

Paper:

# Tsunami Fragility – A New Measure to Identify Tsunami Damage –

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**Abstract.** *Tsunami fragility (fragility curve, or fragility function) is a new measure, we propose, for estimating structural damage and fatalities due to tsunami attack, by integrating satellite remote sensing, field survey, numerical modeling, and historical data analysis with geographic information system (GIS). Tsunami fragility is expressed as the structural damage probability or fatality ratio related to hydrodynamic features of tsunami inundation flow, such as inundation depth, current velocity and hydrodynamic force. It expands the capability of estimating potential tsunami damage in a quantitative manner.*

**Keywords:** fragility curve, tsunami damage estimation, remote sensing, numerical modeling, historical tsunamis

## 1. Introduction

In tsunami damage estimation efforts, several empirical relationships between tsunami hazard and vulnerability have been used. Shuto (1993) proposed the tsunami intensity scale to discuss the structural damage based on the empirical data from historical tsunamis in Japan, in terms of the damage and local tsunami height [1], and this has been widely used in tsunami disaster assessment by the Japanese government as a measure of tsunami damage. When the local tsunami inundation depth exceeds 2 m, for example, Shuto's tsunami intensity scale suggests, complete destruction of wooden houses as shown in **Fig. 1**. Izuka and Matsutomi (2000) suggested a structural destruction threshold related to the hydrodynamic features of tsunami inundation flow throughout the field surveys and laboratory experiments [2]. And some engineering studies have proposed tsunami design forces on structures based on the laboratory experiments [3, 4], but have not suggested the procedures for estimating structural damage.

Since the 2004 Sumatra-Andaman earthquake tsunami disaster, numerous efforts have been made to identify the tsunami damage mechanisms by widely deployed post-tsunami survey teams reporting tsunami height, inundation zone extent and damage [5–9]. These efforts have led to new understandings of local aspects of tsunami inundation flow and damage mechanisms.

However, their findings based on the inspection of local aspects of tsunami damage make it difficult to identify the “vulnerability” in a quantitative manner. The nature of vulnerability is associated with multitude of uncertain sources, such as hydrodynamic features of tsunami inundation flow, structural characteristics, population, land use, and any other site conditions. To view tsunami vulnerability comprehensively requires humongous amounts of damage data, whereas post-tsunami survey rarely provides sufficient data because of limited survey time and human resources. As Shuto (1993) concluded, degree of damage may change with these uncertainties and a statistical approach to these uncertainties should be taken.

Herein, we propose *Tsunami fragility* (fragility curve or fragility function) as a new measure for estimating tsunami damage. Tsunami fragility is defined as the structural damage probability or fatality ratio with particular regard to the hydrodynamic features of tsunami inundation flow, such as inundation depth, current velocity and hydrodynamic force. In principle, the development of tsunami fragility requires that tsunami hazard information and damage data should be used synergistically. We thus incorporate several approaches to constructing the tsunami fragility.

In order to obtain tsunami hazard information such as inundation depth and current velocity, we performed a numerical modeling of tsunami inundation with some model validations, especially focusing on the 2004 Sumatra-Andaman earthquake tsunami. In terms of the damage data including structural damage and fatalities, we use the recent advances of remote sensing technologies expanding capabilities of detecting spatial extent of tsunami af-

Tsunami intensity	0	1	2	3	4	5
Tsunami height (m)	1	2	4	8	16	32
Damage : wooden house	partly damaged	completely destroyed				
Damage : masonry house	withstand		no data	completely destroyed		
Damage : reinforced concrete building	withstand			no data		completely destroyed
Damage : fishing boats		damage	50% damage	completely damaged		

**Fig. 1.** Tsunami intensity scale and damage [1], modified from the original figure.

affected areas and damage on structures. In addition, some field data and historical documents are used to obtain the tsunami fragility from historical events.

Throughout the data integration and statistical analysis, we propose a concept and framework developing tsunami fragility, and apply it in several approaches according to available data types from recent and historical events.

## 2. Developing Tsunami Fragility – Methods

Fragility curves (or fragility functions) have conventionally been developed in performing seismic risk analysis of structural systems to identify structural vulnerability against strong ground motion using damage data associated with historical earthquakes and spatial distribution of observed or simulated seismic responses [10]. And they have been implemented in estimating structural damage against potential seismic risks in which various uncertain sources such as seismic hazard, structural characteristics, soil-structure interaction are involved [11, 12].

In earthquake engineering studies, the fragility curves are defined by the following Eq. (1) or (2) ;

$$\begin{aligned}
 P_D(x) &= \Phi\left[\frac{\ln x - \lambda}{\xi}\right] \\
 &= \int_{-\infty}^x \frac{1}{\sqrt{2\pi}\xi t} \exp\left(-\frac{(\ln t - \lambda)^2}{2\xi^2}\right) dt \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 P_D(x) &= \Phi\left[\frac{x - \mu}{\sigma}\right] \\
 &= \int_{-\infty}^x \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(t - \mu)^2}{2\sigma^2}\right) dt \quad (2)
 \end{aligned}$$

where  $P_D(x)$  is the damage probability of structures, as a function of  $x$  or  $\ln x$  such as the maximum ground acceleration, velocity, and seismic intensity. Here,  $P_D(x)$  is expressed by the standard lognormal or normal cumulative distribution function  $\Phi[(\ln x - \lambda)/\xi]$  or  $\Phi[(x - \mu)/\sigma]$ , with two statistical parameters  $(\lambda, \xi)$  or  $(\mu, \sigma)$ , as the mean of  $\ln x$  (or  $x$ ), and the standard deviation respectively.

To develop tsunami fragility, we take a statistical approach synergistically using remote sensing, numerical model results, field surveys and historical documents, in five steps.

- 1 Damage data acquisition : obtaining damage data from satellite images, field surveys or historical documents, e.g. numbers of destroyed or survived structures with its spatial information.
- 2 Tsunami hazard estimation : estimating the hydrodynamic features of tsunami by numerical modeling, field surveys and from historical documents.
- 3 Data assimilation between the damage data and tsunami hazard information : correlating the damage data and the hydrodynamic features of tsunami through the GIS analysis.
- 4 Calculating damage probability : determining the damage probabilities by counting the number of damaged or survived structures, for each range of hydrodynamic features above.
- 5 Regression analysis : developing the fragility curves by regression analysis of discrete sets of damage probability and hydrodynamic features of tsunami.

In the sections that follow, we apply the above procedure in several approaches to construct tsunami fragility, according to the data types such as satellite data, numerical models, field surveys and historical documents.

## 3. Tsunami Fragility Determined from Satellite Remote Sensing and Numerical Modeling

Taking an advantage in satellite remote sensing, we identify the spatial distribution of structural damage by tsunami. The highest spatial resolution of commercial optical satellite imaging is up to 60-70 centimeters (QuickBird owned by DigitalGlobe) or 1 meter (IKONOS operated by GeoEye). **Fig. 2** shows the result of visual interpretation [13] on structural damage by using a set of pre and post-tsunami (the 2004 tsunami) satellite images (IKONOS) from Banda Aceh, Indonesia. Through inspecting a set of pre and post-tsunami satellite images visually or manually, presence of building roofs can be interpreted. The advantage of using high-resolution optical satellite images for damage interpretation is the capability of understanding structural damage visually and enables us to comprehend its spatial extent in regional scale where post-tsunami survey hardly get through because of