DEVELOPING THE TSUNAMI FRAGILITY CURVES FOR STRUCTURAL DESTRUCTION ALONG THE THAILAND COAST

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The 2004 Indian Ocean tsunami damaged and destroyed numerous buildings and houses in Thailand. This study was undertaken to develop fragility curves using visual inspection of high–resolution satellite images (IKONOS) taken before and after tsunami events to classify whether the buildings destroyed or survived based on the remaining roof with regard to the hydrodynamic conditions of tsunami inundation flow. Then, a tsunami inundation model is created to re-simulate the tsunami features such as inundation depth, current velocity, and hydrodynamic force of the event. Assuming that the fragility curves are expressed as normal or lognormal distribution functions and assuming that estimation of the median and log-standard deviation is performed using the maximum likelihood method. The buildings started to collapse at 2–3 m inundation depth and totally destroyed when the depth became greater than 6 m.

Keywords: *Tsunami fragility curve, 2004 Indian Ocean tsunami, building damage, tsunami inundation model*

1. INTRODUCTION

The 2004 Indian Ocean megathrust earthquake occurred on 26 December 2004, creating a gigantic tsunami striking coastal communities over a large area. Thailand was among the most affected Asian countries, with total dead and missing of 8,212 and 8,457 injured. Regarding structural damage, 4,806 houses were affected; 3,302 houses were destroyed completely. As many as 1,504 were partly damaged. The maximum water level of about 15 m reported at Khao Lak in Phang Nga province and of 7 m at Patong and Kamala Beach in Phuket gave these areas their respective distinctions as the first and second worst areas of structural damage of 2,508 and 1,033 houses. Using the investigated damage data with tsunami numerical simulation, the fragility function would be a proper tool for damage estimation against a potential tsunami in the future.

2. STUDY BACKGROUND

(1) Tsunami fragility curves

Koshimura et al. (2009a) proposed the term "Tsunami fragility" 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. They described three measures to develop tsunami fragility for structural damage,

a) Tsunami fragility determined from satellite remote sensing and numerical modeling,
b) Tsunami fragility determined from satellite remote sensing and field surveys and
c) Tsunami fragility determined from historical data.

(2) Tsunami fragility for Thailand

Although the tsunami fragility for Thailand using the first method conducted by Foytong (2007) is more convenient and reliable as a real surveyed building data were used. However, the method might be unable to indicate fragility curves for the whole area because of the limited number of sampled buildings. In contrast, the method developed by Koshimura et al. (2009b) was apparently more complicated and time-consuming because numerical simulation in a very fine grid is necessary and visual interpretation of such thousands or tens of thousands of buildings requires great effort. Nevertheless, this method represents the fragility function of all buildings located in the specific area against the hydrodynamic features of the tsunami.

3. TSUNAMI NUMERICAL MODEL

(1) Tsunami source model

Performances of eight-proposed tsunami source models for the 2004 Indian Ocean tsunami were compared by Suppasri et al. (2008). They concluded that, especially for the water level and waveform, the model developed by Koshimura et al. (2009b) with some modification is the best model to reproduce a tsunami characteristic for a study in Thailand. The vertical sea surface displacement field (considered as the initial condition of tsunami) of each sub-fault's rupture with unit dislocation was calculated using the theory presented by Okada (1985).

(2) Tsunami inundation model

Tsunami inundation model was performed in the two study areas in Khao Lak (Phang Nga province), and Patong and Kamala Beach (Phuket province).

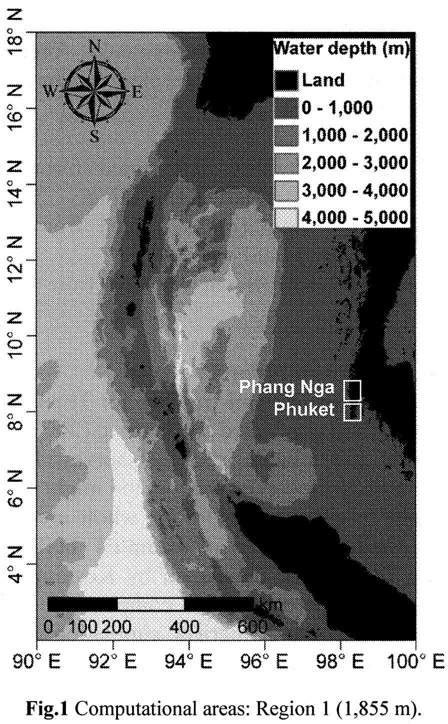

Fig.1 Computational areas: Region 1 (1,855 m).

A set of nonlinear shallow water equations are discretized using the Staggered Leap-frog finite difference scheme (Imamura, 1995) with bottom friction in the form of Manning's formula according to a land use condition. Four computational domains used as a nesting grid system. The largest grid size of 1,855 m (**Fig.1**) is obtained from the General Bathymetric Chart of the Oceans (GEBCO), where 465 m, 155 m, and 52 m are obtained from the digital photogrammetric mapping and navigation charts (Foytong, 2007).

(3) Resistance law within an inundation zone

The equivalent roughness with appropriate consideration of the hydraulic characteristics is introduced by Aburaya and Imamura (2002). For the flow resistance in a non–residential area, the roughness coefficient is inferred from land use map in the study area during 2000–2002 provided by the land development department. It is used to quantify the Manning's roughness coefficient. For the flow resistance in a residential area, the ground-surface's roughness is mainly affected by the tsunami inundation because of a high building occupation ratio. The resistance law with the composite equivalent roughness coefficient according to land use and building conditions can be shown in Eq. (1).

$$n = \sqrt{n_0^2 + \frac{C_D}{2gd} \times \frac{\theta}{100-\theta} \times D^{4/3}} \tag{1}$$

In that equation, n_0 signifies the Manning's roughness coefficient (n_0=0.025), θ denotes the building/house occupation ratio in the finest computational grid of 52 m and obtained by calculating the building area over grid area using GIS data, C_D represents the drag coefficient (C_D=1.5 (Koshimura et al., 2009b)), d stands for the horizontal scale of houses (15 m in average is used), and D is the modeled flow depth. The average occupation ratio in residential areas for Phang Nga and Phuket are, respectively about 25% and 40%. The simulated tsunami propagation was validated with waveforms recorded by tidal gauges surrounding Thailand. The tsunami inundation model results were validated and found to be consistent with the survey data of water levels, inundation depths, and current velocity from the survivor videos.

4. BUILDING DAMAGE INSPECTION USING SATELLITE IMAGES

According to their report for housing damage in six provinces (Department of Disaster Prevention and Mitigation (DDPM), 2007), 3,302 houses were totally damaged and 1,504 were partially damaged. In Phang Nga, reported figures were 1,904 and 604 for totally damaged and partially damaged, but 742 and 291 in Phuket. High–resolution satellite images (IKONOS) taken before and after the tsunami event were used for visual damage interpretation. The pre-event images were acquired on 13 January 2003 and 24 January 2004 for Phang Nga and Phuket; the post-event images were both acquired on 15 January 2005. Regarding the limitations in using a 1 × 1 m resolution of IKONOS satellite image, classification of the building damage would be survived and damaged buildings. The remaining roof buildings were interpreted as "survived" and the ones that had disappeared were "destroyed". Results of the building damage inspection in residential areas are presented in **Fig.2**. Figure 2(a) shows damaged buildings in residential areas in Khao Lak, Phang Nga where Fig. 2(b) represents for populated residential area in Patong, Phuket. The visual interpretation data have high accuracy as more than 90 percent after checked with the investigation data above.

5. RESULTS AND DISCUSSION

(1) Developing fragility curves

From the visual inspection of damaged buildings based on the remaining roof structure, a histogram of tsunami features (inundation depth, current velocity, and hydrodynamic force) and the number of buildings including those that survived and destroyed is presented herein. Here the hydrodynamic force acting on a structure is defined as its drag force per unit width (Eq. (2)), as

$$F = \frac{1}{2} C_D \rho u^2 D \tag{2}$$

where C_D denotes the drag coefficient (C_D = 1.0, convenience when a different value of C_D is to be applied), ρ is the density of water (= 1, 000 kg/m^3), u stands for the current velocity (m/s), and D is the inundation depth (m).

The Damage probabilities of buildings and a discrete set were calculated and shown against a median value within a range of about 100 buildings in Phang Nga and 50 buildings in Phuket. Linear regression analysis was performed to develop the fragility function. The cumulative probability P of occurrence of the damage is given as either Eq. (3).

$$P(x) = \Phi\left[\frac{\ln x - \mu'}{\sigma'}\right] \tag{3}$$

In those equations, Φ represents the standardized lognormal distribution function, x stands for the hydrodynamic feature of tsunami (e.g., inundation depth, current velocity and hydrodynamic force as shown in **Fig.3**), and μ' and σ' respectively signify the mean and standard deviation of ln x. Two statistical parameters of fragility function, μ' and σ', are obtained by plotting ln x against the inverse of Φ^{-1} on lognormal probability papers, and performing least-squares fitting of this plot. Consequently, two parameters are obtained by taking the intercept (= μ') and the angular coefficient (= σ') in Eq. (4):

$$\ln x = \sigma' \Phi^{-1} + \mu' \tag{4}$$

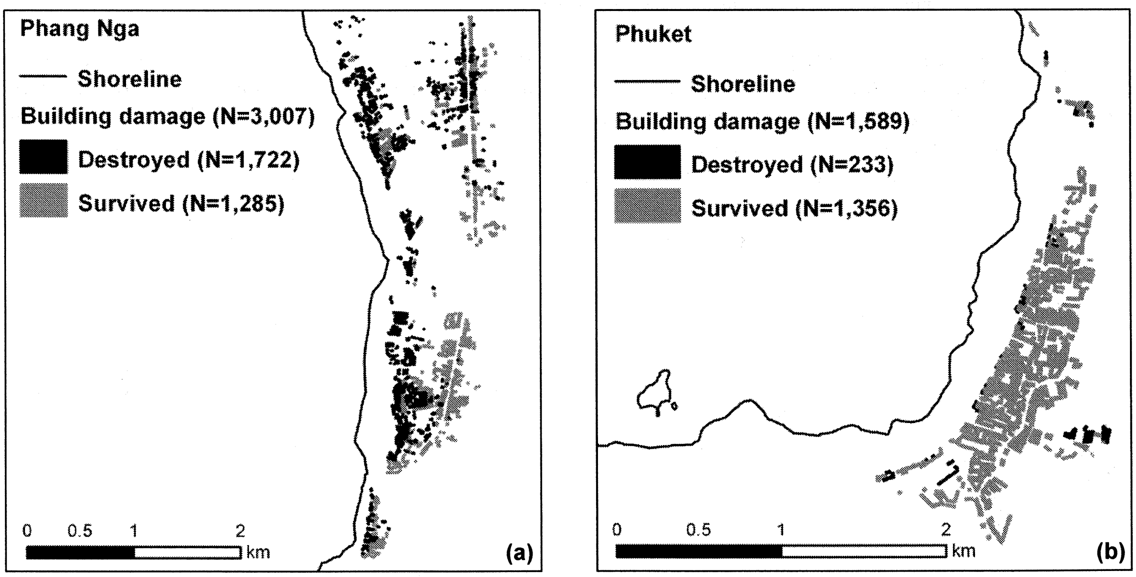

Fig.2 Building damage in residential areas in Khao Lak and Patong.

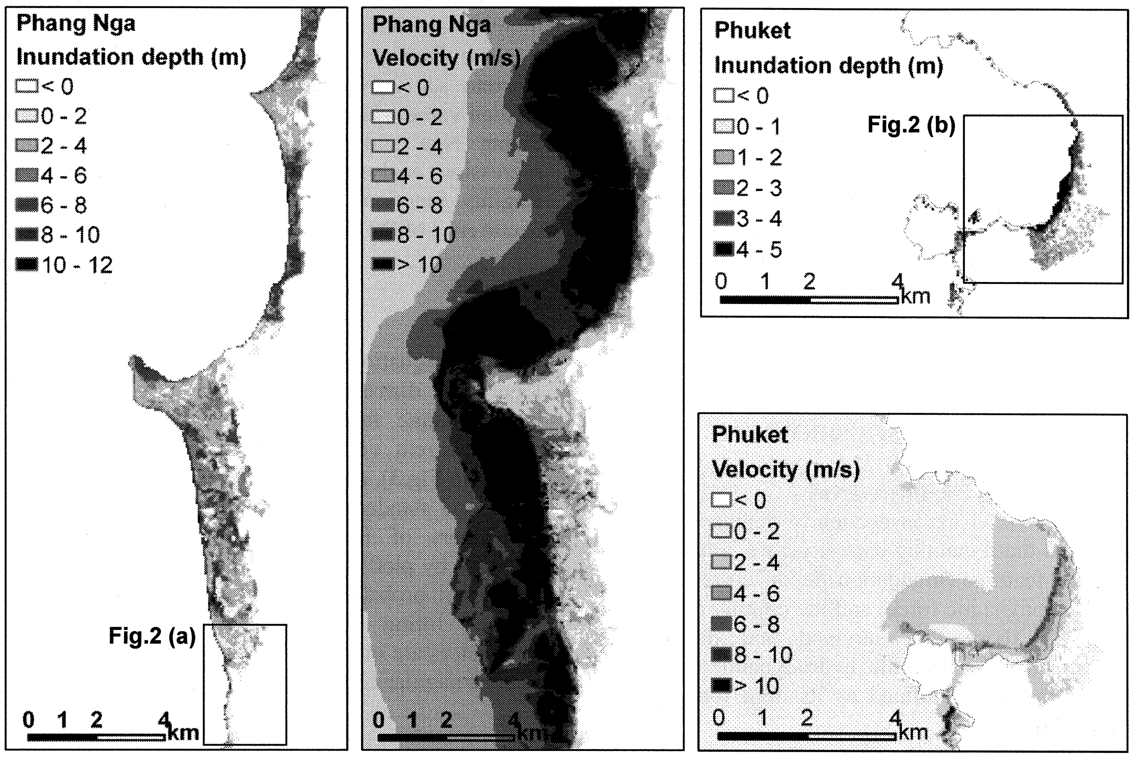

Fig.3 Modeled maximum inundation depth and current velocity at Phang Nga and Phuket.

Throughout the regression analysis, the parameters are determined to obtain the best fit of fragility curves with respect to the inundation depth, the maximum current velocity and the hydrodynamic force on structures per unit width. From this result, all the fragility function in Thailand with respect to the inundation depth, current velocity and hydrodynamic force are given by the standardized lognormal distribution functions with μ' and σ' (**Fig.4**).

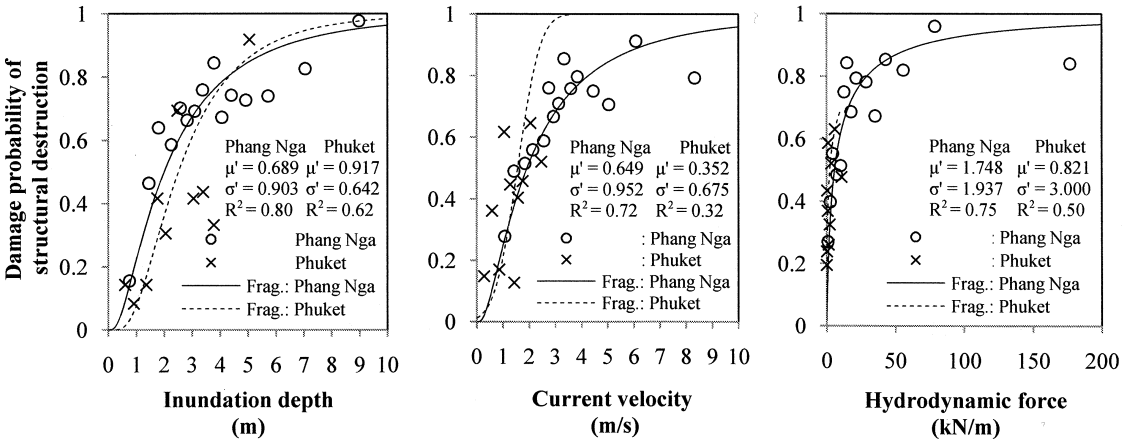

Fig.4 Tsunami fragility curves for structural destruction as a function of the hydrodynamic variables.

(2) Tsunami fragility curves for different building types

According to the surveyed tsunami runup database in Thailand from Foytong (2007) and Chulalongkorn University (CU−EVR, 2009), the tsunami fragility curves for three damage levels of reinforced concrete (RC) building are re-plotted (**Fig. 5**−left). Damage levels of 1, 2, and 3 respectively represent the structural damage in secondary members only, damage in primary members, and collapse. On the other hand, the raw data of structural damage in Phang Nga and Phuket were then mixed and used to develop the fragility curves as a function of inundation depth for the mix type of building materials in Thailand (**Fig.5**–right). It can be presumed that the structural damage of the inundation depth less than 2 m is regarded for the wooden building (Matsutomi et al., 2010). Structural damage of brick or concrete block buildings then starts from 2 and almost destroys the structure. Then the inundation depth reaches 7−8 m, as seen from the different area of the black line and dotted line. Finally, the structural damage of RC building is apparent from **Fig.5** when the inundation depth is greater than about 10−12 m.

6. CONCLUSIONS

From the developed tsunami fragility, the buildings started to collapse at 2–3 m inundation depth and destroyed entirely when the depth exceeded 6 m. The fragility curves proposed using the surveyed data show higher performance because they were developed only from the reinforced-concrete building data. The tsunami fragility curves also developed for constructed building material of different types in Thailand by separating the RC buildings (direct survey data) from mixed type buildings (satellite image inspection). The proposed fragility curves are useful for producing loss estimations of potential tsunami in Thailand, but they are applicable for various countries.

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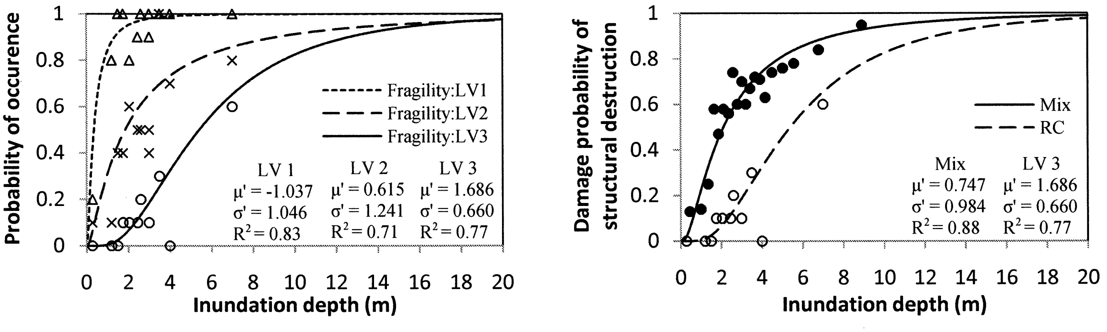

Fig.5 Tsunami fragility for structural destruction of reinforced concrete and mix type structure as a function of the inundation depth.