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Fragility curves of reinforced-concrete buildings damaged by the 2004 tsunami

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Abstract

The December 26th, 2004 Indian Ocean tsunami caused damage to many buildings and killed many people in the South of Thailand. It is important to mitigate the damage by tsunamis in the future. Fragility curves are key parameters for the tsunami risk assessment. The fragility curves are developed by the data of observed building damage in the December 26th, 2004 Indian Ocean tsunami. In this study, the fragility curves are established using a maximum likelihood method and describe the damage probability corresponding to a specific damage level for different inundation heights. Four different damage levels are defined ranging from no structural damage to collapse. The fragility curves for reinforced-concrete buildings are classified into two types: one-story buildings and buildings taller than one story. For one-story buildings under the inundation height of 4 m, the probability of exceeding the damage in primary members is 90%. For buildings taller than one story under the same inundation height, the probability of exceeding the damage in primary members is only about 25%.

Keywords: Tsunami fragility curves, 2004 Indian Ocean tsunami, Reinforced-concrete building

1. Introduction

The December 26th, 2004 Indian Ocean tsunami caused damage to many engineering structures, lifeline and killed many people in the Indian Ocean countries. The damage from this event emphasizes the need of tsunami risk assessment for evacuation planning, estimation of loss and estimating residential damage from tsunami hazard. The primary components in risk assessment are hazard, fragility curves and structural inventory. The structural damage in risk assessment can be estimated by fragility curves. The fragility curves are widely developed using the maximum likelihood method and least-square method.

This study proposes the fragility curves of reinforced-concrete buildings damaged in Thailand as a function of tsunami inundation height from damaged buildings in the December 26th, 2004 Indian Ocean tsunami. 109 tsunami damaged reinforced-concrete buildings were observed in Thailand [1]. The fragility curves are established using a maximum likelihood method and describe the damage probability corresponding to a specific damage level for different inundation heights. The damage levels are classified into 4 damage levels ranging from no damage to collapse. The fragility curves for reinforced-concrete buildings are classified into two types: one-story buildings and buildings taller than one story.

2. Data of damaged buildings

The December 26th, 2004 Indian Ocean tsunami caused damage to buildings in Indian Ocean countries. 6 provinces in Thailand suffered damage, which are Ranong, Phung-Nga, Phuket, Krabi, Trung and Satun. The damage of buildings was collected in the damage database [1]. There are 109 reinforced-concrete buildings in the database: 73 buildings in Phuket, 25 buildings in Phang-Nga, 8 buildings in Ranong, 2 buildings in Krabi, and 1 building in Trang. Figure 1 shows the distribution of building functions. Residences share the majority of the buildings observed.

This study develops fragility curves of reinforced-concrete buildings and evaluates the effect of the numbers of stories. The capacity of buildings and the construction quality are reflected in the number of stories. The buildings taller than one story are usually constructed with better quality and higher capacity than one-story buildings. In Figure 2, these two buildings were located in Khaolak area in Phang-Nga province. The inundation height was about 5.5 m. One-story buildings (Figure 2(a)) collapsed but 3-stories buildings (Figure 2(b)) suffered slight damage in secondary members. Hence reinforced-concrete building data are grouped in two types: one-story buildings and buildings taller than one story. The distribution of data classified according to the number of stories is shown in Figure 3. There are 63 one-story buildings and 46 buildings taller than one story.

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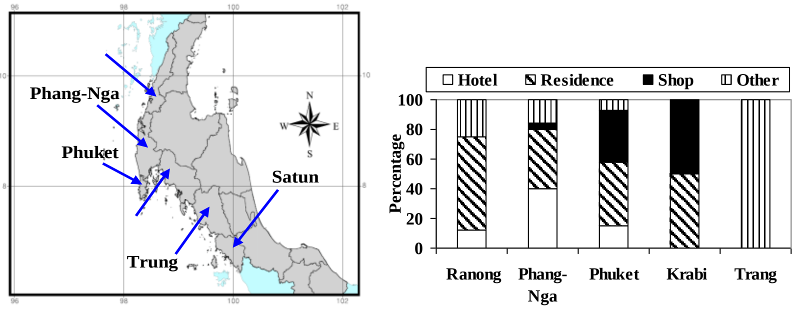

Figure 1 Building functions

(a) One-story building was collapse (b) Three-stories building was damaged in secondary members only

Figure 2 Damage of buildings under the inundation height 5.5 m. in Phang-Nga province

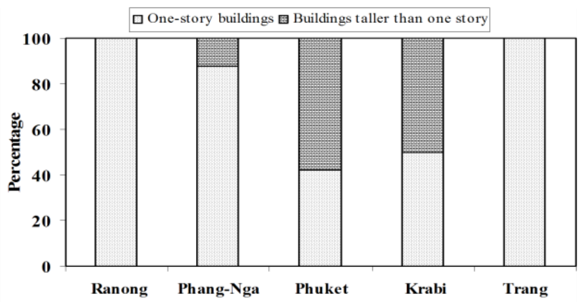

Figure 3 The number of stories

3. Definition of damaged levels

Damage levels are defined in terms of the overall damage of buildings and classified into four damage levels 1) no damage, 2) damage in secondary members only, 3) damage in primary members and 4) collapse. The details are explained below.

- No damage (damage level 0): There is no damage in a building as shown in Figure 4.
- Damage in secondary members only (damage level 1): There is damage only in non-structural components, i.e., walls and/or roofs. At this damage level, there are cracks on wall or wall punching, or tiles are wiped out. But there is no damage in a beam or a column as shown in Figure 5.
- Damage in primary members (damage level 2): There is damage in structural components, i.e., a column, a beam, or a foundation. At this damage level, there are cracks on a beam or a column, but the building is still reparable and it can sustain its gravitational load as shown in Figure 6.

Collapse (damage level 3): A building cannot sustain its gravitational load and it is unreparable. At this damage level, a structure may fail at a major joint or absolutely collapse as shown in Figure 7.

Figure 4 No damage

(a) Cracks on a wall

(b) Wall punching

Figure 5 Damage in secondary members only

Figure 6 Damage in primary members

(a) Joint failure

(b) Absolute destruction

Figure 7 Collapse

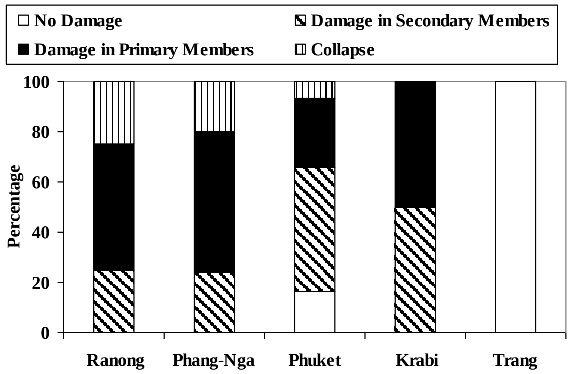

Figure 8 Damage levels of buildings in each province

Figure 8 shows the distribution of damage levels of buildings. In Phuket province, the damage of observed buildings ranges from no damage to collapse. Most of buildings up to 41.3% suffered damage in secondary members.

4. Fragility curve

Fragility curves are represented here as a function of the inundation height, although there are other wave characteristics such as wave velocity. An inundation height can be observed in the field but wave velocity on land may have several uncertainties. The tsunami velocity is a function of tsunami inundation depth ranging from $0.7\sqrt{gh}$ to $2.0\sqrt{gh}$ [2-4]. For simplicity, an inundation height is used in developing fragility curves. Fragility curves can be expressed in form of two-parameter lognormal distribution functions which are median and lognormal standard deviation. The lognormal is used because it agrees well with a variation of failure data [5]. The estimation of these two parameters is done by the maximum likelihood method [6-8]. The likelihood function can be written as

$$M = \prod_{k=1}^{N} \left[F\left(a_k\right) \right]^{y_k} \left[1 - F\left(a_k\right) \right]^{1-y_k} \quad (1)$$

The fragility curve can be written under the lognormal function, $F(a)$ as

$$F(a) = \Phi\left[\frac{\ln\left(\frac{a}{\alpha}\right)}{\beta}\right] \tag{2}$$

where

a_k = the inundation height of the k-th damaged building

y_k = the variable equal to 1 when the building suffered the specific damage level and equal to 0 when the building not suffered the specific damage level under an inundation height equal to a_k

$\Phi(.)$ = the standardized normal distribution function

N = the total number of buildings

α, β = median and lognormal standard deviation of inundation height in unit of meter

The parameters α and β are computed in order to maximize ln (M) by differentiating ln (M) with respect to α and β and equating to zero as

$$\frac{d\ln M}{d\alpha} = \frac{d\ln M}{d\beta} = 0 \tag{3}$$

Eq. (3) is solved numerically using a standard optimization algorithm. The process starts from separating data, depending on whether or not the building sustains a specific damage level. Then, the variable y_k and inundation height are computed. These values are substituted into the likelihood function in Eq. (1) and then a standard optimization algorithm is used to obtain two parameters α and β. Finally, the variable y_k, inundation height and two parameters are used to plot the fragility curve. Inundation heights are arranged from minimum to maximum, and separated with a 0.5-m interval. After that, the average inundation height and probability is calculated for each interval.

Fragility curves of one-story buildings damaged in the 26 December 2004 tsunami are shown in Figure 9. For the damage level 1, it is obvious that damage occurs for inundation higher than 3.5 m. with a probability closes to 100%. Figure 9(d) shows the comparison of fragility curves of each damage level for one-story buildings. The probability reduces for higher damage levels at the same inundation height. To avoid the intersection of the fragility curves of the damage level 1 and the damage level 2, the lognormal standard deviation of the damage level 1 is constrained to be equal to the lognormal standard deviation of the damage level 2 [8]. Figure 10 shows the fragility curves for buildings taller than one story. The trend of fragility curves for buildings taller than one story is similar to the fragility curve for one-story buildings, but the probability of damage is less for the same damage level and inundation height. There is no fragility curve of the damage level 3 because there is no data on collapse of buildings taller than one story. The results of the standard optimization algorithm, median and lognormal standard deviation of inundation height are summarized in Table 1.

Table 1 Parameters of fragility curves for reinforced-concrete buildings with respect to inundation height

Structural types	Damage level 1		Damage Level 2		Damage level 3	
	α	β	α	β	α	β
One-story buildings	0.467	0.757	1.464	0.757	5.028	0.603
Buildings taller than one story	0.804	0.814	8.433	1.156	-	-

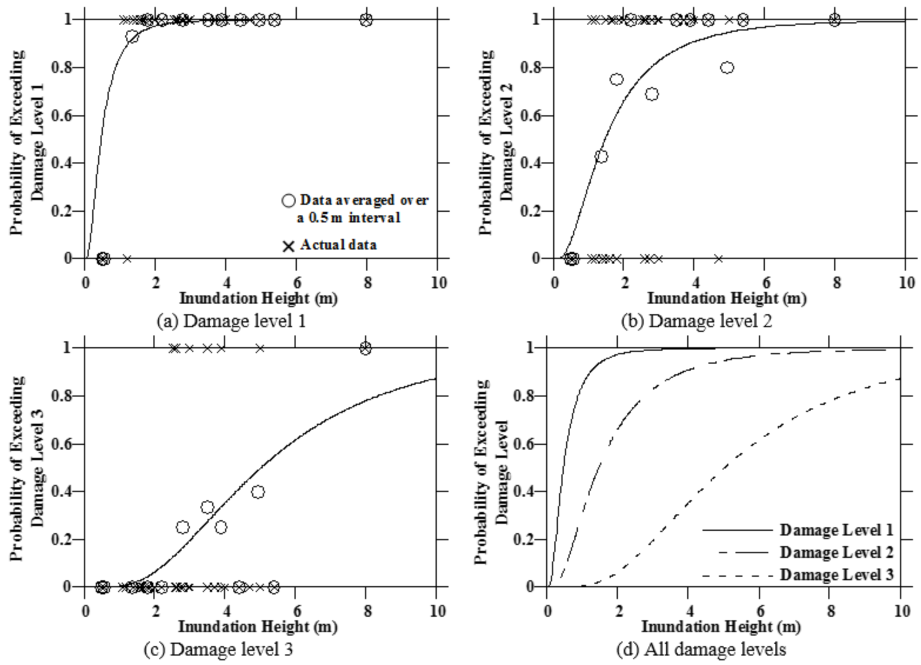

Figure 9 Fragility curves of one-story buildings

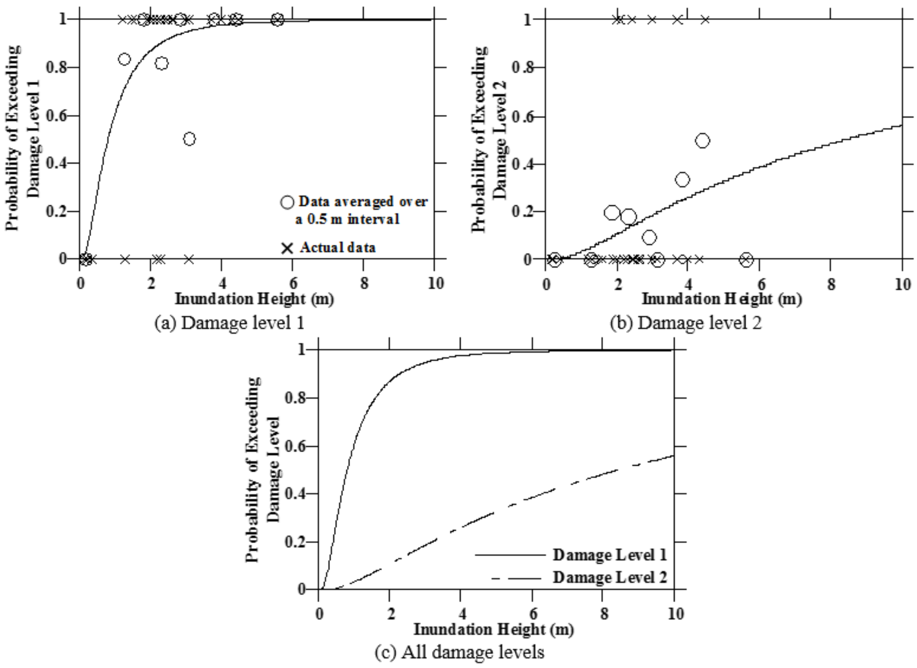

Figure 10 Fragility curves of buildings taller than one story

5. Conclusions

This study proposes fragility curves of reinforced-concrete buildings damaged by the December 26th, 2004 Indian Ocean tsunami for one-story buildings and buildings taller than one story. Fragility curves are developed using the data of observed building damage from the December 26th, 2004 Indian Ocean tsunami. The fragility curve is expressed by a maximum likelihood method as a function of tsunami inundation heights. The fragility curves are obviously dependent on building capacity because the buildings taller than one story are usually constructed with higher capacity than one-story buildings. For one-story buildings under the inundation height of 4 m, the probability of exceeding the damage level 2 (damage to primary members) is 90%. For buildings taller than one story under the same inundation height, the probability of exceeding the damage level 2 is about 25%.

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