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AN AUTOMATIC SEISMIC SCENARIO LOSS METHODOLOGY INTEGRATED ON A GEOGRAPHIC INFORMATION SYSTEM

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SUMMARY

The objective of the present paper is to present the new LNEC automatic Seismic Scenario Loss estimate methodology (SSL), integrated on a Geographic Information System (GIS), which comprises modules evaluating bedrock seismic input, local soil effects, vulnerability and fragility analysis and human losses analysis.

Results of seismic risk scenarios studies for the Metropolitan Area of Lisbon are presented.

INTRODUCTION

In order to achieve a significant progress in seismic risk mitigation it is necessary the development of a straightforward and automatic methodology to estimate seismic losses in a region. With that in mind, an automatic seismic loss estimate methodology was developed at LNEC, integrated on a Geographic Information System that stores databases suitable for Portugal.

Methodologies using hysteretic displacement-based assessment and fragility analysis for building loss estimation are novel approaches in seismic risk analysis of urban areas. Such tools require equally refined approaches for seismic input simulation reflecting the seismotectonic environment of the urban area under study.

The 40km radius Metropolitan Area of Lisbon (MAL), which is under study, has been historically stricken by scarce, though intense, earthquakes, such as the 1755 Lisbon earthquake estimated as 8.70 magnitude and reported with 20 000 deaths and 14 000 building collapsed or damaged.

The SSL is being developed in the framework of seismic risk mitigation projects in course in Portugal, mainly one coordinated by the Portuguese national civil protection authority (SNPC, [1]) and other entitled "Seismic Risk Mitigation in Portugal" funded by the *Fundação para a Ciência e a Tecnologia* of the Portuguese Ministry for Science and Tecnology [2].

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AUTOMATIC SEISMIC LOSS ESTIMATE METHODOLOGY

General overview

The automatic seismic scenario loss estimate methodology, integrated on a Geographic Information System (ArcGIS, or other) comprises several modules to perform seismic risk analysis that are developed in an high level programming language and compiled in DLL (Dynamic Link Library-DLL) that may be accessed rather efficiently by any Windows program environment (ArcView, EXCEL, MathLab, etc.).

The several modules are schematically represented in figure 1 and take into account the following aspects:

<u>Bedrock Seismic Input</u> - Given a seismic scenario (magnitude and epicentral location) it computes the Power Spectral Density Function (PSDF) of the strong ground motions at bedrock level of any site at a given epicentral distance.

<u>Local Soil Effects</u> - Given a stratified soil profile units it computes the new PSDF for any location at the surface level, taking into account the nonlinear behaviour of the stratified geotechnical site conditions.

<u>Vunerability Analysis</u> - Giving the PSDF at surface level, it computes the response of building typologies following a displacement-based methodology based on the capacities curves.

<u>Fragility Analysis</u> - For a particular site, taking into account damage observed in each typology, the number of existing buildings in each typology (inventory) and respective occupancy, it computes number of building in each damage state.

<u>Human Losses</u> - Taking into account damages in each typology and the occupancy per typology it computes human casualties and homeless.

<u>Economic Losses</u> - Taking into account damages in each typology and damage state it computes building floor lost areas, that can be multiplied by the repair and replacement cost to obtain economic losses. This module is under development.

Input data

The required input data to SSL operation includes:

Shallow Geology – Data Base containing information on stratified soil profile units for the region under analysis. Each record comprises the thickness of shallow layers, shear waves velocity, density and plasticity index.

Building stock – Residential building database, geographically desegregated by small administrative divisions (parishes), surveyed in the Portuguese 2001 Census [INE, 3] and classified by epoch of construction, building construction materials and number of floors.

Population at risk - Inhabitants database, with the same level of geographic desegregation, surveyed in the Portuguese 2001 Census [INE, 3], This database settles accounts for the number of inhabitants living in buildings classified according to their age, structural elements and height.

Economic parameters – Average floor areas, repair and replacement costs by parish and typology.

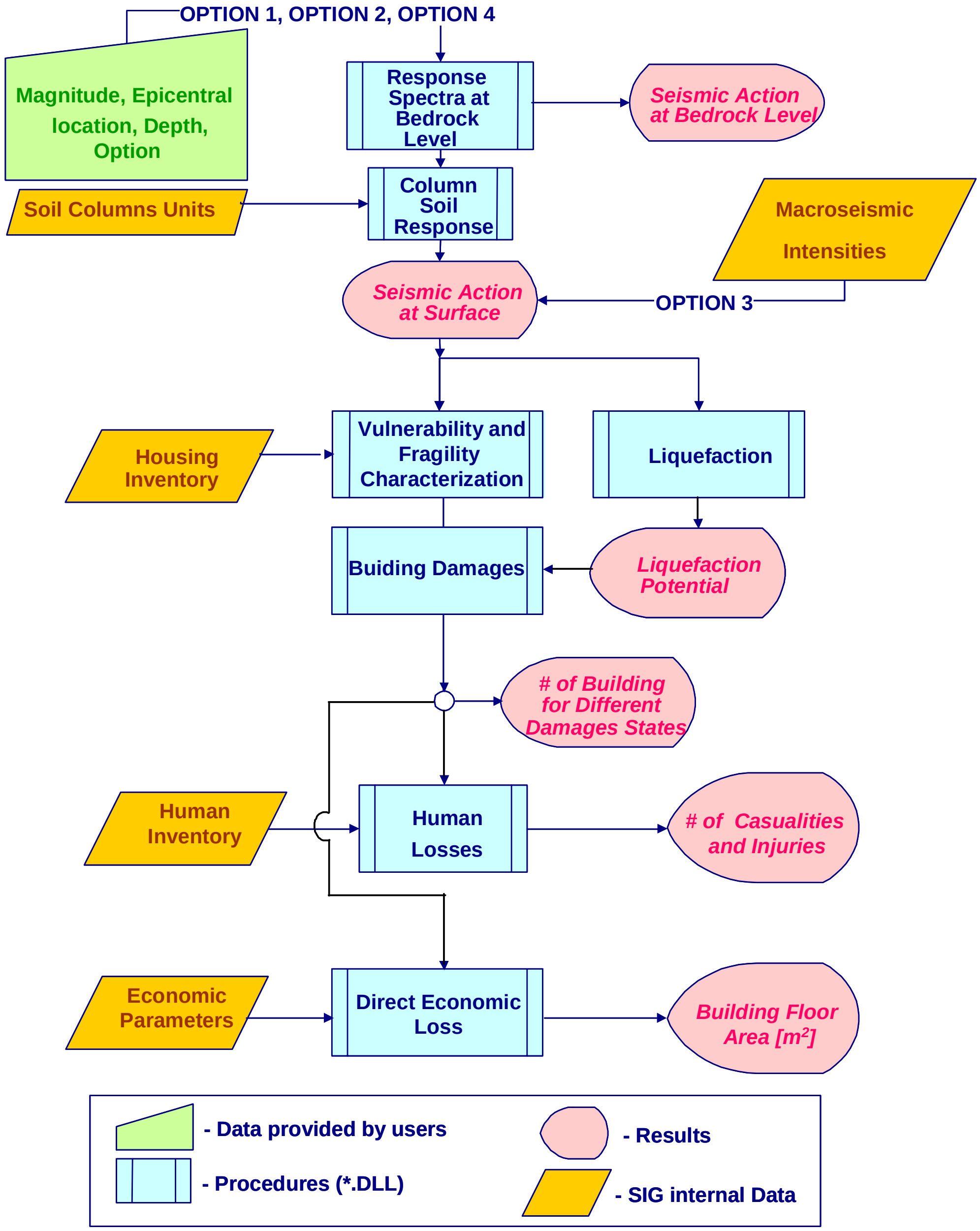

Figure 1: Diagram of LNEC automatic seismic scenario loss methodology.

The user should provide the following information: (i) *x*, *y* coordinates of the scenario epicentre in a rectangular (planar) coordinate system, (ii) the scenario magnitude and (iii) the option to evaluate seismic intensities in each site (see the following section).

Procedures and results

seismic action at bedrock level

Spectral characterisation of seismic action at bedrock level of each unit is determined. Given a seismic scenario (magnitude and location) it computes the Power Spectral Density Function (PSDF) of the strong ground motions at bedrock level of any site at a given epicentral distance.

Spectral characteristics can be computed using empirical relations, real data or seismological models. The different approaches are the following:

<u>Option 1</u> – uses the statistical empirical attenuation relationships developed by Boomer [4];

<u>Option 2</u> – uses Sousa [5] attenuation model based on macroseismic intensities, that accounts for different types of soil conditions (hard, intermediate and soft). These models were achieved by integrating intensity data concerning the events of the Portuguese catalogue. Intensity results are then converted into response spectra after Trifunac [6];

<u>Opção 3</u> – uses real macroseismic intensities of a specific earthquake, which are, then converted into response spectra after [6]; by using this approach, the seismic action is evaluated not at a bedrock level but at surface. User is required to provide a file with intensities;

<u>Opção 4</u> – uses seismological models. It performs non-stationary stochastic finite – fault modeling, based on random vibration theory. Carvalho [7] describe theoretical aspects of this approach.

The characterization of seismic input was performed applying the stochastic simulation technique, namely a stationary Gaussian process.

Once the response spectrum has been achieved, from options 1, 2 or 4, the Power Spectral Density Function may be quantified. This quantification is performed through an iterative procedure, which is based on the possibility of computing the maximum values of the response spectrum, SD, from the power spectrum by equation

$$SD_j = \sqrt{2\ \lambda_{0;j}\left[\ln\left(\frac{T}{2\pi}\sqrt{\frac{\lambda_{2;j}}{\lambda_{0;j}}}\right) - \ln(-\ln p)\right]} \tag{1}$$

where p is the fractile and $\lambda_{0;j}$ and $\lambda_{2;j}$ are moments of order zero and two, respectively, of the Power Spectral Density Function and are defined as

$$\lambda_{0;j} = \int_0^{+\infty} S_j(\omega)\ d\omega \tag{2}$$

$$\lambda_{2;j} = \int_0^{+\infty} \omega^2 S_j(\omega)\ d\omega \tag{3}$$

where $S_j(\omega)$ is defined by the transfer function $H_{a;j}(\omega_k)$ and the power spectral density function of acceleration $S_a(\omega_k)$:

$$S_j(\omega_k) = H^*_{a;j}(\omega_k) S_a(\omega_k) H_{a;j}(\omega_k) \tag{4}$$

To begin the iterative procedure values are chosen for the first $S_j(\omega)$. Then successive procedure cycles are carried out until a satisfactory approximation of the desire response spectrum is obtained.

In general less than 5 iterations are necessary to obtain a response spectrum within 1% of the desired response spectrum.

As a result, each seismic input is defined by the power spectral density function of acceleration.

Figure 2 presents, for the 1755 earthquake, the peak ground acceleration at bedrock level for MAL (right), considering option 4, using the fault source geometry based on Terrinha [8](left).

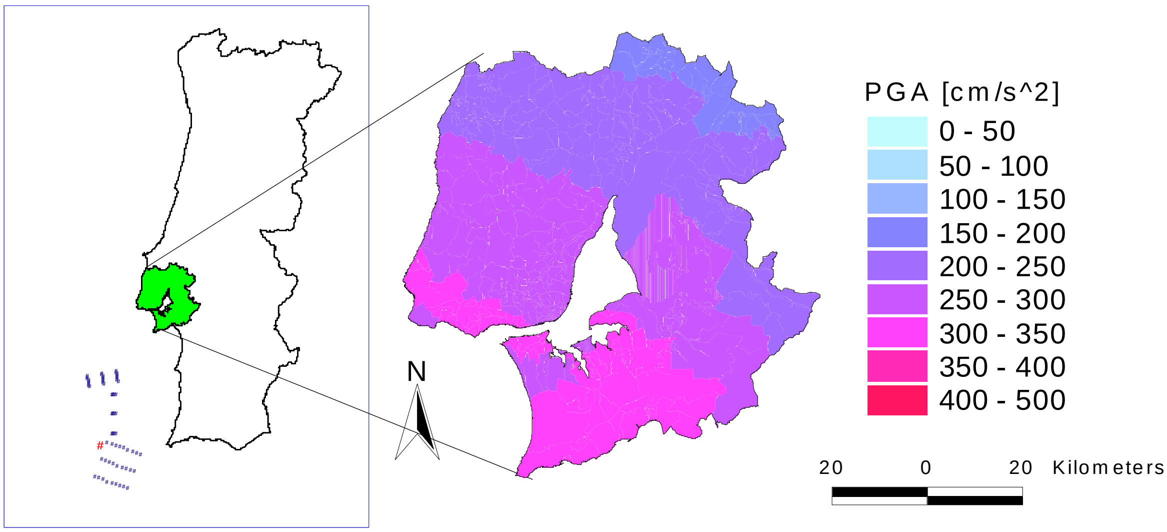

Figure 2: Left: Surface projection of the fault source geometry after Terrinha [8]. The blue circles show the center of the subfaults. Red circle shows localization 37ºN – 10ºW, corresponding to the accepted epicentral coordinates of the 1755 earthquake and considered as the initial point of rupture. Right: Peak Ground Acceleration at bedrock lever, for MAL.

Seismic action at surface

Given a stratified soil profile units it is computed the new PSDF for any location at the surface level. The computer algorithms now developed and implemented at LNEC introduced some major improvements to take into account site effects due to soil dynamic amplification in rather efficient way. These effects are evaluated by means of an equivalent stochastic nonlinear one-dimensional ground response analysis of stratified soil profile units designed for the region (37 soil columns units as shown in Figure 3, left).

In the framework of the project conducted by the national civil protection authority (SNPC [1]), it was carried out an geological - geotechnical inquiry that allowed the assessment of soil columns for each parish of MAL, and the respective transfer function $H(\omega)$ between the acceleration at the bedrock level, $S_b(\omega)$, and the acceleration at surface.

The power density function at surface, $S(\omega)$, is then estimated following the expression:

$$S(\omega) = H^*(\omega) S_b(\omega) H(\omega) \tag{5}$$

The respective moments which then allowed estimating the peak ground acceleration are obtained using equations (2) and (3).

Figure 3 presents the soil columns units for MAL (left) and peak ground acceleration at surface, for option 4 and fault geometry shown in figure 2.

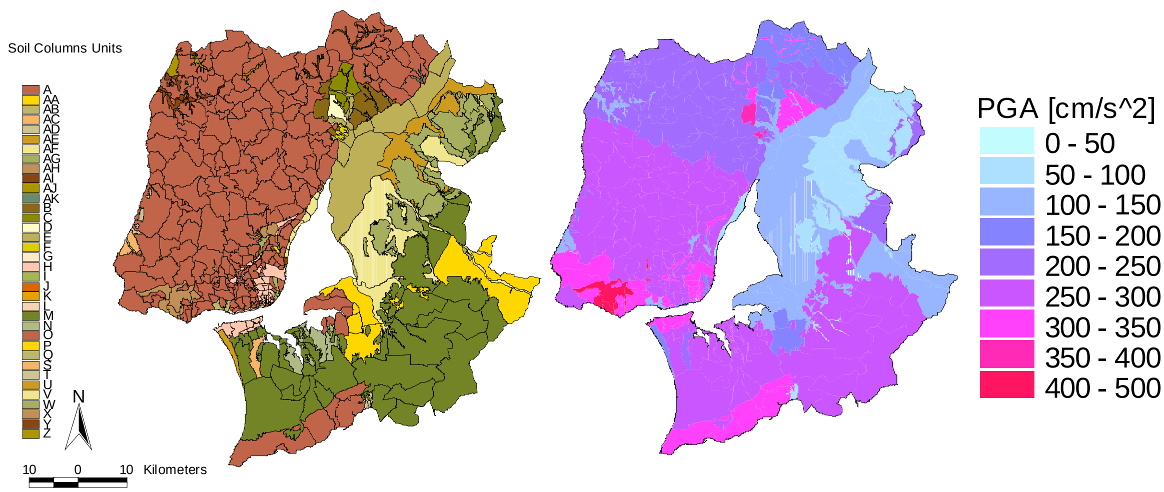

Figure3: Left: Soil columns units for MAL (after [1]). Right: Peak ground acceleration at surface.

As an example of a different approach, figure 4 presents the real macroseismic intensity for the 1755 earthquake after Pereira [9] and peak ground acceleration as a result of option 3 that converts macroseismic intensity into response spectra following [6].

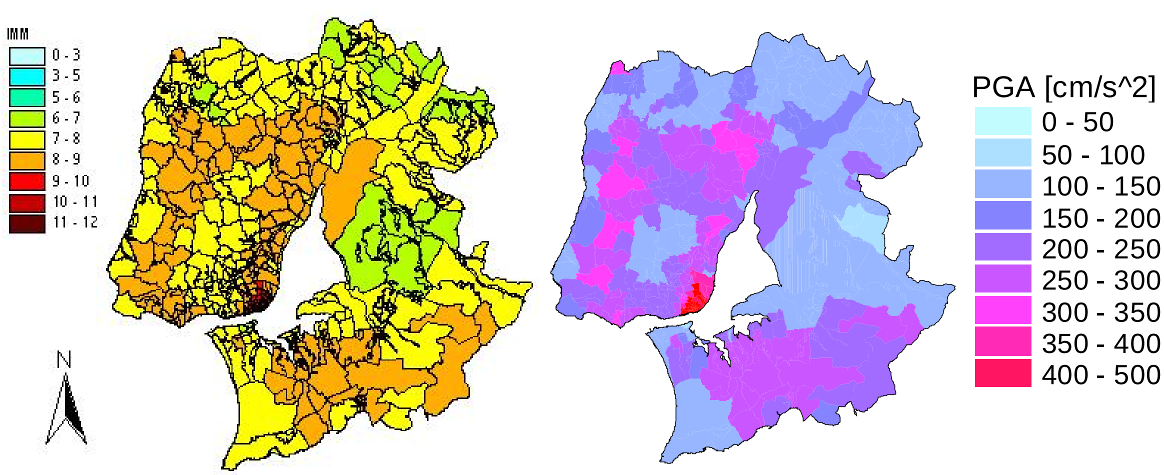

Figure 4: Left: Macroseismic intensities for MAL based on Pereira [9]. Right: Peak ground acceleration at surface, option 3.

Vulnerability and fragility characterization

Damage procedures require a previous classification of the vulnerability of the building stock.

Sousa [10, 11] analyzed the 2001 Portuguese Census with three main purposes: (i) to build the statistics of the number of buildings and inhabitants in Portuguese mainland, (ii) to characterize their geographic distribution and (iii) to identify the most representative and frequent building types by region.

In the *Building Questionnaire* of that Census there were identified some variables representing structural characteristics that are expected to influence buildings performance when stricken by an earthquake: *epoch of construction*; *resisting elements*; *number of floors*.

Table 1 presents the classes of those variables available in Census 2001.

Table 1. Classes of vulnerability variables obtained in Portuguese Census 2001.

Epoch of construction	*Building structure*	*Number of floors*
Before 1919	Reinforced concrete	1
1919 to 1945	Masonry with RC floors	2
1946 to 1960	Masonry without RC floors	3
1961 to 1970	Adobe ruble stone	4
1971 to 1980	Others (wood, steel, etc)	5 to 7
1981 to 1985		8 to 15
1986 to 1990		+ 15
1991 to 1995		
1996 to 2001		

Carvalho [1] established a typological classification of Portuguese building stock taking into account a first analysis of Portuguese Census 1991 and expert opinion. Experts gave information on the most relevant building practices in the Country, materials and technologies employed in construction, their evolution over time and space. The history of building seismic upgrade in Portugal is mainly related to the occurrence of earthquake disasters (*eg.* 1755 earthquake) or to the enforce of building codes.

The authors identified seven typological classes allowing for the two Census 1991 variables *Epoch of construction* and *Resisting elements*. Each of those classes was further subdivided in seven categories, considering building height, leading to forty-nine building types with similar seismic response characteristics. For those 49 typologies of buildings Carvalho [1] proposed capacity (pushover) and fragility curves, with a view to a future implementation of a performance-based procedure for the evaluation of building damages.

Those 49 typologies were now updated taking into account the new features included in Census 2001, namely a more reliable classification of the building structure.

Fragility curves allow the evaluation of the probability to exceed the threshold of a given damage state. As purposed by HAZUS 99 [12] five damage states were considered: No damage, Slight, Moderate, Severe and Complete Damage. The threshold of those damage states are established in terms of global drift for each typology.

Figure 5 shows capacity curves and thresholds of damage states for the typologies identified in Census 2001.

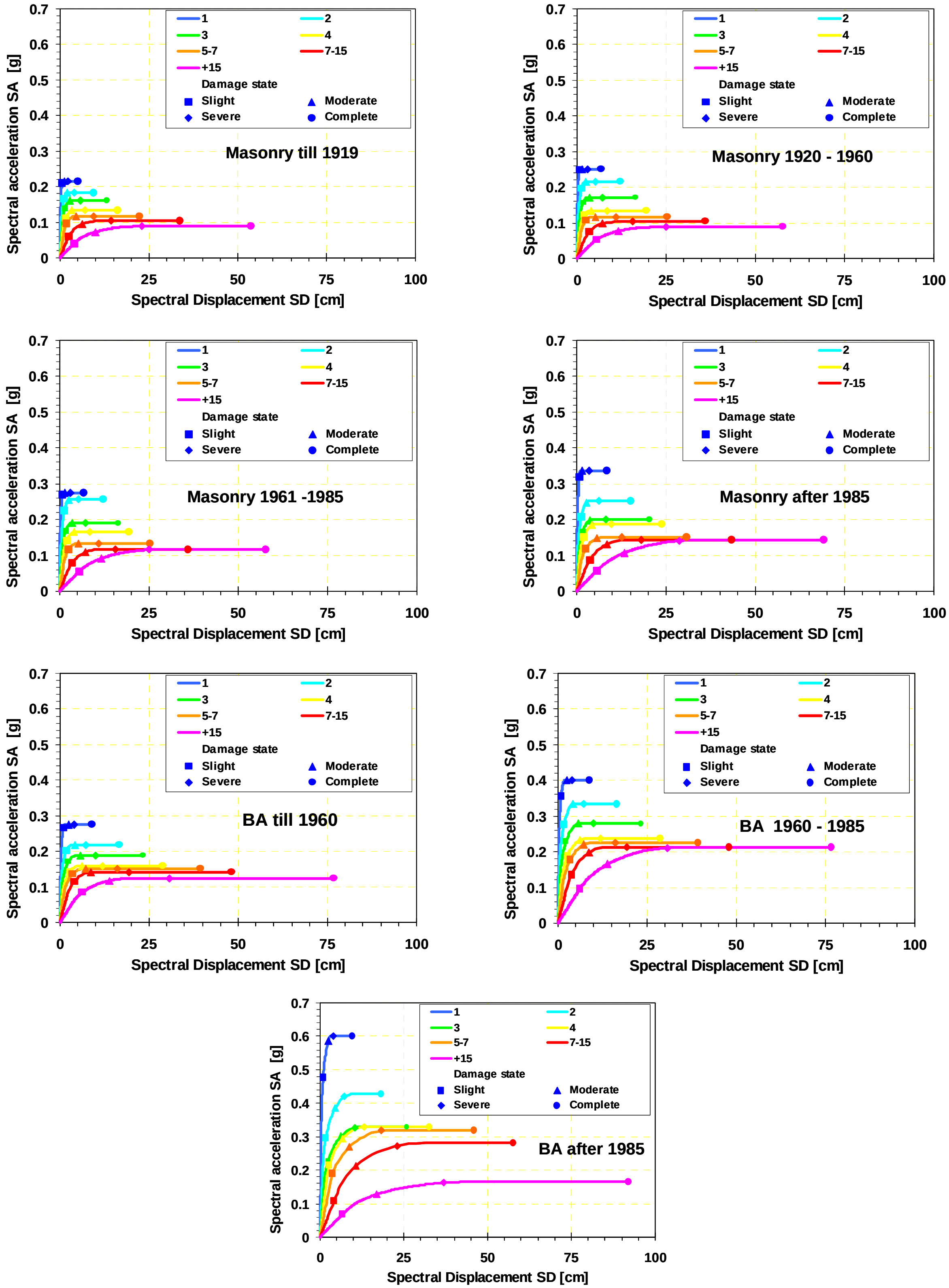

Figure 5: Capacity curves and thresholds of damage states for typologies identified in 2001 Portuguese Census.

Building damage

The evaluation of peak response for each type of building relies on the intersection of its capacity curve with the seismic spectral demand at the site. This technique is called the "capacity spectrum method" ATC-40 [13] and is worldwide divulged by the HAZUS loss estimation methodology [12].

The capacity spectrum method is based on performance-based procedures for the design of new buildings and on the reduction of the initial elastic response spectra to the so called demand spectra, taking into account the degradation of the building exposed to the seismic motion.

An innovative technique was introduced in the SSL taking into account an iterative procedure that estimates sequential demand spectra, with increasing damping, reflecting structure degradation during its cyclic response. While in HAZUS the modifications of spectral demand are represented by reduction factors, in SSL those modifications were performed through an iterative equivalent non-linear stochastic methodology, similar to that presented in the section entitled "seismic action at bedrock level". Progressive building responses are obtained over the demand spectra till the convergence with the median capacity curve is achieved. The so-called 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 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.

Figure 6 presents the number of buildings in MAL in Severe and Complete damage states for 1755 scenario and choosing seismic action computed with option 3.

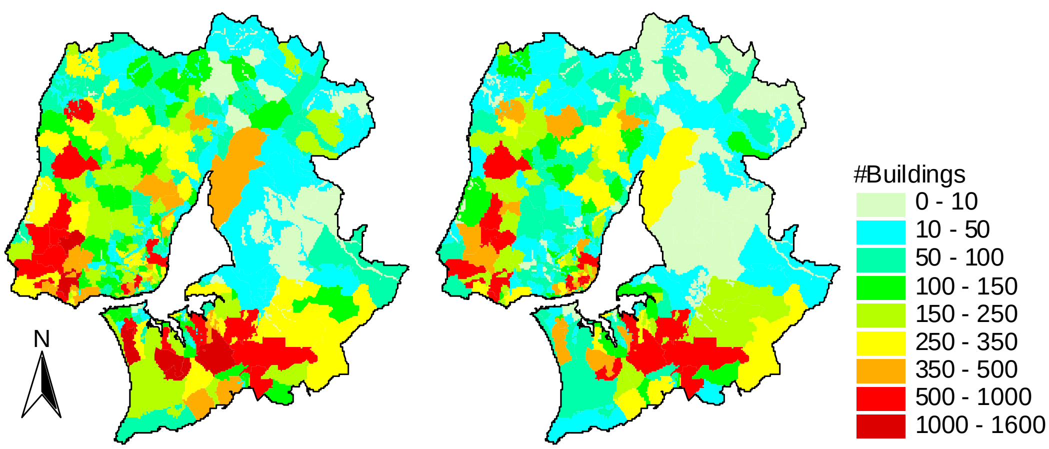

Figure 6: Number of damaged buildings in MAL for 1755 scenario – option 3 – observed macroseismic intensities model. Severe (left) and Complete (right) damage state.

Human losses

Most methods to estimate human casualties as a consequence of earthquakes are based on the correlation between building damages and the number of people killed, injured or homeless. Those estimations are always affected by a great level of uncertainty, because the same seismic intensity causes an heterogeneous number of victims in different countries and regions. In addition to this great variance on the number of casualties, the statistics following an earthquake are poor turning the casualty estimation a rather difficult task [Coburn, 14].

SSL routine for casualty estimation implemented two methods to evaluate death rate and injuries as a consequence of earthquakes: option Tiedemann [15]e option HAZUS 99 [12].

Bearing in mind that the seismic impact on people is manly dependent on the seismic intensity and on the vulnerability of buildings, Tiedemann [15] presents vulnerability curves relating Death Rate, *DR*, with Mercalli Modified Intensity (MMI) for different typologies of buildings.

Beta distribution functions were fitted to those vulnerability curves, in which the distribution parameters *p* and *q* depend on the seismic coefficient of each building typology:

$$DR(MMI, Cs) = \text{Beta}\,(MMI, p, q) \quad (6)$$

Where $p = 5.76 * Cs^{0.07}$ and $q = 0.2225 * Cs^{-0.7743}$.

If option Tiedemann is chosen the SSL routine on human losses estimates for each geographic/soil unit, and for each building typology, the Death Rate for a given seismic scenario.

On the other hand, if HAZUS 99 option is chosen the SSL routine on human losses estimates for each geographic/soil unit, and for each building typology, the casualties for four levels of injury severity: Light injuries, Hospitalization, Life threatening and Death.

Figure 7 presents the number of death victims as a consequence 1755 scenario and choosing seismic action computed with the option 3 and for Tiedemann and HAZUS-99 methodologies. It is notorious the variance of results.

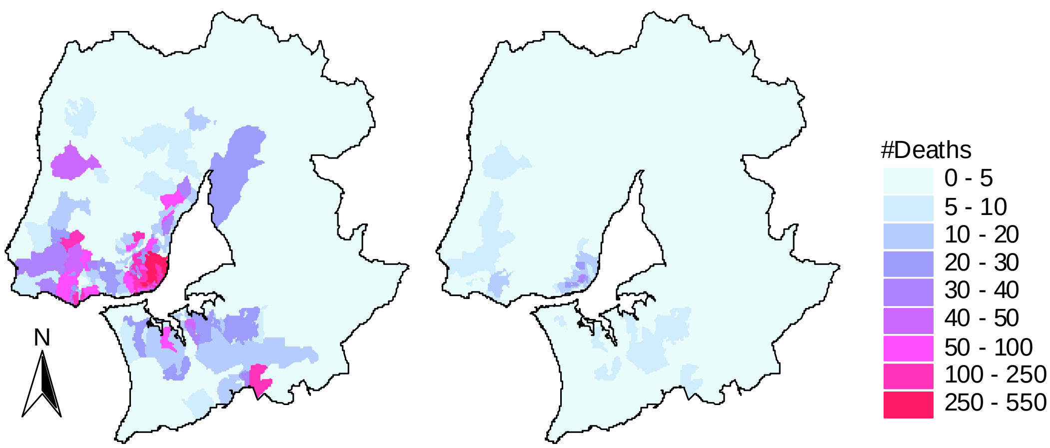

Figure 7: Number of death victims in MAL for 1755 scenario – option 3 – observed macroseismic intensities. Left: Tiedemann method; right: HAZUS-99 method.

Economic losses

Economic losses are computed in terms of the lost area of building floors (figure 8) obtained by a weighted linear combination of the probability of the building type being in a given damage state summed over all the elements at risk. The lost area is simple multiplied by the actual values of the replacement costs by parish and typology. This module is presently under development.

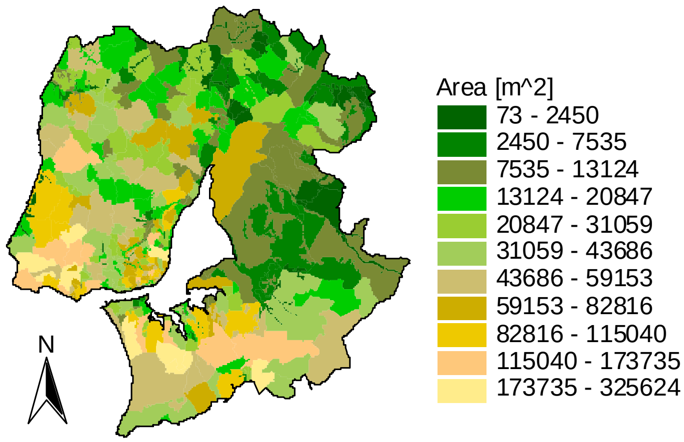

Figure 8: Economic Losses in MAL for 1755 scenario – option 3 – observed macroseismic intensities. Building floor area losses.

SSL UPDATING

LNEC Seismic Scenario Simulator is constantly being updated. At this moment the following topics are being developed to be included in the SSL [10]:

1. Besides prediction damage methods, the SSL is being updated with methods based on observed damage, like the statistics of European earthquakes [SSI, 16, Zuccaro, 17]. Vulnerability and fragility evaluation underlined by the European Macroseismic Scale EMS-98 [Grünthal, 18, Giovinazzi *et al*, 19] are also being included. A methodology aiming to calibrate the calculated performance of buildings with the statistics of European earthquakes and with EMS-98 is being developed [Sousa, 10].

2. Inclusion of Coburn [14] to the evaluation of human losses as a consequence of earthquakes.

CONCLUSIONS

The SSL is an important tool to achieve a significant progress in seismic risk mitigation in Portugal, being useful for several issues, such as: (i) decision support for the establishment of rational emergency planning, since it operates in real time, (ii) definition of policies for seismic retrofitting of the building stock, allowing the study of the influence of interventions by geographical areas and by type of construction, and the subsequent identification of the most efficient intervention strategies by means of a cost-benefit study, (iii) definition of technical insurance premiums for insurance policy.

Another important new feature of this procedure are the algorithms based on non-linear (or equivalent linear) non stationary stochastic analysis. This introduces a more robust algorithm, comparing to time history response, and, more important, with much faster results.

Being a modular structure, the SSL can be updated in a very simple way, both in terms of data and methodologies.

This tool should be supplied to local and regional authorities to provide a decision support system to evaluate seismic risk and to found mitigation programs.

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