Simulations of damage on architectural structures due to an unexpected tsunami disaster

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15 WCEE
LISBOA 2012

SUMMARY:
The approximate number of architectural structures in Hyogo prefecture, Japan that will be damaged due to tsunamis caused by a possible great Nankai earthquake is counted using a Geographic Information System (GIS) software. Seismic intensity and tsunami height distributions are obtained by numerical simulations of the 1854 Ansei-Nankai earthquake model for three different moment magnitudes (M8.4, M8.6, and M9.0). To avoid double counting, the damage only for survived architectural structures after initial earthquake motion is measured. The numbers of destruction of houses are estimated as about 300 (M8.4), 2,300 (M8.6), and 41,000 (M9.0). The result for M8.4 is roughly consistent with the estimate by the Central Disaster Management Council, the Cabinet Office, Government of Japan in 2003.

Keywords: Damage estimate, Tsunami by Nankai earthquake, GIS

1. INTRODUCTION

A significant number of temporary houses are required to accommodate people affected by a massive earthquake. After the Great Hanshin-Awaji Earthquake Disaster, approximately 30,000 temporary houses were constructed. The Great East Japan Earthquake in March 11th 2011 was a magnitude 9.0 (M9.0) undersea megathrust earthquake off the Pacific coast of Tohoku, which caused extensive and severe human and structural damage in the broad area in north-eastern Japan due to earthquake ground motion and tsunami waves. Approximately 52,000 temporary houses were constructed at 905 sites in Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Chiba, and Nagano prefectures. It is crucially important to prepare temporary housing construction including site selection to take immediate action to support the disaster victim.

The Central Disaster Management Council (hereafter called CDMC) of the Cabinet Office already summarized damage estimate due to the Tonankai, Nankai earthquakes in “the expert panel on the Tonankai, Nankai earthquakes” in 2003 (CDMC 2003). An earthquake along the Nankai Trough was discussed in the panel, where the number of collapsed houses was estimated to be about 1,000 by earthquake motion, and about 600 by tsunami in Hyogo. However, following the 2011 Tohoku Earthquake, the consideration was forced to re-examine. CDMC has established a new panel on a megathrust earthquake at the Nankai Trough, and has recently published the first report (CDMC 2012): based on the principle that every possibility leading mega-earthquakes and tsunamis should be taken into consideration, the most significant levels of seismic intensity and tsunami height distributions have been predicted.

This paper is organized as follows. Section 2 describes the Nankai earthquake model and tsunami simulation results. For M8.4, M8.6, and M9.0 cases, we perform tsunami simulations to obtain tsunami height distributions in Hyogo prefecture and adjacent sea. In Sec. 3, damage on architectural structures is estimated using a Geographic Information System (GIS) software, ArcGIS, based on the calculated tsunami inundation heights. The number of destroyed houses is calculated by multiplying the number of houses in the inundation area by the ratio determining how many buildings will be damaged induced by tsunamis depending on their heights (called the damage function). For the purpose of preparing temporary housing, information of house damage situation is necessary. We only consider structures less than 6 meters high as they are assumed to be timber buildings. We summarize the result in Sec. 4.

2. TSUNAMI SIMULATION

2.1. Nankai earthquake model

There are roughly two types of earthquakes: one is intraplate that occurs in the interior of a tectonic plate, and the other is interplate that occurs at the boundary of two plates. Since the interplate earthquake occurs when the stored strain energy due to plate motion is released, it occurs periodically depending on the relative velocity of the plates. The Nankai earthquake is one of such interplate earthquakes that have periodically occurred and have caused damage in the Kansai (including Hyogo prefecture) and Shikoku areas in Japan. According to the record (Utsu 2009), they occurred in 1605 (Keicho era, M7.9~8.0), 1707 (Houei era, M8.4), 1854 (Ansei era, M8.4), and 1946 (Showa era, M8.0). The Nankai earthquake repeat intervals are generally in the range of 100-150 years, therefore a great earthquake is likely to happen in the near future.

In this paper, we perform numerical simulations of tsunamis using the Ansei-Nankai earthquake model to estimate damage on architectural structures resulting from a great earthquake. To perform a tsunami simulation, we need to determine information of faults causing the earthquake (the fault parameters) and the released energy of the earthquake (the moment magnitude). Those parameters are summarized for the earthquakes occurred in the past. The fault parameters of the Ansei-Nankai earthquake are given in Tab. 2.1 (Sato 1989). And, the fault position is mapped in Fig. 2.1. The Philippine Sea Plate is subducting beneath the Eurasia Plate at the Nankai Trough from the south. We perform tsunami simulations of three different magnitudes by changing the released energy. Since the released energy is given by (Fault area)×(Dislocation)×(Rigidity), there are several ways to change the amount of the energy.

Table 2.1. Fault parameters of 1854 Ansei-Nankai earthquake (M8.4)

Latitude [degree]	Longitude [degree]	Length [km]	Width [km]	Depth [km]	Strike [degree]	Dip [degree]	Slip [degree]	Dislocation [m]
32.7	134.74	150	120	1	250	20	117	6.3
33.41	136.15	150	70	10	250	10	127	4.7

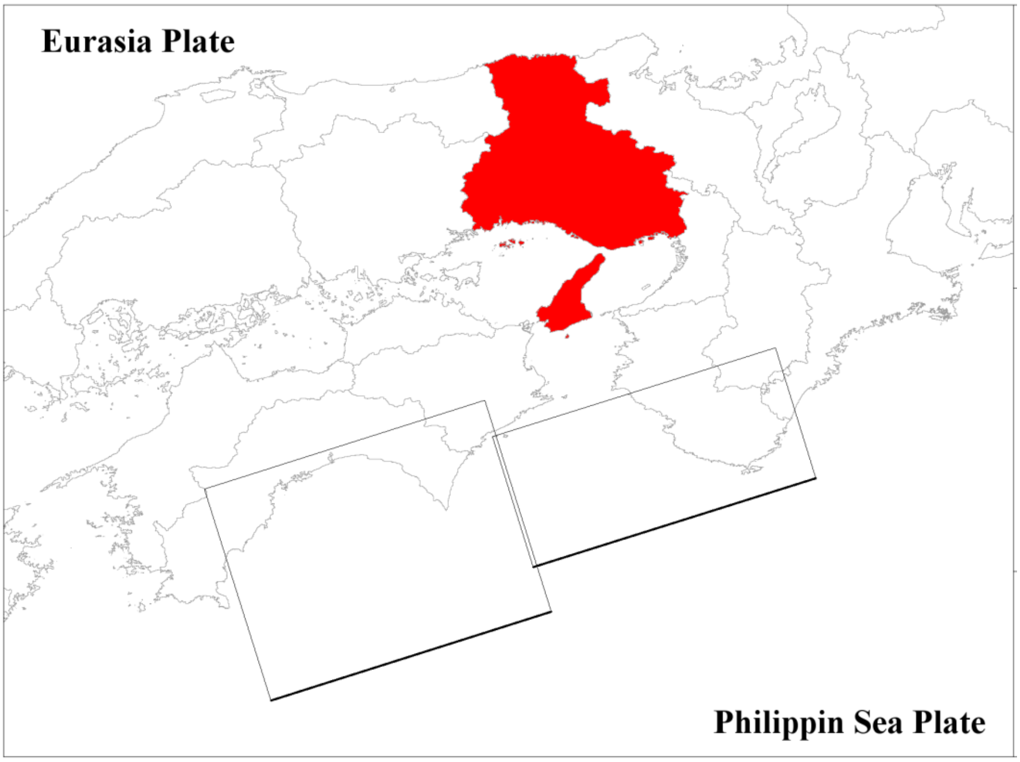

Figure 2.1. Model faults positions of 1854 Ansei-Nankai earthquake. Faults are modelled by two squares mapped on the western Japan. The red area shows the target analysis area (Hyogo prefecture).

2.2. Tsunami simulation result

Given the earthquake model in Sec. 2.1., we perform numerical simulations to obtain tsunami height distributions in Hyogo prefecture using TSUNAMI Simulator (KOZO KEIKAKU ENGINEERING Inc. 2011). The simulation is performed for M8.4, M8.6, and M9.0 cases. TSUNAMI Simulator can change the released energy by changing the dislocation. Since the stored energy for M8.6 (M9.0) is twice (eight times) as large as that for M8.4, we multiply the dislocation for M8.4 in Tab. 2.1 by 2 (8) to achieve the M8.6 (M9.0) energy.

TSUNAMI Simulator first calculates land deformation assuming the land as an elastic body using the method by Mansinha and Smylie (1971). An initial tsunami profile is considered to be equal to the land deformation as the motion of seawater is much slower than the land deformation. TSUNAMI Simulator solves the equations of the shallow water theory with the bottom friction (Goto *et al*. 1997) on uniform grid points. A central finite difference method on the staggered grids and the leap-flog method are used to discretize space and time. For the sake of efficiency of the calculation, it allows to specify multi-level mesh sizes: the largest mesh size is 1350m×1350m and the mesh size becomes smaller by a factor of 1/3 to the next level until the smallest 17m×17m mesh (5 levels). In this study, we use 3 level meshes. The most coarse grid region (region A) includes the faults and the coastal lines of Hyogo. Inside the region A, we take finer grid regions (B and C) to perform a more accurate simulation. Note that, in the region A, we only solve linearized equations for simplicity. Waves are freely transmitted offshore, while run-up on land. Tsunami height is defined by the wave height from the average sea level of Tokyo bay. On land, inundation height is calculated by subtracting the elevation from the tsunami height. Geographic data used in the simulation are Digital Map 50m Grid (Elevation) available from Geospatial Information Authority of Japan (2010), and J-EGG500 of Japan Oceanographic Data Center (2005). We also note that, in the simulation, we do not consider any artificial constructions, such as breakwaters.

TSUNAMI Simulator calculates time evolutions of tsunami heights. We report the simulation results for the coastal lines of Hyogo prefecture facing to the Seto Inland Sea (Setonaikai). We place three observation points of the tsunami heights: A. South of Awaji island, B. Nishinomiya, C. Himeji shown in Fig. 2.2. Figure 2. 3 shows time series of the tsunami heights observed at the points A, B, and C for three different magnitude cases. A tsunami wave reaches the point B in about one hour, the points A, C in about two hours. An initial amplitude of tsunami increases as the magnitude increases, and the amplitude decays as time goes. We also show in Fig. 2.4 the distribution of the peak tsunami height for three cases. We use this peak tsunami height for damage estimate described in the next section.

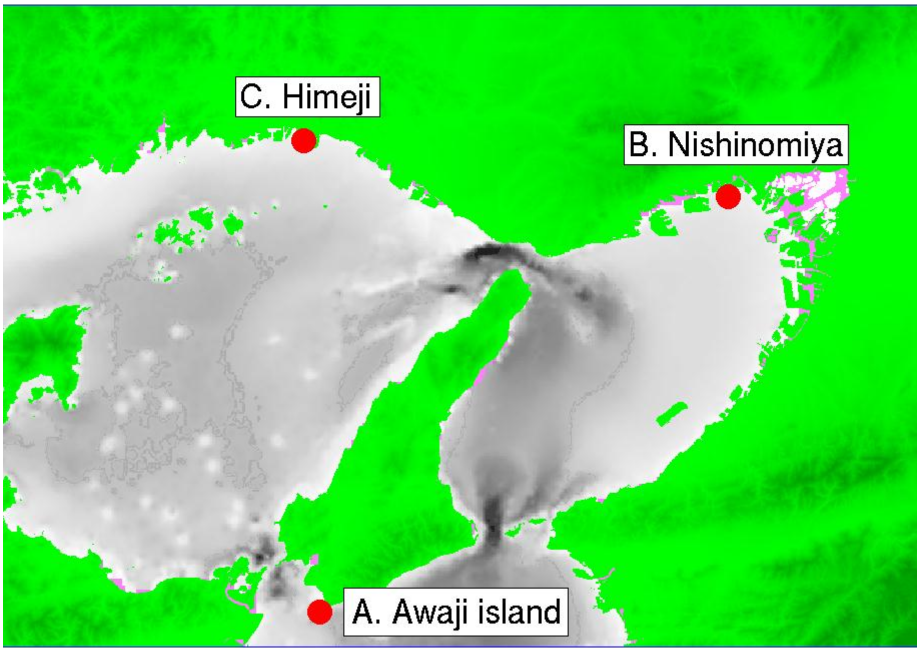

Figure 2.2. Tsunami height observation points

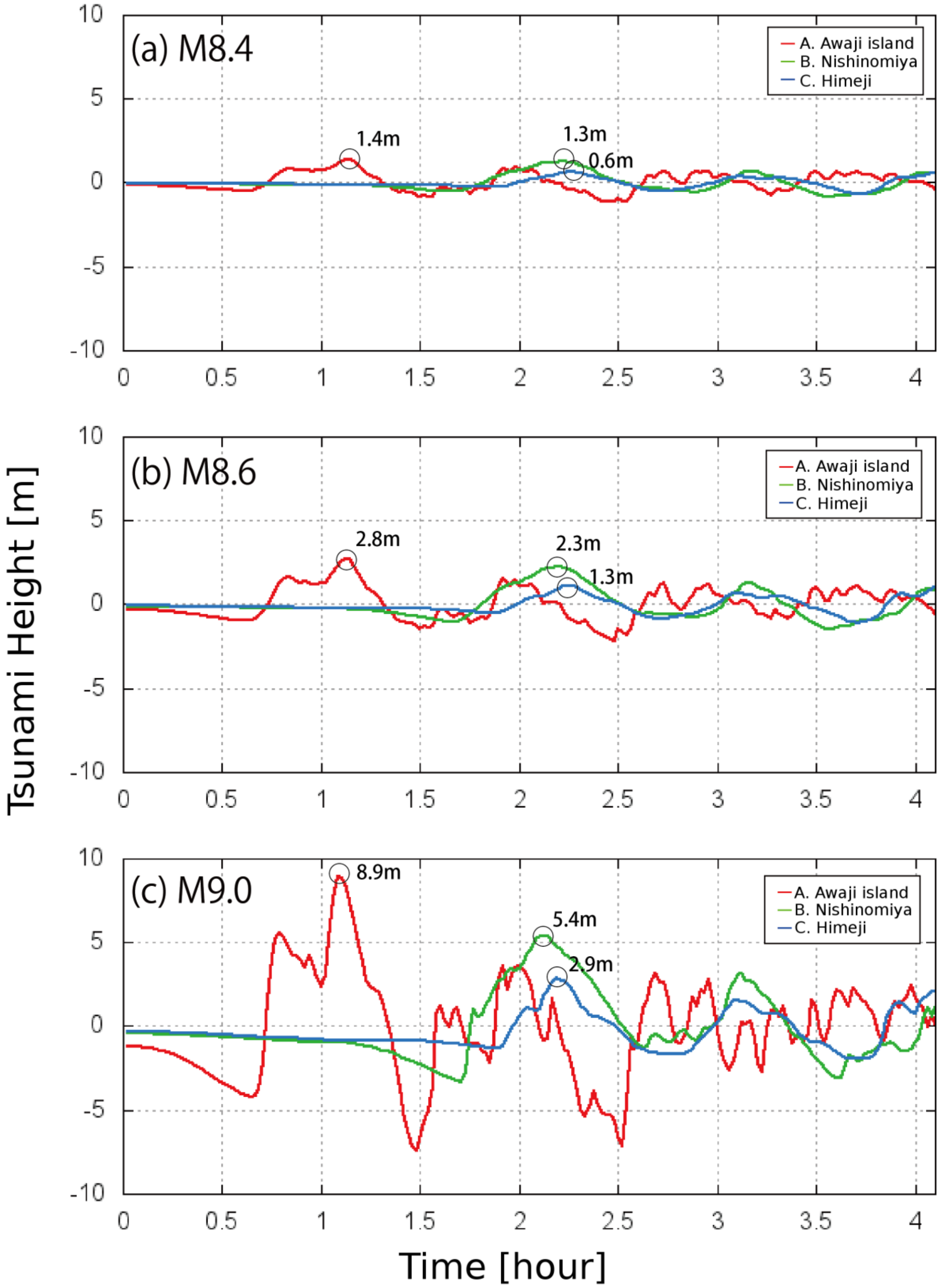

Figure 2.3. Time series of tsunami height at three observation points

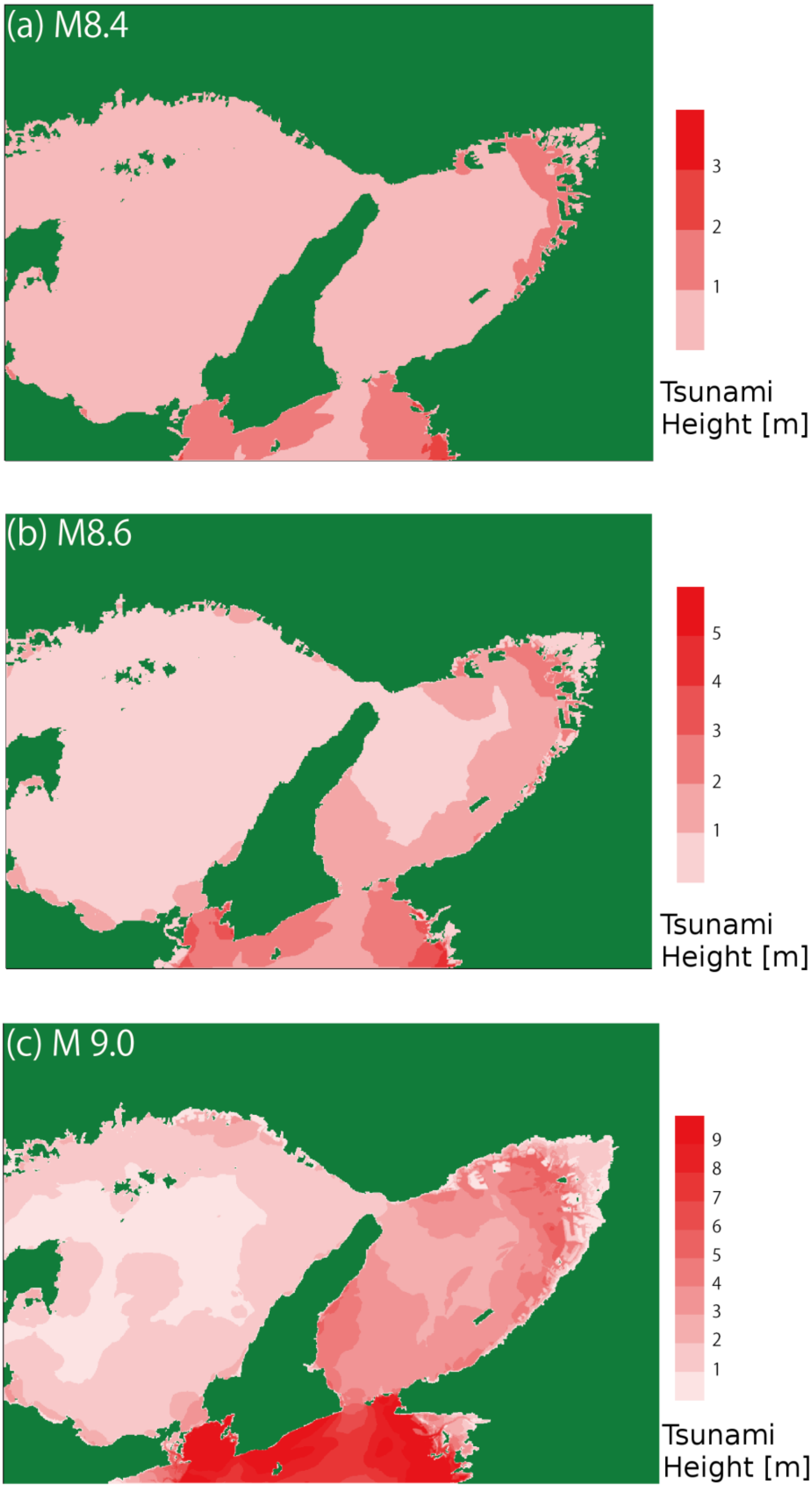

Figure 2.4. Peak tsunami height distribution

3. DAMAGE ESTIMATE ON ARCHITECTURAL STRUCTURES

In this section, we report damage estimate on architectural structures in Hyogo prefecture based on the tsunami simulations of the Nankai earthquake model described in Sec. 2. Utilizing a GIS software (ArcGIS), we count the number of architectural structures in the segmented areas depending on the tsunami heights. By multiplying the total number of architectural structures by the damage function, we estimate damage induced by tsunamis triggered by the Nankai earthquake. To avoid double counting of damage due to earthquake motion and tsunami, we exclude the number of architectural structures which are marked as destroyed from the total number of them. (See Nagano *et al.* (2012) for damage estimate due to earthquake motion.)

“ArcGIS Data Collection–Premium Series 2011 Detailed Map (Shosai Chizu)” made by ESRI Japan is used in the analysis. Only the number of architectural structures prepared in this map is counted.

Summarized in Tab. 3.1 is the damage rate of timber buildings depending on the inundation height. Among all the timber structures in the area, given damage rates of structures are considered to be collapsed. The damage rate due to tsunami is taken from the CDMC report (2003). Table 3.2 shows the obtained number of damaged structures: the number in each inundation height, and the total number are given. The total number of timber architectures in Hyogo according to the map used in the analysis is approximately 1,600,000. CDMC performed a similar damage estimate for the Nankai earthquake, and estimated about 600 of structures will be damaged by tsunami (CDMC 2003), which is roughly equal to our estimate for M8.4. After Tohoku 2011, they are re-examining the impact of great earthquakes.

To graphically illustrate potential tsunami hazard in Hyogo prefecture, we show randomly selected architectures that are considered to be damaged in Figs. 3.1-3. Each green point corresponds to one collapsed house. The total number of damaged architectures shown in the map is equal to that obtained from the analysis. We focus on three major areas in Hyogo, and only show the result for M9.0.

Table 3.1. Damage rate classification by inundation height

Inundation height (h)	h<50cm	50cm≤h<1m	1m≤h<2m	h≥2m
Damage rate [%]	0	10	50	100

Table 3.2. The number of damaged timber structures due to tsunami for three magnitudes cases

Magnitude	Inundation height (h)			Total number of damaged structures
	50cm≤h<1m	1m≤h<2m	h≥2m	
M8.4	90	186	64	340
M8.6	449	1,250	671	2,370
M9.0	1,302	14,037	26,099	41,438

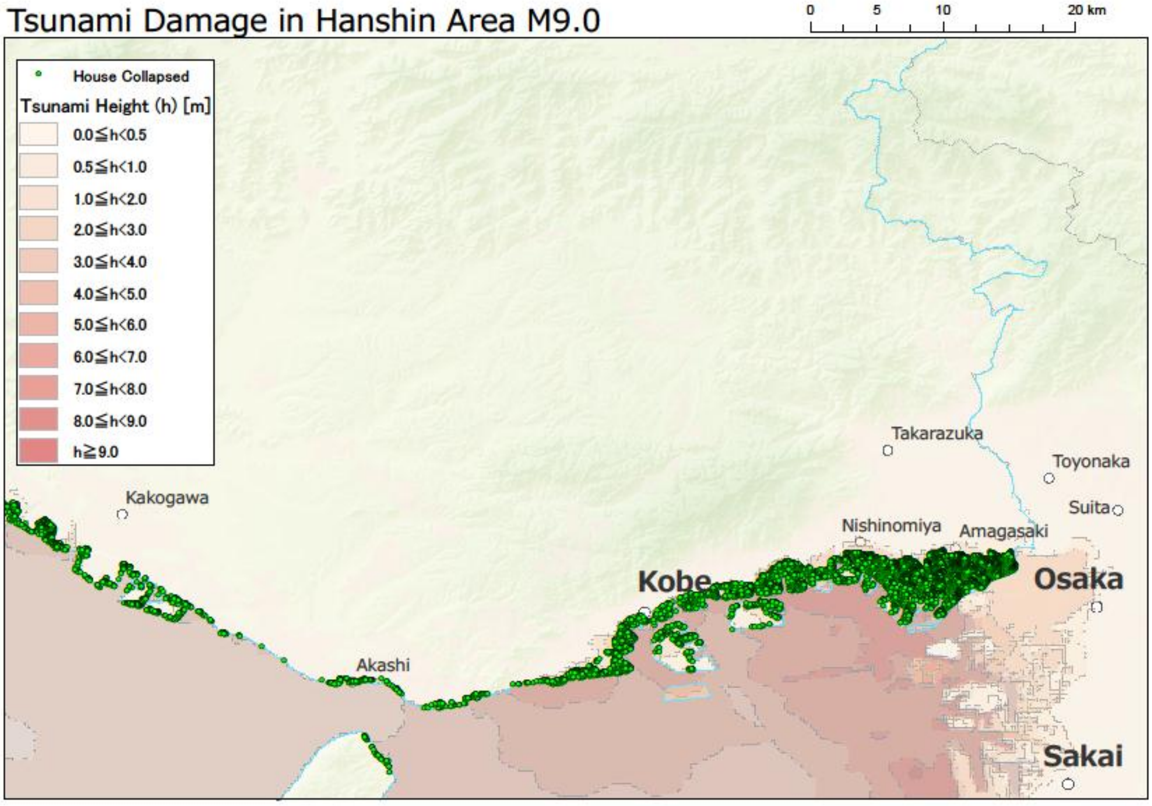

Figure 3.1. Damage on Architectural Structures in Hanshin Area (M9.0)

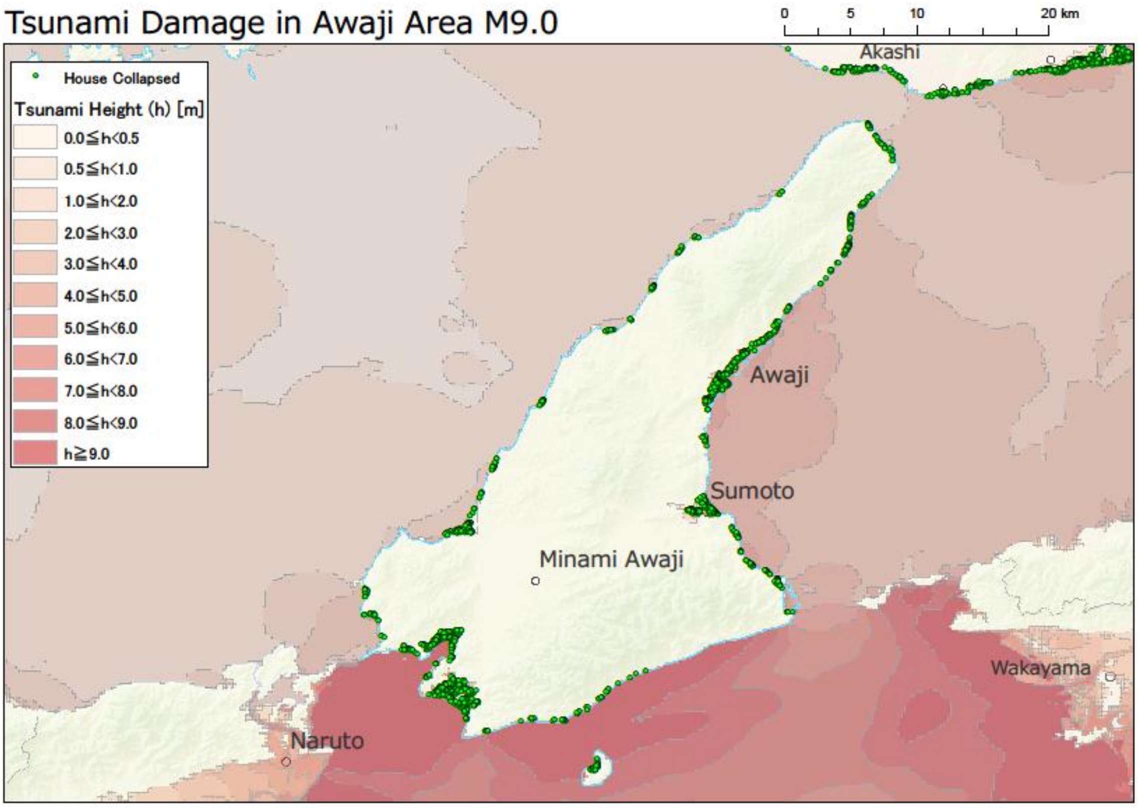

Figure 3.2. Damage on Architectural Structures in Awaji Area (M9.0)

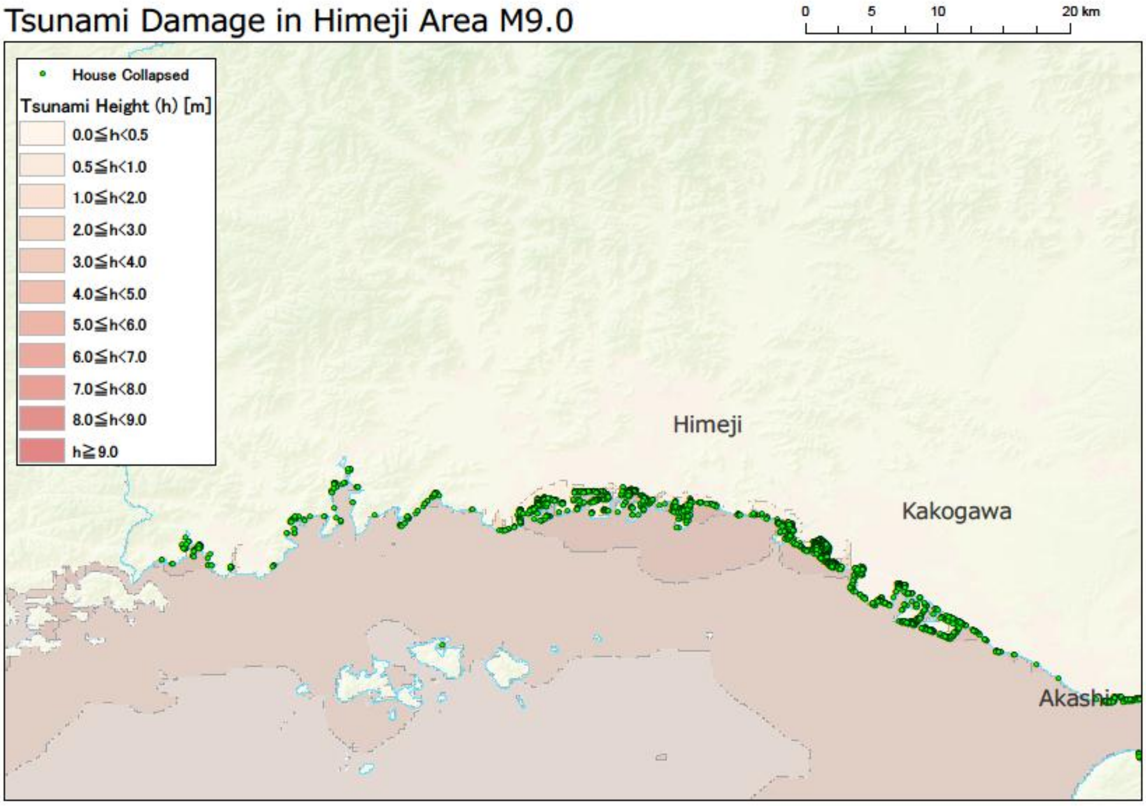

Figure 3.3. Damage on Architectural Structures in Himeji Area (M9.0)

4. SUMMARY

We have performed tsunami simulations for the Ansei-Nankai earthquake model for three magnitude cases. Time series of tsunami height distributions in the Seto Inland Sea and on the coastal lines of Hyogo prefecture are obtained. Tsunami reaches at the south of Awaji island in about one hour, and at densely populated urban areas in about two hours. Peak tsunami heights at the south of Awaji island (closest to the faults) are about 1.5, 3, and 9 meters for M8.4, M8.6, and M9.0, respectively. The peak tsunami height distributions are used for damage estimate on architectural structures.

Using a GIS software, we have counted the number of architectural structures in inundated areas. We only consider damage on timber structures in Hyogo in this study. Among all architectural structures in the map, we exclude the buildings higher than 6 meters by assuming that they are steel constructions. And, we also exclude the number of structures damaged by earthquake motion obtained in Nagano *et al*. (2012) to avoid double counting. For the rest of the structures, we estimate the number of structures damaged due to tsunami by counting the number in the inundated areas and multiplying the damage function. The obtained numbers are 300, 2,300, and 41,000 for M8.4, M8.6, and M9.0, respectively. The damage estimate for M8.4 is roughly equal to that by the Central Disaster Management Council in 2003 (CDMC 2003)–the pre-2011 Tohoku estimate. CDMC has started re-consideration of damage caused by a larger Nankai earthquake after the 2011 Tohoku Earthquake.

To simulate larger scale earthquakes than the original Ansei-Nankai earthquake model, we have changed the released energy of the earthquake by changing the dislocation of the faults from the original model rather than changing the areas of the faults. To make the energy twice (M8.6) and eight times (M9.0) larger than that of M8.4, we have increased the dislocation by factors of two and eight in the simulations. This simply makes the initial tsunami height higher, therefore this method may overestimate damage due to tsunamis.

The analysis presented here can be used as preliminary information to prepare temporary housing. The number of damaged timber architectures can be rough estimate of necessary numbers of temporary houses, and the tsunami simulation results provide information to select safe and convenient sites for temporary housing.

AKCNOWLEDGEMENT
This work was funded by Daiwa Lease Co., Ltd.

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