A Review of Structural Vulnerability Assessment Methods in the Advent of a Tsunami.

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Abstract. The interaction between hazard and exposure gives rise to risk. Tsunami risk assessment is derived from both hazard assessment and vulnerability assessment. Exposure can manifest in various aspects, such as social factors (e.g., population), environmental factors (e.g., agricultural areas), or economic factors (e.g., infrastructure). Our focus in this review paper is specifically on economic exposure, with an emphasis on structural vulnerability assessment. The approaches employed in tsunami vulnerability assessment are diverse. In this paper, we categorize them into simplified and in-depth methods, encompassing: (1) Empirical vulnerability functions, (2) Index-based approach, (3) Building tsunami vulnerability model (BTV).

1 Introduction

Tsunamis possess the capacity to inflict substantial economic harm on vital infrastructures, lead to widespread social devastation through mass casualties, and induce adverse environmental impacts such as erosion, sediment accumulation, and inundation. Morocco is one of the countries that experienced a catastrophic earthquake and tsunami on November 1, 1755 constituting one of the most devastating natural disasters in history. The earthquake's magnitude was approximately Mw=7.8, significant damage and fatalities were reported in all Morocco coastline. The primary aim of this study is to conduct a comprehensive review of international scientific literature pertaining to tsunami structural vulnerability assessment in coastal communities. The focus is specifically on the methodologies employed in evaluating vulnerability measures, both simplified and in-depth methods, at global and detailed scale, across various countries. To achieve these objectives, we have constructed a database founded on academic articles, theses, conference papers, textbooks, and publicly available materials that address structural vulnerability tsunami assessment models.

2 Methodology

Initially, we delve into the scientific literature concerning tsunami risk assessments. For each study, we focused on the following aspects: (1) The reliance on references that considers constructions and infrastructure as elements at risk; (2)Identifying the type of vulnerability assessment approach :calculation of damage or fragility functions, calculation of vulnerability index , BTV model; (3) Classifying the approach as either a simplified or in-depth tsunami Structural vulnerability assessment Method; (4) Demonstrating the scale of the approach, whether it operates at a global, local, or detailed scale.

2.1 Simplified vulnerability methods

The most simplified methods were applied to a sample of about a thousand building. While more detailed methods, needing more information, were applied to a smaller sample, Ceroni et al. [1].

They are a global scales approach. Based on the utilization of numerical simulation results. Through database analysis, and GIS mapping. Including the calculation of the percentage of buildings likely to be affected by potential tsunamis. Furthermore, they involve the implementation of development plans in coastal areas, restricting construction in zones that may be prone to flooding from future tsunamis.

Hani et al. [2], used a simplified approach, to calculate the physical vulnerability of residential buildings. It based on three key parameters: the elevation of buildings, the materials and condition of building, and number of floors. Buildings were classified into three categories (good, moderate, and poor). Each building within the inundation area has been assigned a vulnerability level, using a modified vulnerability matrix (Table.1) of Eckert et al. [3].

Table 1. Tsunami Risk Matrix used by Hani et al. [2].

		Hazard Levels		
		Low	Medium	High
Vulnerability level	Low	1	2	3
	Medium	2	4	6
	High	3	6	9

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The results are provided as a graph showing the percentage of the exposed buildings (Fig.1) and building vulnerability Map.

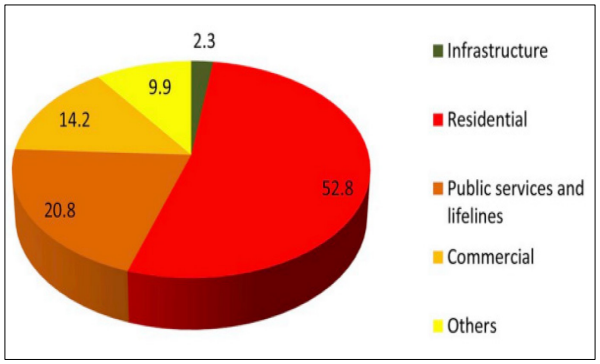

Fig. 1. The percentage of the exposed buildings per category, Hani et al. [2].

2.2 In-depth vulnerability methods

2.2.1 Empirical venerability functions

In the context of tsunami, two types of empirical vulnerability functions have been developed: fragility functions and damage functions. Fragility functions (Fig.2), are a family of cumulative distribution functions that provide the probability of a given type of building exceeding specified damage states (where each individual curve represents a specific damage state, such as "collapse" or "heavy damage") over a range of values of a tsunami intensity measure (TIM, e.g., inundation depth), Charvet et al. [4]. Conversely following Tarbotton et al. [5]. Damage curves typically represent a structure's damage response as an index or a percentage, referring to the overall level of damage that the building would incur (e.g. 80% damaged).

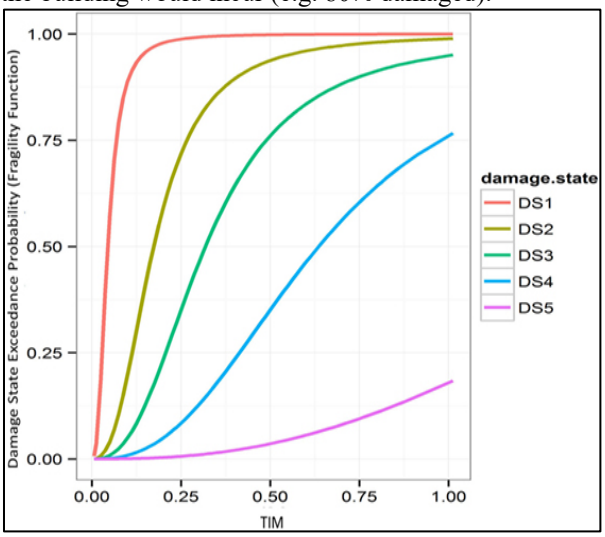

Fig. 2. Example fragility functions. IM, intensity measure; DS, damage state. The y-axis represents the probability of damage exceedance for each damage state (P{ds < DS} versus IM) Charvet et al. [4].

To date, more than 20 empirical vulnerability function studies have been published in the English scientific literature, applied at local scale. Table 2 compiles some of these studies.

Table 2: Published empirical vulnerability functions

References	Data source	Model Parameters	Building Typology	Damage classification
Damage functions				
Reese et al. (2007) [6].	Survey	Construction material, number of floors /Water depth	Four (4) typologies: 1. Timber/bamboo. 2. Brick traditional. 3. Brick traditional with reinforced-concrete (RC) columns. 4. RC-frame with brick infill walls.	Ratio between cost to repair and cost to replace the structure
Valencia et al. 2011[7].	Remote, Survey	Structure, construction material, number of storeys/flow depth	Four (4) typologies: 1. The light constructions. 2. The masonry constructions. 3. The masonry constructions with reinforced colum. 4.non engineered concrete building	D0: (No damage). D1: (Light damage). D2: (Moderate damage). D3: (Important damage). D4: (Heavy damage). D5: (Collapse).
A. Atillah et al.2011[8].	Remote, Survey	Structure, construction material, number of storeys/ maximum flow depth	Five (5) typologies: 1. Light constructions (divided in two subclasses A1, A2). 2. Masonry constructions, not reinforced concrete (divided in two classes C, D and two subclasses B1, B2). 3. Reinforced concrete constructions (divided in Two subclasses E1, E2)	D0: (No damage). D1: (Light damage). D2: (Important damage). D3: (Heavy damage). D4: (Partial collapse). D5: (Total collapse).
Kamakura et al.2018[9].	Remote, Survey	The number of buildings exposed to flooding	Wooden houses	Inundation damage Partial damage Total destruction
Fragility functions				

References	Data source	Model Parameters	Building Typology	Damage classification
Dias et al 2009[10].	Survey	Structure, construction material, number of storeys	Two (2) single-storey unreinforced masonry dwellings type: 1. houses having permanent materials. 2. houses having temporary materials	The damage state of complete damage
Mas et al 2012[11].	Remote, Survey	Structure type/inundation depth	Three (3) structural material type: 1. Wood. 2. Masonry. 3. Mixed	1.Washed away 2. survived
Charvet et al 2015[12].	Numerical simulation	Structural material, /inundation depth,	Four (4) typologies: 1. Building on Wood. 2. Building on masonry. 3. Building on steel. 4. Reinforced concrete	DS1: Minor damage DS2: Moderate damage DS3: Major damage DS4: Complete damage DS5: Collapse
De Risi et al 2017[13].	Survey	Structural material, /inundation depth,	Four (4) structural material type: 1. Wood. 2. Masonry. 3. Steel. 4. Reinforced concrete	DS1: No damage DS2: Minor damage DS3: Moderate damage DS4: Major damage DS5: Complete damage DS6: Collapse DS7: Washed away
Dias et al.2019[14].	Remote, Survey	Structure, construction material /inundation depth	Timber, masonry and reinforced concrete single-storey structures	DS1: Light (non-structural) DS2: Moderate (structural) DS3: Heavy (structural) DS4: Collapse
S. Syamsidik et al 2023[15].	Remote, Survey	Structure, construction material, number of storeys/flow depth	Five (5) typologies 1.Concrete frame with unreinforced masonry 2.Reinforced Concrete 1 storey 3. Reinforced concrete with 2 storeys 4. Reinforced concrete with 3 or more storeys Wooden frame with 1 storey Steel frame	DS0: Light or minor DS1: Moderate DS2: Severe DS3: Partial collapse, Major DS4: Demolished, swept away

2.2.2 Index-based vulnerability models

These models evaluate the degree of vulnerability by determining a Relative Vulnerability Index (RVI) score, for each individual building unit situated within the inundation zone area. The most popular model in the literature is the PTVA model. It was proposed by Papathoma et al. [16]. The vulnerability parameters employed in the initial PTVA model, have been consolidated in Table 3.

To date, four versions of the model have been published: PTVA1 developed by (Papathoma et al.2003 [16], Papathoma and. Dominey-Howes.2003 [17]); PTVA2 by Dominey et al.2009 [18]; PTVA3 by (Dall'Osso et al. 2009 [19], Dall'Osso et al. 2010 [20],) and PTVA4 by Dall'Osso et al. 2016 [21].
The PTVA4 model integrates the judgment of international experts through the utilization of a questionnaire. It computes the Relative Vulnerability Index (RVI) for each building using the same formula (1) as the PTVA-3, with differences detailed by Dall et al.in [21]. The same index has been used by Turchi et al. [22]:

$$PTVA_{[1,5]} = 2/3\ (SV_{[1,5]}) + 1/3(WV_{[1,5]}) \quad (1)$$

$$SV_{[1,125]} = Bv_{[1,5]}\, Surr_{[1,5]} \mathrm{Ex}_{[1,5]} \quad (2)$$

Table 3: Vulnerability parameters associated with the level of vulnerability (HV: High Vulnerability, MV: moderate Vulnerability, LV: Low Vulnerability, VHV: Very High Vulnerability).

The built environment	Parameters	Level
Number of stories in each building	One floor	HV
	More than one floor	LV
Description of ground floor	Open plan with movable objects	HV
	Open plan or with big glass windows without movable objects	MV
	None of the above	LV
Building surroundings	No barrier	VHV
	Low/narrow earth embankment	HV
	Low/narrow concrete wall	MV
	High concrete wall	LV
Building material, age, design	Buildings of fieldstone, unreinforced, crumbling and/or deserted	HV
	Ordinary brick buildings, cement mortar, no reinforcement	MV
	Precast concrete skeleton, reinforced concrete	LV
Movable objects	That can cause injuries to people, damage to buildings or block evacuation routes	HV
	No movable objects	LV

The main characteristics used to define the index are: the "structural vulnerability" (SV) (2) and the "structural vulnerability in case of water intrusion" (WV). Both parameters are range between the values of +1.00

(minimum vulnerability) and +5.00 (maximum vulnerability). SV depends on building vulnerability (Bv), building surroundings (Surr), and exposure (Ex).

Bv (3) depends on six components: main construction material (m), number of storeys (s), ground floor hydrodynamics (g) foundation type (f), shape of building footprint and orientation (so), and preservation condition (pc). The index is defined as follows:

$$Bv_{[-1,+1]} = 1/409\ (100 \cdot m + 85 \cdot s + 69 \cdot g + 69 \cdot f + 52 \cdot so + 34 \cdot pc) \quad (3)$$

S*urr* (4) depends on five components: main construction material (br), number of storeys (sw), ground floor hydrodynamics (nb), foundation type (mo), and shape orientation (w). It is defined as follows:

$$Surr[-1, +1] = 1/356\ (100 \cdot br + 84 \cdot sw + 72 \cdot nb + 58 \cdot mo + 42 \cdot w) \quad (4)$$

The building exposure (Ex) (5) depends on two components: the water depth above the terrain level at the building location, WD, and the maximum value of WD among all buildings exposed (WD_{max} WD). The Wv index depends on the water depth normalised by the building height. The two indices are defined as follows:

$$Ex\ [-1, +1] = WD/\ WDmax \quad (5)$$

2.2.3 Building tsunami vulnerability Model (BTV):

Model proposed by Omira et al. [23]. The authors proposed a GIS approach to evaluate the impacts of tsunami on buildings based on the same principle of the PTVA model. Nevertheless, the work was not done for each building unit, but for whole block of buildings. Six typologies of building have been identified: Single-storey structureless dwelling, non-engineered timber construction, brick traditional buildings of the ancient Medina, non-engineered RC building with masonry infill walls, engineered RC frames with infill masonry walls, and multi-storeys well-designed engineered RC buildings.

According Omira et al. [23]. The key to the BTV assessment methodology is the identification of the factors that control the expected building damage related to the impact of tsunami waves. They used three parameters: The building condition, the inundation zone and the quality of the sea defence, the choice of this parameters is based on studies conducted by: Boen [24]; Maheshwari et al. [25]; Murty et al. [26]; Ruangrassamee et al. [27]; Saatcioglu et al. [28] .

Omira et al. [23] have adopted the following formula (6) to evaluate the Building Vulnerability Index (BTV) for each building class:

$$BTV\ (\%) = \frac{(Fc.b \times Fw.b) + (Fc.i \times Fw.i) + (Fc.s \times Fw.s)}{\sum_{k=1}^{3}(Fc.max \times Fw)k} \quad (6)$$

Where:

$F_{c.b}$ Building classification factor corresponding to the building class for which the BTV is calculated.

$F_{c.i}$ The classification factor of the flood zone class where the building class is located.

$F_{c.s}$ The classification factor of the sea defence class existing in front of the building class.

$F_{w.b}$ The weighting factors for building condition.

$F_{w.i}$ The weighting factors for inundation zone.

$F_{w.s}$ The weighting factors for sea defence.

$F_{c.max}$ The maximal value of the classification factor established in the k-criterion; where k is the criterion.

The values of the BTV calculated from the Eq. 6 are associated with a grade of expected building damages. Five degrees of building damage are considered:

D0- no damage.
D1- slight no structural damage.
D2- slight structural damage.
D3- severe structural damage.
D4- total collapse

The same model has been applied by Benchekroun et al. [29], and Moussaoui et al. [30].

The results were presented in the form of vulnerability maps (Fig.3).

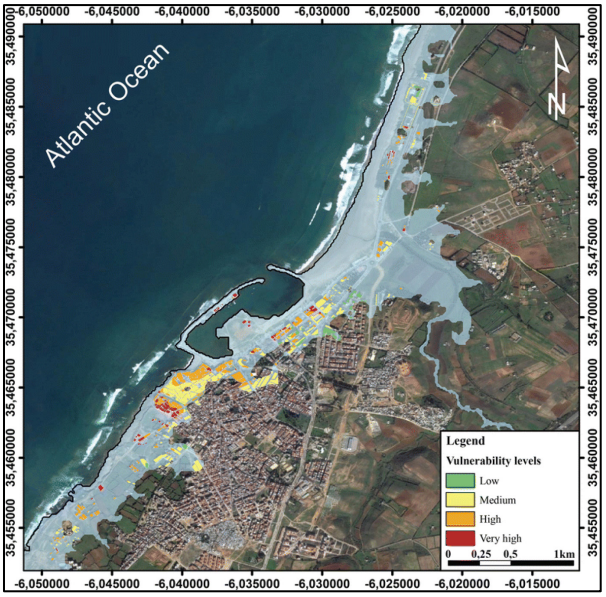

Fig. 3. Building tsunami vulnerability Map, El Moussaoui et al. [30].

3 Results and Discussion

The results of our bibliographic research are grouped in table 4. Based on the analysis of tsunami vulnerability assessment approaches; several simplified methodologies applied at global scale, focused on the numerical simulation of tsunamis, involving the calculation and analysis of outcomes, such as inundation distances, arrival times at various locations and wave heights; generation of hazards map and offering an overview of the percentage of buildings that may potentially be impacted by a future tsunami in a country.

Moreover, certain simplified methods can be applied on a local and detailed scale. This can be achieved through the utilization of a vulnerability matrix or by calculating the percentage of exposed buildings in a specific city.

The in-depth method involves the meticulous collection of building data through a comprehensive field survey. Subsequently, researchers study the behavior of each type of building in the event of a tsunami. This involves creating equations, index, empirical functions, building vulnerability model and other analytical tools. The effectiveness of each method is primarily contingent on the date of its creation and the database available during that specific period.

Table 4: structural Vulnerability methods

Scale / Method	Global	Local	Detailed
Simplified	Analysis Result of Numerical Simulation	Building database analysis (e.g. The percentage of the exposed buildings)	
	Risk Matrix		
In-depth	-	Fragility Curves	
	-	Damage Curves	
	-	PTVA Model	
	-	BTV model	

4 Conclusion and Recommendations:

In summary, structural vulnerability assessment can be categorized into two types. Simplified methods involve macroscopic approaches at a large or regional scale, employing straightforward techniques that require less information. These methods assess vulnerability across multiple cities simultaneously, utilizing the analysis of numerical simulation results.

On the other hand, in-depth methods are a microscopic approach at a local or detailed scale. More detailed methods used additional information and are applied in specific cities or constructions, to study the behavior of structures or block of buildings in the face of a tsunami. We highlight empirical vulnerability functions, index-based vulnerability models and building tsunami vulnerability Model (BTV).

Structural vulnerability assessment plays a pivotal role in the broader context of tsunami risk assessment. Previous results highlight the crucial contribution of each country in facilitating effective vulnerability assessment. Additionally, factors such as data accessibility are key considerations in this process.

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