VULNERABILITY FUNCTIONS FOR BUILDINGS BASED ON DAMAGE SURVEY DATA IN SRI LANKA AFTER THE 2004 INDIAN OCEAN TSUNAMI

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Abstract

The authors investigated building damage conditions as a result of the 2004 Indian Ocean Tsunami in five areas of Galle, Matara, and Hambantota, Sri Lanka. This paper presents tsunami vulnerability functions for the buildings, a relationship between building damage and inundation, in the country. In order to develop the functions, the authors used 1,535 building damage data in terms of structural types, solid (mainly reinforced concrete) and non-solid (masonry and timber-frame), and 166 inundation height data obtained by the field surveys. The developed fragility curves are compared with other curves previously developed by other researchers, and those future usages are discussed.

Keywords: *fragility curve, Sri Lanka, the 2004 Indian Ocean Tsunami, building damage, inundation*

1. Introduction

Sri Lanka was the most affected country by the 2004 Indian Ocean Tsunami after Indonesia. Following the tsunami disaster, the Department of Census and Statistics (DCS) (2005a) reported that approximately 40,000 people were killed, and 96,000 houses in coastal areas were destroyed in the country. Those devastating experiences should be utilized for future urban safety and disaster reduction not only in the affected countries by the 2004 tsunami but also in other tsunami-prone areas. Building damage data can be used to develop tsunami vulnerability functions, which are helpful for building damage estimation in urban disaster management, if adequate inundation data is prepared. Aiming at developing vulnerability functions for building damage for tsunami in Sri Lanka, the authors conducted field surveys to collect building damage and inundation data after the 2004 tsunami, and consequently the vulnerability functions in terms of structural type were developed. Explaining how the authors developed the fragility curves, this paper discusses some characteristics and difference between the developed fragility curves and other curves constructed by other researchers. It also presents those usages for sustainable urban development in Sri Lanka.

2. Literature Review and Methods

2.1 Literature Review of Tsunami Vulnerability Functions for Buildings

The relationship between building damage and inundation height was quantitatively examined by Hatori (1984) for the first time in Japan, based on damage data due to the 1896 and the 1933 Sanriku Tsunami, and the 1960 Chilean Tsunami. Shuto (1994) deduced the relation between the damage ratio of housings and tsunami height in the past tsunamis in Japan by numerical analysis and proposed "tsunami intensity and damage" table.

After the 2004 Indian Ocean Tsunami, Koshimura et al. (2007) developed fragility functions "by an integrated approach using the numerical modeling of tsunami inundation and GIS analysis of post–tsunami survey data" for Banda Aceh Indonesia. However, the consideration was not given to building structure because the used data were obtained by satellite images.

As for Sri Lanka, Peiris (2006) developed vulnerability functions based on the statistical data released by DCS (2005b), and Kimura et al. (2006) proposed other vulnerability functions through an investigation in Matara. However, those functions are not distinguished by building structural type. Then, the authors constructed other ones in terms of structural type using the actual damage data obtained by field surveys and reported them in Japanese paper (Murao and Nakazato, 2010). Adding new information, the following sections explain how to develop the vulnerability functions and discuss the differences among the existing fragility curves.

2.2 Methods

This paper has two main parts: outline of the vulnerability functions developed by the authors, and comparison of tsunami vulnerability functions based on building damage in Sri Lanka.
The authors' vulnerability functions are developed in the following procedures: (1) collecting damage data by field surveys in Galle, Matara, and Hambantota, (2) defining building damage rank, (3) classifying building structural types, (4) collecting inundation height data by field surveys, (5) arranging the obtained data, (6) applying the dataset to normal distribution, and (7) constructing fragility curves. The procedure is outlined in Section 3.
In Section 4, the developed vulnerability functions mentioned above are compared with those by Peiris (2006) and Kimura et al. (2006). For the comparative study, differences of collecting data and developing methods are considered first. Then the developed curves by three research groups are examined in a same figure. Finally, meanings and usage of the vulnerability functions are discussed.

3. Development of Tsunami Vulnerability Functions for Buildings

With some additional information, this section explains how Murao and Nakazato (2010) developed the tsunami vulnerability functions.

3.1 Collecting Damage Data

Field surveys were carried out twice in February and November 2005 in the Coastal Conservation Zone for five characteristic districts chosen from Galle, Matara, and Hambantota based on the regional map of Sri Lanka Survey Department, which contained polygonal building-shaped data. The total coastline length of the investigated areas were approximately 7km, and the total number of buildings was 1,535.

3.2 Defining Building Damage Rank

Building damage due to the tsunami was classified into four categories defined in Table 1. The authors visually investigated each building damage condition on the ground first and then interviewed residents to confirm the adequacy through the field surveys.

Table 1 Building damage rank and definition

Damage Rank	Complete Damage	Heavy Damage	Moderate Damage	No/Slight Damage
Definition	Complete structural damage	Structural damage and unusable	No visible structural damage and reusable	No visible mentionable damage
Image				

3.3 Buildings Structural Types

Most of the houses were one or two storied buildings in the districts, and most of the one-story houses were brick-built, block-built, or wooden. On the other hand, two or more storied houses including apartments in the residential area and public, commercial, or office buildings with several stories in the central area of Galle were mainly reinforced concrete or steel buildings. Building structure is one of the important factors to differentiate the damage condition for tsunamis in general. Therefore, the objective buildings were classified into two structural types in this research: non-solid buildings and solid buildings, shown in Table 2.

Table 2 Building structural types

Type	Non-solid buildings	Solid buildings
Structure (material)	Brick-built, block-built, or wooden	Reinforced concrete, steel
The number of floors	One or two	Two or more
Usage	Housing (commercial)	Public, commercial, or office
Image		

3.4 Collecting Inundation Height Data

In the field surveys, the authors collected inundation height information by interviews with residents or checking water level sign remaining on buildings or concrete block walls. According to regional characteristics, the inundation data was collected at an interval of dozens or hundreds of meters.

3.5 Arranging the Obtained Data

In order to analyze the relationship between building damage and tsunami inundation height, the investigated areas were divided by grid of 100m x 100m first. The total number of grids was 166. Then the representative inundation height of each district was determined based on the acquired data by the surveys gathering with information from contour models the authors made and existing materials about tsunami height in the areas. An example is shown in Figure 1. Finally, the building data—1,202 non- solid buildings, 333 solid buildings, and 1,535 all buildings—were sorted into appropriate groups by inundation height respectively. As a result of the arrangement, necessary data was prepared for the next step.

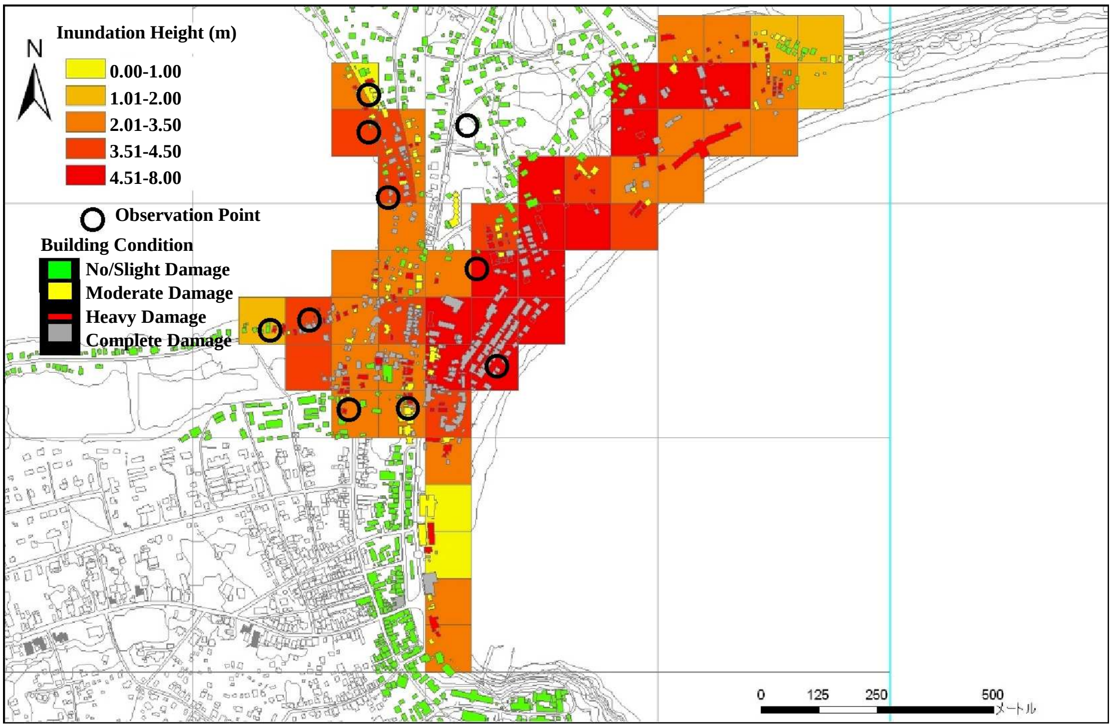


Fig. 1 Inundation height and observation points on grids in Hambantota

3.6 Applying the Dataset to Normal Distribution

Such grouping was adopted to obtain reliable damage statistics that correspond to the inundation height. For an inundation index x, the cumulative probability P_R (x) of the occurrence of damage equal or higher than rank R is assumed to be normal as follows:

$$P_R(x) = \Phi[(x - \lambda)/\varsigma] \quad (1)$$

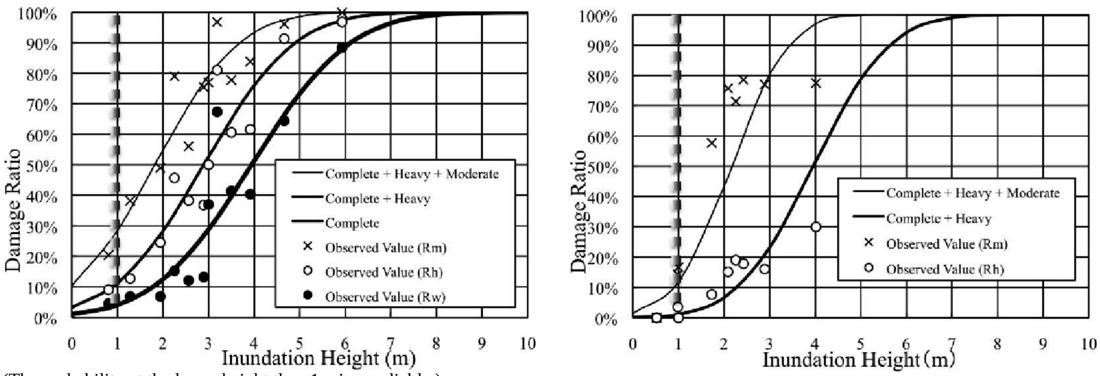
In which Φ is the standard normal distribution, and and are the mean and the standard deviation of x. The two parameters of the distributions, and , were determined by the least square method on logarithmic normal probability paper as shown in Table 3.

Table 3: Parameters of tsunami vulnerability functions for buildings in Sri Lanka

	Damage Rank			R^2
Non-solid Buildings	Complete (R_c)	3.94	1.69	0.846
	Complete + Heavy (R_h)	2.89	1.56	0.908
	Complete + Heavy + Moderate (R_m)	1.82	1.45	0.859
Solid Buildings	Complete (R_c)	-	-	-
	Complete + Heavy (R_h)	3.96	1.31	0.684
	Complete + Heavy + Moderate (R_m)	2.16	0.98	0.641
All Buildings	Complete (R_c)	4.25	1.74	0.931
	Complete + Heavy (R_h)	3.19	1.60	0.971
	Complete + Heavy + Moderate (R_m)	1.87	1.65	0.901

3.7 Constructing Fragility Curves

By the above means, fragility curves were constructed. The curves for non-solid buildings and solid buildings are shown in Fig. 2, and those for all buildings are shown in the next section to be compared with others. Herein the probability of the lower height than 1m is unreliable because the damage in the shallowly inundated areas was too light to distinguish moderate/slight damage from non-damage.



(The probability at the lower height than 1m is unreliable.) (The probability at the lower height than 1m is unreliable.)

(a) Non-solid buildings (b) Solid buildings

Fig. 2 Fragility curves with respect to inundation height for different structural types

4. Comparison between the Developed Fragility Curves and Other Curves in Previous Research

The vulnerability functions developed by the authors are compared with those of Peiris (2006) and Kimura et al. (2006) in this section. Table 4 shows the differences focused on data source and methods.

Table 4: Comparison of the developing methods by three research groups

	Murao and Nakazato (2010)	Peiris (2006) (southwest)	Kimura et al. (2006)
Objective Area(s)	Galle, Matara, and Hambantota (7km-coast line)	11 DS Divisions	Matara
Building Data Source	Field surveys (1,535 buildings)	Department of Census and Statistics (2005b)	Questionnaire survey (586 buildings)
Data Unit	Building	Division	Building
Inundation Data Source	Estimated by altitude and tsunami height, and obtained by field surveys	Department of Census and Statistics (2005b)	Numerical simulation
Data Unit	100m x 100m grid	Division	50m x 50m grid
The median (mean) value (m)	Complete: 4.25 Complete + Heavy: 3.19 C +H +Moderate: 1.87	Complete: 2.80 Partial (Unusable): 2.05 Partial (Usable): 1.55	Heavy: 2.70 Partial: 0.6
Characteristics	Classified by structural type as well as all buildings	Using statistical macro data	Maximum inundation height is 4.1m

4.1 The vulnerability functions developed by Peiris (2006)

The vulnerability functions by Peiris (2006) were developed based on the statistical data reported by DCS. The functions were approximated as follows:

$$P[ds|H] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{H}{\overline{H}_{ds}}\right)\right] \quad (2)$$

In which, " $\overline{H}_{ds}$ is the median value of tsunami water height corresponding to the damage state, ds…. Φ is the standard normal cumulative distribution function and $\boldsymbol{\beta}_{ds}$ is the standard deviation of the natural logarithm of tsunami water height, *H* for damage state, ds."

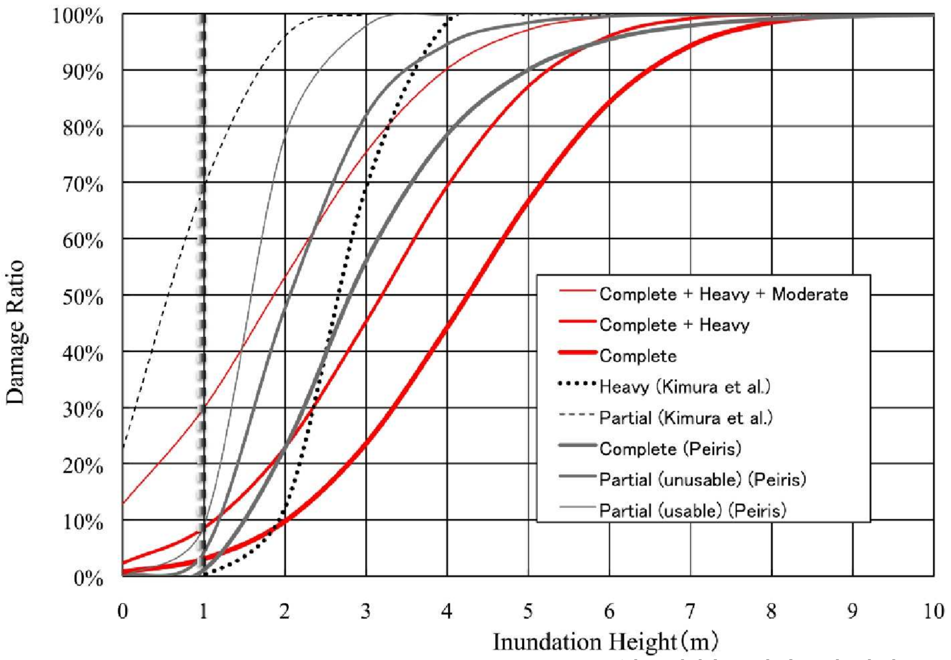
Although the research comprehensively covers the damage in whole Sri Lanka, there is a problem to represent the actual relationship between building damage and inundation height with the dataset. One reason is that the used value is DS unit data, which only shows several representative values for one DS district. Another one is that the data does not contain non-damage building data. It means that the denominator for the damage ratio consists of only damaged buildings, so the ratio at one inundation height value tends to be higher than actual condition.

4.2 The vulnerability functions developed by Kimura et al. (2006)

Kimura et al. (2006) obtained the dataset of buildings by questionnaire survey in Matara and calculated inundation data by numerical simulation. The concept of approximation is same as ours as shown in Sec. 3.6. However, it cannot demonstrate the actual damage incurred in higher inundation areas such as Hambantota, since the maximum inundation height in their research is 4.1m.

4.3 Comparison of the fragility curves

The fragility curves for all buildings developed by the authors are compared with other two-research based curves in Fig. 3. As mentioned in the above subsections, the curves by the other researchers show higher damage ratio than ours: for example, the curve for "heavy damage" by Kimura et al. reaches to 100% damage at 4m, and the curve for "complete damage" by Peiris demonstrates 80% at the same height, where our curve for "complete damage shows 45%.



(The probability at the lower height than 1m is unreliable.)

Fig. 3 Comparison of fragility curves for buildings in Sri Lanka

We saw some non-collapsed buildings in 4m estimated inundation areas. In order to solve the problems pointed out in the above subsections, our approach in the survey was to collect data of various building condition and inundation by ourselves along the 7km coastline areas in five districts with different characteristics, including slight damaged blocks or atrocious areas, in Galle, Matara, and Hambantota. The fragility curves in our research appropriately demonstrate the building vulnerability based on the surveys.

5. Conclusion

This paper presented how authors obtained building damage and inundation data in Galle, Matara, and Hambantota in Sri Lanka after the 2004 Indian Ocean Tsunami and how the vulnerability functions were developed based on the dataset. Also, the developed fragility curves were compared with those by other two research groups focused on the data and methods.

The developed functions in this research have two advantages for damage estimation over the previous ones. The first one is adequacy. The dataset acquired by the authors' elaborate surveys covered various districts in the country ranging from slightly damaged area to seriously damaged area. The surveys were conducted in order to solve the problems in the previous research, so the developed vulnerability functions represent the actual damage more adequately than the others. The second one is structural classification. The authors investigated the damage condition considering structural types. As a result, the vulnerability functions for non-solid buildings (brick-built, block-built, or wooden) and solid buildings (reinforced concrete, or steel) were developed as well as for all buildings.

Those vulnerability functions, which were built on the catastrophic experience in Sri Lanka, can significantly contribute to building damage estimation for future urban safety. As Nakazato and Murao (2007) pointed out, several regional problems such as the building regulation in the Coastal Conservation Zone appeared in the post-tsunami recovery process in the country. According to regional situation and usable data, the vulnerability functions can be used for tsunami damage estimation and proper tsunami management toward the future sustainable society.

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