Seismic vulnerability assessment of the old city centre of Seixal, Portugal

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SUMMARY:
The seismic vulnerability assessment of old traditional masonry building stocks, in a seismic risk mitigation perspective, is truly essential not only for buildings with recognized historical and patrimonial value, but also, in relation to regular buildings. In this sense, this paper approaches the issue of the seismic vulnerability assessment of masonry buildings through the application of a simplified methodology to building stock of the old city centre of Seixal, Portugal. This methodology is based on a vulnerability index, suitable in the evaluation of damage and in the creation of large scale loss scenarios (economical and human). Over 500 buildings were evaluated in accordance with the referred methodology and the results obtained were then integrated into a Geographical Information System tool. The integration of this kind of vulnerability and loss results into a GIS tool allows that city councils or regional authorities make their decisions based on a global view of the site under analysis, which led to more accurate and faster decisions either in terms of risk mitigation strategies or rehabilitation plans. This tool can also assumes great importance in the construction of safety and rescue plans.

Keywords: Seismic vulnerability, masonry buildings, old city centre, damage scenarios, GIS mapping

1. INTRODUCTION

1.1 Scope

Development of vulnerability studies in urban centres should be conducted aiming to identify building fragilities and reduce the seismic risk. Moreover, the selection of a seismic vulnerability assessment methodology should take into account the nature, the function and the constructive typology of the buildings to be evaluated. The criteria to use should be sensitive to the existing construction typologies, regardless the building usage and its patrimonial value.

The main purpose of this research is to present and discuss the strategy and results obtained from the application of a seismic vulnerability method to the masonry buildings of the old city centre of Seixal, Portugal. The methodology adopted is based on a vulnerability index, used for the evaluation of damage and for the study of loss scenarios at a large scale. Over 500 buildings were assessed in accordance with the referred methodology and the results obtained were analysed using an integrated Geographical Information System tool. The integration of the vulnerability and loss results allows the city councils, or regional authorities, to plan the interventions based on a global view of the site under analysis, leading to more accurate and comprehensive decisions in terms of risk mitigation strategies as well as it may support the definition of safety and emergency planning.

1.2 The old city centre of Seixal: Inspection procedure and database

Supported by the National Strategic Reference Framework (7th Framework European Program) and commissioned by the Seixal City Council, this study involved a complete identification and inspection survey of the old masonry buildings. The data gathered from the inspection of 504 buildings, spread over 166 000 m^2, were processed and a database management system integrated into a GIS application was developed to manage, compare and analyses the information. The 504 buildings inspected were divided in three groups, in function of the detail of the information available and used on its seismic vulnerability assessment; The first group, composed by 99 buildings for which it was possible to perform a detailed analysis based on drawings with accurate dimensions and complete photographic information; the second group, composed by 197 buildings for which only a non-detailed exterior inspection was possible to perform. And finally, a third group composed by 208 buildings which are not included in this study, due to their constructive characteristics (reinforced concrete buildings – RC), actual conservation state (rehabilitated or in ruin – R) or present occupation state (Unoccupied – U).

In order to optimize the referred survey actions, the project area was divided into five zones, in function of the constructive and morphological characteristics of buildings. Figure 1 presents the project perimeter and the respective subzone definition.

Figure 1. Project perimeter and subzone definition (image supplied by Seixal City Council - SIG Division)

The GIS application software adopted in this study was ArcGis 9.3 (ESRI 2005). This toll combines geo-referenced graphical data (vectorized information and orthophotomaps) with building parameters information. In this specific case, each polygon (corresponding to a building) is associated with several features and attributes allowing their visualization, selection and search. Two types of spatial views are possible: a global view of the whole area studied and a local view of each one of the five defined zones.

2. VULNERABILITY INDEX METHODOLOGY

The vulnerability index is calculated as the weight sum of 14 parameters (see Table 1). These parameters are related to 4 classes (C_{vi}) of growing vulnerability: A, B, C and D. Each parameter evaluates one aspect related to the seismic response of the masonry building facade wall, calculating or defining the vulnerability class through the analysis of different properties associated with geometrical, mechanical and conservation state characteristics (Ferreira, 2010).

Subsequently, for each one of the 14 parameters, a weight, p_i, is assigned. As shown in Table 1, this weight can assume the value of 0.5, for the less important parameters in the calculation of the seismic vulnerability, I^*_v, or 0.75 for the more important ones. Therefore, the vulnerability index, I^*_v, is given by:

$$I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i \tag{2.1}$$

The value of I^*_{v} ranges between 0 and 650. For ease of use, this was normalized through a weighted sum, varying between 0 and 100, whereby the lower the value, the lower will be the building seismic vulnerability, I_f. The vulnerability index calculated can be used to estimate the building damage under a specified seismic intensity, as will be discussed and presented further.

Table 1: Vulnerability index (I_v)

PARAMETERS		Class C_{vi}				Weight	VULNERABILITY INDEX
		A	B	C	D	p_i	
P1	Type of resisting system	0	5	20	50	0.75	
P2	Quality of the resisting system	0	5	20	50	1.00	
P3	Conventional strength	0	5	20	50	1.50	$I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i$
P4	Maximum distance between walls	0	5	20	50	0.50	
P5	Number of floors	0	5	20	50	1.50	
P6	Location and soil conditions	0	5	20	50	0.75	
P7	Aggregate position and interaction	0	5	20	50	1.50	
P8	Plan configuration	0	5	20	50	0.75	
P9	Regularity in height	0	5	20	50	0.75	Normalized index $0 \le I_v \le 100$
P10	Wall facade openings and alignments	0	5	20	50	0.50	
P11	Horizontal diaphragms	0	5	20	50	1.00	
P12	Roofing system	0	5	20	50	1.00	
P13	Fragilities and conservation state	0	5	20	50	1.00	
P14	Non-structural elements	0	5	20	50	0.50	

The vulnerability index formulation applied here is originally based on the GNDT II level approach (GNDT-SSN 1994), for the vulnerability assessment of masonry buildings. This methodology is based on post-seismic damage observation and survey data covering a vast number of elements, focusing on the most important aspects/features that define building damage. Originally created in Italy, and largely used during the last 25 years, this methodology was adapted for use with Portuguese masonry buildings by Vicente (2008), improving by: (i) introducing a more detailed analysis, for the case of a good level of building stock information exists; (ii) the discussion and redefinition of the criteria of some of the most important parameters; and (iii) the introduction of new parameters that take into account the interaction between buildings and other overlooked building features (Vicente *et al.* 2011).

3. APPLICATION OF THE VULNERABILITY INDEX METHOD TO THE MASONRY BUILDING OF THE OLD CITY CENTRE OF SEIXAL

3.1 Seismic vulnerability assessment results

The masonry building stock of the city centre of Seixal was assessed, quantifying for each building the vulnerability index, I_v. For the first group of buildings (99) detailed assessment resulted in a mean value of the seismic vulnerability index of 34.16. For the second group of buildings a non-detailed assessment was carried out, resulting in a slight decrease of the mean vulnerability index to 32.81. The standard deviation, σ_{Iv}, associated with the vulnerability index distribution of the detailed assessed buildings is 9.51. Considering the results for the non-detailed assessed buildings, as expected, the standard deviation value reduces to 7.03, corresponding to a 26% reduction.

Figure 2 shows the histogram and the best-fit normal distribution curves resulted from the detailed (99 buildings) and non-detailed (296 buildings) assessment of buildings.

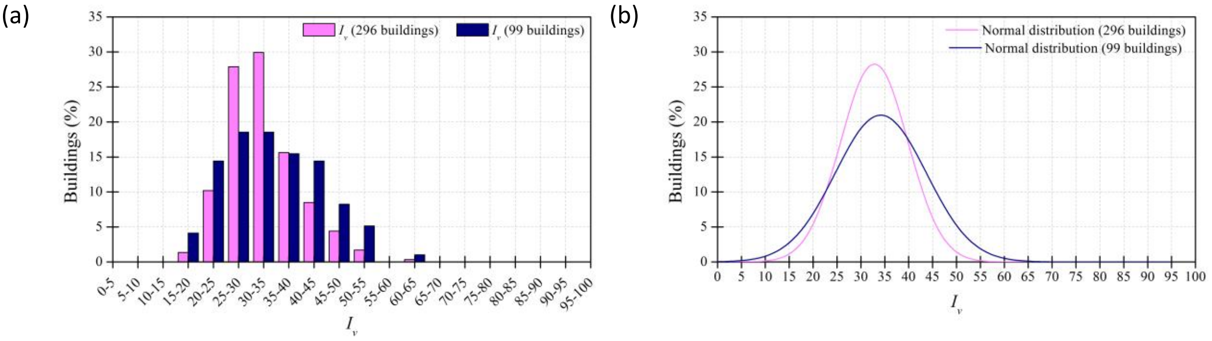

Figure 2. Vulnerability index distributions: (a) histograms; and (b) best-fit normal distributions

About 44% of the assessed buildings have a vulnerability index value over 40 (see Figure 5) and 16% over 45 (equivalent to vulnerability class A in the EMS-98 scale (Grünthal 1998)). In opposition, only 4% of buildings have an I_v below 20 (equivalent to vulnerability class B). The maximum and minimum I_v values obtained from the detailed assessment are 63 and 15, respectively.

3.2 Integration of the vulnerability results into a GIS tool

A relational database with all the vulnerability index assessment results and the building information was created. The GIS tool (Geographical Information System) developed allows to intercross different results and building features, namely, the seismic vulnerability index with building characteristics. Two types of spatial view are possible: a global view of the whole area studied and, alternatively, a local view of a subzone (see Figure 3).

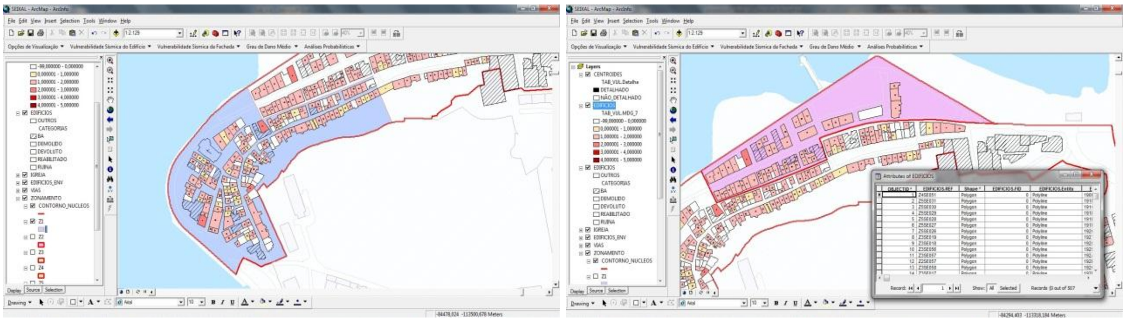

Figure 3. GIS tool application environment

In the GIS platform, specific commands were created to allow an easy access to all the information, as well as for the implementation of the damage and loss estimation algorithms (mathematical and probability functions). All subroutines used were programmed in Phyton and compiled in Visual Basic®, ArcGis 9.3 compatible programming language, on a Microsoft Windows 7 platform.

Figure 4 and Figure 5 present the seismic vulnerability index distribution for all the buildings evaluated. Through the overall analysis of Figure 5, it is possible to identify the critical buildings, as well as the urban areas where an expressive concentration of buildings with high seismic vulnerability index.

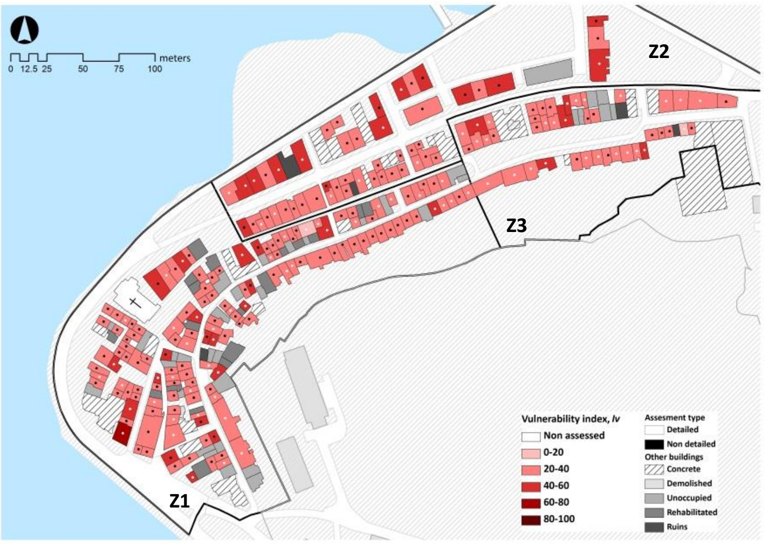

Figure 4. Vulnerability mapping of buildings in zones Z1, Z2 and Z3

Observing Figure 5 it is also possible to conclude that the corner and end row buildings of street blocks are in general more vulnerable due to their particular location and interaction conditions with adjacent buildings (Vicente *et al.* 2011b). For this reason, these buildings are recommended do to be reassessed with particular detail concerning eventual retrofitting or/and strengthening actions. According to the same author, it is recommended that masonry buildings with values of I_v over 45 should undergo a more detailed assessment (Pagnini *et al.* 2011).

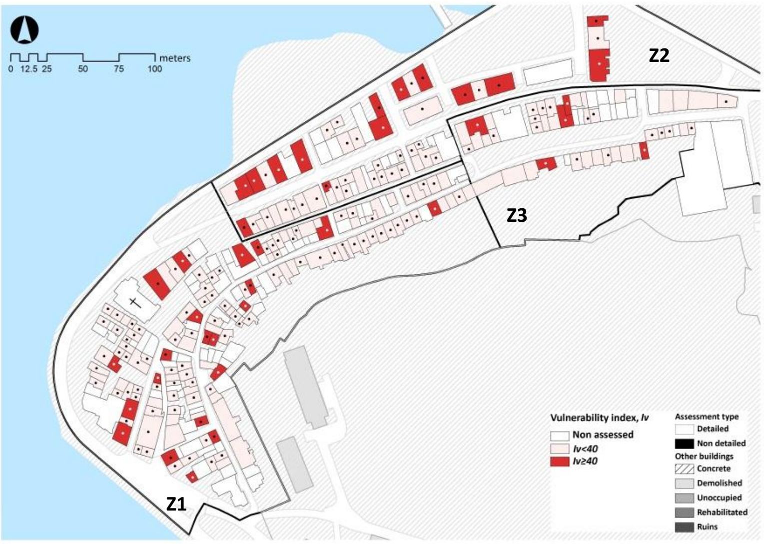

Figure 5. Identification of buildings with I_v≥40 in zones Z1, Z2 and Z3

4. DAMAGE ESTIMATION AND SCENARIOS

Mean damage grades, μ_D, are estimated for different macroseismic intensities based on the vulnerability index. For this purpose, an analytical expression which correlates hazard with the mean damage grade ($0< \mu_D <5$) of the damage distribution, in terms of vulnerability value - as shown in Eq. (4.1) - was proposed by Bernardini *et al.* (1984):

$$\mu_D = 2.5 \times \left[1 + tanh\left(\frac{I + 6.25 \times V - 13.1}{Q}\right)\right] ; 0 \leq \mu_D \leq 5 \tag{4.1}$$

where I is the seismic hazard described in terms of macroseismic intensity, V the vulnerability index (Eq. (4.2)) and Q a ductility factor which describes the ductility of a certain constructive typology (ranging from 1 to 4). In this research a ductility factor, Q, of 2.0 was adopted, as suggested by various authors (Sandi & Floricel, 1995; Vicente, 2008) providing the best fit for the comparison between the GNDT curves and EMS-98 functions. The V value defines the position of the vulnerability function, and the ductility coefficient (Q) defines the slope of the vulnerability function, that is, the growth of the damage with the seismic intensity. The vulnerability index, I_v, can be related to the vulnerability index, V (used in the Macroseismic Method), given by Eq. (4.2), enabling the calculation of the mean damage grades through Eq. (4.1).

$$V = 0.592 + 0.0057 \times I_v \tag{4.2}$$

Figure 6 shows the vulnerability curves for the mean value of the vulnerability index, $I_{v,mean}$, as well as for the upper and lower bound ranges ($I_{v,mean} - 2\sigma_{Iv}$; $I_{v,mean} - 1\sigma_{Iv}$; $I_{v,mean} + 1\sigma_{Iv}$; $I_{v,mean} + 2\sigma_{Iv}$) for events of different macroseismic intensities. The same figure also presents two mean damage grade distributions, using a beta probability distribution for seismic intensities VIII and IX. The variance of the beta distribution was defined using the value of 8 for parameter t, 0 for parameter a and 5 for parameter b.

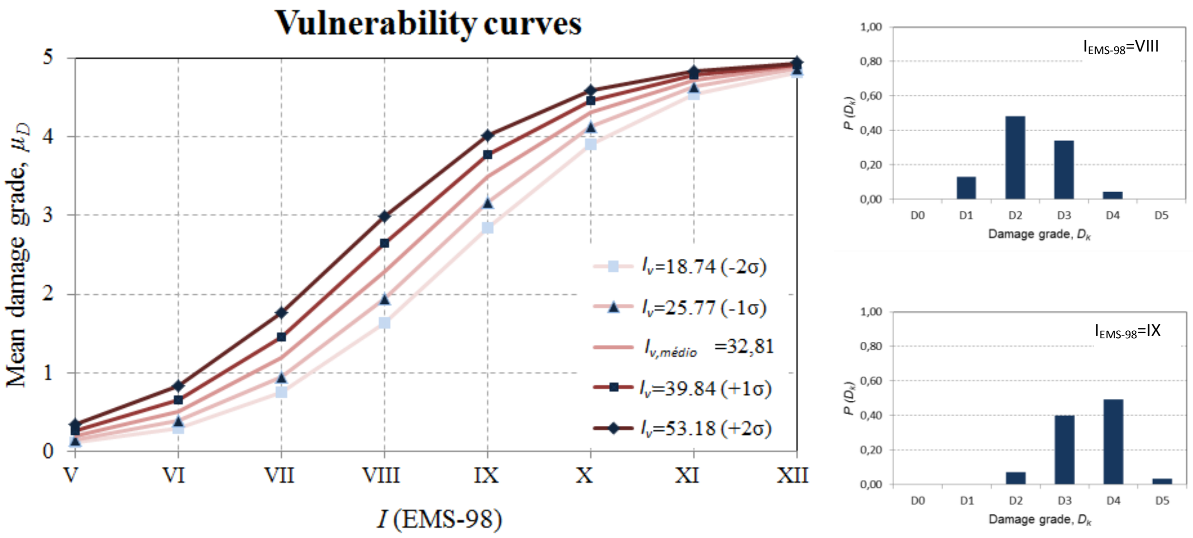

Figure 6. Vulnerability curves and mean damage grade distributions for Iv,mean=32.81

Taking advantage of a GIS tool it is possible to spatially represent the global damage distribution, μ_D, of the building stock in analysis, enabling the identification of more vulnerable areas and buildings, which can be very useful for the planning of urban management and protection strategies.

Figure 7 and Figure 8 present damage scenarios for earthquake intensities I(EMS-98)=VIII and I(EMS-98)=IX respectively (Ferreira, 2010).

Figure 7. Damage scenario for *I*(EMS-98)=VIII

Figure 8. Damage scenario for *I*(EMS-98)=IX

The damage estimative ranges from 1.47 to 3.71 for the earthquake scenario corresponding to *I*(EMS-98)=VIII and from 2.66 to 4.43 for *I*(EMS-98)=IX. Note that, buildings with a vulnerability index higher than the mean value ($I_v > I_{v,mean}$), and for which moderate damages ($2 \leq \mu D < 3$), severe damages ($3 \leq \mu_D < 4$) and potential local collapses, $\mu_D > 4$, are expected, should be reassessed.

4. FINAL COMMENTS

The results obtained in this work correlate well with the observed buildings construction features and general fragilities of built-up environment, proofing the reliability of the seismic vulnerability assessment methodology used. Even though the old city of Seixal is located in a moderate seismic hazard region, the level of damage associated to an eventual moderate seismic event can be considerable. The level of damage estimated for these buildings is an indicator of its low resistance against seismic actions and the moderate to high values of damage and loss obtained for intensities VIII and IX are consequence of the high vulnerability of these buildings.

The integration of the results in a GIS tool is fundamental in a vulnerability assessment at this urban scale, thus being useful for its management and analysis. The possibility of spatial presentation of results, associating the whole probabilistic algorithm, makes SIG an effective tool in the support of the mitigation strategies and management of seismic risk.

A rigorous vulnerability assessment of existing buildings and the implementation of appropriated retrofitting solutions can reduce significantly the physical damage and economical losses in future seismic events. In this sense, these kind of studies based on macroseismic approaches may play an important role in the seismic vulnerability assessment of built heritage in seismic prone regions.

REFERENCES

Benedetti D, Petrini V (1984) Sulla Vulnerabilità Di Edifici in Muratura: Proposta Di Un Metodo Di Valutazione. L'industria delle Costruzioni, 149(1), 66-74 (in Italian).

ESRI (2005) Geographic Information Systems. 310 New York Street, Redlands, 92373-8100, USA

Ferreira, T (2010) Seismic vulnerability assessment of old urban centres - Case study of the old city centre of Seixal, Portugal, 2010. Thesis of the post-graduate course in Rehabilitation of the Built Heritage. Faculty of Engineering of the University of Porto, Portugal (in Portuguese)

Gruppo Nazionale per la Difesa dai Terremoti - GNDT-SSN (1994). Scheda di esposizione e vulnerabilità e di rilevamento danni di primo e secondo livello (murata e cemento armato). Gruppo Nazionale per la Difesa dai Terremoti, Roma (in Italian)

Grünthal G (1998) European Macroseismic Scale 1998 (EMS-98), European Seismological Commission, Subcommission on Engineering Seismology, Working Group Macroseismic Scales. Cahiers du Centre Européen de Géodynamique et de Séismologie, 15

Pagnini L, Vicente R, Lagomarsino S, Varum H (2011) A mechanical model for the seismic vulnerability assessment of old masonry buildings. Earthquake and Struc-tures, 2(1), 25-42

Sandi H, Floricel I (1995) Analysis of seismic risk affecting the existing building stock. In: Proceedings of the 10th European Conference on Earthquake Engineering, 3, 1105-1110

Vicente R (2008) Strategies and methodologies for urban rehabilitation interventions. The vulnerability assessment and risk evaluation of the old city centre of Coimbra. PhD thesis, University of Aveiro (in Portuguese)

Vicente R, Parodi S, Lagomarsino S, Varum H, Mendes da Silva JAR (2011). Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal. Bulletin of Earthquake Engineering, 9(4), 1067-1096. Springer Netherlands

Vicente R, Rodrigues H, Varum H, Mendes da Silva JAR (2011b) Evaluation of Strengthening Techniques of Traditional Masonry Buildings: Case Study of a Four-Building Aggregate. Journal of Performance of Constructed Facilities, 25(3), 202. doi:10.1061/(ASCE)CF.1943-5509.0000164