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

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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 tsunamis, 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 inundation 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.
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].

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 $f_y$: steel), the tsunami force
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.

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

(1)

Where the \( \text{erfc} \) function is the complementary Gauss error function, it has a sigmoidal shape and is widely used to describe vulnerability problems [13]. \( c_m \) and \( \xi \) 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.

| Damage Level/State | \( c_m \) | \( \xi \) | 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 |
4.1.2 Palafitte Houses

Rivas [14] developed a methodology to assess the vulnerability, due to the combined effect of earthquake and tsunami, of the typical palafitte houses found along the coast of Tumaco, this consisted of performing a static pushover analysis, being the EDP the peak ground acceleration. Later, when the final displacement of the earthquake acceleration is obtained, the tsunami lateral load was applied on the already damaged structure, performing a second pushover analysis.

This procedure was repeated varying the seismic acceleration and the tsunami flow depth, also it was assumed that the damage of the structure is determined by accumulating the displacement of the structure caused by the effect of the two forces and the structure remains in the elastic range after the earthquake pushover, then the tsunami loads adds to the elastic displacement.

This methodology included the mechanical characterization of wood was carried out following the procedures described in ASTM D 143 [15]. The typical joint consists of a column cut to half of the frame height and joined to the beam by a nail, the failure mechanism occurs when the nail begins to move through the pillar until being ejected, it was characterized, as shown in Figure 5, following the
procedure described by the RILEM [16], performing a load protocol to determine its energy dissipation [14].

![Experimental setup](image)

**Figure 5.** Experimental setup [14]. Taken on: February 22nd, 2019. *Source: Reproduction authorized by the GIES research group.*

![Typical palafitte house](image)

**Figure 6.** Typical palafitte house in Tumaco, Colombia [14]. Taken on: July 26th, 2018. *Source: Reproduction authorized by the GIES research group.*

The damage states were the same as the previously described in the methodology for reinforced concrete buildings and the fragility curves where represented using a log-normal distribution:

\[
P_J = F(X) = \Phi \left( \frac{\ln X - c_m}{\xi} \right)
\]  

(2)

Where \( \Phi \) is the standard normal distribution, \( X \) is the intensity parameter taken into consideration, and \( c_m \) and \( \xi \) are the mean and standard deviation of the log-normal \( X \) data, respectively. Table 2 shows the obtained statistical parameters. The fragility curve is reproduced in the Figure 7.

Table 2. Statistical parameters used to build the proposed analytical fragility curves for palafitte houses [14].

| Damage Level/State | \( c_m \)  | \( \xi \)  |
|-------------------|-----------|-----------|
| Slight            | 0.014     | 0.005     |
| Moderate          | 0.020     | 0.007     |
| Severe            | 0.116     | 0.120     |
| Collapse          | 0.402     | 0.466     |
Figure 7. Reproduction of the analytical collapse fragility curve for a palafitte/wood house in Tumaco [14].

4.2. Empirical Methods

The building damage inventory related to adequate flood data can be obtained directly from field surveys. These data can be used to develop tsunami fragility functions helpful for building damage estimation [1]. Additionally, with the help of satellite remote sensing images and using numerical modelling along with historical data analysis, it is also possible to obtain enough data to build fragility functions [4].

In order to build tsunami fragility curves, the first step is to collect the damage data related to a building type, this data is classified according to the damage intensity; such intensities could be slight damage, moderate damage, severe damage and collapse. Then the buildings must be classified according to their structural type. Depending on the region analyzed, the most common building structural systems are those made of reinforced concrete, masonry, or wood. The flow depth is normally the EDP, it can be determined directly from field surveys, remote sensing imager or by running tsunami numerical models [1].

The fragility curves can be represented as a lognormal distribution function (Eq. 1) or as a normal distribution function (Eq. 3).

\[ P_f = F(X) = \Phi \left[ \frac{X-\mu}{\sigma} \right] \] (3)

Where \( \Phi \) is the standard normal distribution, \( X \) is the intensity measure (EPD), and \( \mu \) and \( \sigma \) are the mean and standard deviation of the normal \( X \) data, respectively; these parameters are determined through a regression analysis to obtain the best fit curve [4]. Tables 3 and 4 show the obtained statistical parameters.

Table 3. Statistical parameters used to build the collapse fragility curves in Figure 8 for reinforced concrete buildings [11].
5. Results and discussion

This paper compares the probability of collapse for a 2-story reinforced concrete building and for a palafitte house. The fragility curves resulting from the analytical and empirical methods are plotted in the Figures 7 and 8. For both building types the engineering demand parameter (EDP) will be the flow depth.
Figure 8. Reproduction of comparison of collapse tsunami fragility curves for RC structures for the tsunami events of 2004 in the Indian Ocean, 2010 in Chile and 2011 in Japan [11].

Table 5. Comparison of the proposed tsunami fragility functions and the previously developed empirical functions for reinforced concrete buildings [11].

| Event/Location | Flow Depth for Collapse Probability (m) | RC buildings |
|----------------|----------------------------------------|--------------|
|                | Indian Ocean, 2004                     | Indian Ocean, 2004 | Indian Ocean, 2004 | Chile, 2010 | Japan, 2011 | Colombia |
| Damage Probability, Collapse (%) | Sri Lanka | Banda Aceh | Thailand | Dichato | Miyagi Prefecture | Tumaco |
| 25             | 3.00        | 2.25        | 4.00      | 0.50      | 4.00      | 1.70      |
| 50             | 4.30        | 3.00        | 6.25      | 1.10      | 5.00      | 2.30      |
| 75             | 5.50        | 4.00        | 10.00     | 2.60      | 6.00      | 3.20      |
| 100            | 8.50        | 6.00        | >10       | >10       | 8.50      | 6.00      |

For the analytical method, a damage probability of 25% occurs approximately 1.70 m, of 50% at 2.30 m, of 75% at 3.2 m, and 100% at a depth of 6 m or above [11]. Table 5 is a summary of the different flow depths at each damage probability of the developed analytical curves and the literature empirical curves in the case of collapse. Most empirical fragility curves showed the same damage probabilities for higher flow depth values, except from the curves developed for Dichato in Chile [4]. However, for this function, at a depth exceeding 10 m there is a 100% probability of collapse.

The reinforced concrete buildings in Tumaco showed in general lower strength values and higher damage ratios than the previously developed empirical curves. The analytical curves were developed by modelling the impact of tsunami waves, this includes the floating debris, which was considered as a random parameter [10]. This uncertainty may miscalculate the strength of the impacted buildings, resulting in the variations found in Table 5.
Figure 9. Comparison of collapse tsunami fragility curves for palafitte/wood houses for the tsunami events of 2004 in the Indian Ocean, 2010 in Chile and 2011 in Japan.

In the case of the palafitte houses the reproduced curves are plotted in Figure 9, this Figure shows, at first glance, that for the developed fragility curve for Tumaco a damage probability of 25% occurs approximately 0.50 m, of 50% at 0.70 m, of 75% at 1.0 m, and 100% at a tsunami depth of 2.20 m or above. In all cases the fragility curves developed using empirical methods showed higher strength and lower damage ratios.

It is important to note that Rivas [14] considered a combined fragility, the palafitte has been damaged by both the earthquake and the later tsunami. This consideration, combined with the used construction methods in the zone, may produce this higher structural fragility of this wooden houses. Table 6 shows the values of flow depth in meters to reach a certain percentage of damage probability for all the selected curves.

Table 6. Comparison of the proposed tsunami fragility functions and the previously developed empirical functions for palafitte/wood houses.

| Event/Location | Indian Ocean, 2004 | Indian Ocean, 2004 | Indian Ocean, 2004 | Chile, 2010 | Japan, 2011 | Colombia |
|----------------|--------------------|--------------------|--------------------|------------|------------|----------|
| Damage Probability, Collapse (%) | Sri Lanka | Banda Aceh | Thailand | Dichato | Miyagi Prefecture | Tumaco |
| 25 | 3.00 | 2.25 | 0.70 | 0.50 | 4.00 | 0.50 |
| 50 | 4.30 | 3.00 | 1.30 | 1.10 | 5.00 | 0.70 |
| 75 | 5.50 | 4.00 | 2.00 | 2.60 | 6.00 | 1.00 |
| 100 | 8.50 | 6.00 | 6.00 | >10 | 8.50 | 2.20 |
6. Conclusions

The empirical fragility curves may be applicable to different regions in the world, but they might also differ because of the building materials and construction methods, resulting in a wrong estimation of the loss for potential tsunamis. The proposed analytical method of Medina [10] and Rivas [14] for developing tsunami fragility curves is useful for regions located in tsunami risk areas, which have no information from past tsunami events, allowing the possibility to consider the local attributes of the structures that may differ from the ones found in other regions that have already obtained empirical curves. An advantage for the analytical methods is that the determination of the structural damage levels as well as the building materials is not restricted by the resolution of the post-disaster satellite imagery or the absence of post-disaster field surveys.

For the analysed 2-storey reinforced concrete structures in Colombia, the collapse started at 2.30 m, and the total collapse occurred at 6 m. In the case of the empirical studies developed in Japan, Thailand, Sri Lanka, and Indonesia the buildings started to collapse at a flood depth of 3-5 m and collapsed entirely when the water level reached 6-10 m. As a result, the Colombian structures have a lower structural performance. Medina [10] consider the debris impact and the tsunamic impact, both of which are considered as random parameters.

Rivas [14] considered that the palafitte structure was first hit by the earthquake and then loaded with the tsunami impact, this combined damage consideration and the generally poor construction methods showed in Figure 6 have as a result the higher structural fragility found in the analytical method, where the structures start to collapse when the flow depth reaches 0.70 m and at 2.20 m they all collapse. These inundation values are lower than the found for the selected empirical fragility functions for wooden structures.

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