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A comparative analysis of empirical and analytical tsunami fragility functions for buildings in Tumaco, Colombia

Juan Paez-Ramirez[1] Juan Lizarazo[1], Sergio Medina[1], Miguel Rivas[1], Patricia Luna[1], Erick Mas[2] and Shunichi Koshimura[2]

[1] Departamento de Ingeniería Civil y Agrícola, Universidad Nacional de Colombia, Bogotá, Cololombia;
[2] International Research Institute of Disaster Science, Tohoku University, Sendai, Japan.

Contact e-mail: jspaezr@unal.edu.co

Abstract. The Pacific coast of Colombia has witnessed several tsunami events in the last century. However, the physical damage to structures at the time was not recorded, even when these events have brought overwhelming destruction to coastal communities. This lack of data increases uncertainties when assessing future tsunami impacts. Nonetheless, other regions of the world, which have been also affected by tsunami, have collected damage information that has been used to build empirical tsunami fragility functions. Based on a demand parameter, such as the tsunami inundation depth, a fragility function expresses the probability of building damage. Hence, regions with no recent tsunami damage cannot develop empirical fragility functions since post-disaster damage survey data is not available. One alternative for these regions is to develop analytical fragility functions out of computational nonlinear structural analysis. Reinforced concrete buildings and palafitte houses are selected to perform a comparative analysis of collapse damage assessment expressed in empirical and analytical fragility functions.

1. Introduction

The city of Tumaco has been affected throughout history by several earthquakes, the 1906 and 1979 events also produced tsunamis. The damage caused by those past events was not recorded, therefore, there is a lack of data for constructing fragility curves from traditional empirical methods. Using computational models, it is possible to predict the behaviour of the structures under the loads of tsunami. This also permits to considerate the typical structures found in the area and their self-construction techniques and low-quality materials that are generally used.

The traditional fragility curves are based on historical data and post-event records of building damage and are constructed from photointerpretation surveys or field data collection from recent tsunami events, such as the 2004 tsunami in the Indian Ocean, the 2010 Chilean tsunami and the 2011 tsunami on the northeast coast of Japan. They have been obtained from empirical relationships between the tsunami flood depth and the structural vulnerability [1, 2, 3, 4, 5].

This paper provides a comparative analysis of empirical and analytical fragility functions used to estimate the damage to buildings due to tsunami events. On the one hand, analytical fragility functions for structures present in the municipality of Tumaco, Colombia, have been developed. On the other hand, the empirical fragility curves are taken from the damage survey data and studies of recent tsunami events in the Pacific. The differences on the resulting damage assessments for collapse produced by the two functions, in the case of a two-storey reinforced concrete and a wooden or palafitte building in the city of Tumaco, are discussed.

2. Study Area

The urban area of the municipality of San Andrés de Tumaco, is located on a group of islands located on the south-Colombian Pacific coast, near the border with Ecuador on the delta of the Rosario river. It is a highly populated city. The city lies approximately 100 Km from the subduction zone of the Nazca Plate beneath the South American Plate (Colombia-Ecuador Trench), this collision area is located under the Pacific Ocean, causing a high tsunami risk. Additionally, the geology of the islands shows that the soil is sandy and susceptible to soil liquefaction [6].

Because of several anthropic and social issues that the city faces [7], the socioeconomic situation of the region is of extreme poverty, resulting in the use of low-quality construction materials in self-built precoded structures, which are neither endorsed by the competent authority nor have the legal permits for their construction. Most of the buildings in Tumaco have these characteristics [8].

Recent studies have determined different building typologies along the towns of the Colombian Pacific region, finding that the predominant ones are palafitte houses, wood panel houses, simple masonry houses and reinforced concrete buildings. The palafitte and wood buildings are prone to rebuilding or remodelling according to the financial capability of the owner [9].

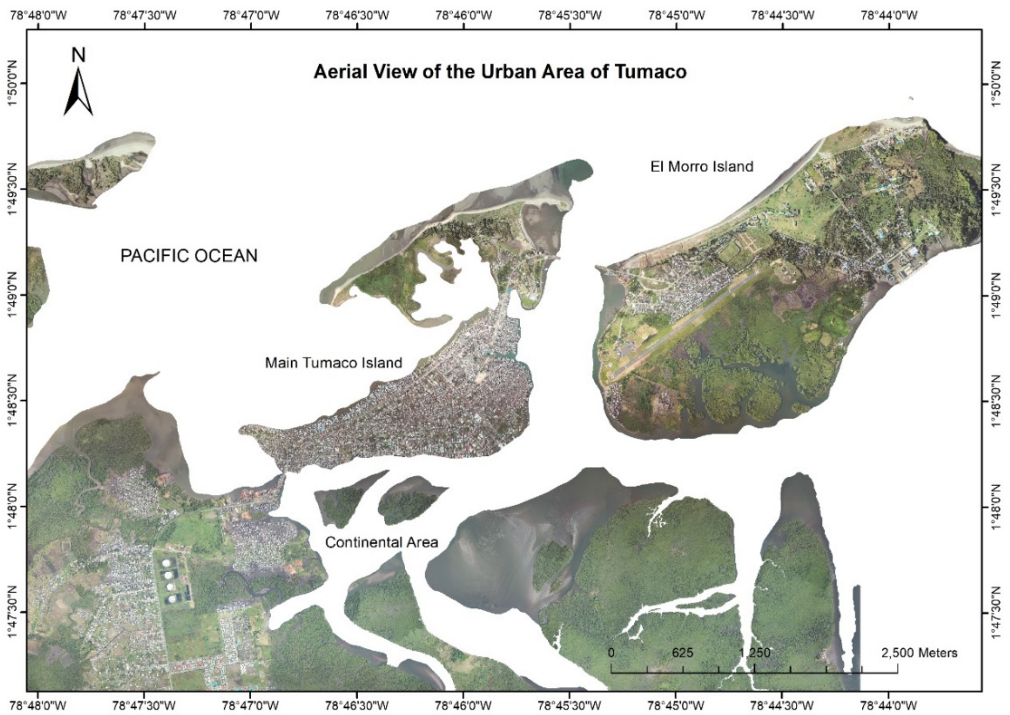

Figure 1. Study area, islands, and urban zone of Tumaco.

3. Exposure Model

The buildings of the urban area of Tumaco have been structurally classified. In a joint research effort led by the Japan Cooperation Agency – JICA, data were collected from high-resolution aerial photographs, provided by the Colombian Maritime General Directorate – DIMAR and with the help of Google Street View and field surveys, the exposure model was constructed. More than 20,000 urban constructions were classified in 7 different structural typologies [10], which are as follows:

- Palafitte
- Wood panels
- Simple masonry
- Reinforced concrete frames – 1 Story (Type 1, square plant layout houses)
- Reinforced concrete frames – 1 Story (Type 2, rectangular plant layout houses)
- Reinforced concrete frames – 2 Story
- Reinforced concrete frames – 3 Story

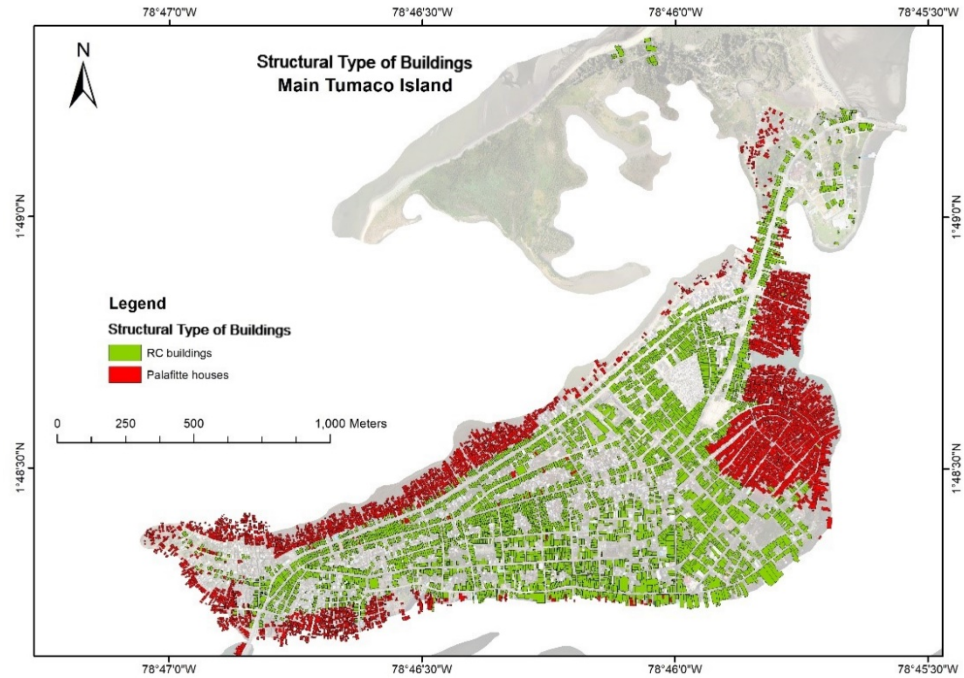

Figure 2. Location of the RC buildings and palafitte houses found in the main Tumaco Island according to the exposure model.

4. Tsunami Vulnerability Assessment Methodologies

In the South-Colombian Pacific coast, there is no quantitative information about the damage caused by past tsunami events to the buildings. Because of this limitation, it is not possible to build local empirical fragility curves, proposing the possibility of using curves developed from other tsunami events or developing analytical fragility curves for the typical buildings of this area [11]. Though the empirical curves are a valuable resource and allow an approximation of the building's vulnerability, some studies [1, 2, 3, 4, 5] conclude that fragility functions may not be suitable for the consideration of tsunami vulnerabilities in areas different from where they were initially developed.

4.1. Analytical Methods

4.1.1 Reinforced Concrete Buildings

To develop a set of fragility curves using a computational nonlinear structural analysis Medina [10] proposed a methodology. This methodology combines a statistical algorithm that relies on repeated random sampling to obtain probabilistic curves. The finite element method along with nonlinear structural simulations were used to obtain the structural capacity of the buildings.

The tsunami inundation or flow depth is the engineering demand parameter (EDP) or the intensity measure (IM) used in the analytical tsunami fragility, which is the most used parameter to represent this hazard. Uncertainty was considered by randomly varying six properties for a RC building: the strength of the three construction materials involved ($f'c$: concrete; $f'm$: masonry; and fy: steel), the tsunami force

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parameters of the drag coefficient (CD) and opening coefficient (Co), and the orientation of the building, representing the direction of the tsunami in relation to all of the building's possible orientations (0 to 360 degrees) [10]. This research did not include any experimental tests to calibrate models.

To obtain the probability of exceeding a specific level due to the intensity of a tsunami event four different damage states were defined. The fragility curves were represented by a log-normal function, in which the hazard intensity parameter was defined as the flow depth for all the damage states, they were defined as follows:

• Slight damage: the building is still available for use.
• Moderate damage: the building has some damage on its structure.
• Severe or extensive damage: the structure needs an urgent reinforcement.
• Collapse damage: the structure has lost its stability.

The damage limits for the drift-based damage model adopted by Medina [10] were taken from the building classification reported by HAZUS [12]. The following log-normal function was selected for the fragility functions.

$$F(X) = \frac{1}{2} erfc\left[\frac{-ln(X) - c_m}{\xi\sqrt{2}}\right] \quad (1)$$

Where the *erfc* function is the complementary Gauss error function, it has a sigmoidal shape and is widely used to describe vulnerability problems [13]. *Cm* and ξ are the mean and standard deviation of the *log-normal X* data, respectively. The parameters used to build the fragility curves and the correlation error for a 2-story reinforced concrete structure are presented in Table 1. The fragility curve is reproduced in the Figure 3 and the layout of the typical 2-story RC building is shown in the Figure 4.

Table 1. Statistical parameters used to build the proposed analytical fragility curves for reinforced concrete buildings [10].

Damage Level/State	c_m	ξ	**Error**
Slight	-0.159	0.423	0.00299
Moderate	-0.607	0.427	0.00944
Severe	-0.898	0.457	0.00508
Collapse	-1.010	0.504	0.00526