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FRAGILITY EVALUATION OF BUILDING STRUCTURES BASED ON DAMAGE SURVEY RESULTS OF TSUNAMI DISASTER FROM HUNGA TONGA – HUNGA HA'APAI VOLCANO ERUPTION ON 15 JANUARY 2022.

Mele Siale Manu[1]
MEE21715

Supervisors: Toshiaki YOKOI[2], Tatsuya AZUHATA[3]

ABSTRACT

On 15 January 2022, Tonga was hit by a tsunami caused by the eruption of the HUNGA TONGA – HUNGA HA'APAI (HT-HH) volcano. This study aims to detect the vulnerable structural systems from this disaster, using fragility curves for future disaster mitigation planning. I gathered data on the inundation depth and structural damages through the government ministries' post-disaster field surveys and completed the required dataset on an independent field survey. This study focused on Hihifo and Nuku'alofa on Tongatapu island. The method used to determine fragility functions was the Grid Search method. Structural damages have two classifications: destroyed and survived. Fragility curves for structural damages were developed for all building types of Hihifo and Nuku'alofa, timber buildings of Hihifo and Nuku'alofa, and Reinforced Concrete (RC) buildings with masonry infill of Hihifo. The result showed that the Hihifo area has a stronger structural system than Nuku'alofa. The fragility curves of Hihifo and Nuku'alofa were compared with those developed in other countries. It showed that the timber buildings and RC structures with masonry infill of Hihifo are stronger than in other countries. However, American Samoa's RC structures are more resilient than Hihifo at higher inundation depths. Therefore, the timber buildings of Nuku'alofa need to be assessed in detail. The RC with masonry infill buildings of Hihifo must follow the building code so that all RC buildings will be equally resilient to a tsunami. Lastly, areas exposed to tsunami disasters should have RC structures instead of timber.

Keywords: Fragility function, tsunami, Hunga Tonga-Hunga Ha'apai, structural damages

1. INTRODUCTION

Tonga is vulnerable to tsunami disasters due to its geographical location and geological formation. It is in a subduction region where the level of seismicity is high, with 22 active volcanoes. Seismic and volcanic activities are two of the three leading causes of a tsunami. The last tsunami to hit Tonga was in 2009, caused by a tsunamigenic earthquake known as the Samoa 2009 earthquake and tsunami. The tsunami swept the island of Niuatoputapu, leaving people homeless. On 15 January 2022, at 5:15 pm local time, the HTHH eruption explosion reached its maximum strength, equivalent to around ten megatons of TNT (National Emergency Management Office, 2022). The grounds and buildings were shaking, which was also felt and heard in other South Pacific islands (World Bank & GFDRR, 2022). It was followed by a tsunami warning, which immediately triggered a mass evacuation of the communities of Tonga. Nevertheless, tsunami waves with a height of up to 15 meters swept away the islands of Mango and Fonoi and other coastal communities, leading to the misplacing of the people. The tsunami affected nearby Pacific countries and distant shores such as Japan, California, Mexico and

[1] Ministry of Lands and Natural Resources, Tonga.
[2] Japan International Cooperation Agency.
[3] Department of Structural Engineering, Building Research Institute.

Peru (Ramírez-Herrera et al., 2022). Such damages caused by the tsunami in Tonga lead to the main objective of this study: to detect the vulnerable structural systems using fragility curves for future disaster mitigation planning. Fragility curves were introduced as one of the main tools for assessing damage and loss from natural disasters. For example, it is defined as the probability of reaching or exceeding a specific damage state under inundation depth and other parameters for a tsunami. The curves can be used as a decision-making tool for pre- and post-disasters.

2. METHODOLOGY

2.1. Research target areas

Two main areas were chosen from the main island, Tongatapu, as the study areas. First is the Hihifo area, which covers the three affected villages: 'Ahau, Kanokupolu and Ha'atafu. HT-HH is about 53 km away from the north of Hihifo. The affected areas were mainly resorts and residential areas. There are also church buildings, church halls, city halls, and primary schools within these residential areas. The Hihifo area has higher elevations on the western side, where the tsunami wave came from (Figure 1).

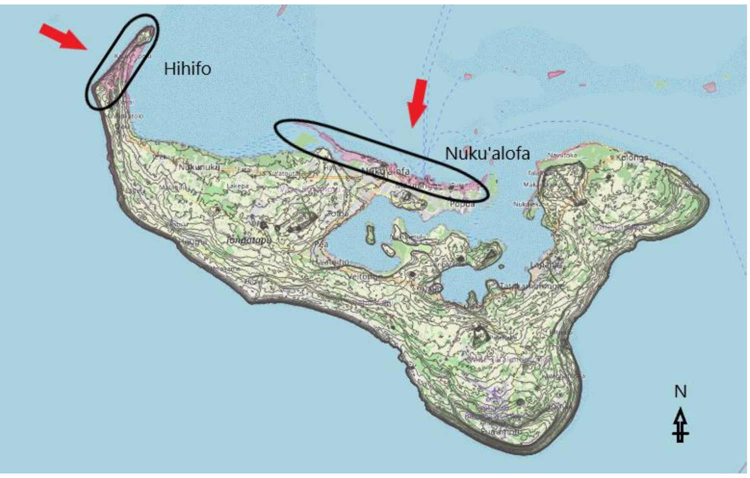

Figure 1. A map showing the inundation area of Tongatapu island (light pink shade), the study areas (black oval), contour lines showing elevations (grey lines), and the direction of incoming tsunami waves (red arrows).

The second study area is the Nuku'alofa area which includes Kolomotu'a, Fasi, and Tukutonga. These are also residential areas with similar buildings to Hihifo. However, the affected area of Kolomotu'a village has some motels and restaurants on the waterfront, which were not affected by the tsunami. The affected areas of Nuku'alofa are almost flat throughout, with a bit lower toward the northern side, where the wave came from (Figure 1). However, Nuku'alofa has a rock revetment shoreline protection which may intervene in the wave's energy. HT-HH is about 68 km away from the north-northwest of Nuku'alofa.

2.2. Data

The inundation data for the two study areas were from a field survey conducted by the Ministry of Lands and Natural Resources (MLNR). The Hihifo area had an inundation depth of up to 8.5 meters, while Nuku'alofa had an inundation depth of up to 1.6 meters. The inundation depth was measured from the local ground level.

On the other hand, the Ministry of Infrastructure (MOI) and disaster-related ministries conducted an initial damage assessment, which collected damaged data used in this study. The data did not have the location and the damaged building type, except for a few that MLNR collected. Therefore, I went out to the field and completed data collection independently. I used the QField application to collect data on the field and then analyzed it with the QGIS. The spatial distribution of damaged buildings in the Hihifo area showed that the survived buildings were away from the shoreline of its northern side (Figure 2A). In contrast, the damaged buildings were distributed along the shoreline in the Nuku'alofa area (Figure 2B).

The structures considered by the MOI as destroyed or washouts and severely damaged buildings were classified in this study as destroyed buildings. The destroyed buildings are defined in this study as structural damages that are not repairable. Structures with moderate and minor damage and buildings that were not damaged were classified as survived. Survived buildings were then defined in this study as damaged houses that were repairable and houses that were not affected at all. There were 85 destroyed buildings with 112 in the Hihifo area and 27 destroyed buildings with 237 survived buildings in the Nuku'alofa area.

Figure 2. Spatial distribution of damaged buildings in (A) Hihifo and (B) Nuku'alofa areas. It shows the destroyed buildings (white dots) and survived buildings (grey dots).

2.3. Analysis procedure

There are two approaches used in trying to attain the fragility curves for the study area. The first method is a linear regression analysis that follows the equation used by Koshimura et al. (2009b), as shown in Eq. (1).

$$P_D(x) = \Phi\left[\frac{\ln x - \lambda}{\xi}\right], \qquad (1)$$

where x represents the inundation depth, while λ and ξ represent the mean and standard deviation (SD) of $\ln x$ respectively, and Φ is the cumulative log-normal distribution function. However, this procedure was not used because the inundation depth ranges with damage probabilities of 0 or 1 were not considered in determining the fragility function. Therefore, I think the data is not well represented.

The second method used for calculating the fragility function is the Gird Search method suggested by Dr Yokoi. Whereby the simulated damage probability for every value of the inundation depth (*x*) was calculated using the log-normal cumulative distribution function, and the hyperparameters mean (ln *x*) and SD (ln *x*). Then the misfit function was estimated using Eq. (2) for all available *x*, where ODP is the observed damage probability, and the CSDP is the calculated simulated damage probability. This procedure was repeated for all pairs of the hyperparameters within the given search ranges.

$$Misfit\ function = (ODP - CSDP)^2 \qquad (2)$$

Table 1: Hyperparameters for fragility curves of each area and building types

Area	Mean (ln *x*)	SD (ln *x*)
Hihifo – all building types	1.08	0.405
Hihifo – timber structures	0.78	0.21
Hihifo – RC with masonry infill structures	1.18	0.40
Nuku'alofa – all building types	0.83	0.38
Nuku’alofa – timber structures	0.67	0.32

The search ranges were modified until I found a minimum of the misfit. Also, the search ranges were shrunk until I obtained the mean (ln x) and SD (ln x) values with sufficient resolution, as summarised in Table 1. The best fit, the fragility curve, for each study area was given by the mean (ln *x*) and the SD (ln *x*) that gives this minimum.

3. RESULTS AND DISCUSSION

The data was categorized into ranges of inundation depth with an interval of 0.5 meters (Figure 3). The midpoints of the inundation depth ranges are used in drawing the histograms. After around 3.75 meters of inundation depth, all building types in the Hihifo area were destroyed. However, in the Nuku'alofa area, the inundation depth did not reach any point where such destruction would occur.

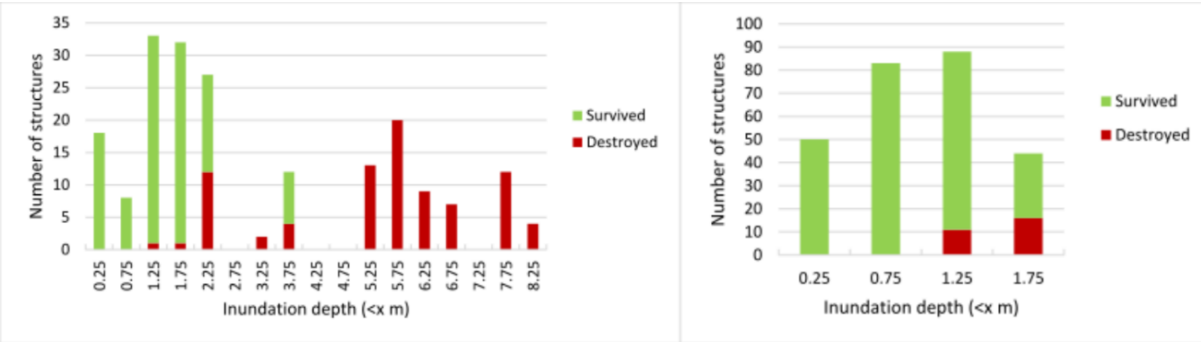

Figure 3. Histograms of the number of survived (green) and destroyed (red) buildings in each inundation depth range in the tsunami inundated area of Hihifo (left) and Nuku'alofa (right).

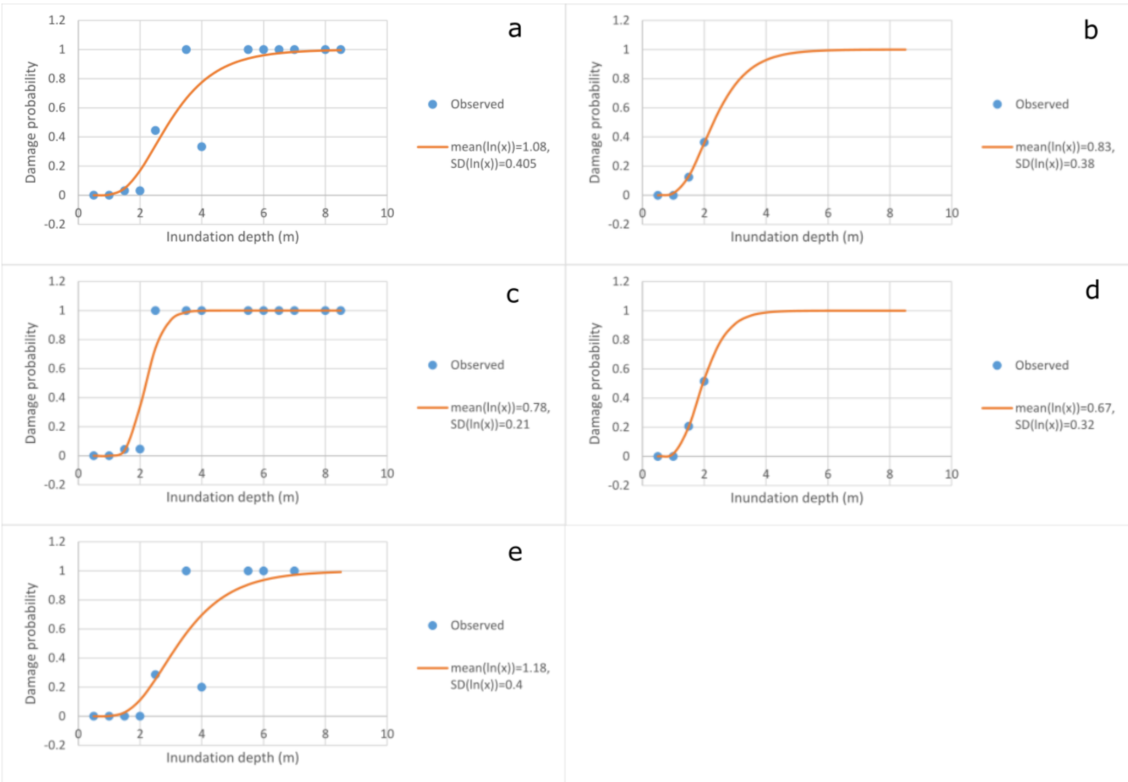

Figure 4. Fragility curves (orange curves) and the observed damage probability (blue dots) for (a) all types of buildings for Hihifo, (b) all types of buildings for Nuku'alofa, (c) timber buildings for Hihifo, (d) timber buildings for Nuku'alofa, (e) RC structures with masonry infill in Hihifo.

In comparing the fragility curves obtained, the buildings of the Hihifo area (Figure 4a) are stronger than those of the Nuku'alofa area (Figure 4b). Though both the fragility curves start rising after one meter, indicating damages start to occur when inundation depth is above one meter, the fragility curve for Hihifo's all types of buildings rises gently after one meter. In contrast, the fragility curve for Nuku'alofa's all types of buildings rises steeply after one meter. It means that the same degree of destruction occurred in Nuku'alofa at a higher inundation depth also occurred in Hihifo at a lower inundation depth, indicating the vulnerability of structures in Nuku'alofa. Comparing these fragility curves with the existing fragility curves of Banda Aceh, Indonesia and Dichato, Chile (Figure 5), the structures of my study areas are more resilient than Dichato's. At the same time, Hihifo's buildings are similar to Banda Aceh's, while Nuku'alofa's buildings are more vulnerable than Banda Aceh's.

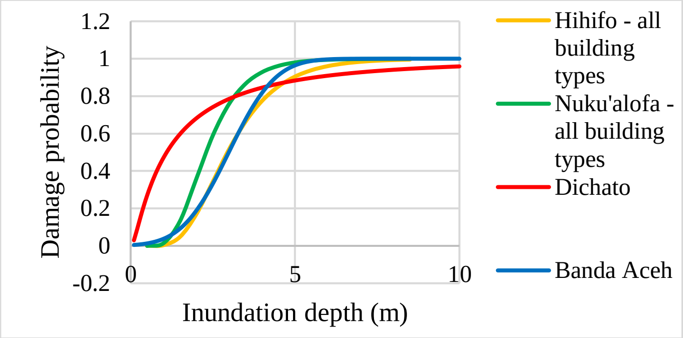

Figure 5. Comparison of tsunami fragility curves for different types of buildings. It shows Hihifo's (orange) and Nuku'alofa's (green) all types of buildings; wood, timber, and RC buildings in Banda Aceh, Indonesia (blue); wood, masonry, and mixed buildings in Dichato, Chile (red) (Mas et al., 2012).

Moreover, comparing the fragility curves for timber buildings, the fragility of timber buildings in Hihifo (Figure 4c) began after 1.5 meters of inundation depth, while Nuku'alofa (Figure 4d) began after one meter. Nuku'alofa's fragility curve is a bit steeper than Hihifo's (Figure 6), indicating that the Nuku'alofa area has more destroyed timber buildings than those in Hihifo at the same inundation depth. For example, the timber buildings of Hihifo will be 60% destroyed at 2.3 meters, while 60% of Nuku'alofa's timber buildings will be destroyed at 2.1 meters. Hence a slight difference was observed in the curves. The starting inundation depth of destruction shows that the timber buildings of Hihifo are somehow strong enough to withstand tsunami to some extent because, in other countries such as Japan, the timber structures are completely destroyed when the inundation depth is higher than two meters (Koshimura et al., 2009a). Timber buildings in Tonga, both Hihifo and Nuku'alofa, are designed to withstand the impacts of tropical cyclones, and therefore, they are resilient to tsunamis to some extent. Therefore, the timber buildings in my study areas are stronger than those on Okushiri Island, Japan (Figure 6).

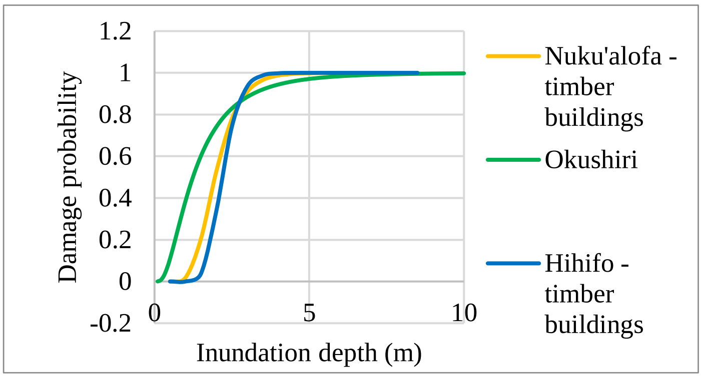

Figure 6. Comparison of tsunami fragility curves for timber buildings of Hihifo (blue) and Nuku'alofa (orange) with wood buildings in Okushiri, Japan (green) (Mas et al., 2012).

Furthermore, a close look at the building types of Hihifo shows that the RC structures with masonry infill are stronger than the timber structures. The pattern of the fragility curves shows this (Figure 7). The fragility curve of the RC with masonry infill structures rises gently after 1.5 meters, while the timber structures' fragility curve rises steeply. However, comparing the fragility curves of RC with masonry infill structures of

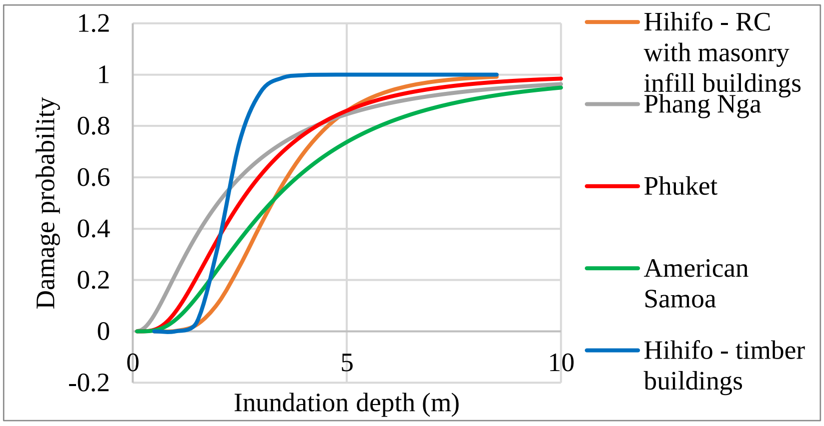

Figure 7. Comparison of tsunami fragility curves developed for RC with masonry infill structures (orange) and timber buildings (blue) of Hihifo with those of RC buildings in Phang Nga (grey) and Phuket (red), Indonesia and American Samoa (green) (Mas et

Hihifo with that of RC structures of Phang Ga and Phuket, Thailand, the RC structures of Hihifo are stronger (Figure 7). On the other hand, the fragility function of RC buildings in American Samoa is stronger than that of the Hihifo area when looking at higher inundation depth (Figure 7). Nevertheless, at inundation depths lower than three meters, the Hihifo RC structures are stronger than American Samoa's. It can also be observed in the fragility curve for RC structures with masonry infill of Hihifo (Figure 4e) that the damage probability varies, unlike Hihifo's timber structures (Figure 4c) where the damage probability is uniform.

4. CONCLUSIONS

From comparing the fragility curves of all building types of Hihifo and Nuku'alofa, the structural system of the Nuku'alofa area needs to be surveyed and analyzed for disaster mitigation purposes. Since no RC with masonry infill structure was destroyed in Nuku'alofa, we concluded that the timber buildings are too vulnerable as they start to be destroyed when the inundation depth is higher than one meter. Therefore, the timber structural system of Nuku'alofa needs to be assessed in detail to address the vulnerability of structures to tsunami hazards.

However, the observed damage probability of timber structures shows a uniform pattern while the RC structures show variation in the damage probability. We concluded that this variation is due to some RC structures with masonry infill not following the building code while the others do. Therefore, there is a need for all RC buildings to follow the building code and for the existing ones to be retrofitted so that all RC buildings will have the similar strength to endure tsunamis.

Since RC structures with masonry infill of Hihifo are stronger than timber buildings, we recommended that areas exposed to tsunamis build RC with masonry infill structures instead of timber structures. RC buildings are more resilient to tsunamis than timber buildings. However, we can liaise with American Samoa on what makes the differences in fragility function of RC structures at higher inundation depth to modify the RC structures of Hihifo and Tonga to be more resilient to tsunamis.

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