COMPARISON OF CASUALTY AND BUILDING DAMAGE BETWEEN SANRIKU RIA COAST AND SENDAI PLAIN COAST BASED ON THE 2011 GREAT EAST JAPAN TSUNAMI

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The 2011 Great East Japan tsunami caused damage to casualty and building in wide range. Different damage characteristic can be analyzed from the damage data that was resulted by human experience and geography background. Casualty data and measured tsunami height were used to calculate a fatality ratio for each area. The fatality area in Sendai plain coast shows that 10% fatality occurred when tsunami height was 10 m. However, tsunami height in Sanriku area was much higher than 10 m but the fatality ratio stops at 10%. This might be an effect from high tsunami awareness and fast evacuation of coastal residence in the Sanriku coast. Building damage ratio against tsunami inundation depth was calculated using surveyed data from Ishinomaki city. The data was separated into two locations, ria coast and plain coast. Result shows that the damage ratio of building in ria coast is much higher than plain coast in the same inundation depth. This is because of the high hydrodynamic force as a result of high flow velocity in ria coast. Measured tsunami flow velocity data was summarized and numerical simulation was performed to support the result and explanation. Results of fatality ratio and building damage ratio will help to assess future tsunami and support town construction plan in case of different coast type.

Keywords: *Great East Japan Tsunami, casualty damage, building damage, Sanriku coast, Sendai coast*

1. INTRODUCTION

Tohoku region in the east of Japan had long experience as they were attacked by many tsunamis in the past such as in 1611, 1896, 1933 and 1960. (Suppasri et al., 2012). Only the 1611 tsunami that caused devastated damage in both Sanriku ria coast of Iwate prefecture and Sendai plain coast of Miyagi prefecture. Other tsunamis caused large damage only in the Sanriku coast. Thus, coastal residences in Sanriku area have high tsunami awareness and evacuation recognition. Because of its ria (saw-toothed) coastline, tsunami can be easily amplified to be larger than 10 m. In contrast, Sendai area is a plain coast. Tsunami attack the area without the amplification like in the Sanriku coast but the tsunami can inundate inland as far as few kilometers. Therefore, communities in Sendai plain was considered to have comparatively low tsunami hazard in terms of tsunami height or velocity but the damage is expected to be in wide area.

The great tsunami in 2011 caused serious damage in both areas again. However, different casualty and building damage characteristics were found due to their historical background, experience of tsunami and geography in the Sanriku ria coast and Sendai plain coast. Maximum tsunami height measured in the Sanriku ria coast area was as high as 40. On the other hand, maximum tsunami height in Sendai plain coast of about 10 m was observed but the tsunami penetrated inland as far as 5 km (Suppasri et al., 2012).

2. OBJECTIVES

This study used damage data from the 2011 Great East Japan tsunami that caused serious damage to both Sanriku and Sendai coasts to explain the different of damage characteristics as mentioned above. This is to prove that tsunami experience and awareness of residence in Sanriku area that led to fast evacuation helped to reduce casualty damage. Also this study will show the different damage characteristics of building based on their coastal type using measured inundation depth, flow velocity and numerical simulation. Results from data analysis mentioned above will show effect from tsunami experience and evacuation recognition to the reduction of casualty damage and effect from strong tsunami power to the vulnerability of building damage.

3. DATA AND METHODS

(1) Casualty damage

Number of casualty and population for each location (Onagawa town, Ishinomaki city, Natori city, Iwanuma city and Watari district) was obtained from a report from each city and town. Maximum tsunami heights for each area were obtained by the 2011 tsunami joint survey group (2011). These data were used to calculate the fatality ratio against maximum tsunami height.

(2) Building damage

Building damage and tsunami inundation depth data provided by Ishinomaki city which is separated into two categorizes plain coast and ria coast were used to plot the vulnerability curves for damaged building. The building damage was classified into five levels, washed away, collapsed, major damage, moderate damage and partial damage for every 0.5 m interval of the measured maximum tsunami inundation depth. Therefore, building damage ratio for each damage level (among damaged buildings) can be plotted against the maximum inundation depth.

4. RESULTS

(1) Fatality ratio

Fig. 1(a) depicts a comparison of fatality ratio between historical Sanriku tsunamis in 1896 and 1933, and the 2011 tsunami in ria and plain coasts. **Fig. 1**(b) shows a comparison of the fatality ratio for the 2011 tsunami for each local area in ria and plain coast in some areas of Miyagi prefecture. Both figures show very clear results that although the maximum tsunami height in ria coast is larger than 10 m, the fatality ratio is limited to about 10%. On the other hand, just 3 m height of tsunami could cause 10% of fatality in Sendai plain area.

The 1896 Meiji-Sanriku tsunami led to the highest fatality ratio because of the weak ground shaking characteristic of a tsunami earthquake that occurred at night. Because the 1933 Showa-Sanriku tsunami occurred only 37 years later, people in many areas still had strong tsunami awareness. People in the Sanriku area were again awakened by the 1960 Chile tsunami. Therefore, the fatality ratio from the 2011 Great East Japan tsunami, occurring 41 years later, was greatly reduced. However, the tsunamis in 1896, 1933 and 1960 affected mainly northeast Japan along the ria coast. Therefore, 400 years had passed since the great tsunami in 1611 where a tsunami had not caused severe damage in the plain areas, leading to a similar fatality ratio to that observed for other historical events in Japan.

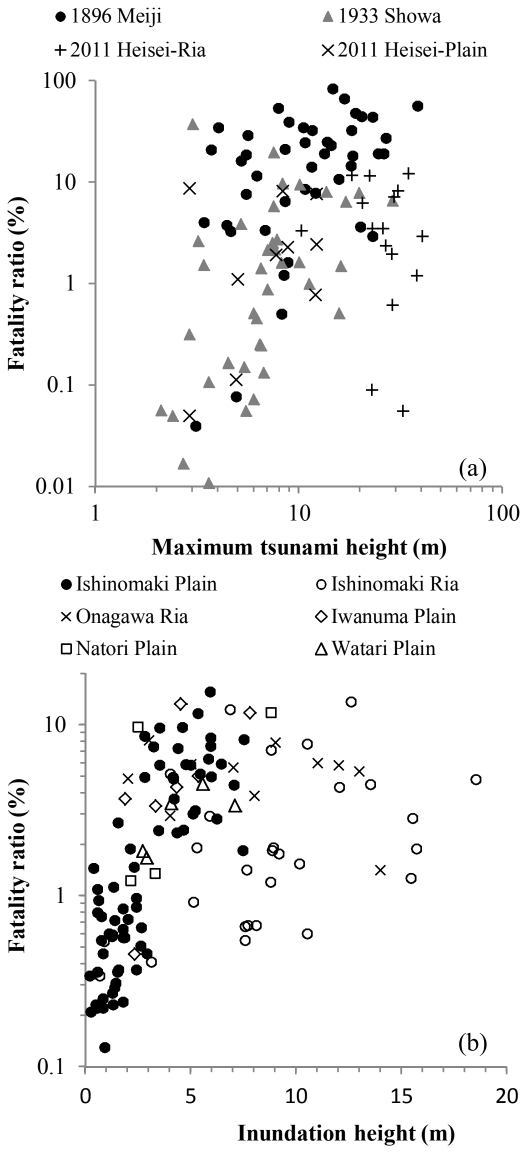
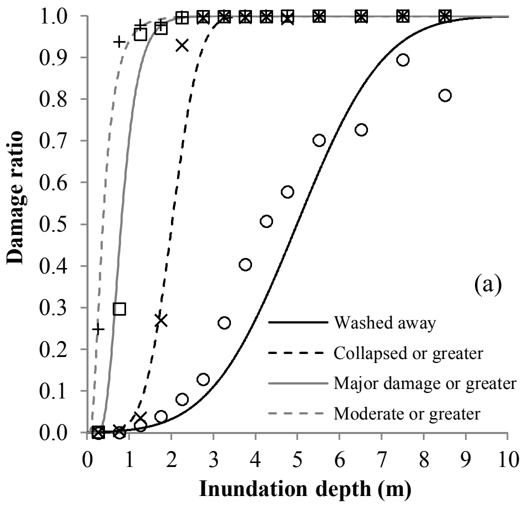


Fig.1 Tsunami fatality ratio in Tohoku region from (a) Historical tsunamis in Sanriku and (b) the 2011 tsunami

(2) Building damage ratio

Building damage and tsunami inundation depth data provided by Ishinomaki city which is separated into two categorizes plain coast and ria coast were used to plot the vulnerability curves. The building damage was classified into five levels, washed away, collapsed, major damage, moderate damage and partial damage for every 0.5 m interval of the measured maximum tsunami inundation depth. Therefore, building damage ratio for each damage level (among damaged houses) can be plotted against the maximum inundation depth. Curves to fit the calculated damage ratio were constructed using the regression analysis and normal or lognormal distribution function as explained by Suppasri et al. (2011). Tsunami vulnerability curves for plain and ria coasts in Ishinomaki city are shown in **Fig. 2**(a) and (b) respectively. It can be seen that, for example, damage ratio for washed away at 2 m inundation depth is less than 0.05 in plain coast while about 0.4 in ria coast. Damage ratio in plain coast increase to 0.5 at 5 m inundation depth while the damage ratio is 0.8 for ria coast. **Table 1** show a summary of parameters for constructing the tsunami vulnerability curves



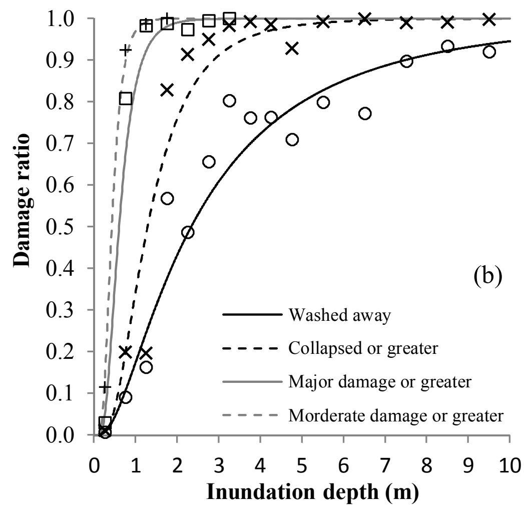


Fig.2 Vulnerability curves developed from damaged buildings in Ishinomaki city in (a) Plain coasts and (b) Ria coasts

Table 1 Summary of parameters for constructing the tsunami vulnerability curves

X for vulnerability function $P(x)$		$\boldsymbol{\mu}$ *or* μ'	$\boldsymbol{\sigma}$ *or* σ'	R^2
Sendai plain coast	D4	**4.982**	**1.625**	0.89
	D3	**2.009**	**0.515**	0.91
	D2	-0.2178	0.3905	0.98
	D1	-1.0028	0.6402	0.96
Sanriku ria coast	D4	0.8465	0.9087	0.95
	D3	0.2498	0.6278	0.88
	D2	-0.5135	0.5185	0.93
	D1	-0.8598	0.4575	0.99

(D4=Washed away, D3=Collapsed or greater, D2=Major damage or greater and D1=Moderate damage or greater)

5. DISCUSSIONS

(1) Hydrodynamic characteristics of tsunami estimated by survivor videos

To verify the different damage characteristic at the same inundation depth, flow velocity should be investigated. Foytong et al. (2012) estimated tsunami flow velocity using moving object shown in survivor videos in Kamaishi city, Ofunato city, Kesennuma city, Iwaki city and Oarai city. Koshimura and Hayashi (2012) performed the same analysis of survivor video in Onagawa town and also aerial videos in Sendai city and Natori city. In addition, Fritz et al. (2012) measured flow velocity from survivor videos at Kesennuma using LiDAR. All of their results are summarized in **Table 2**. It is clear from the results that tsunami flow velocity in Sanriku ria coast (4-11 m/s) is higher than in plain area in Sendai and Fukushima (1-3 m/s in average). Although, there are some areas in Sendai city that the flow velocity as high as 6-8 m/s. This is because they were located near the Natori river and will not use in the comparison. Tsunami flow along river might faster than inundation flow inland. Based on the tsunami flow velocity results, hydrodynamic force of tsunami can be estimated using the drag force from a formula here.

$$F_D = 0.5\rho v^2 C_d A \tag{1}$$

Where, C_d = drag coefficient, ρ = water density (1,000 kg/m^3), V = flow velocity (m/s) and A = force projected area (m^2). Inundation depth of tsunami can be roughly estimated using tsunami inundation height data measured by the Tohoku Tsunami Joint survey Team (2011) and subtract by land elevation data provide by the cabinet office. The results of calculated hydrodynamic force per unit width are also shown in **Table 2**. In general, hydrodynamic force in Sanriku ria coast (70-180 kN/m) is higher than in plain area (2-52 kN/m). It can be confirmed that at 3.0-3.5 m inundation depth, hydrodynamic force estimated in Kesennuma city (182 kN/m) is greatly higher than in Sendai city and Natori city (16-52 kN/m).

Table 2 Summary of tsunami flow velocity in each area

Location	Velocity (m/s)	Average (m/s)	Depth (m)	Force (kN/m)
Kamaishi	4.53	4.12	8.14	69
	4.18			
	2.88			
	4.17			
	4.85			
Ofunato	2.75	2.41	8.46	25
	2.06			
Kesennuma 1	5.38	4.63	6.34	68
	3.65			
	4.88			
	4.52			
	4.74			
	2.63	2.63	10.84	37
Kesennuma 2	11.00	11.00	3	182
Onagawa	6.30	6.30	6	100
Sendai 1	9.30	7.99	3.44	110
	9.26			
	8.85			
	7.68			
	6.75			
	6.09			
Sendai 2	6.04	5.88	3.03	52
	5.69			
	5.69			
	5.54			
	5.63			
	6.70			
Natori 1	3.46	3.02	3.45	16
	2.58			
Natori 2	3.43	2.80	1	4
	2.87			
	0.98			
	3.91			
Iwaki	1.42	1.42	1.7	2
Oarai	2.55	2.55	0.88	3

(2) Hydrodynamic characteristics of tsunami estimated by numerical simulation

Tsunami numerical simulation was performed to provide a general overview of tsunami characteristics such as inundation depth and flow velocity in the whole region. Tsunami source model proposed by Imamura et al. (2011) was applied in the simulation as their model results were verified with the survey results from the Tohoku Tsunami Joint Survey Team (2011). Initial tsunami on the sea surface was assumed to be equal to the sea bottom deformation calculated by equations proposed by Masinha and Smylie (1971). Sets of bathymetry and topography data provided by the Central Disaster Mitigation Council, Cabinet Office, Government of Japan were used in the calculation. The data comprises of three nested regions in Cartesian coordinates with the grid size of 1,350 m, 450 m and 150 m respectively. Tsunami simulation was performed followed the methods explain in the IUGG/IOC TIME project (1997). Linear long wave theory with neglecting the effects from bottom friction was applied in region 1 (1,350 m mesh) while non-linear long wave theory with considering the effects from bottom friction (assuming Manning's roughness coefficients of 0.025 $m^{-1/3}s$) was applied in region 2 (450 m) and 3 (150 m). Tsunami simulation time was set as three hours from the earthquake with the temporal grid size of 2.7 s, 0.9 s and 0.3 sec respectively. In general, average of the maximum flow velocity obtained after three hours in the Sanriku ria coast (10-20 m/s) is higher than in Sendai plain coast (5-10 m/s). These results agree with the results estimated by survivor videos. By this reason, damage in the ria coast is higher as they experienced higher velocity and can be confirmed by the distribution of hydrodynamic force (**Fig. 3**).

From the simulated results in the plain coast, the maximum hydrodynamic force along shoreline is found to be larger than 150 kN/m and less than 20 kN/m inland respectively. According to criterion for degree of damage to building based on historical tsunami damage data in Japan that concrete and timber building will be destroyed if the fore is higher than 155-281 and 9.7-17.6 kN/m (Matsutomi and Harada, 2010) the force of 150 kN/m can destroy all types of building material along the coast. The force was reduced to less than 20 kN/m for locations where buildings were located at more than 2 km from the coast. Therefore, most of buildings were observed as small or partially damage. In contrast, Sanriku coast had comparatively smaller inundation distance but higher force of larger than 500 kN/m in most areas. This caused devastated damage to all building types in the Sanriku area.

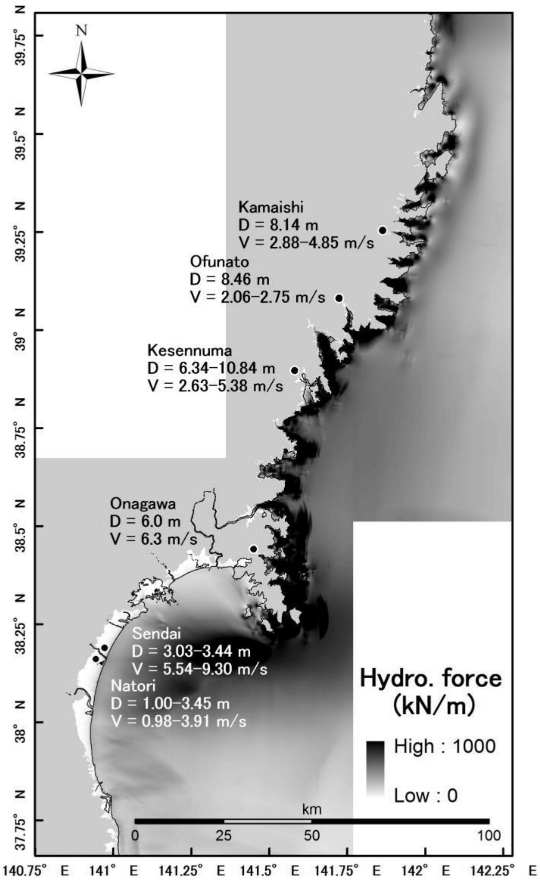


Fig.3 Simulated hydrodynamic force and estimated flow velocity in 150*150 m^2 grid

6. CONCLUSIONS

Fatality ratios show that experience and awareness of past tsunamis help to reduce casualty in the Sanriku ria coast as the great tsunami occurred almost in every people's generation. On the other hand, people in Sendai plain coast was lack of experience of the great tsunami for 400 years and lose their tsunami awareness.

Comparison of tsunami vulnerability curves show that damage ratio in ria coast increase rapidly when inundation depth is higher than 1-2 m. This was because not only the higher tsunami height but also stronger current velocity. Therefore, even the same inundation depth but due to the stronger current velocity that cause greater hydrodynamic force attacking to each building.

Different hydrodynamic characteristics of tsunami in ria coast and plain coast were discussed. Flow velocity estimated by survivor videos and numerical simulation agreed that this value is higher in the ria coast. This leads to the higher hydrodynamic force that attacked the buildings.

Results from this study show some examples of different damage characteristic based on historical background and topography for each tsunami prone area which are important issues for a future tsunami damage assessment and city planning for disaster management.

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