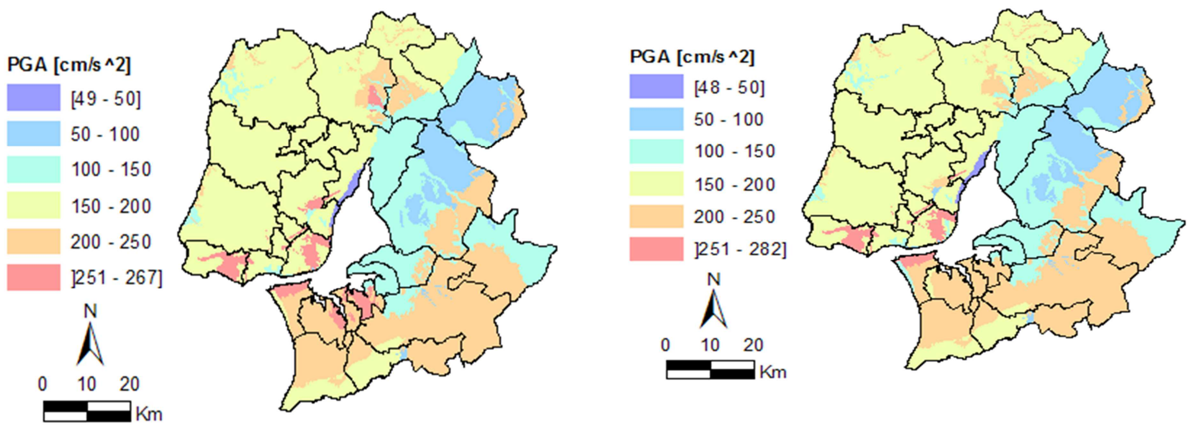

Figure 6: Peak ground acceleration at surface for MAL. Left: considering seismic action Type 1; Right: considering seismic action Type 2.

Figure 7 and Figure 8 show the elastic response spectrum for one parish of the Metropolitan Area of Lisbon (Sesimbra parish) at bedrock and at surface.

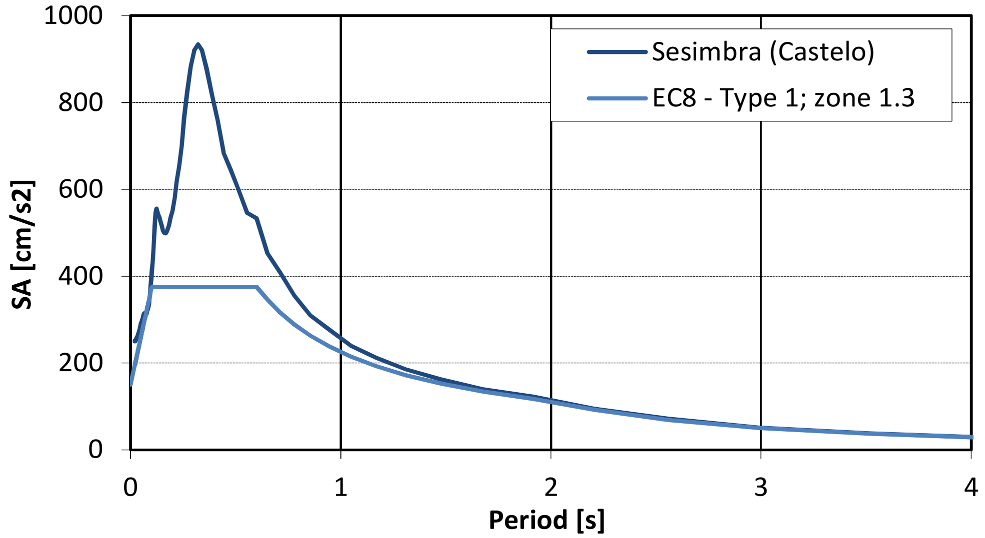

Figure 7: Elastic response spectra for Sesimbra, at bedrock and considering soil effects, for seismic action Type 1.

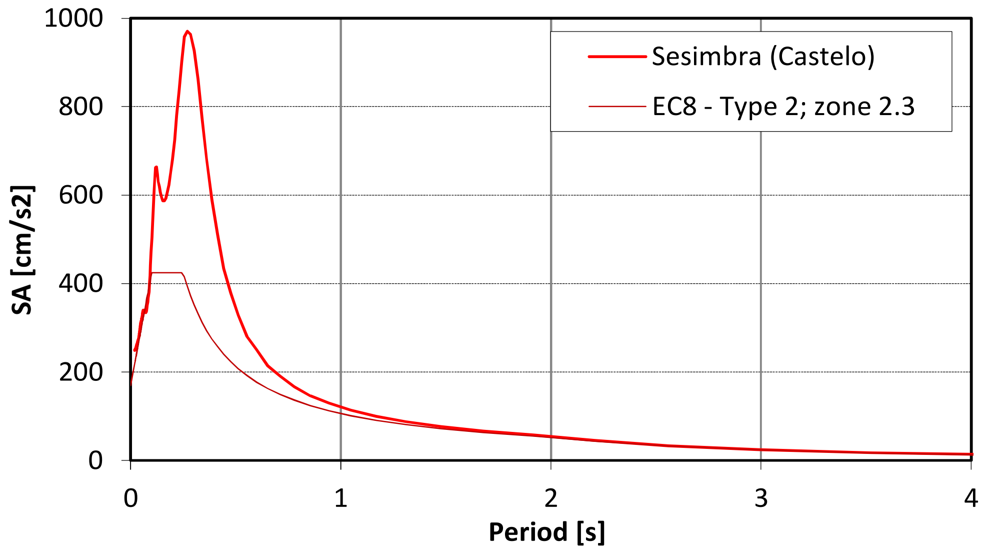

Figure 8: Elastic response spectra for Sesimbra, at bedrock and considering soil effects, for seismic action Type 2.

Figure 6 evidences a reduction of PGA values on intermediate and soft soils, for both Type 1 and Type 2 seismic actions, whereas parishes where soil type A (rock) prevails (mainly parishes to the north and west of Lisbon, as shown in Figure 5) do not evidence any change on PGA values. This reduction of PGA had already been reported in previously studies [LESSLOSS, 2007; Carvalho *et al*., 2008] for strong seismic motions, not being so prominent for weak seismic motions, a clear evidence of nonlinear soil response during earthquakes. However, as shown in Figures 7 and 8, local soil effects can amplify some ranges of spectral values up to a factor of 2, approximately.

This equivalent stochastic nonlinear one-dimensional ground response analysis will also be the procedure applied to evaluate seismic action at surface when SHARE seismic hazard results become available.

4. Inventory

In 2011, a new statistical survey for population and residential building was conducted in Portugal [INE, 2011]. Despite the fact that, in December 2011, some provisional results are available, only some variables were accessible on that date. Final results are scheduled for the 4th quarter of 2012; on that date it will be possible to obtain the inventory of residential buildings and crossings of the variables relevant to characterize the seismic vulnerability of buildings.

Due to these reasons, in this report, the number of residential buildings and individuals, for each typology, or vulnerability class, has been obtained from the database of 2001 Census, whereas the plot of the geographic distribution of the total number of buildings and population will be based on Census 2011. The 2001 inventory was used in the seismic risk evaluation both to evaluate building damages and social losses.

As referred in section 2, in 2011, about 2.8 millions of people live in MAL administrative region and about 3.1 millions of people live in the broader agglomeration of the MAL and neighbouring counties, representing an increase of 11% and of 8%, respectively, in the number of inhabitants between 2001 and 2011 (see Table 1). In what concerns existing buildings, in 2011, there were about 0.46 million buildings in MAL administrative region and about 0.55 million buildings in MAL and neighbouring counties, representing an increase of 16% and of 15%, respectively, in the number of buildings relatively to 2001.

Considering the 2001 survey, the building stock was classified in 315 different typologies crossing, simultaneously, the following variables: *date of construction*, *structural type*, and *number of floors* (9 epochs of construction per 5 structural types and per 7 classes of number of floors – see Table 4) [Carvalho *et al*., 2002; Sousa *et al.*, 2003]. Census databases were also inquired to obtain dwellings and inhabitants classified in those building typologies.

Table 4: Vulnerability factors identified in Census 2001 [Carvalho et al., 2002; Sousa et al., 2003].

Epoch of construction or reconstruction
Before 1919
1919 – 1945
1946 – 1960
1961 -1970
1971 – 1980
1981 – 1985
1986 – 1990
1991 – 1995
1996 – 2001

Structural type
RC
Masonry with RC floors
Masonry without RC floors
Adobe and rubble stone
Others

Number of floors
1
2
3
4
5 to 7
8 to 15
15 or more

5. Exposure and Vulnerability Assessment

5.1. Building Exposure and Vulnerability

Following previous research projects, [LESSLOSS, 2007], in order to simplify the analysis of results, the original 325 typologies obtained from Census 2001 were aggregated in 7 typological classes (see Table 5), taking into consideration two vulnerability factors referred in Table 4: e*poch of construction or reconstruction* and *structural type.* In order to have into consideration the building height in the seismic response of vulnerability classes, each typological class was then subdivided in 7 classes of *number of floors*, obtaining a total of 49 vulnerability classes.

Note that loss estimations were based on the original 325 typologies and the 49 classes were created with the only goal of analysing the correlation of losses estimates and building classes [LESSLOSS, 2007].

This classification aims at characterizing Portuguese constructive practices, the evolution of materials and technologies along time and, simultaneously, making the connection with the available inventory. Actually, typological classes presented in Table 5 were chosen in order to take in account the evolution of Portuguese seismic regulation, also considering the two years transition period adopted for its application. In fact, the first Portuguese seismic code dates from 1958 [RSCCS, 1958] that was successively updated and substituted in 1961 [RSEP, 1961], and 1983 [RSA, 1983] [Carvalho et al., 2002]. Consequently, buildings constructed in 1960 and before are assumed to have no earthquake-resistant design; buildings constructed between 1961 and 1985 are assumed to be designed and constructed according RSCCS and RSEP codes and buildings constructed after 1985 are assumed to be designed and constructed according to RSA. This is, of course, an overly optimistic assumption for constructive panorama in Portugal.

Table 5: Vulnerability classes considered for MAL building stock [LESSLOSS, 2007].

Typological classes	Number of floors
Adobe and Rubble Stone	1
Masonry before 1960	2
Masonry 1961 – 1985	3
Masonry 1986 – 2001	4
RC before 1960	From 5 to 7
RC 1961 – 1985	From 8 to 15
RC 1986 – 2001	More than 15

Table 6 shows the number of buildings inventoried in 2001, in MAL and neighbouring counties, distributed per vulnerability class, and building totals derived from Census 2011.

Table 6: Number of residential buildings per vulnerability class.

Number of floors	Adobe + rubble stone	Masonry ≤ 1960	Masonry 1961-85	Masonry 1986-01	RC ≤ 1960	RC 1961-85	RC 1986-01	Total 2001
1	27 277	36 826	55 426	19 084	10 707	42115	20 225	211 660
2	9 468	14 704	26 114	17 115	6 458	38 608	29 585	142 052
3	3 048	5 303	5 691	3 429	3 516	13 482	10 982	45 451
4	1 879	3 956	2 768	1 289	3 273	12 531	6 245	31 941
From 5 to 7	1 088	3 726	138	68	4 868	14 441	9 523	33 852
From 8 to 15	0	0	0	0	847	6 039	4 826	11 712
More than 15	0	0	0	0	0	278	224	502
Total 2001	42 760 (9.0 %)	64 515 (13.5 %)	90 137 (18.9 %)	40 985 (8.6 %)	29 669 (6.2 %)	127 494 (26.7 %)	81 610 (17.1 %)	477 170 (100 %)
Total 2011	548 376							

The main conclusions drawn from the presented information are the following:

- Over 50 % of the housing stock is classified in the reinforced concrete structural type;
- reinforced concrete becomes progressively more important in the different construction epochs, since its appearance around 1935-40; the opposite has been verified in relation to the masonry structural type;
- the majority of the buildings, 44% and 30%, have 1 and 2 floors, respectively;
- in 2001, about 71% of buildings were constructed after 1961, date assumed to correspond to the start of application of seismic codes.
- There was an increase of 15% in the number of buildings in MAL and neighbouring counties in the last 10 years. If those buildings were designed and constructed according to the last code [RSA, 1983] this would be favourable to the reduction of seismic vulnerability in this region.

However, Carvalho et *al*. [2002] argue that these results should be carefully considered, since it is not possible to assure that buildings constructed after 1958 follow all design requirements, especially with resisting elements different from reinforced concrete. Those authors also highlight that other aspects should be accounted for, such as building maintenance and construction supervision.

In Figure 9 the geographical distribution of buildings belonging to different vulnerability classes are presented. Percentage of buildings per parish is shown. Building totals presented in Figure 9h) refers to Census 2011.

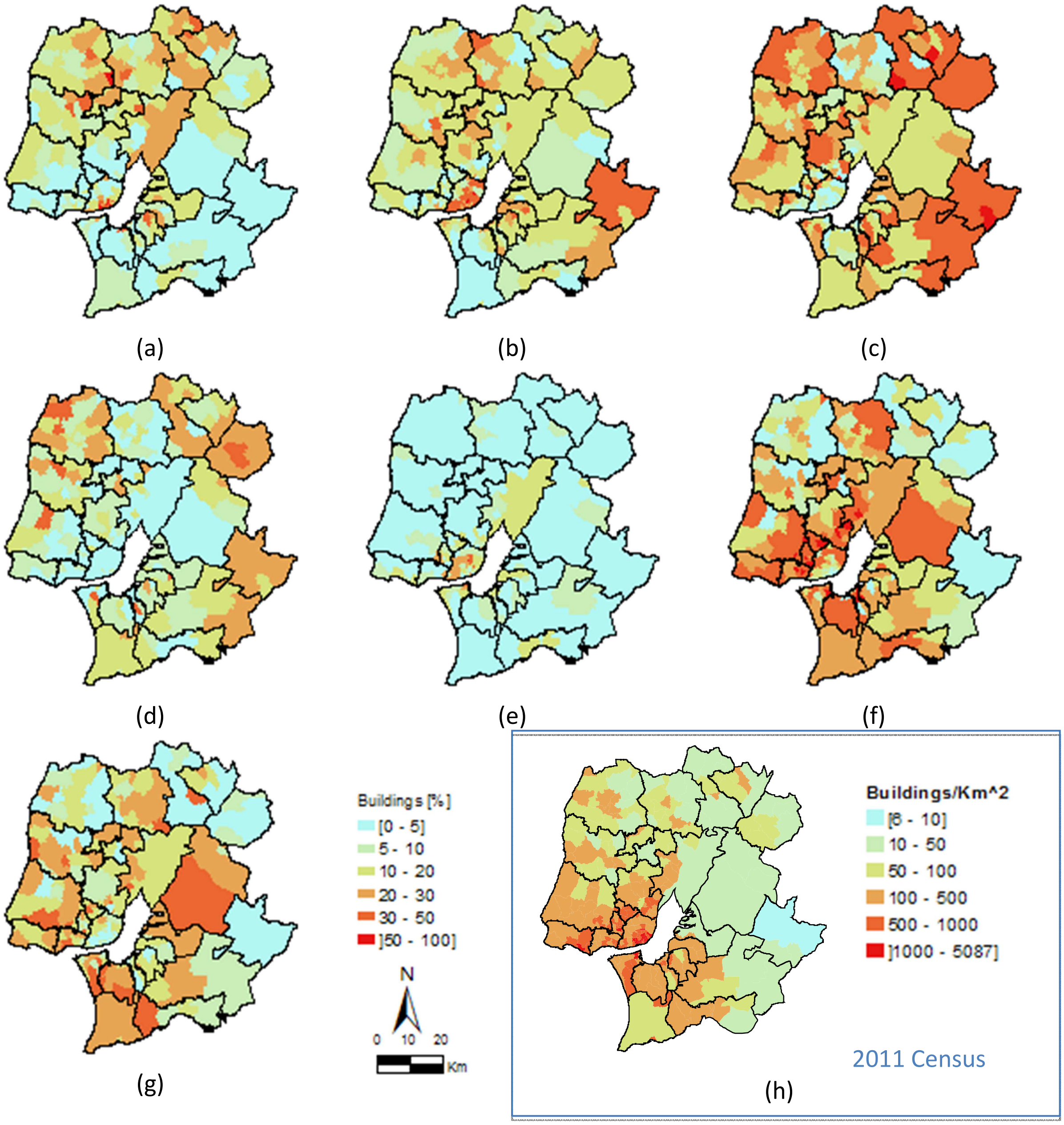

*Figure 9: Seismic vulnerability maps; percentages of buildings per parish in each vulnerability classes and totals. Figures (a-g) are based on **2001** inventory a) Adobe and Rubble Stone; b) Masonry before 1960; c) Masonry 1961 – 1985; d) Masonry 1986 – 2001; e) RC before 1960 f) RC 1961 – 1985 g) RC 1986 – 2001; Figure (h) is based on **2011** inventory.*

5.2. Population Exposure and Vulnerability

Table 7 shows the number of resident individuals, per vulnerability class, and inhabitants totals derived from Census 2011.

Table 7: Number of individuals per vulnerability class.

Number of floors	Adobe + rubble stone	Masonry ≤ 1960	Masonry 1961-85	Masonry 1986-01	RC ≤ 1960	RC 1961-85	RC 1986-01	Total 2001
1	43 348	67 510	121 290	39 715	22 292	98 267	44 084	436 506
2	25 720	42 894	82 872	45 366	21 065	125 044	76 884	419 845
3	16 403	33 706	35 647	17 048	26 911	91 463	54 966	276 144
4	14 734	41 393	42 816	15 363	42 600	209 633	83 012	449 551
From 5 to 7	10 437	53 171	2 650	855	91 717	337 137	209 821	705 788
From 8 to 15	0	0	0	0	22 395	276 399	217 043	515 837
More than 15	0	0	0	0	0	20 913	16 483	37 396
Total 2001	110 642 (3.9 %)	238 674 (8.4 %)	285 275 (10.0 %)	118 347 (4.2 %)	226 980 (8.0 %)	1 158 856 (40.8 %)	702 293 (24.7 %)	2 841 067 (100 %)
Total 2011	3 059 070							

Table 7 shows that, in 2001, over 75% of the inhabitants of MAL and neighbouring counties lived in reinforced concrete buildings, which is a much higher percentage than of the buildings belonging to this structural type (over 50%, as presented in Table 6). On that date about 80% of the individuals lived in buildings constructed after 1961 (date assumed to correspond to the start of seismic codes application).

Figure 10 shows the distribution of people throughout MAL, belonging to different vulnerability classes. Percentages of resident individuals per parish are shown. Population totals presented in Figure 10h) refer to Census 2011.

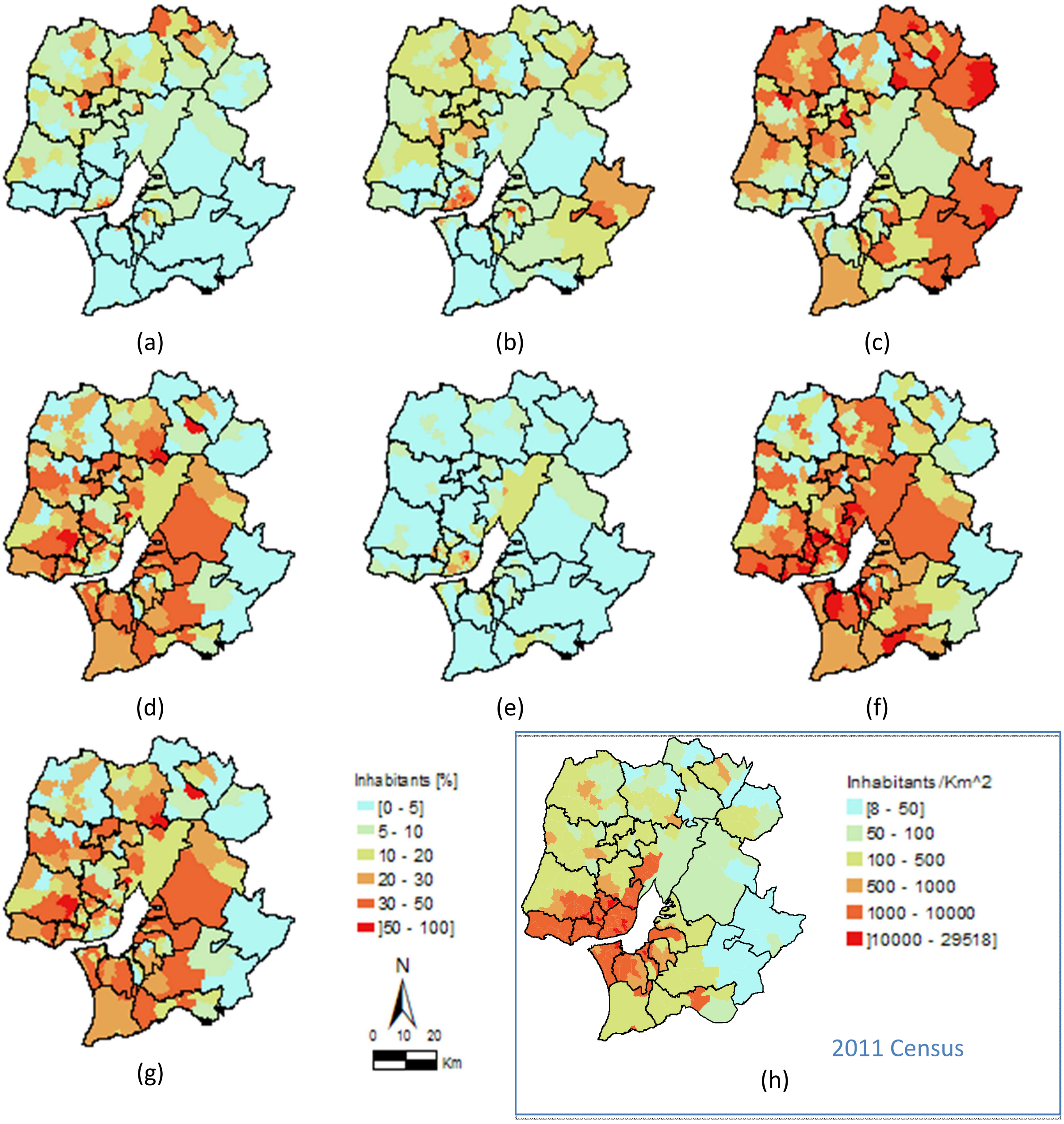

Figure 10: Percentages of individuals per parish in each vulnerability. Figures (a - g) are based on ***2001*** *inventory; a) Adobe and Rubble Stone; b) Masonry before 1960; c) Masonry 1961 – 1985; d) Masonry 1986 – 2001; e) RC before 1960 f) RC 1961 – 1985 g) RC 1986 – 2001; Figure (h) is based on* ***2011*** *inventory.*

5.3. Building damage model

LNECloss uses the capacity spectrum method [ATC, 1996], worldwide divulged by the HAZUS loss estimation methodology [FEMA & NIBS, 1999; FEMA, 2003], to evaluate building damages.

Carvalho *et al.* [2002] proposed capacity and fragility curves for the 315 typologies above mentioned taking into account (i) a first analysis of Portuguese Census 1991 and (ii) expert opinion in what concerns the Portuguese construction practice, design criteria and the evolution of seismic regulation. Those curves were then updated taking into account the new features included in Census 2001 and a more reliable classification of the building structures has been developed [Campos Costa *et al.,* 2005]. The capacity curves were derived from estimates of acceleration and displacement values corresponding to yield and ultimate capacity (in terms of strength and ductility) of typical buildings. Both these values and the global drift limit values were established by adjusting HAZUS parameters to the characteristics of Portuguese construction [Carvalho *et al*., 2002].

FEMA [2003] methodology presents simple rules to define capacity curves in a spectral acceleration (SA) *vs* spectral displacement (SD) domain. Those rules are based on parameters related to the design of structures allowing the definition of capacity curves by distinct sections, delimited by the two control points above mentioned, the yield capacity (SD_y, SA_y) and the ultimate capacity (SD_u, SA_u), as it is exemplified in Figure 11 and defined in the following equations:

$$SA_y = Cs\,\gamma / \alpha \qquad SD_y = SA_y\,T_e^2 / (2\pi)^2 \tag{1}$$

$$SA_u = \lambda\,SA_y \qquad SD_u = \lambda\,\mu\,SD_y \tag{2}$$

where Cs is the design strength coefficient (fraction of building weight); T_e is the elastic fundamental mode period of buildings; α_1 is the fraction of building weight effective in push over mode; γ is the overstrength factor relating yield strength to design strength; λ is the overstrength factor relating ultimate strength to yield strength; μ is the ductility factor relating ultimate displacement to λ times the yield displacement.

Both capacity and fragility curves take into account the number of storeys and the period of construction, except for adobe and rubble stone that represents a separate class which depends only on the number of storeys, because the vast majority of these buildings are low rise structures. Design strength coefficient (Cs) and the natural frequency of the typical building were based on the analysis of code provisions. Those parameters vary according to seismic zonation in force on the date of the building construction. Regarding the RSA code, all counties of the MAL region are located in seismic zone A; this is the zone of higher seismicity in RSA; in what concerns RSCCS code most counties of MAL are located in seismic zone A (of higher seismicity) and a few are located in seismic zone B. Seismic zonation for this Portuguese codes are presented in Annex A.

Figure 11 also sows the threshold points of four damage limit states. The threshold of those damage states are established in terms of global drift for each building typology. Five damage states were considered, dependent on the typology, «Slight Damage (S), «Moderate Damage» (M), «Extensive damage» (E) and «Complete Damage» (C). Approximately 10 to 25% of the total area of buildings in «Complete Damage» state is likely to collapse totally, whereas the remaining is expected to collapse partially [LESSLOSS, 2007].

Annex B presents, for each vulnerability class, the design strength coefficient (Cs), the natural frequency and the height of typical buildings. The others parameters that define capacity and fragility curves were based on FEMA & NIBS [1999] proposals and on the classification of MAL buildings in HAZUS typologies [see LESSLOSS, 2007]. Variables that define capacity and fragility curves, used in LNECloss to characterize vulnerability of buildings in MAL, are also presented in Annex B.

The evaluation of peak response relies on the intersection of the capacity curve of a given vulnerability class with the seismic spectral demand at the site. The initial elastic response spectrum is iteratively reduced to the so called *demand spectra*, taking into account the building degradation when exposed to the seismic motion. The procedure is illustrated in Figure 12 [Campos Costa & Sousa, 2010; Campos Costa *et al*., 2010].

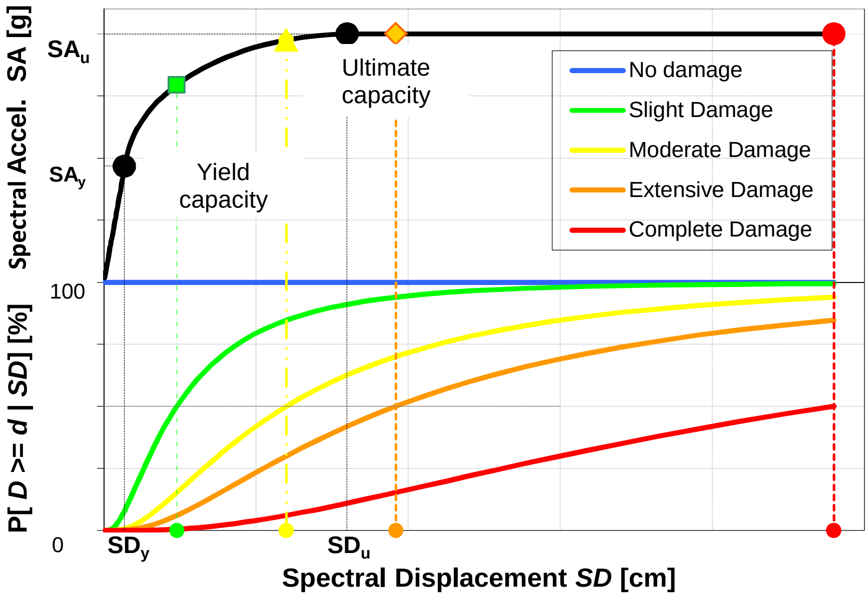

Figure 11: Example of a capacity curve (in black) and of fragility curves for 5 damage states.

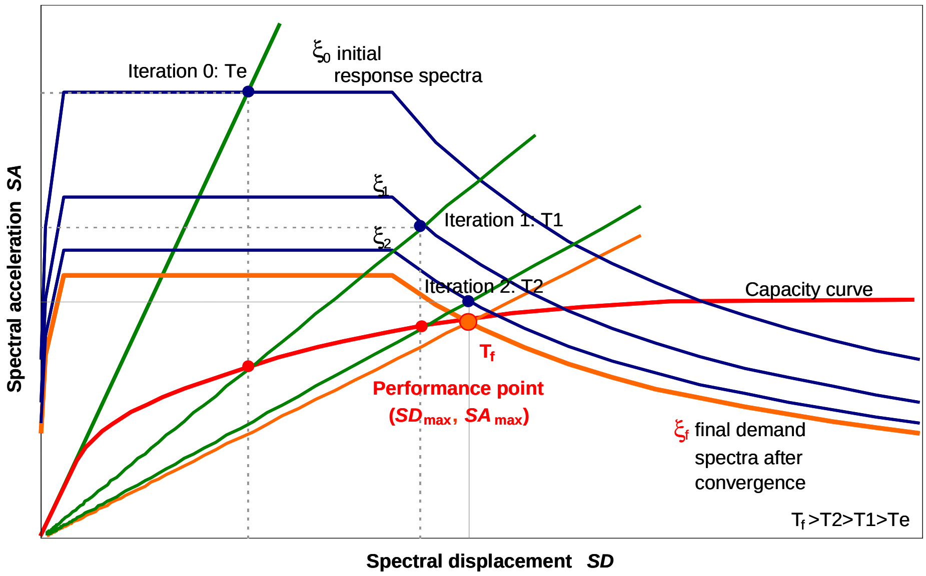

Figure 12: Iterative process to obtain the peak of building response in the capacity spectrum method [Campos Costa et al., 2010].

As stated in LESSLOSS [2007] an innovative technique was introduced in LNECloss operational procedure that takes into account an iterative process that estimates sequential demand spectra, with increasing effective damping, reflecting structure degradation during its cyclic response. While in HAZUS the modifications of spectral demand are represented by reduction factors, in LNECloss those modifications were performed through an iterative equivalent non-linear stochastic methodology. Progressive building responses are obtained over the demand spectra, till the convergence with the median capacity curve is achieved. The performance point, obtained this way, corresponds to the peak of the dynamic response of a structure idealized by a single degree of freedom system.

The authors [LESSLOSS, 2007] also present the main advantages of the equivalent non-linear stochastic approach relatively to the method that relies on the graphic intersection and on the reduction factors: (i) it is more efficient computationally, because it avoids the successive evaluation of the entire reduced demand spectra (ii) it give us an exact evaluation of building peak response, instead of an approximate evaluation obtained by interpolation methods, (iii) it does not use empirical relations to reduce demand spectra due to effective damping and (iv) it allows the explicit inclusion of the duration of seismic demand on the peak response of building.

The abscissa of this performance point corresponds to the effect of seismic action, measured in terms of a spectral displacement, *SDmax*. Mathematical notation is simplified omitting the suffix *max* in the variable spectral displacement, *i.e.*, $SD_{\max} \equiv SD$. This ground motion value conditions the cumulative lognormal probability distributions of the variable damage, $\mathrm{P}_D(d)$, that model building fragility:

$$\mathrm{P}_D(D \geq d \mid SD) = \Phi\left[\frac{1}{\beta_d}\ln\left(\frac{SD}{\overline{SD}_d}\right)\right] \tag{3}$$

Building fragility curves allow the evaluation of the probability to exceed the threshold of a given damage state, conditioned by the level of seismic ground motion, *SD*, where Φ is the standard normal cumulative distribution function; $\overline{SD}_d$ is the median of spectral displacement at which the building reaches the threshold of the damage state *d*; β_d is the standard deviation of the natural logarithm of spectral displacement of the damage state *d*. For structural components of buildings $\overline{SD}_d$ is established in terms of global drift for each building typology or vulnerability class:

$$\overline{SD}_d = \delta_d\, \alpha_2\, h \tag{4}$$

where δ_d is the drift ratio at the threshold of structural damage state, *d;* α_2 is the fraction of the building height at the location of pushover and *h* is the typical height of building typologies.

The evaluation of damages is obtained multiplying the relative frequencies of the buildings in each damage state by the number of buildings for each typology in a given geographic unit, that is, as Kircher *et al.* [1997] say, fragility curves are used to distribute the set of buildings belonging to a typology by the considered damage states.

With that goal, one differentiate the cumulative distribution function $\mathrm{P}_D(D < d \mid SD)$, in order to obtain the discrete probability, that a given typology, is in a given damage state, where $d = 0$ corresponds to the state *No Damage* and $d = N_D$ corresponds to the *Complete Damage* state:

$$\mathrm{P}_D(D = d \mid SD) = \begin{cases} 1 - \mathrm{P}_D(D \geq d+1 \mid SD) \\ \mathrm{P}_D(D \geq d \mid SD) - \mathrm{P}_D(D \geq d+1 \mid SD) \\ \mathrm{P}_D(D = ND \mid SD) \end{cases} \tag{5}$$

5.4. Human loss model

LNECloss estimates human casualties and direct social losses caused by building damages, taking into account building damage state and occupancy per typology. Human casualties correspond to the expected number of occupants killed or classified in different injured severity levels, estimated by FEMA [2003]. Buildings existing in MAL were classified according to HAZUS typologies. Casualty rates are presented in the Annex C by injury level, typology and damage state. Human losses estimation refers to night time, because as the only Portuguese building exhaustive inventory is relative to the housing stock one must admit that population is at home when the earthquake scenario occur [LESSLOSS, 2007].

5.5. Economic loss model

The estimation of economic losses due to direct physical damage in residential buildings, relies on a non-dimensional variable *Damage Ratio*, DR_d, defined as the ratio of the cost of repair or reconstruction and the replacement cost of the building, in a certain damage state, at the time of the earthquake. These variables are considered, approximately, as the percentage of building lost area due to earthquakes for each damage state and vulnerability class. Damage ratio values purposed by FEMA & NIBS [1999] were used (Table 8).

Table 8: Damage ratio for each damage state.

Damage state	Damage ratio [%]
No Damage	0
Slight Damage	2
Moderate Damage	10
Extensive Damage	50
Complete Damage	100

An integrated impact indicator was obtained represented by the expected loss value conditioned by a seismic hazard level, *h*, *i.e.*, $E(L|h)$. This conditional expected loss is obtained averaging the number of buildings that belongs to a given damage state and typological class, weighted by the referred damage ratios:

$$E(L|h) = Ne_T \cdot \sum_d \sum_v A_v \cdot DF_d \cdot P_D(D=d|h) \cdot P_V(V=v) \qquad (6)$$

where Ne_T is the total number of buildings in the studied region; A_v is the average floor area of the buildings belonging to a vulnerability class *v*; $P_D(D=d|h)$ is the damage probability matrix understood as the percentages of buildings, belonging to the vulnerability class *v*, that are in a damage state, *d*, and suffered a seismic action with severity *h* and $P_V(V=v)$ is the probability that the buildings belong to a vulnerability class *v*, and it assumed equal to the frequency of that typological classes, in the studied region. After converting floor lost area in monetary values, assuming a certain cost of repair or reconstruction (per square meter), it is possible to evaluate, in a simple away, the economic losses for a given seismic scenario.

6. Seismic Risk

Five structural damage states have been considered in the analyses (No Damage, Slight, Moderate, Extensive and Complete Damage) and the percentages of the damaged structures, per parish for each damage state have been computed, considering current seismic hazard maps and two different spectrum shapes (see Figure 13 and Figure 16). Social and economic losses conditioned by the current seismic hazard scenarios are also presented (Figure 14, Figure 15, Figure 17 and Figure 18).

Four levels of severity of injuries were considered, similar to HAZUS-MH [FEMA, 2003]: light injuries, hospitalization, severe injuries and mortal wounds.

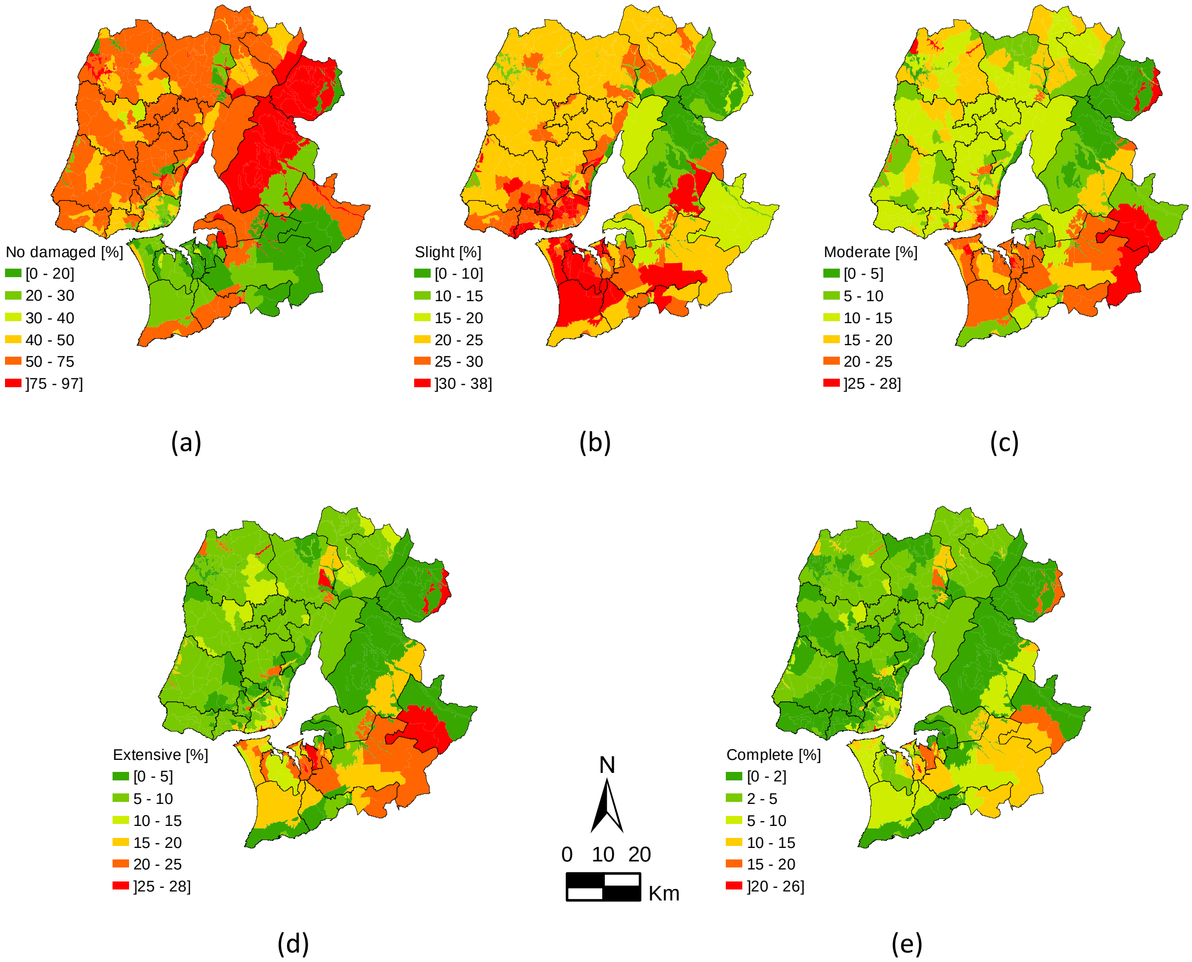

Figure 13: Conditional seismic risk for a return period of 475 years in term of the percentage of (a) no damaged buildings (b) slight damaged buildings (c) moderate damage buildings (d) extensive damaged buildings and (e) complete damaged buildings. Current seismic hazard map, seismic Action Type 1.

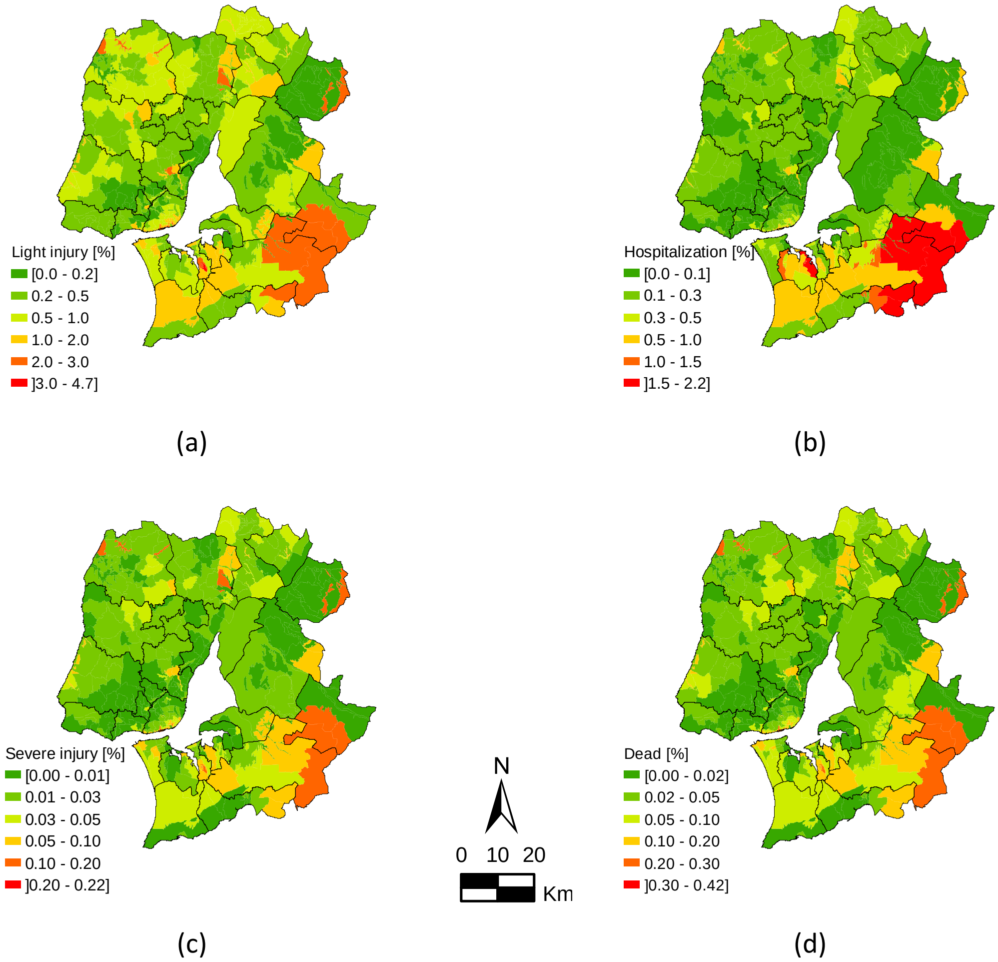

Figure 14: Social losses: (a) light injury (b) hospitalization (c) Severe injury and (d)dead. Current seismic hazard map, seismic Action Type 1.

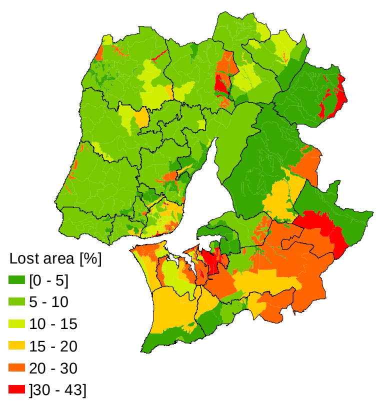

Figure 15: Economic losses: lost building area. Current seismic hazard map, seismic Action Type 1.

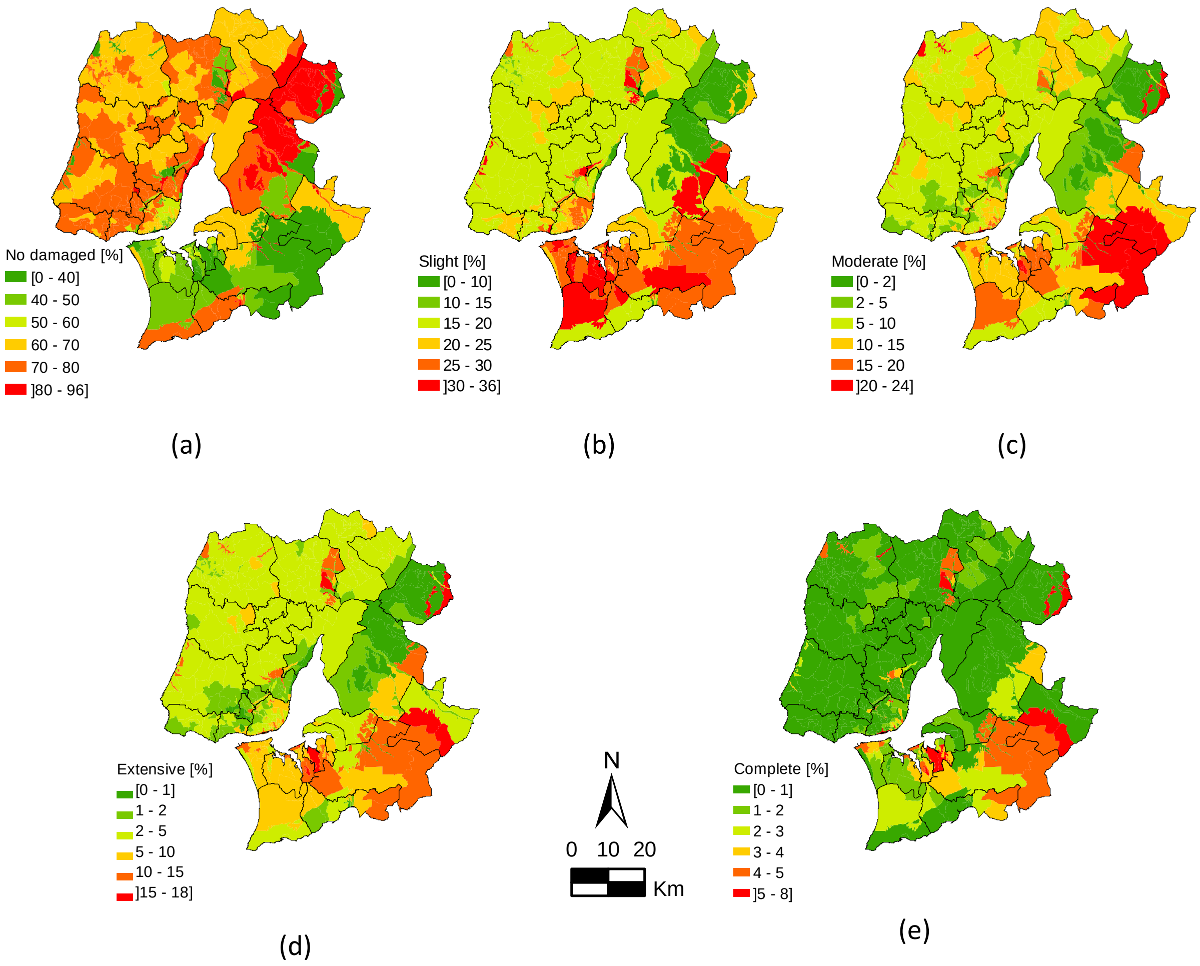

Figure 16: Conditional seismic risk for a return period of 475 years in term of the percentage of (a) no damaged buildings (b) slight damaged buildings (c) moderate damage buildings (d) extensive damaged buildings and (e) complete damaged buildings. Current seismic hazard map, seismic Action Type 2.

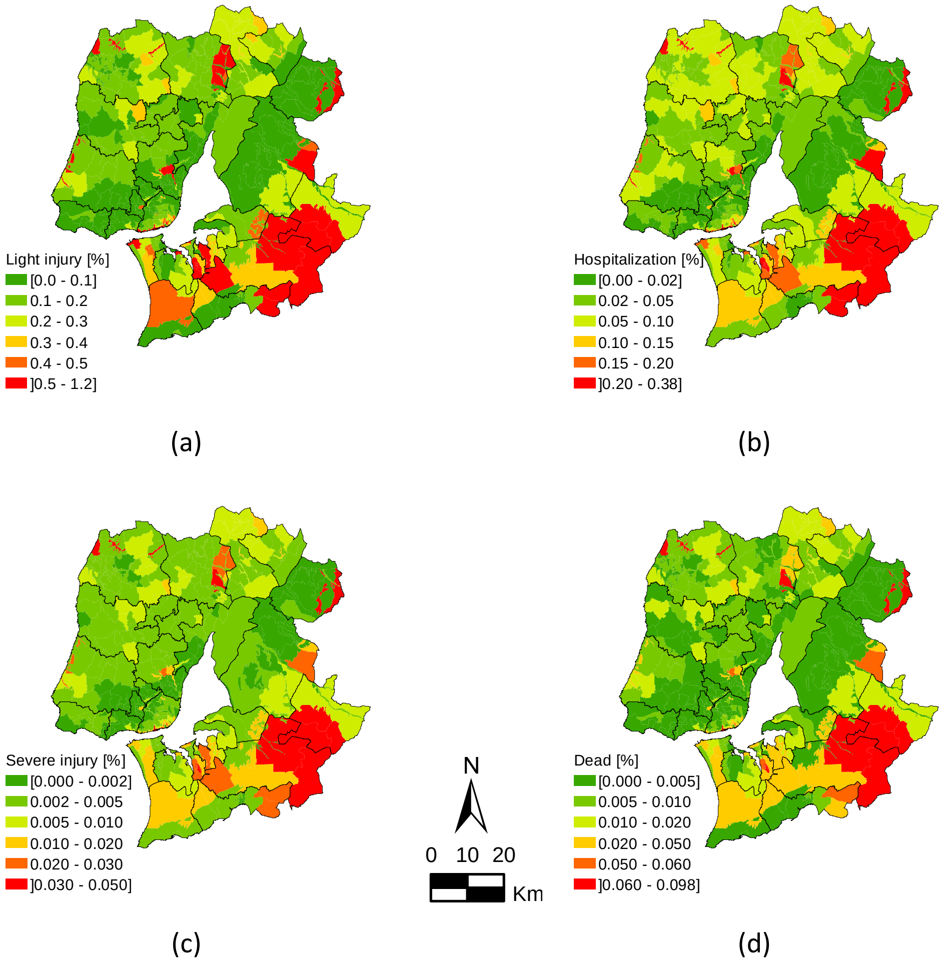

Figure 17: Social losses: (a) light injury (b) hospitalization (c) Severe injury (d) dead. Current seismic hazard map, seismic Action Type 2.

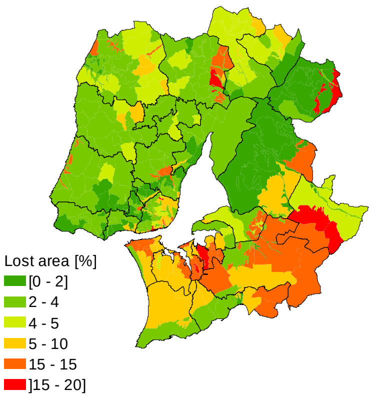

Figure 18: Economic losses: lost building area. Current seismic hazard map, seismic Action Type 2.

7. Final considerations

This progress report, developed within SHARE project, addresses seismic loss assessments for Lisbon Metropolitan Area, and some neighbouring counties, (MAL), taking into account seismic hazard scenarios provided by Portuguese National Annex of EC8 [NP EN 1998-1, 2010].

The earthquake motion at a given point on the surface, for each parish of MAL, is firstly represented by the elastic ground acceleration response spectrum for two seismic actions (seismic action Type 1, characterizing earthquakes with their epicentres mainly offshore and seismic action Type 2, referring to events with their epicentres mainly inland), as described in EC8, considering a soil type A.

Local site effects have been considered based on information on stratified soil profile units for MAL and on the algorithm (an equivalent stochastic nonlinear one-dimensional ground response analysis) implemented at the computer tool LNECloss. Results indicate a nonlinear response of the local soil conditions that have a great influence on intensity ground motion distribution during earthquakes, PGA values being prominently reduced on intermediate and soft soils for strong ground motions, while some ranges of spectral values are amplified up to a factor of 2, approximately.

Loss estimations were obtained using LNECloss, that was developed and updated in previous projects [LESSLOSS, 2007]. This loss estimation tool has been continuously updated as new models and data are available. For instance, [LESSLOSS, 2007] evaluated seismic losses based on FEMA & NIBS [1999] casualty rates, after some adaptation considering historical Portuguese earthquakes. Present report also considers that revision but most casualty rates are based in FEMA [2003].

Parishes with high percentage of losses are manly located in the south region of Tagus reflecting the combination of high values of seismic action and high incidence of exposure of vulnerable typologies. A few very small parishes located in Lisbon city also shows high percentages of losses.

Present loss estimations will be compared with losses estimated with the new hazard model that will be proposed in SHARE aiming at analysing the risk impact of updating hazard scenario.

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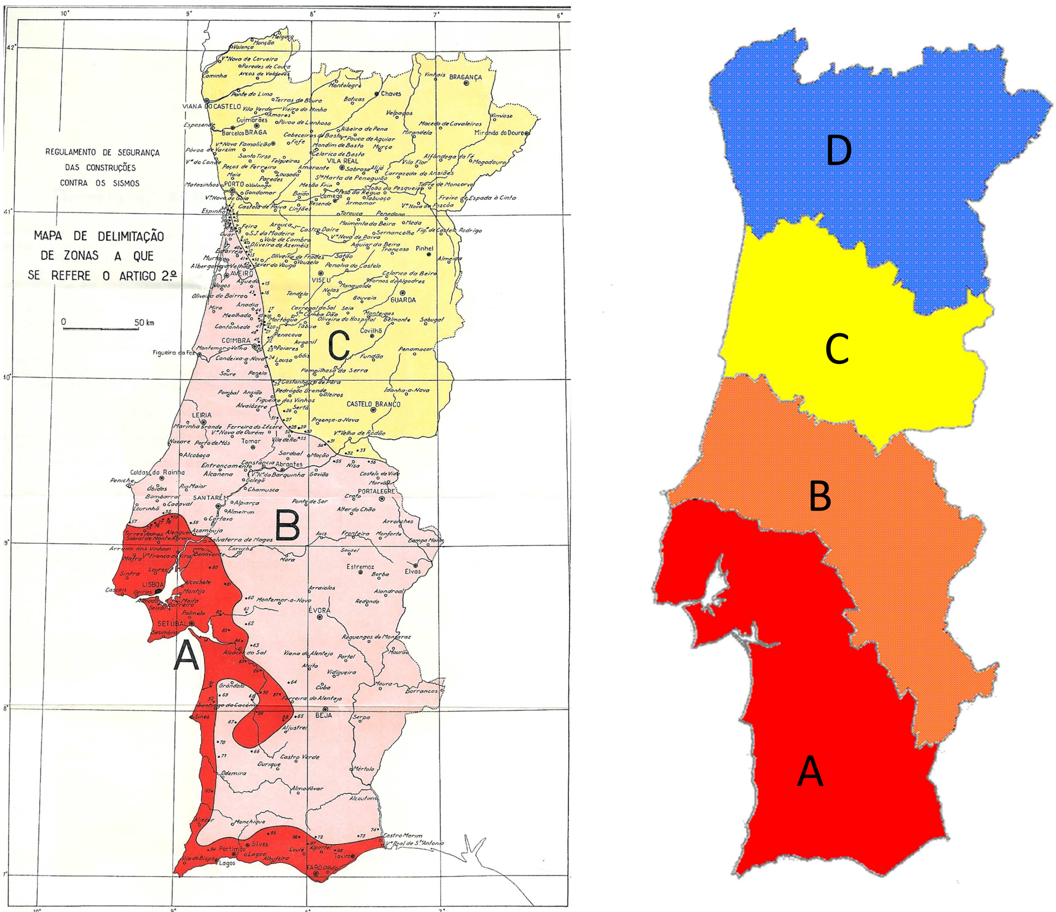
ANNEX A – Seismic zonation for the first Portuguese earthquake resistant codes



a) *b)*

Figure A.1 – Seismic zonation in a) RCSSC [1958] and b) RSA [1983].

ANNEX B – Parameters of building damage model

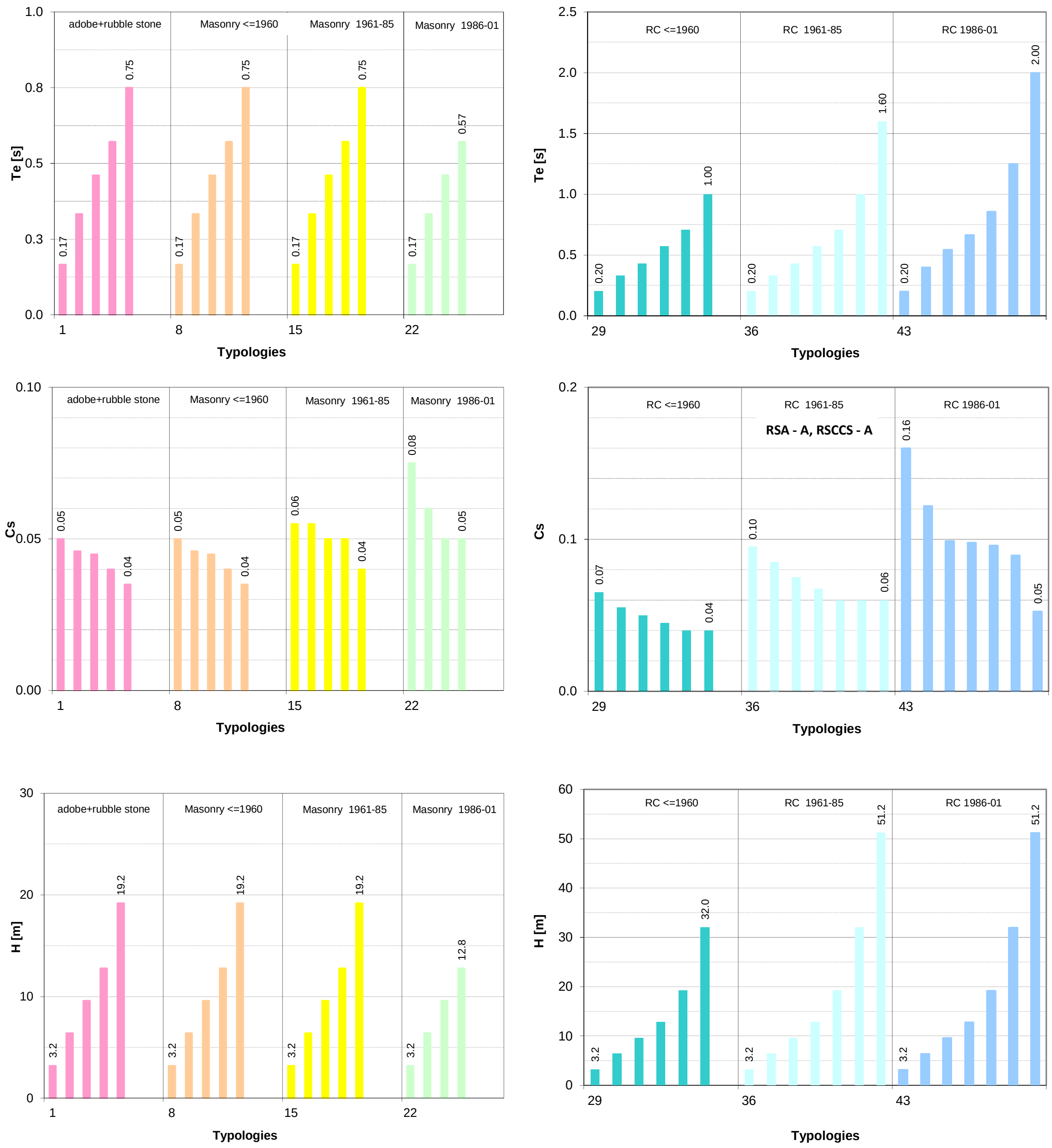


Figure B.1 – Parameters of capacity curves by vulnerability class / typology.

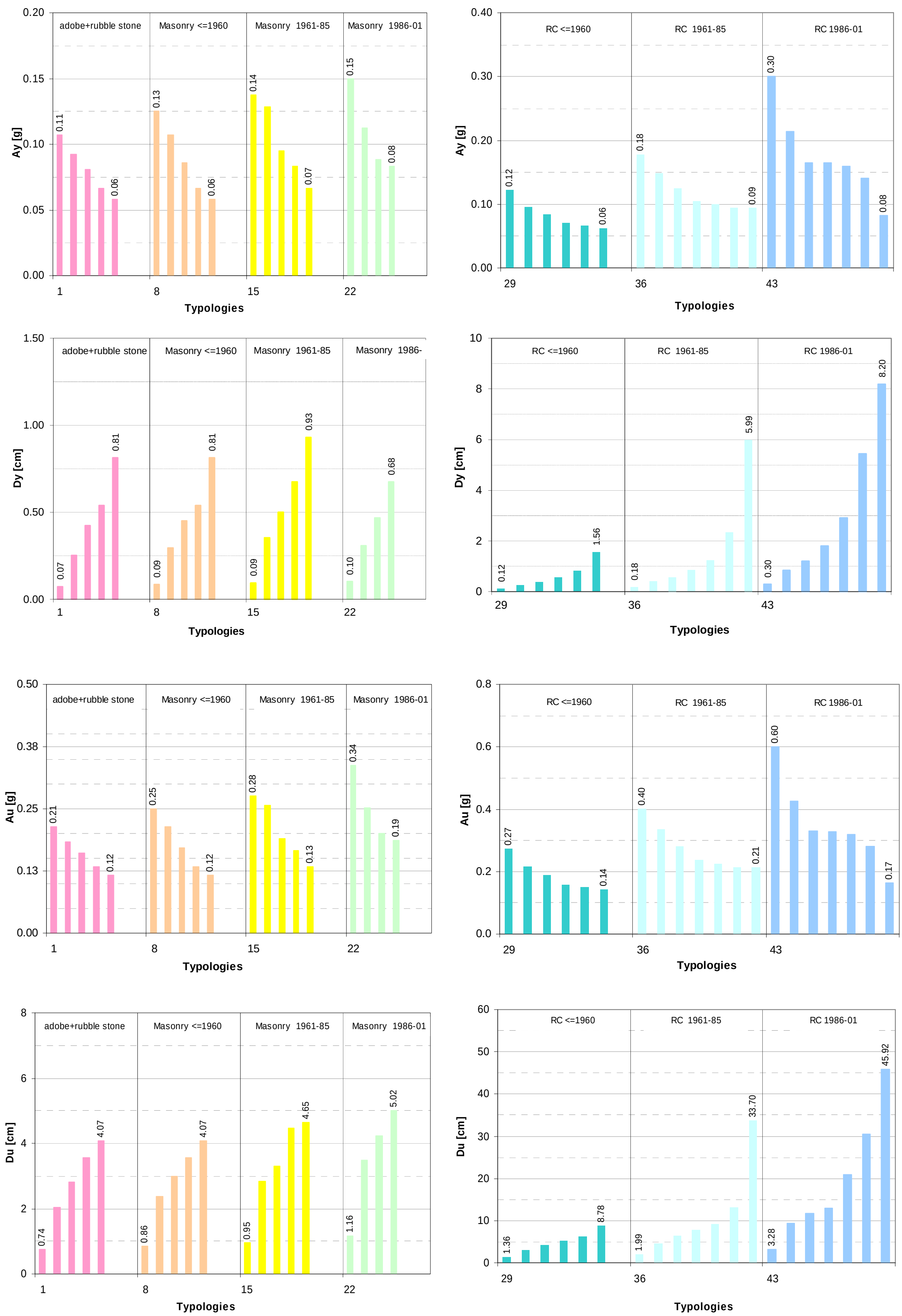


Figure B.2 – Variables that define capacity by vulnerability class / typology [LESSLOSS, 2007].

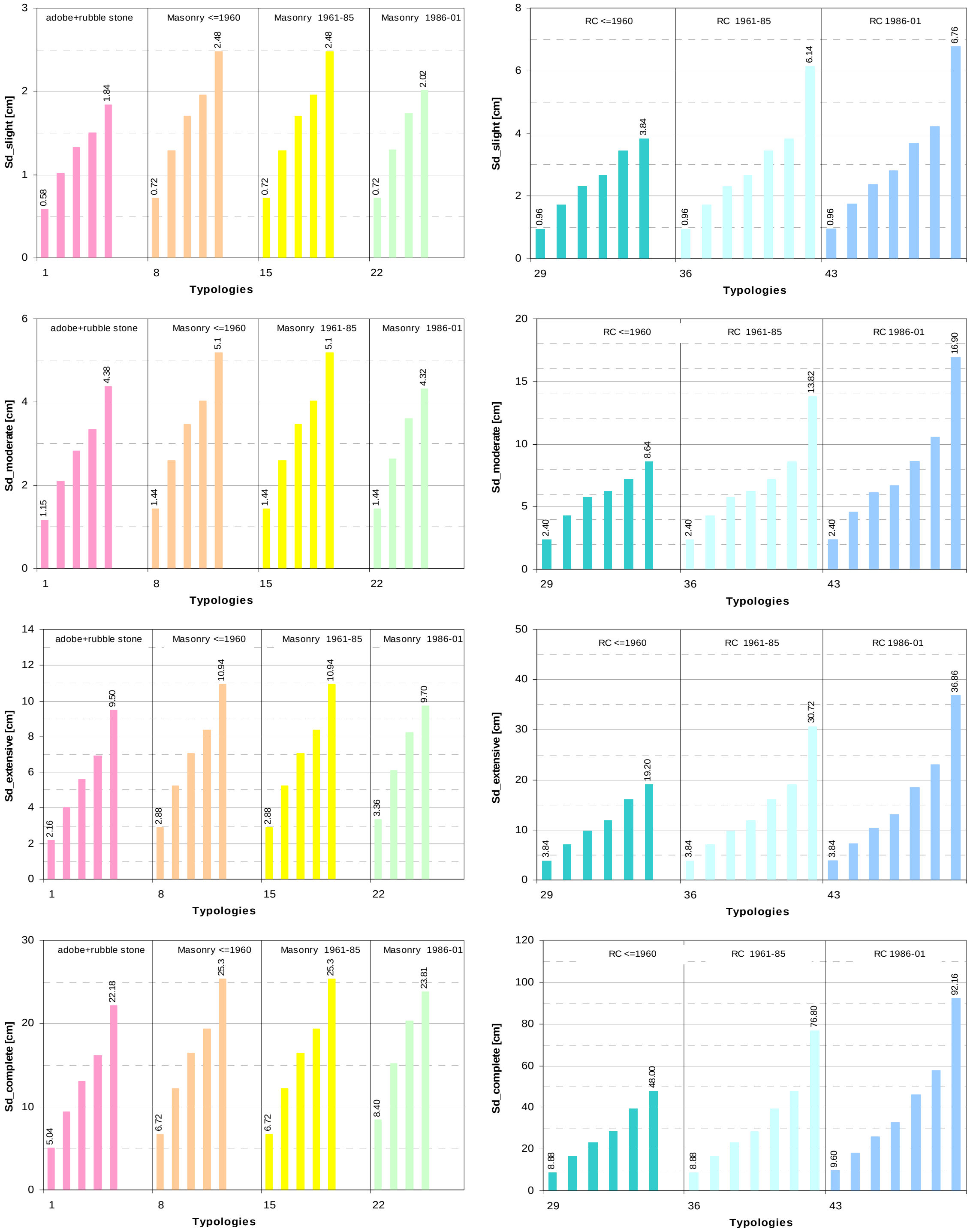


Figure B.3 – Parameters of fragility curves by vulnerability class / typology - median of spectral displacement [LESSLOSS, 2007].

ANNEX C – Parameters of social loss model

Table C.1 – Probability of human losses by injury severity level, typology and damage state [adapted from FEMA, 2003].

<table>
<tr><th colspan="2" rowspan="2">Damage state</th><th rowspan="2">Typology No. of Floors</th><th rowspan="2">Typological class</th><th colspan="4">Injury severity level [%]</th></tr>
<tr><th>Slight Injuries</th><th>Injuries requiring Hospitalization</th><th>Severe Injuries</th><th>Deaths</th></tr>
<tr><td colspan="2">Slight</td><td>All</td><td>All</td><td>0.05</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="2" rowspan="3">Moderate</td><td>All</td><td>Adobe + rubble stone + Masonry till 1985 + Others</td><td>0.35</td><td>0.4</td><td>0.01</td><td>0.01</td></tr>
<tr><td rowspan="2">All</td><td>Masonry 1986-01</td><td>0.2</td><td>0.05</td><td>0.0</td><td>0.0</td></tr>
<tr><td>RC</td><td>0.25</td><td>0.03</td><td>0.0</td><td>0.0</td></tr>
<tr><td colspan="2" rowspan="2">Extensive</td><td>All</td><td>Adobe + rubble stone + Masonry till 1985 + Others</td><td>2.0</td><td>0.2</td><td>0.001</td><td>0.001</td></tr>
<tr><td>All</td><td>Masonry 1986-01 + RC</td><td>1.0</td><td>0.1</td><td>0.002</td><td>0.002</td></tr>
<tr><td rowspan="5">Complete</td><td rowspan="2">Partial Collapse</td><td>All</td><td>Adobe + rubble stone + Masonry till 1985 + Others</td><td>10.0</td><td>2.0</td><td>0.02</td><td>0.02</td></tr>
<tr><td>All</td><td>Masonry 1986-01 + RC</td><td>5.0</td><td>1.0</td><td>0.01</td><td>0.01</td></tr>
<tr><td rowspan="3">Total Collapse</td><td>1-2</td><td>ATAPS + Others</td><td rowspan="3">40.0</td><td rowspan="3">20.0</td><td rowspan="3">5.0</td><td rowspan="3">10</td></tr>
<tr><td>1-2</td><td>Masonry + RC</td></tr>
<tr><td>+ 2</td><td>Masonry + RC</td></tr>
</table>

Table C.2 – Probability of collapse in the Complete damage state [adapted from FEMA 2003].

<table>
<tr><th>Typological class</th><th>No of floors</th><th>[%]</th></tr>
<tr><td>Adobe + rubble stone + Others</td><td>All</td><td>15.0</td></tr>
<tr><td>Masonry till 1985</td><td>All</td><td>15.0</td></tr>
<tr><td rowspan="3">Masonry till 1986-01</td><td>1-3</td><td>15.0</td></tr>
<tr><td>4-7</td><td>13.0</td></tr>
<tr><td>+ de 7</td><td>10.0</td></tr>
<tr><td rowspan="3">RC</td><td>1-3</td><td>13.0</td></tr>
<tr><td>4-7</td><td>10.0</td></tr>
<tr><td>+ 7</td><td>5.0</td></tr>
</table>