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Seismic Risk at the Urban Scale: Assessment, Mapping and Planning

Romeu Vicente[a*], Tiago Ferreira[a], Rui Maio[a]

[a]*University of Aveiro, Campus Universitário de Santiago, Aveiro 3810-193, Portugal*

Abstract

In the last decades the evaluation of the seismic risk is of rising concern, considered essential in the activity and definition of strategy planning and urban management. The evaluation of the seismic vulnerability of the existent building stock in the perspective of seismic risk mitigation should not be placed only in relation to the isolated buildings of relevant historical and cultural importance, but also, in relation to residential buildings within old urban centers. When assessing the seismic vulnerability of buildings it is essential to first establish the project objectives, before subsequently choosing the most appropriate strategy and tools necessary for building assessment and fulfillment of these objectives. It is also extremely important to understand the difference between the detailed approaches used for individual building assessment and those methods most efficient for larger scale analysis, pursued for city center assessment. In this work, the results attained from the vulnerability assessment of the old city center of Faro, in Portugal, allowed the estimation of physical damage scenarios, economical and human losses. The methodology applied herein and results are presented resourcing to a GIS application and database management system, enabling the storage of building features and survey, seismic vulnerability and risk mapping, as well as the continued upgrading and improvement of the collected data.

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Keywords: Old urban city centers; Sesmic vulnerability; Damage scenarios; Emergency planning.

* Corresponding author. Tel.: +351 234 370 845 / Ext.: 24615; Fax: +351 234 370 094.
E-mail address: romvic@ua.pt.

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Nomenclature

C_{vi}	vulnerability classes (from *A* to *D*)
I	macroseismic intensity
$I_{(EMS-98)}$	macroseismic intensity in accordance to the European Macroseismic Scale (EMS-98)
I_v	vulnerability index
$\overline{I_v}$	mean vulnerability index of a detailed building
$\overline{\overline{I_v}}$	vulnerability index of a non-detailed building
$I_{v,mean}$	final mean vulnerability index, accounting both detailed and non-detailed assessment of buildings
p_i	weight of each 14 parameters accounting for the vulnerability index, I_v
Q	ductility factor representing the ductility of the study case masonry (constructive typology)
t, a, b	control and limit parameters of the beta probability function
V	vulnerability index used in the macroseismic method

Greek symbols

μ_D	mean damage grade

1. Introduction

1.1. Framework

Recently, European partnerships constituting various workgroups for assessing different aspects of vulnerability and earthquake risk mitigation have defined, particularly for the former, methodologies that are grouped into essentially three categories in terms of their level of detail, scale of evaluation and use of data (first, second and third level approaches). The methodology herein applied is included in the first level approaches group, which uses a considerable amount of qualitative information gathered in a reasonable time frame, being suitable for the development of seismic vulnerability assessment for large-scale analysis. One of the great advantages of first level assessment approaches consists on identifying the most vulnerable buildings within an urban area, for which more detailed assessment is required, as well as the definition of priorities for both retrofitting and in support of earthquake risk management and emergency planning (Vicente et al. 2014).

Lately in Portugal, great concern has been given to the seismic risk of our territory by various institutions and organizations, which also have been tirelessly alerting to both structural and seismic vulnerability of the Portuguese building stock, from historic districts to more recent suburbs. This increasing concern has generated a positive boost in society's awareness, due to a shared national effort among scientists, media and civil protection. Typically without sufficient seismic resistance, old masonry buildings, prevailing in historical city center environment, are in need of competent retrofitting interventions, due to their acknowledged incalculable historical, cultural and architectural value. In recent years the amount of resources spent on the seismic vulnerability assessment and structural safety evaluation has slightly increased.

1.2. The case study of the Ribeirinha area (Faro, Portugal)

As documented in several historical documents related to its historical evolution, the city of Faro and particularly the study case *Ribeirinha* area, has been victim of countless invasions and transformations throughout the centuries. Two of the most significant catastrophes happened during the 18th Century, with the well-known 1755 earthquake followed two years after by a hurricane and also by the devastating wars occurred in the early 19th Century. The knock-on effect that these events have had, led to collapse the majority of the existing building stock. Once the reconstruction process was understandably long and complex and naturally realized new construction technologies, which were implemented over the ruined buildings, during this period Faro witnessed a densification of its building stock, supporting the complex architectural nature recurrently observed in the majority of the surveyed building's backyards. As shown in Fig. 1, to optimize the referenced survey actions and the subsequent data analysis, the study case area was divided into three zones based on the construction and morphological characteristics of buildings.

(a) (b)

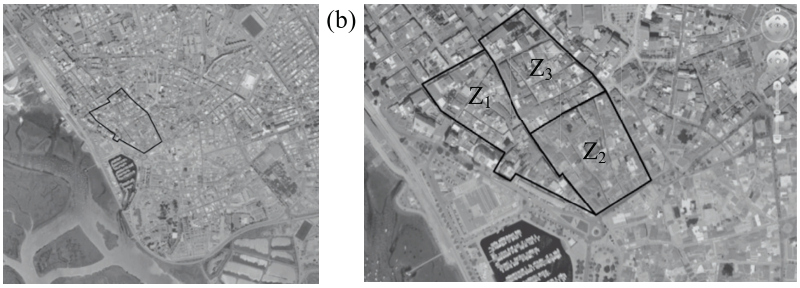

Fig. 1. *Ribeirinha* area within the city centre of Faro (a) and the corresponding areas assessed (b)

2. Assessment Methodology

2.1. Inspection period

As part of a research supported by the URBSIS project – Assessing Vulnerability and Managing Earthquake Risk at Urban Scale - and commissioned by the Faro City Council, a complete identification and inspection survey of the old masonry buildings inserted in the *Ribeirinha* area of Faro was carried out (Vicente et al. 2014). The data gathered from the inspection of 354 buildings, spread over 80,000 m^2, were processed and then crosschecked with the corresponding case files existing at the local Department of Urban Regeneration, allowing a better knowledge of the existing structural typologies and their evolution throughout the years.

Due to the difficulties encountered in accessing the interior of all the buildings and time constraints, two different levels of detail were carried out. Thus, the 354 buildings were divided into three groups based on the detail of the available information, subsequently used on the seismic vulnerability assessment. The first group, composed of the 53 buildings for which it was possible to perform a detailed inspection, was inspected and appraised by filling in detailed specific checklists adapted from a similar research project developed in the city of Seixal (Ferreira et al. 2013). These inspection and diagnosis checklists were used to survey each construction element (roof, façade walls, timber floors, internal partition walls, etc.). The second group was composed of 138 buildings for which a non-detailed exterior inspection was possible. A third group composed of 163 buildings was not included in this study due to different reason's: reinforced concrete buildings, buildings refurbished or in ruin, unoccupied buildings.

2.2. Vulnerability index methodology

Originally based on the GNDT II level approach (Benedetti & Petrini 1984) and adapted by Vicente et al. (2011) for the Portuguese reality, this hybrid methodology has been successfully applied on the seismic vulnerability assessment of old city centers of Coimbra (Vicente et al. 2011) and Seixal (Ferreira et al. 2013), Portugal. Summarizing, the masonry building stock of the old city center of Faro (*Ribeirinha* area) was assessed by assigning a vulnerability index score for each building as the weighted sum of 14 parameters. These 14 parameters were distributed into 4 vulnerability classes of growing vulnerability: *A*, *B*, *C* and *D*. Each parameter evaluated one aspect related to the building's seismic response. Subsequently, a weight, p_i, was assigned to each of the parameters, ranging from 0.50 for the less important parameters (in terms of structural vulnerability) to 1.5 for the most important (Ferreira et al. 2013).

However, as the methodology applied in this work requires accurate knowledge of the building characteristics, which can be obtained only with thorough and detailed inspection, the vulnerability assessment was undertaken in two phases. In the first phase, an evaluation of the vulnerability index was made for those buildings for which detailed information was available (53 buildings out of 354). In the second phase, a more expeditious approach for the assessment of the remaining 138 buildings was adopted, using the mean values obtained from the detailed analysis of the first group of buildings, assuming the masonry building characteristics homogeneous in this area. Starting from this principle, the mean vulnerability index value obtained in the first detailed evaluation was used as a typological vulnerability index (mean value) that could be affected by modifiers of the mean vulnerability index for each building (Ferreira et al. 2013). The classification of these modifiers influenced the final vulnerability index as a sum of the scores for all modifiers. Their scores in relation to the mean vulnerability value for each parameter are shown in the following Table 1. The vulnerability index of each non-detailed building, $\overline{\overline{I_v}}$, is defined in the following Eq. (1):

$$\overline{\overline{I_v}} = \overline{I_v} + \sum \Delta I_v \tag{1}$$

where $\overline{I_v}$ is the mean vulnerability index from the detailed assessment, and $\sum \Delta I_v$ is the sum of the modifier scores. It is important to note that this strategy is valid only if a reliable detailed assessment of a large number of buildings in the study area is initially obtained and the strategy is applied to a single building typology (in this case, rubble stone masonry).

Table 1. Vulnerability modifier factors and scores

Vulnerability modifiers		Class C_{vi}				Modifier score:
		A	*B*	*C*	*D*	$\frac{p_i}{\sum_{i=1}^{7} p_i} \times (c_{vi} - \bar{c}_{vi})$
P5	Number of floors	-1.03	0.00	3.10	9.31	pi - parameter, i, weight assigned $\sum_{i=1}^{7} p_i$ - sum of parameter weights cvi - modifier factor for vulnerability class $\bar{c}_{vi}$ - mean vulnerability class of parameter i, defined by the detailed analysis
P6	Location and soil conditions	0.00	0.52	2.07	5.17	
P7	Aggregate position and interaction	-1.03	0.00	3.10	9.31	
P8	Plan configuration	-2.07	-1.55	0.00	3.10	
P9	Height regularity	0.00	0.52	2.07	5.17	
P12	Roofing system	-2.76	-2.07	0.00	4.14	
P13	Fragilities and conservation state	-2.76	-2.07	0.00	4.14	

2.3. GIS tool/application

The outputs from this assessment were mapped using a GIS tool connected to a relational database of structural building characteristics obtained from a series of detailed inspection actions. The GIS application software adopted in this study was ArcGis® 10.2 (Esri 2012), which environment combines geo-referenced graphical data with building parameter information. All of the implemented routines were programmed in Phyton® and compiled in Visual Basic® (a compatible programming language) on a Microsoft Windows® 7 platform. Various modules were developed for different tasks, including vulnerability assessment, damage and loss estimation (such as number of collapsed buildings, death rate, number of unusable buildings and repair costs) for different macroseismic intensities, allowing for the construction of multiple physical damage and loss scenarios.

3. Mapping and Scenarios

3.1. Vulnerability index mapping

According to the application of the vulnerability index methodology to 53 buildings in a detailed manner, which corresponded to the first phase of the assessment, a mean value of their seismic vulnerability index, $\overline{I_v}$, of 36.15 was obtained. With the introduction of the complementary approach, used in the assessment of the remaining 138 buildings for which the information was incomplete (second phase of assessment), the final mean vulnerability index, $I_{v,mean}$, decreased to 34.12, which represented a difference of 6% in relation of its initial value $\overline{I_v}$. Approximately 15% of the assessed buildings had a $I_{v,mean}$ value over 40 and 5% over 45 (equivalent to vulnerability class A in the EMS-98 scale) (Grünthal 1998). The maximum and minimum I_v values obtained from the detailed assessment were 53 and 20, respectively.

Fig. 2. Vulnerability index mapping of buildings within the *Ribeirinha* area (a) and the highlight of buildings with $I_v \geq 40$ (b)

Globally, the results observed in Fig. 2 were considered well adjusted to the characteristics and fragilities of the evaluated buildings, allowing for the identification of areas where more vulnerable buildings were located. These results must be interpreted statistically, by identifying a representative mean value and defining the upper and lower bounds of the vulnerability index results. Thus, by the one hand, from analyzing Fig. 2 (a), one observes that Z_3 is broadly the most vulnerable zone within this area. By the other hand, Fig. 2 (b) highlights the corner and end row buildings of street blocks as the most vulnerable ones due to their particular locations and interaction conditions with adjacent buildings (Vicente et al. 2014). For this reason, these buildings are recommended for reassessment, with a particular focus on eventual retrofitting and/or strengthening actions. Once more, it is important to refer that unoccupied and "in ruin" buildings (78 buildings out of 354) would seriously exacerbate this scenario.

3.2. Damage distribution and scenarios

Based on the previous mean value of the vulnerability index, $I_{v,mean}$, mean damage grades, μ_D, were estimated for different macroseismic intensities, using the well-known analytical expression proposed by Bernardini et al. (2007), which correlates hazard with the mean damage grade ($0 < \mu_D < 5$) of the damage distribution, as shown in Eq. (2):

$$\mu_D = 2.5 \times \left[1 + tanh\left(\frac{I + 6.25 \times V - 13.1}{Q}\right)\right] ; 0 \leq \mu_D \leq 5 \qquad (2)$$

where I, V, and Q are defined in the nomenclature. The vulnerability index I_v can be related to the vulnerability index used in the macroseismic method through Eq. (3). The ductility Q, ranging from 1 to 4, was considered equal to 3.0, providing the best fit for the comparison between the GNDT curves and EMS-98 functions (see (Ferreira et al. 2013; Vicente et al. 2011)).

$$V = 0.592 + 0.0057 \times I_v \qquad (3)$$

Fig. 3 (a) shows the vulnerability curves related to $I_{v,mean}$, and the respective upper and lower bound ranges ($I_{v,2stvn}$; $I_{v,stvn}$; $I_{v,stvp}$; $I_{v,2stvp}$) for events of different $I_{(EMS\text{-}98)}$. Fig. 3 (b) and (c) shows the corresponding mean damage grade distributions obtained through the use of a beta probability distribution for seismic intensities $I_{(EMS\text{-}98)} = \text{VIII}$ and $I_{(EMS\text{-}98)} = \text{IX}$, respectively. The variance of the beta probability function was defined using the following values: $t = 8$, $a = 0$ and $b = 5$.

The use of the mentioned GIS tool allowed for the mapping of the global damage distribution, μ_D, of the building stock under analysis, enabling the identification of more vulnerable areas and buildings, extremely useful for planning urban management and protection strategies. Fig. 4 (a) and (b) present the damage scenarios for seismic intensities $I_{(EMS\text{-}98)} = \text{VIII}$ and $I_{(EMS\text{-}98)} = \text{IX}$, respectively. The estimated damage ranged from 1.71 to 3.12 for the earthquake scenario corresponding to $I_{(EMS\text{-}98)} = \text{VIII}$ and from 2.93 to 4.09 for $I_{(EMS\text{-}98)} = \text{IX}$. In particular, buildings with $I_v > I_{v,mean}$, for which severe damages ($3 \leq \mu_D < 4$) and potential local collapse ($\mu_D > 4$) are expected, require reassessment with a more detailed methodology.

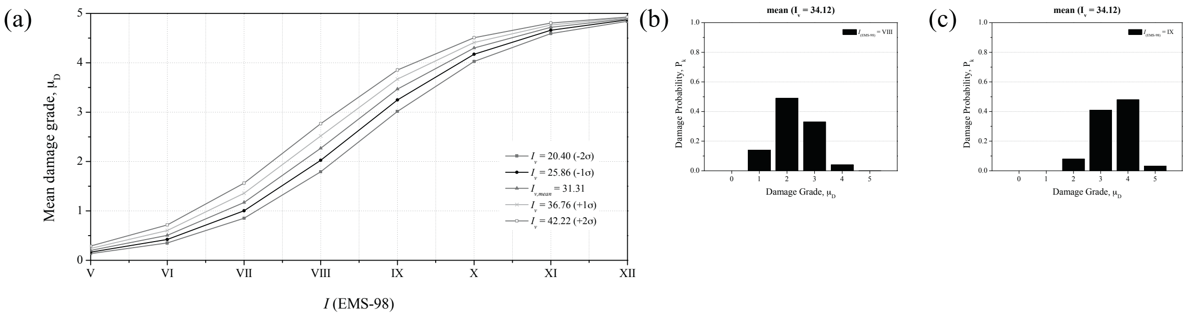

Fig. 3. Vulnerability curves (a) and mean damage grade distributions of $I_{v,mean} = 34.12$ for $I_{(EMS\text{-}98)} = \text{VIII}$ (b) and $I_{(EMS\text{-}98)} = \text{IX}$ (c)

Fig. 4. Damage scenario for $I_{(EMS\text{-}98)} = \text{VIII}$ (a) and $I_{(EMS\text{-}98)} = \text{IX}$ (b)

3.3. Fragility curves

Fragility curves, being another way to represent the estimated damage, are defined as the probability of exceeding a certain damage grade or state, D_k ($k \in [0;5]$) and influenced by the parameters of the beta distribution function, allowing for the estimation of damage as a continuous probability function. This probability is obtained directly from the physical building damage distributions derived from the beta probability function for a determined building typology. As shown in Eq. (4), the discrete probabilities, $P(D_k = d)$, are derived from the difference of cumulative probabilities $P_D[D_i \geq d]$. Fig. 5 (a) and (b) show the fragility curves obtained for $I_{v,mean} = 34.12$ and $I_{v,\,2stvp} = 39.70$, respectively.

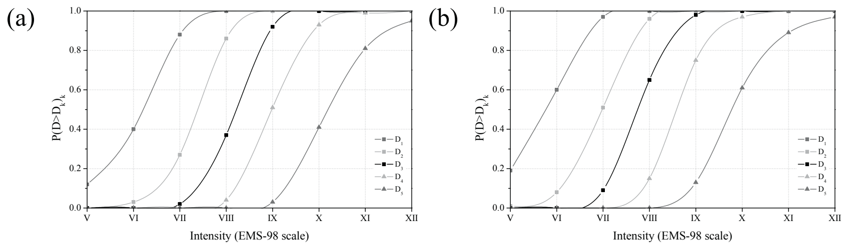

Fig. 5. Fragility curves for $I_{v,mean}$=34.12 (a) and $I_{v,\,2stvp}$=39.70 (b)

$$P(D_k = d) = P_D[D_k \geq d] - P_D[D_{k+1} \geq d] \tag{4}$$

4. Loss estimation

Loss estimation plays an important role in the implementation of urban planning and retrofitting strategies, enabling costs to be placed alongside various beneficial measures such as reduced repair costs and life safety (D'Ayala et al. 1997; Ferreira et al. 2014). In this work, the loss estimation was covered and discussed by the construction of damage scenarios based on global probabilistic distributions, using the same representative upper and lower bounds of the mean vulnerability index.

4.1. Collapsed and unusable buildings

The loss estimation model herein applied is based on damage grades that relate the probability of exceeding a certain damage level with the probability of collapse and functional loss and involves the analysis of data associated with the probability of buildings to be deemed unusable after minor and moderate seismic action. In Italy, data processing undertaken by Bramerini et al. (1995) has enabled the establishment of multiplier factors and respective expressions for their use in the estimation of building losses. These probabilities are affected by the mentioned multiplier factors, which range from 0 to 1. The following Eq. (5) and (6), were used for the analysis of collapsed and unusable buildings:

$$P_{collapse} = P(D_5) \tag{5}$$

$$P_{unusable\ buildings} = P(D_3)\times W_{ei,3} + P(D_4)\times W_{ei,4} \tag{6}$$

where $P(D_i)$ is the probability of the occurrence of a certain damage grade (from D_1 to D_5) and $W_{ei,j}$ indicates the percentage of buildings associated with the damage grade, D_i, that suffer collapse or are considered unusable. Although Bramerini et al. (1995) and HAZUS (FEMA-NIBS 1999) methodologies have indicated distinct values for these multiplier factors, $W_{ei,j}$, the ones applied in this study were: $W_{ei,3}$ = 0.4; $W_{ei,4}$ = 0.6. Fig. 6 presents the probability of building collapse and unusable buildings again for $I_{v,mean}$ = 34.12 and the above mentioned bounds. It is important to note that the number of unusable buildings decreased with the intensity, as the number of buildings that suffered collapse increased.

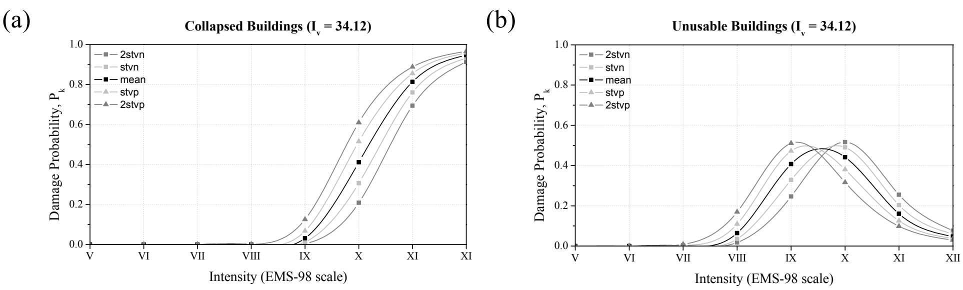

Fig. 6. Probability of collapse (a) and unusable buildings (b) for different I_v values

4.2. Human casualties and homelessness

The proposal by Bramerini et al. (1995) was also used to estimate the casualty rates (dead and severely injured) and homelessness. While casualty rates was accounted as being 30% of the residents living in collapsed and unusable buildings, where the survivors were assumed to require short-term shelters (see Eq. (7)), the homelessness rates was determined using Eq. (8). Fig. 7 shows an estimation of the number of deaths, severe injuries and homelessness for $I_{v,mean}$ and the corresponding mentioned bounds. It is important to note the significant percentage of potential homeless people for a $I_{(\text{EMS-98})}$ = IX scenario. This result stresses the importance of efficient logistical preparation by competent authorities for the temporary relocation of residents.

$$P_{dead\ and\ severely\ injured} = 0.3 \times P(D_5) \tag{7}$$

$$P_{homeless} = P(D_3) \times W_{ei,3} + P(D_4) \times W_{ei,4} + 0.7 \times P(D_5) \tag{8}$$

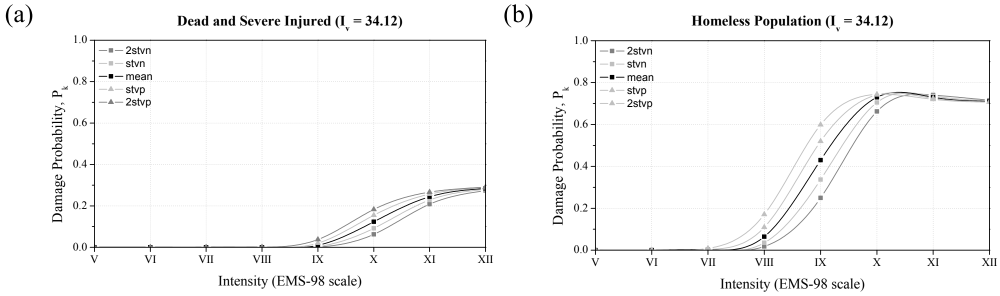

Fig. 7. Estimation of casualties and homelessness for different vulnerability values

4.3. Economic loss and repair cost estimation

The estimated damage grade can be interpreted either economically or as an economic damage index that represents the ratio between the repair costs and the replacement costs (Benedetti & Petrini 1984). The correlation between damage grades and the repair/rebuilding costs was proposed by Dolce et al. (2006), once more through the processing and analysis of post-earthquake damage data. These statistical values derived from analysis of the data collected, using the GNDT-SSN procedure, after the Umbria-Marche (1997) and Pollino (1998) earthquakes (Dolce et al. 2006) and were based on the estimated cost of typical repair interventions for more than 50,000 buildings (Vicente et al. 2011). The repair cost probabilities for a certain seismic event characterized by an intensity I, $P[R|I]$, can be obtained from the product of the conditional probability of the repair cost for each damage level, $P[R|D_k]$, with the conditional probability of the damage condition for each level of building vulnerability and seismic intensity, $P[D_k|I_v,I]$, as shown in the following Eq. (9):

$$P[R|I] = \sum_{D_k=1}^{5} \sum_{I_v=0}^{100} P[R|D_k] \times P[D_k|I_v, I] \tag{9}$$

To estimate the repair costs associated with the different vulnerability values used in the loss evaluation ($I_{v,\,2stvn}$; $I_{v,mean}$; $I_{v,\,2stvp}$), an average cost value per unit area of 482 €/m^2 was considered for the building stock in the *Ribeirinha* area of Faro (Ministerial Ordinance no.370 2013). The estimated global repair costs within the study case area is shown in Fig. 8, in which the range between repair costs varies significantly for the estimated regional intensities in the Algarve region, $I_{(\text{EMS-98})}$ = VIII and $I_{(\text{EMS-98})}$ = IX (Mota de Sá 2009). The repair costs estimated in terms of building area range from 6.6% for $I_{(\text{EMS-98})}$ = VII to 56.1% for $I_{(\text{EMS-98})}$ = VIII.

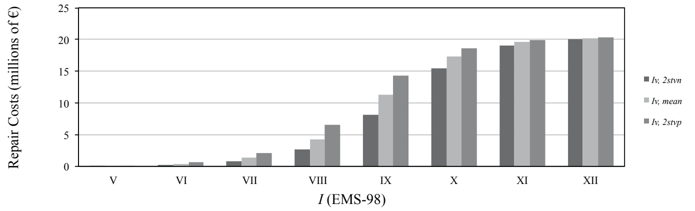

Fig. 8. Estimation of repair cost for the *Ribeirinha* area of Faro

5. Conclusions

The resilience of urban areas is highly dependent on the quality and level of conservation of the building stock, therefore the study of simple to more complex vulnerability assessment methodologies is crucial to support post-disaster validated decisions based on damage scenarios, as well as aid emergency and relief planning by competent and skilled authorities. The methodology presented previously together with the GIS applications and database management system is acknowledged to be of great advantage on interpreting outputs, providing a good spatial overview of the vulnerability assessment and risk scenarios, including potential damage mapping and loss scenarios. The application developed will be used to foresee the impact or retrofitting strategies in the reduction of vulnerability and consequent economic losses as further ongoing research tasks. This integrated tool is extremely helpful for the development of strengthening strategies, cost-benefit analyses, and aid decision making of civil protection bodies.

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References

Benedetti, D. & Petrini, V., 1984. Sulla vulnerabilita sismica di edifici in muratura: un metodo di valutazione. A method for evaluating the seismic vulnerability of masonry buildings. *L'industria delle costruzioni*, (149), pp.66–74

Bernardini, A. et al., 2007. Vulnerabilità e previsione di danno a scala territoriale secondo una metodologia macrosismica coerente con la scala EMS-98. In *In Proceedings of the 12th Conference of the Italian National Association of Earthquake Engineering - ANIDIS*. 10-14 June, Pisa, Italy

Bramerini, F. et al., 1995. *Rischio sismico del territorio Italiano: proposta per una metodologia e risultati preliminary, Technical report SSN/RT/95/01*, Rome, Italy

D'Ayala, D. et al., 1997. Earthquake Loss Estimation for Europe's Historic Town Centres. *Earthquake Spectra*, 13(4), pp.773–793

Dolce, M. et al., 2006. Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies. *Engineering Structures*, 28(3), pp.357–371

Esri, 2012. Environmental Systems Research Institute, Inc. (ESRI)

FEMA-NIBS, 1999. *Earthquake loss estimation methodology, Technical report HAZUS99*, Washington DC, USA

Ferreira, T.M. et al., 2013. Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal. *Bulletin of Earthquake Engineering*, 11(5), pp.1753–1773

Ferreira, T.M., Vicente, R. & Varum, H., 2014. Seismic Vulnerability Assessment of Masonry Facade Walls: Development, Application and Validation of a New Scoring Method. *Structural Engineering and Mechanics*, 50(4)

Grünthal, G., 1998. *European Macroseismic Scale 1998 (EMS-98), European Seismological Commission, Subcommission on Engineering Seismology, Working Group Macroseismic Scales* R. Musson, J. Schwarz, & M. Stucchi, eds., Luxembourg: Cahiers du Centre Européen de Géodynamique et de Séismologie

MinisterialOrdinanceno.370, 2013. *Portaria no. 370/2013 de 27 de Dezembro do Ministério das Finanças*, Portugal. Available at: www.dre.pt.

Mota de Sá, F., 2009. *"Simulador sísmico do Algarve - Manual de Utilização", Technical report WP22 for the Seismic and Tsunami Risk Assessment of the region of Algarve, FUZZY*

Neves, F. et al., 2012. Seismic vulnerability assessment and characterisation of the buildings on Faial Island, Azores. *Bulletin of Earthquake Engineering*, 10(1), pp.27–44. Available at: http://link.springer.com/10.1007/s10518-011-9276-0 [Accessed February 19, 2014].

Vicente, R. et al., 2011. Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal. *Bulletin of Earthquake Engineering*, 9(4), pp.1067–1096

Vicente, R., Ferreira, T.M. & Mendes da Silva, J.A.R., 2014. Supporting urban regeneration and building refurbishment. Strategies for building appraisal and inspection of old building stock in city centres. *Journal of Cultural Heritage*