Composite methodology for tsunami vulnerability assessment based on the numerical simulation of 1755 Lisbon tsunami—application on two Portuguese coastal areas

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ABSTRACT: Different methodologies for tsunami risk assessment have been developed, namely for reconstitution of previous hazardous events and for planning awareness and alert systems and civil protection resources. The vulnerability analysis is frequently based on simulations using precursor impact damages and on modeling hydrodynamic floods. Our innovative approach is applied on two distinctive coastal Atlantic areas, with urban and rural/natural context from Setúbal and Figueira da Foz counties. We presented a deepened methodology for assessing vulnerability to tsunamis in its social, structural and morphological component that results of new inputs that distinguish this from previous studies. The tsunami inundated areas were obtained from tsunami numerical modeling. The morphological and structural analysis is based on field work element collection using a matrix with 18 parameters. For the social impacts evaluation, a multi-components analysis is performed, using 47 socio-economics variables, expressing the expected impacts. A composite territorial index of vulnerability is presented and mapped.

1 INTRODUCTION

The evaluation of the degree of exposure and vulnerability to natural disasters in the last decade has seen a notable increase (Wisner et al., 2004; Douglas, 2007). Even after the 2004 India Ocean Tsunami, and more recently the 2011 Japan Tsunami there has been a focus on the hazard process assessment and mapping through physical models (Liu et al., 2007; Santos et al., 2007; Santos, 2011; Satake et al., 2011; Singh et al., 2012). Other approaches have been focusing on the analysis of territorial vulnerability resulting from past impact in predicting future events (Dominey-Howes and Papathoma, 2007; Dall'Osso et al., 2009; Dominey-Howes et al., 2009; Hart and Knight, 2009; Dominey-Howes et al., 2010). On the other hand, several studies have been pointing the importance of conceptual requirements and technical problems for territorial vulnerability assessment, like the scale analysis (Fekete et al., 2010; Kienberger et al., 2013), the perception of natural and technological risks (Tavares et al., 2011), the supporting data (Papathoma et al., 2003; Silva and Pereira, 2014) and the comparativeness

of models (Smit and Wandel, 2006), to develop detailed territorial approach and strong risk analysis. Furtermore, different authors underlined the vulnerability assessment and territorial coping capacity on tsunami affected areas based on natural scope (Taubenböck et al., 2008; Kaplan et al., 2009; Hart and Knight, 2009), according the building fragilities (Papathoma and Dominey-Howes, 2003; Ghobarah et al., 2006; Dominey-Howes et al., 2010; Omira et al., 2010; Leone et al., 2011; Reese et al., 2011) or empathizing the support capability (Post et al., 2009; Freire et al., 2013). In addition, an enlarged understanding of vulnerability related with natural hazards has been enhanced (Turner et al., 2003; Cutter et al., 2003; Cardona, 2004; Adger, 2006; Douglas, 2007; Mendes, 2009) emphasize not only in the impacts and coping post events, but also the long term recovery capacity and the adaptation to the reframed conditions.

In this study two coastal areas of Portugal were selected (Fig. 1): Figueira da Foz, located in the central region of Portugal and Setubal located nearby Lisbon. Therefore, the objective of this study is to propose a multidimensional vulnerability analysis for coastal areas with a potential
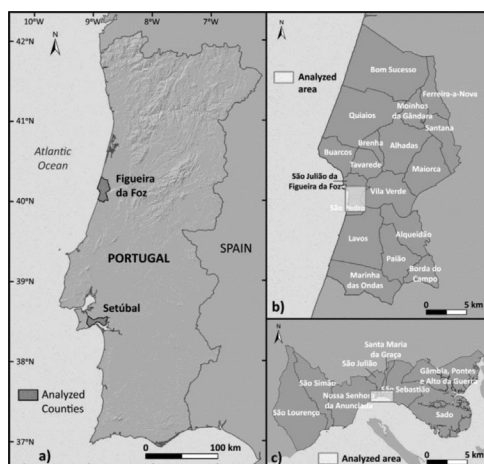
Figure 1. Location of the two studied areas: a) Portugal framework; b) Figueira da Foz; c) Setubal.

tsunami hazardous impact. First is calculated the morphological index of vulnerability (Mv) that combines the different physical and occupation characteristics of the analyzed area. Secondly, is calculated the structural vulnerability index (Bv) that estimates the vulnerability of the different potentially affected buildings. Thirdly, the social vulnerability (Sv) that analyzes the socioeconomic characteristic of the study area is calculated.

Finally, is calculated the Composite Index of Vulnerability (CVI) that aggregates the three indices previously calculated.

The main goal is to assess a potential tsunami impact by considering the coastal natural scope, the existing building characteristics and the societal capability, in the sense of (Deneulin and McGregor, 2010).

2 METHODOLOGY

The tsunami inundated areas used in this study are based on the worst case scenario which is the 1755 Lisbon Tsunami. This is an innovative approach because these results were obtained from the tsunami numerical modeling carried out by Santos et al. (2012) and Santos & Koshimura (2013).

Then, a multidimensional vulnerability analysis for the two coastal areas is proposed. Furthermore, this study presents a new methodological approach to evaluating the structural, morphological and social vulnerability to tsunamis. This methodology was supported on the collection and assessment of large data from fieldwork and databases. The data processing and analysis were supported

by statistical tools for a composite vulnerability index characterizing the potential inundated areas. For the process associated with the morphological component analysis a total of 5 parameters (Table 1) were taken into consideration, in particular by adapting the coastal vulnerability index (Pendleton et al., 2010) and the physical vulnerability index presented in Ismail et al. (2012).

A matrix was built for the data acquisition and evaluation of the parameters. In this matrix, to each parameter was assigned a value ranging from −1 to +1, with positive values representing an increase in vulnerability, and negative values a decrease in vulnerability.

After assigning values to each of the different parameters, the morphological vulnerability index was calculated, ranging from "very low" to "very high". Regarding the structural component, the potential affected buildings by the tsunami inundation were analyzed. A total of 13 parameters were included in the matrix, which characterize the buildings in its structural, architectural and occupational tools (Table 2). On the other hand, the data acquisition was based on fieldwork in order to collect several intrinsic characteristics of the building and the surrounding areas.

Furthermore, in the structural component new parameters were introduced related to the

Table 1. Morphological assessment parameters (Mv).

Morphological assessment parameters
Morphology of the flooded area
Consolidation of geologic materials
Average slope (º)
Distance to coastline
Use and land cover

Table 2. Structural assessment parameters (Bv).

Structural assessment parameters
Number of floors
Construction material
Date of built
Preservations conditions
Hydrodynamics of r/c
Existence of underground floors
Foundations type
Occupation form
Number of utilization units
Average number of daily visitors or residents per unit of use
Occupation floating
Built form plan
Emerged building height in relation to the wave

occupation of the buildings that are not included in the previous methodologies presented by Dall'Osso et al. (2009) and Ismail et al. (2012). The introduction of parameters "form of occupation", "number of units for use"; "average daily number of persons present or visitors per unit of use" and "floating occupation" allow complementary analysis of buildings including through its functional distinction seasonal and occupational, thereby enhancing the analysis. For each attribute is assigned a value that vary from −1 to +1, whereas positive values represent an increase of vulnerability and negative values a decrease of vulnerability. The parameters included in the structural component do not influence the building's vulnerability in the same way. For this reason it was necessary to assign weight for the different parameters. Weights have been calculated via pair-wise matches between each of the factors, using M-Macbeth3 software, that is a platform for multi criteria analysis and decision making processes (Bana e Costa et al., 2004; Bana e Costa & Chagas, 2004). After assigning values to each of the different parameters, the index of structural vulnerability was calculated, ranging from "very low" to "very high". The methodology for assessing social vulnerability was based on the methodology performed by Cutter et al. (2003), Mendes (2009), atribuir Schmidtlein et al. (2008) and Chen et al. (2013) using factor analysis performed in SPSS. Initially were collected a total of 172 variables of social, economic, demographic and the ones related with buildings in the studied areas. Social vulnerability was analyzed by using factor analysis, which allows the elimination of redundant data, their standardization and their grouping factors. The analysis was performed for a total of 15 municipalities and 88 parishes. As a result, the correlation matrix of data was evaluated, where all the data with a correlation higher than 0.7 were removed. A factor analysis was performed until a set of parameters was obtained to validate the sample. These parameters are: KMO of 0.717, more than 0.6 communalities and a variance rate of 78% (Comrey & Lee, 2009).

From this analysis, the initial 172 variables were reduced to 47, which are grouped in Table 3.

Table 3. Social vulnerability variables (Sv).

Group of variables	Number of variables
Agriculture	3
Buildings/sccommodation	19
Economy	6
Population	13
Services	3
Social support	3

After the factor analysis was calculated the social vulnerability for each parish based on SoVI® classification of Cutter et. al. (2003), ranging the vulnerability from "very low" to "very high". After calculating the morphological, structural and social vulnerability a Composite Vulnerability Index (CVI) was calculated, which integrates the three components with the following formula:

$$CVI = Mv + Bv + Sv \qquad (1)$$

where Mv = weighted sum of the morphological parameters; Bv = weighted sum of the structural parameters; and Sv = factorial analysis scores of the social vulnerability.

The final composite vulnerability index, was obtained by the simple mean of three parameters. The index ranging from "very low" to "very high", based on standard deviation, according to the categories: "very low": <−1 SD; "low": [−1, −0.5 [SD; "moderate": [−0.5, +0.5 [SD; "high": [0.5, 1 [SD; "very high": ≥1 SD.

3 STUDY AREAS' CHARACTERIZATION

The municipality of Figueira da Foz is located in the central coastal area of Continental Portugal and has an area of 379 km² (Fig. 1a). According to the 2011 Census (INE, 2011) the county records a population of 62,125 inhabitants, divided unequally by 18 parishes with a population density of 163.3 (hab/km²). In this study the area of Cabedelo, the industrial zone of the port of Figueira and Cova-Gala were analyzed (Fig. 1b). These areas are located on the left bank of the Mondego river, belonging to the parish of S. Pedro. The choice of Figueira da Foz was justified by the fact that of the existence of historical accounts related to the 1755 Lisbon Tsunami (Santos et al., 2009; Santos et al., 2012), the high seasonal population dynamics and the existence of a major harbor and industrial zone along the coast. The analyzed area in Figueira da Foz is characterized by low altitudes between 0 and 8 m with gentle slopes and the existence of dunes. In terms of the sediment consolidation, the area is characterized by the existence of unconsolidated sediments, beaches and mudslides. With regard to land use and occupation the area presents natural/agricultural areas and salines, and an industrial area that includes Cabedelo, industrial harbor. This study area also included artificialized spaces with residential urban fabric, health and social equipments in Cova Gala, on the left bank of the river Mondego.

The second study area has an urban occupation that belongs to the Setúbal city, which is located in the Sado estuarine region (Fig. 1c). According to

the 2011 Census (INE, 2011) the municipality of Setúbal has a population of 121 185 inhabitants distributed by 8 parishes with a population density of 520.1 (hab/km²) and has an area of 172 km². The choice of Setúbal is justified by the fact of the existence of historical accounts related to the 1755 Lisbon Tsunami (Santos & Koshimura, 2013), reporting the existence of many fatalities and severe damage, the urban area is located on low altitudes of about 4 m, and the existence of marinas and an important harbor. The area is mostly represented by alluvial deposits and landfills, observing generally low altitudes (between 3 to 4 m) and very low slopes. The land use and occupation area is characterized by urban fabric and close to the shoreline by harbor and leisure facilities

4 RESULTS AND DISCUSSION

4.1 Morphological vulnerability

The morphological differentiation of vulnerability's mainly result in the distance to the coast, verifying in general, a decrease of vulnerability with increasing their distance (Fig. 2). The Figueira da Foz area also presents "moderate" to "high" levels
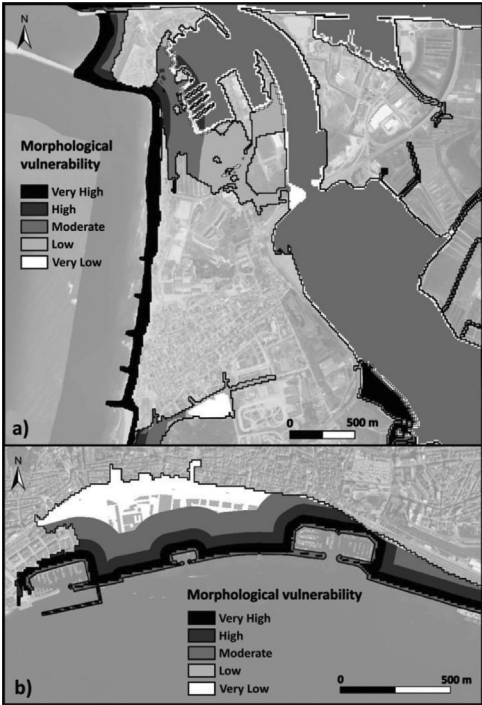

Figure 2. Morphological vulnerability: a) Figueira da Foz; b) Setúbal.

of vulnerability in the estuarine area related with flat zones and narrow channels (Fig. 2a). For the Setúbal area, namely artificialized, the differentiation of morphological vulnerability results from the distance to the shoreline and the low slope, showing a general decrease of vulnerability with increasing their distance (Fig. 2b).

4.2 Structural vulnerability

In the analyzed area in the municipality of Figueira da Foz there were identified a total of 47 buildings potentially affected by the occurrence of a tsunami similar to the 1755. Making an analysis of all the buildings evaluated is concluded that 42% present the following categories: warehouses, shipyards, workshops and outhouses, 30% have take an exclusively residential typology, 13% are industrial buildings, 11% are commercial buildings and 4% represent fabric allocated to services. However, it could be identified two distinct zones within the study area: the Cabedelo zone and the industrial harbor are clearly dominated by industrial buildings, warehouses and buildings belonging to shipyards. Further southern in the Cova-Gala the residential buildings dominate. The different land occupation shows two zones for the structural vulnerability. Also noted was the camping, that was not affected by the tsunami inundation. However, it could be isolated because the only access to it could be completely inundated. The structural vulnerability varies from "high" vulnerability to "low" vulnerability, but where most of buildings (85%) are classified with "moderate" vulnerability. (Fig. 3a).

The analyzed area in the municipality of Setúbal presents an urban riverfront downtown, where are located the recreational and fishermen docks, and also the equipments of Setúbal harbor. The area is bounded on the north by the historic city center and to the south by the Sado estuary. A total of 468 potentially affected buildings were identified, mostly with commercial use or assigned to administrative services (60%). A number of 135 buildings (29%) has mixed function, (ie, residential and commercial use), and only 54 (11%) have an exclusively residential typology. This area also presents two distinctive structural vulnerabilities based on the buildings characteristics, separated by the main city Avenue. One to the north, where the buildings has residential function, among which are some properties degraded in narrow streets located in the historic city center; and another area to the south, where stands out the buildings connected to the two main economic activities characteristic of this riverside area—the shops and restaurants connected to the fishing industry, and the port of Setúbal. As presented on
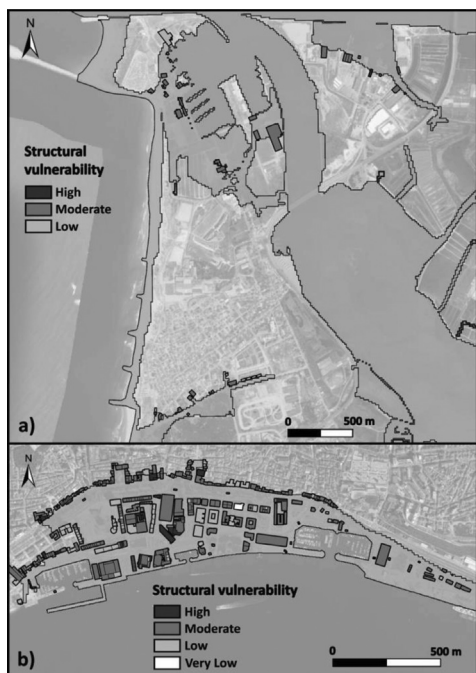
Figure 3. Structural vulnerability: a) Figueira da Foz; b) Setúbal.

the Figure 3b the structural vulnerability of the buildings range from the "very low" vulnerability to the "high" structural vulnerability.

4.3 *Social vulnerability*

For the social vulnerability analysis it was considered the entire county areas (Figueira da Foz and Setubal). Then, the obtained results were projected for the two studied areas. In the Figueira da Foz the social vulnerability for each parishes varies between "low" vulnerability and "very high" vulnerability (Fig. 4a). In the municipality of Setúbal the social vulnerability varies between "very low" and "high" vulnerability (Fig. 4b). In general, the municipality of Figueira da Foz has a social vulnerability higher than the municipality of Setúbal. Regarding to the specific analyzed area part of the municipality of Figueira da Foz, the Cabedelo zone and Cova Gala (located in the parish of S. Pedro) present a "very high" social vulnerability. In the municipality of Setúbal the analyzed area is divided in 4 parishes, which present different social vulnerability rates. The parishes of Nossa Senhora da Anunciada and São Sebastião have a "high" social vulnerability, the São Julião parish presents a "low" vulnerability and the Santa Maria da Graça parish presents a "very low" social vulnerability rate. The studies
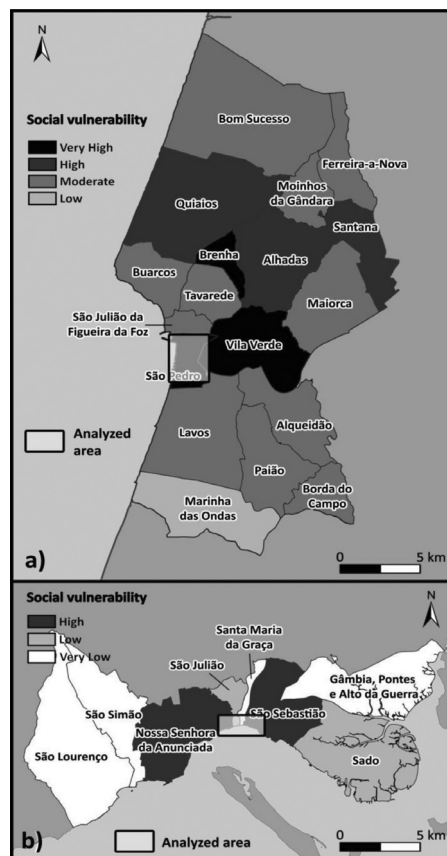

Figure 4. Social vulnerability: a) Figueira da Foz; b) Setúbal.

areas show that social vulnerability rates are very marked by administrative boundaries, as a result of demographic, social and economic variables.

4.4 *Composite vulnerability index*

After calculating the morphological, structural and social vulnerabilities, the Composite Vulnerability Index (CVI) was calculated. This new index combines all the previously calculated indexes. The results in Figueira da Foz study area are: mean = 0.465, and the standard deviation is 0.026. The results also show that the CVI present the highest values in front impact zone (Fig. 5a), with a decrease in vulnerability, with rare exceptions, to the inland of the study area, attending to an indirect relationship between vulnerability and distance to the shoreline. In the analyzed area the CVI varies from "very low" to "very high" (Table 4). 8% of the area is classified as "very high" vulnerability, corresponding almost exclusively to the coastal
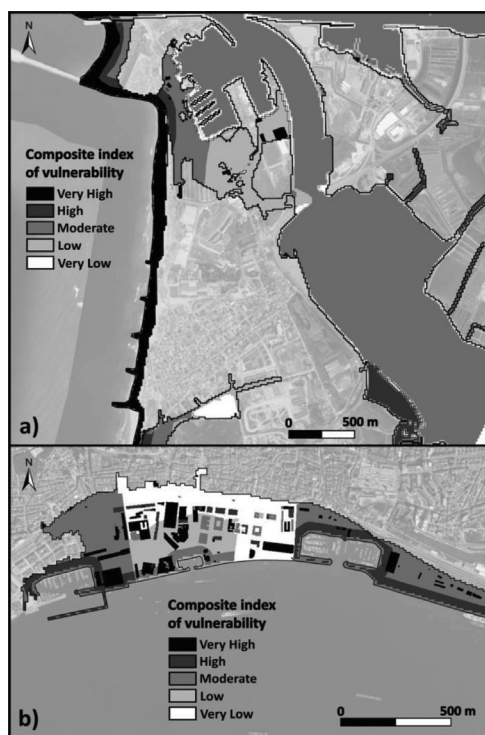
Figure 5. Composite Vulnerability Index (CVI): a) Figueira da Foz; b) Setúbal.

Table 4. Classification of Composite Vulnerability Index (CVI) to Figueira da Foz.

Standard deviation classes	Classification interval	Nominal classification
<−1 SD	0.394–0.439	Very low
[−1, −0.5 [SD	0.439–0.452	Low
[−0.5, +0.5 [SD	0.452–0.478	Moderate
[+0.5, +1 [SD	0.478–0.491	High
≥+1 SD	0.491–0.696	Very high

area and some buildings. With "high" vulnerability rate is classified 4% of the area, which corresponds to the stretch near the coastline and saline areas. 73% of the area presents "moderate" vulnerability that corresponds to the zones near de Mondego river and the harbor zone. With "low" vulnerability (10%) and "very low" vulnerability (5%) are identified the inland areas mostly in the south of Cova Gala and in the fishery and industrial zones.

The results in Setubal study area are: mean is 0.439, and the standard deviation is 0.084.The results of the CVI in Setúbal study area (Fig. 5b)

Table 5. Classification of Composite Vulnerability Index (CVI) to Setubal.

Standard deviation classes	Classification interval	Nominal classification
<−1 SD	0.287–0.356	Very low
[−1, −0.5 [SD	0.356–0.398	Low
[−0.5, +0.5 [SD	0.398–0.481	Moderate
[+0.5, +1 [SD	0.481–0.523	High
<+1 SD	0.5228–0.7028	Very high

show an increase of the vulnerability of the buildings, mainly in western and eastern zones, where the majority of buildings present a rating of "very high" vulnerability. Also noted is a large area in the central zone classified as "low" and "very low" CVI, which is a result of the positive social and economic characteristics of the population, expressed by the social vulnerability index. In this area de importance of the morphological component is still present, namely by the parameter that refers to the distance to the shoreline parameter, standing out essentially on the western and eastern zones with a stretch of high vulnerability around the shoreline.

Analyzing the cartographic output (Table 5), 13% is classified as "very high" composite vulnerability index, corresponding exclusively to buildings. With "high" CVI is classified 15% of the area, which corresponds to the band around the coastline, as well as some buildings. Most of the area (37%) has "moderate" composite index. The "low" (11%) and "very low" vulnerability (24%) CVI rates are presented on the central zone, but representing very few buildings.

5 CONCLUSIONS

The multidimensional approach presented in this article allowed the introduction of new parameters that differentiate it from previous methodologies. The analysis and evaluation of morphological, structural and social vulnerability components allows a comprehensive assessment of the studied areas, which is complemented by calculating the CVI that aggregates all the three vulnerability components. The CVI expresses differences between the two studied areas. In both areas the vulnerability varies from "very low" to "very high". However, there are differences between both. In the Figueira da Foz studied area the CVI is fundamentally influenced by the physical characteristics, namely the distance to the shoreline and the slope. Other parameter that emerge on the vulnerability analysis are the land use occupation characteristics, namely associated with

industrial and harbor activities. In Setúbal the CVI is influenced mainly by the socioeconomic characteristics and the urban fabric, namely by the existence of different types of buildings.

The deepen methodology used for vulnerability analysis made possible a better understanding of local characteristics, highlighting specific parameters or the combination of parameters. The Composite Vulnerability Index (CVI), resulting from structural, morphological and social variables allows to the decision makers a more adequate response. Some specific preparation, reduction and mitigation action or measures related with tsunami impact can be supported by this vulnerability composite analysis.

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