CONCERT-Japan
Research and Innovation Joint Call

Efficient Energy Storage and Distribution
Resilience against Disasters

RAPSODI Project

Risk **A**ssessment and design of **P**revention **S**tructures f**O**r enhanced tsunami **DI**saster resilience

Deliverable D2 Review of post-tsunami field surveys (run up, flow depth, flow velocities, fluxes), damages, and fatalities of the 2011 Tohoku tsunami
1st year of funding

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For NGI

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Publishable summary

The main purpose of the EU CONCERT-Japan RAPSODI project is to develop a tsunami risk analysis model, based on the data from the 2011 Tohoku Tsunami. This will include derivation of empirical relations between damage/fatalities and tsunami flow depth, current velocities, fluxes, and the impact of debris. PARI, as the Japanese project leader, has a responsibility to provide data and knowledge on tsunami damage and fatalities for joint development of tsunami vulnerability models and prevention structures. This report summarizes results of field surveys conducted after the 2011 Tohoku tsunami and provides related literature review on the database for further development of numerical models by co-researchers.

The Tohoku earthquake Tsunami Joint Survey Group assembled 50 organizations (150 people or more) for a field study. From March 12th to May 22th, 2011, tsunami-affected areas along the Pacific coast from Hokkaido to Okinawa Prefecture were surveyed. The trace of the tsunami exceeded a height of 10m on a 530km stretch of coastline centered on Iwate Prefecture. In addition, tsunami trace heights exceeding 20m were recorded in most locations along the Sanriku coast, which is formed as a Rias coast. Furthermore, run up heights of 40 m were confirmed in Ryori Bay at Ofunato City, making this the maximum tsunami height ever recorded in Japan. Comparing with past tsunami events, tsunami heights in the Iwate prefecture were similar to levels observed in the 1896 Meiji Sanriku tsunami, whereas those in the southern Tohoku region were much larger. In the Iwate prefecture, the run up points are near the coast because mountains near the shoreline. In contrast, the topography of Sendai area is flat, hence the end of inundated area is very far from shoreline. This may account for the difference in casualty rates between the two prefectures.

The extent of damage to coastal structures including bay mouth breakwaters, common breakwaters, and seawalls was documented during field surveys. Laboratory experiments have also been conducted to investigate the mechanism of the failure and to explore solutions for improving the resiliency of such protective structures. Detailed field surveys are presented herein as representative examples: one for bay mount breakwaters (Kamaishi Bay) and another for common breakwaters (Hachinohe Port). In the latter example, researchers concluded that implementing countermeasures for overflow scouring is the most important design task for future breakwaters. Finally, the damage to shore protection facilities was surveyed by Kumagai et al. (2011) on 20 districts in 7 ports in Miyagi and Iwate prefecture.

A survey of buildings throughout the region struck by this tsunami (Building Research Institute 2011) has shown that in districts where the inundation depth exceeded 2m, the percentage of buildings that were completely destroyed (including those washed away) was high. Many buildings were washed away by the horizontal force or the buoyancy of the tsunami. Buildings were categorized by construction type: wooden or concrete, steel frame buildings, and others. Field surveys conducted in Natori City, Miyagi Prefecture were discussed to analyze and compare the impact of tsunamis on these different categories of building.

PIANC (2013) shows the relation between the tsunami height-to-design wave height ratio and the damage ratio for breakwaters. The damage ratio is defined as the ratio of the damaged length to the total length. If the tsunami height at the front side of the breakwater is divided by the design wave height, the damage ratio can be predicted with high accuracy by the logarithmic normal cumulative distribution function.

For seawall structures, the relationship between the damage ratio and the wall height was investigated at 60 structures in Iwate Prefecture where the cross-section profiles were known. Analysis showed that the safety factor for sliding was generally lower than the safety factor for overturning. Furthermore, the safety factor for sliding dropped below 1.0 around where the relative height exceeded 3 meters.

MLIT (2012) investigated the proportion of affected buildings in 6 of the tsunami-impacted prefectures. In total, 250,000 buildings were affected, out of which about 140,000 were completely destroyed. Buildings were sorted into seven categories based on their condition after the disaster, ranging from completely destroyed (washed out) to no damage. Wooden structures accounted for 70% of buildings that were completely destroyed, reinforced concrete structure for 2%, steel frame structure for 4%, and others for 7% (weight steel frame, soil structure, and block structures).

Our analysis showed a significant relationship between inundation depth and the condition of a building after a disaster. The proportion of buildings completely destroyed in the case of inundation depth of 2m or below tend to be significantly lower than above that value. Building type also has a significant role. The proportion of buildings completely destroyed was 5% in the case of reinforced concretes structures for inundation depth 1.5 m – 2m. In contrast, at least 20% of wooden structures were completely destroyed at this depth, which is not necessarily a low proportion. Data were further used to analyze the relationship between inundation depth and disaster condition of buildings by structure and by number of floors.

A report from the Central Disaster Management Council (2011) of Japan provided casualty rates in each affected prefecture. The working definition of the casualty rate used was "the ratio of total number of casualties (fatalities and missing persons) to the total population living in the inundated area." The casualty rate was highest in Iwate Pref. at 5.9%, followed by 3.5% in Miyagi Pref. and 2.7% in Fukushima Pref. The larger the tsunami height on coast is, the higher the casualty rate is.

When we compare the relation between the tsunami height and casualty rate with those in past tsunami, the casualty rate of Iwate prefecture in 2011 Tohoku tsunami is much smaller than earlier tsunami events in the same prefecture and other locations in the same event. There, the tsunami preparedness education was more effective, and the hazard mapping was more in-depth and accurate. In comparison, the casualty rate in Miyagi prefecture was larger than that of Iwate prefecture. Some suggested explanations include differences in topography or hazard map accuracy. In Miyagi prefecture, the hazard map in many area underestimated inundation area. This comparison indicates that the preparedness of vulnerable populations is very important.

Contents

1 Introduction

Japan has most experiences of tsunami disaster in the world. “Tsunami” is a Japanese word written with two Chinese Characters. ‘Tsu’ means harbor/port and ‘nami’ means wave, and therefore “tsunami” means harbor/port wave in Japanese. The meaning comes from the fact that tsunami seem to appear suddenly and become very violent in shallow areas, attacking low-lying areas that are actively used and densely populated, such as port areas (PIANC, 2013).

Among many tsunamis that Japan has ever experienced, the 2011 Tohoku Tsunami was one of the widest and worst tsunamis that caused widespread and extensive damages both to human lives and to infrastructures. As the Great East Japan Earthquake, which induced the 2011 Tohoku Tsunami, was of magnitude of 9.0, the largest earthquake ever recorded in Japan. Its focal region extended over a wide area from the coast of Iwate Prefecture to the coast of Ibaraki Prefecture, and because of the breakage of the fault ware over 450 kilometers long and about 200 kilometers wide, resulting in the tsunami of a scale that is rarely seen (City Bureau, MLIT, 2012). Immediately after the tsunami event, extensive field surveys were conducted and efforts to summarize the damages for seeking future rehabilitation planning were made.

The main purpose of the EU CONCERT-Japan RAPSODI (the consortium of Risk Assessment and design of Prevention Structures fOr enhancement tsunami DIsaster resilience) project is to develop a tsunami risk analysis model, based on the data from the 2011 Tohoku Tsunami. This will include derivation of empirical relations between damage/fatalities and tsunami flow depth, current velocities, fluxes, and the impact of debris. PARI, as the Japanese project leader, has a responsibility to provide data and knowledge on tsunami damage and fatalities for joint development of tsunami vulnerability models and prevention structures.

Therefore, this report, Deliverable 2 "Review of post-tsunami field surveys (run-up, flow depth, flow velocities, fluxes), damages, and fatalities of the 2011 Tohoku tsunami", summarizes results of field surveys conducted after the 2011 Tohoku tsunami and provides related literature review on the database for further development of numerical models by co-researchers of this project.

In sections 2.1 of this report, results of post-tsunami field surveys of the 2011 Tohoku tsunami that was focused on tsunami height and flow velocities are presented. In section 2.2, damages to coastal structures such as breakwaters in Kamaishi and other ports and seawalls, land structures, and to humans are briefly summarized with information on important literature. Finally, in section 2.3 some results of the fragility curve based on the statistical analysis for infrastructures and for casualty rate are presented, by using our original data and some databases open for public such as City Bureau, MLIT (2012).

2 Review of post-tsunami field surveys of the 2011 Tohoku tsunami

2.1 Post-tsunami field surveys

2.1.1 Tsunami height

The Tohoku earthquake Tsunami Joint Survey Group assembled 50 organizations (150 people or more) for a field study. From March 12th to May 22th, 2011, tsunami-affected areas along the Pacific coast from Hokkaido to Okinawa Prefecture were surveyed. The largest tsunami heights were recorded north of 34°N (Fig. 2.1). Tsunami heights and inundation heights were recorded separately, as reflected in Fig. 2.1. In this study, inundation height is defined as a water level measured above the sea level, and run-up height denotes the maximum trace of tsunami measured above the sea level.

Note that inundation *depth* is defined as a height of tsunami above the ground (for these definitions, see Fig. A1 in the Appendix). The trace of the tsunami exceeded a height of 10 m on a 530 km stretch of coastline centered on Iwate Prefecture over about 530 km. In addition, tsunami trace heights exceeding 20m were recorded in most locations along the Sanriku coast, a typical Rias coast. Furthermore, run up heights of 40 m were confirmed in Ryori Bay at Ofunato City, making this the maximum tsunami height recorded in Japan.

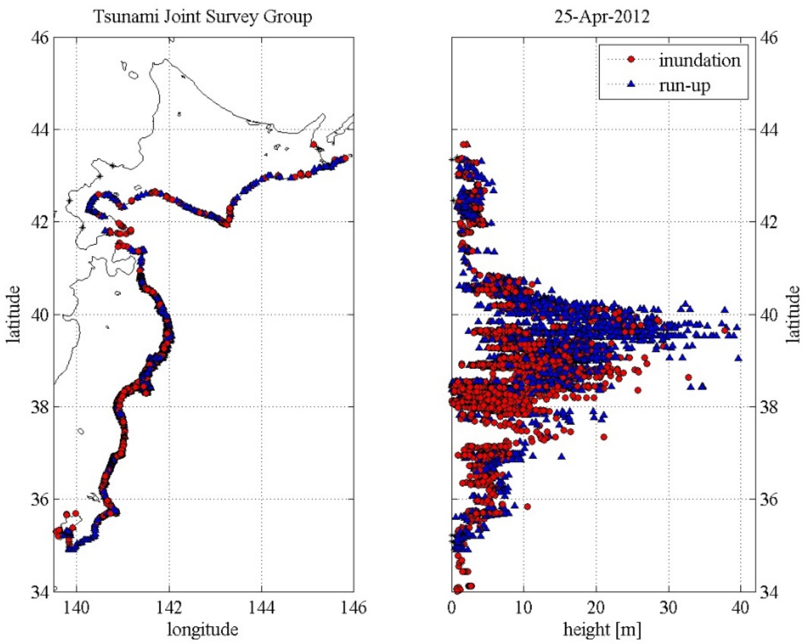


Fig. 2.1 Disturibution of trace of tsunami height by the 2011 Tohoku earthquake Tsunami Joint Survey Group (2012). (Only high-confidence data are included; the date above the right panel gives the time for the last update of survey data).

Fig. 2.2 shows the comparison with tsunami height of past events. It indicates tsunami heights in the Iwate prefecture were similar to levels observed in the 1896 Meiji Sanriku tsunami, whereas those in the southern Tohoku region were much larger.

The run up points of Iwate and Miyagi prefecture are shown in Fig. 2.3. In the Iwate prefecture, the run up coordinates are near the coast because of the mountain range close to shore. In contrast, the topography of Sendai area is flat, so the run up or the end of inundated area is very far from coastal line.

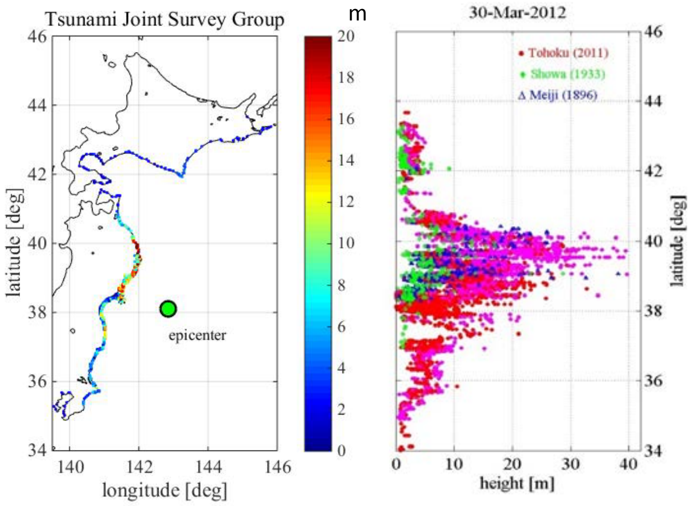


Fig. 2.2 Left panel: Distribution of tsunami height for 2011 event (color denotes level of tsunami height). Right panel: Comparison of tsunami height between the 2011 event and previous events (purple color denotes run-up height and red inundation height). Left panel from Mori et al. (2012); The 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group (2012); the date above the right panel gives the time for the last update of survey data.

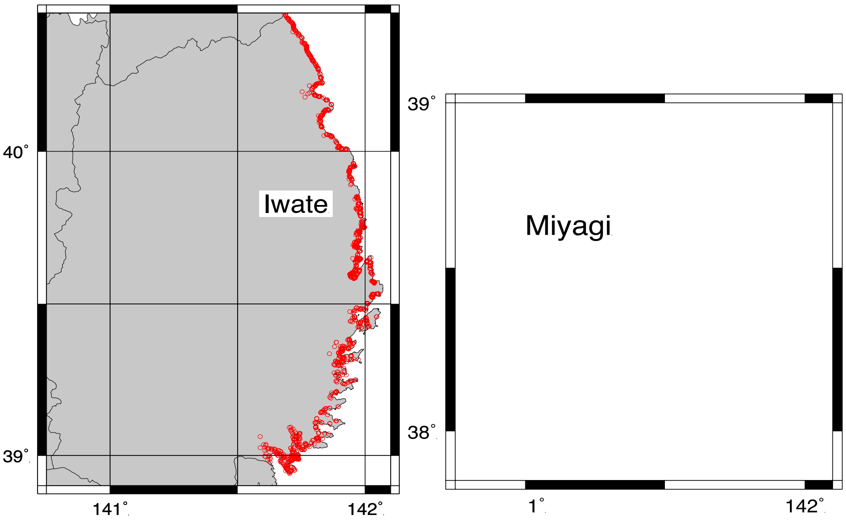


Fig. 2.3 Tsunami run up points at Iwate and Miyagi prefecture.

2.1.2 Flow velocities

Many researchers analyzed the flow velocity using video recordings of the event. For example, Koshimura et al. (2011) conducted the video analysis at the city of Onagawa, and calculated flow depth and velocity (Fig. 2.4). They indicated that the flow depth increased with 1 to 2 m/s vertical speed. However, this was highly dependent on local topography. Hayashi and Koshimura (2012) also estimated aerial distribution of flow velocities in Sendai plain area from video analysis.

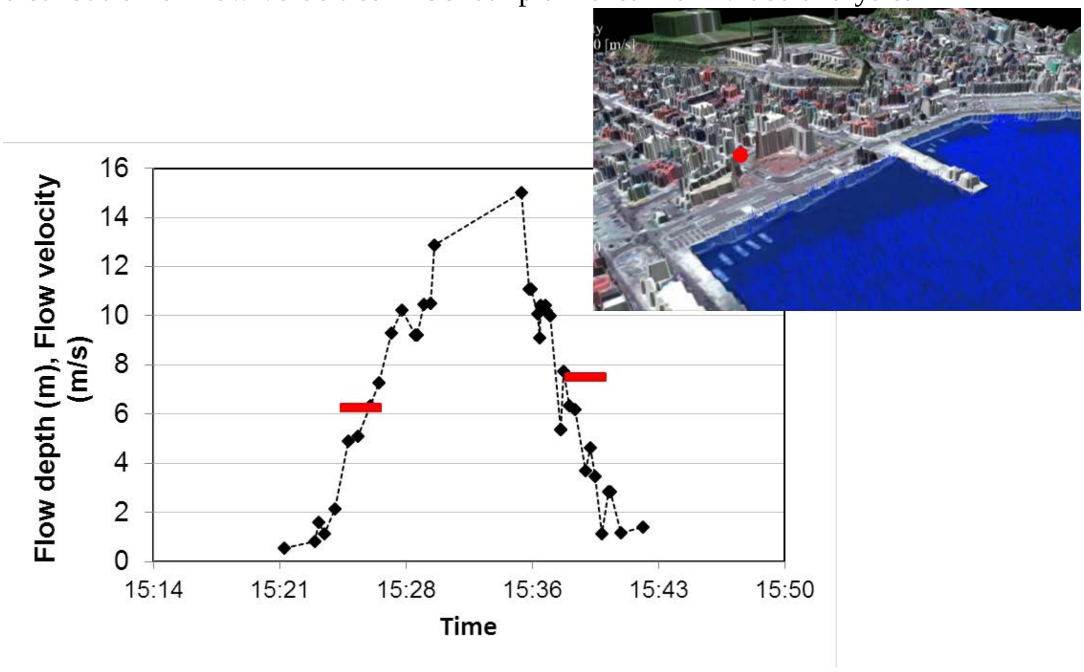


Fig. 2.4 Video analysis of flow depth and velocity near the coast line at Onagawa. Dots are flow depth while red lines denote mean flow velocities (Koshimura et al. 2011).

2.2 Damage

Many surveys were conducted after the 2011 Great East Japan Earthquake Tsunami event by several researchers in collaboration with universities, institutes and other organizations both Japan and other countries to understand the collapse phenomenon of coastal structures, as well as human damages. In this section, damages to coastal structures such as breakwaters, seawalls and coastal dikes are firstly reviewed. Damages to land structures (buildings) and to humans will also be briefly reviewed in later part of this section. On tsunami loads on structures and detailed failure modes of structures, such as coastal dikes and breakwaters, see also *Deliverable D1 "Report on existing tools, data, and literature on tsunami impact, loads on structures, failure modes and vulnerability assessment*" (Tarakcioglu et al., 2014a). Coastal protection measures by artificial structures ever constructed in Japan are summarized in *Deliverable D4 "Report on comparison of mitigation strategies in Europe and Japan*"(Tarakcioglu et al., 2014b).

2.2.1 Bay Mouth Breakwaters

The Kamaishi Bay mouth breakwaters include the North Breakwater (length 990 m), South Breakwater (length 670 m), and the Bay Mouth section (length 330 m) as shown in Fig. 2.5. The maximum depth at the breakwaters is 63 m.

The lowermost portion of the North Breakwater consists almost entirely of trapezoidal caissons shown in Fig. 2.6. Its foundation mound spans an elevation of 60 m to 27 m below sea level. Above it, caissons weighing about 36,000 tons are installed. In shallow parts, the caissons are rectangular with height ranging from 10m to 15m. Similarly, at the South Breakwater, 3 caissons are trapezoidal caissons, but the rest are approximately 32,000 ton rectangular caissons shown in Fig. 2.7. Their crest height is D.L. +6.0m (T.P. +5.14 m), and their foundation mound extends from depth of 55 to 22m below sea level. Finally, at the Bay mouth section, the depth of the submerged breakwater is D.L. -19.0 m (ground level measured from mean low water level), and armor blocks are inserted around it.

Fig. 2.8 shows caissons which laterally displaced or tilted following the tsunami, according to the results of a survey by the Tohoku Regional Development Bureau. The number of total, damaged, and undamaged caissons are summarized in Table 2.1.

Fig. 2.9 shows the state of damage to all the breakwaters, while Fig. 2.10 and Fig. 2.11 show the crest and the deep sections, respectively, of the North Breakwater in greater detail. These detailed views illustrate how in the deep part of the North Breakwater, many of caissons slid without tilting at all. Finally Fig. 2.12 compares cross-sections of the breakwaters before and after the disaster. On the North Breakwater, the mound level was scoured from 5m to 10m.

Overall, at both the North and South Breakwater, the toe of mound facing the inside of the bay was not seriously deformed, and the caissons slid on the mound. The aforementioned observations suggest that the caissons could have been gently pulled back inside the bay.

Fig. 2.5 The Kamaishi Bay mouth breakwaters (courtesy by Tohoku Regional Bureau).

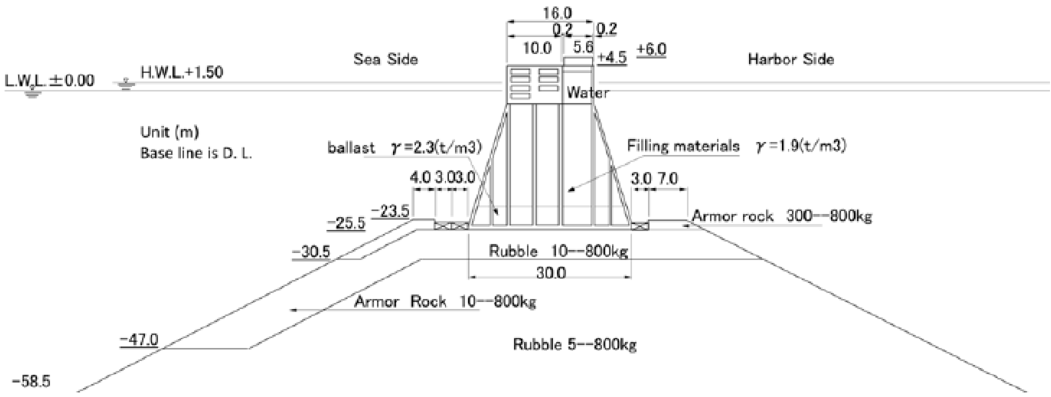


Fig. 2.6 Standard Cross section at the deep portion of the North Breakwater (Takahashi et al., 2011).

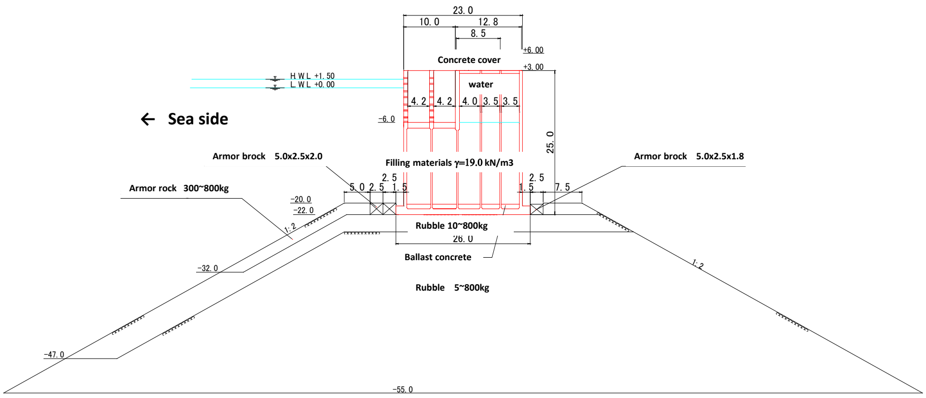


Fig. 2.7 Standard Cross section at the deep portion of the South Breakwater (Takahashi et al., 2011).

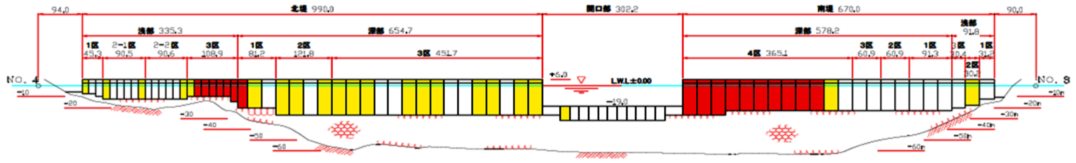


Fig. 2.8 State of damage of Breakwater (Red : No damage, Yellow : Tilted, White : Sliding down) (Takahashi et al., 2011).

Table 2.1 Number of total, damaged, and undamaged caissons.

		total	damaged		undamaged
			displaced	tilted	
North Breakwater	deep section	22	7	14	1
	shallower part	22	11	5	6
Baymouth Breakwater		13	12	1	0
South Breakwater	deep section	19	8	1	10
	shallower part	3	2	1	0

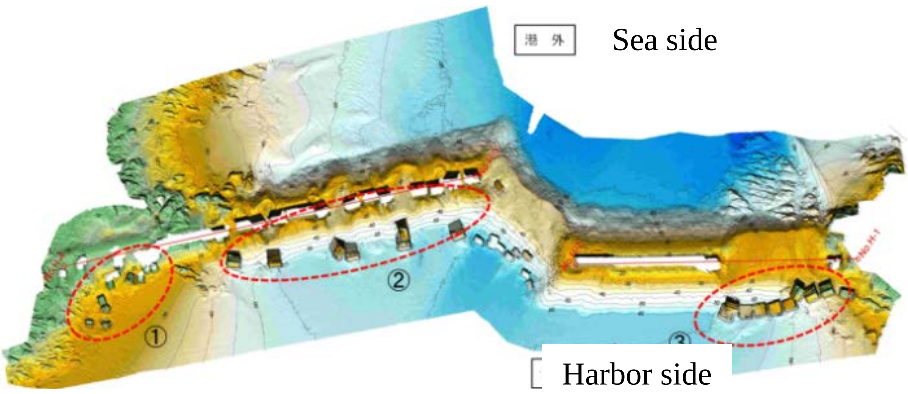


Fig. 2.9 State of damage of breakwater (Takahashi et al., 2011).

Fig. 2.10 State of damage of North Breakwater (Takahashi et al., 2011).

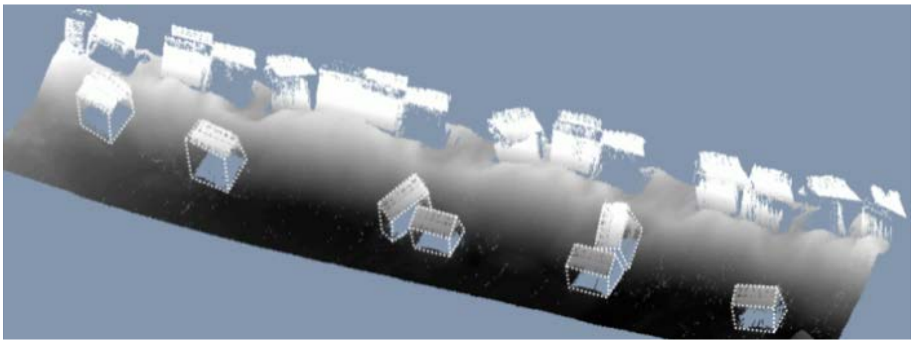


Fig. 2.11 State of damage of North Breakwater (Arikawa et al., 2012).

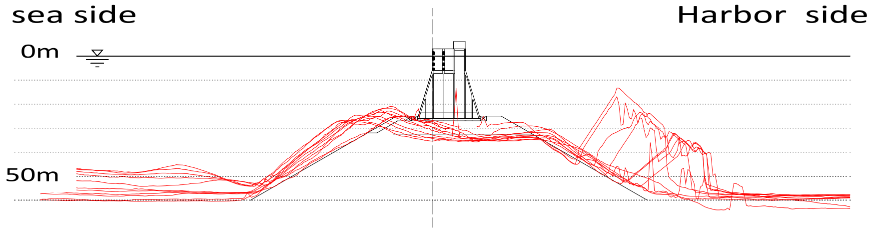


Fig. 2.12 Cross section of damage of North Breakwater (Arikawa et al., 2012).

2.2.2 Common Breakwaters

As shown in Table 2.2, many common breakwaters are damaged by tsunami wave force, but many others are presumably damaged by overflow scouring. Fig. 2.13 shows conditions after damage at Hachinohe Port. Here, the Northern Breakwater was severely damaged. Damage to the entire Northern Breakwater occurred, including toppled caissons (44), disrupted wave absorption blocks, scoured foundation mound over the entire 700 m length of the breakwater. Many of the toppled caissons fell over into the shipping channel (maximum moved distance of about 90 m). Behind near the crest of the breakwaters, the sea bed foundation was locally severely scoured. Main caissons (60), which formed about 50% of the Northern Breakwater (center part), were toppled vertically for along a length of 750 m. Many of the toppled caisson leaned. Another particularly characteristic feature was the scouring of the foundation mound and foundation bedrock at the back surface of the caissons; even where the caissons themselves remained relatively undisturbed.

Table 2.2 State and type of damage of breakwaters (courtesy by Tohoku Regional Bureau).

Port	Area	State of major damage	*HT*(m)	Damage Type
Hachinohe	Hachitaro	Settlement of dissipating blocks	6.2	Scour by OF
	Hachitaro	Scouring of Mound in Harbor Side	6.2	Scour by OF
	Hachitaro	Sliding of Caisson	6.2	T. F.
	Sotominato	Scouring and Falling of temporary H.B.	6.2	Scour of H.B.
	Sotominato	Scouring and Falling of temporary H.B.	6.2	Scour of H.B.
	Sotominat	Scattering of amour blocks and rubble	6.2	Scour by OF
Kuji	Hanzaki	Sliding and overturning of Caisson	8.5	T. F.
	Mouth	Scour	―	Scour of H.B.
Miyako	Desaki	Sliding and overturning of Caisson	8.5	T. F.
	Ryujinzaki	Scouring and Falling of temporary H.B.	7.5	Scour of H.B.
	Fujiwara	Scouring and Falling of temporary H.B.	8.5	Scour of H.B.
	Fujiwara	Scouring and Falling of temporary H.B.	8.5	Scour of H.B.
	Fujiwara	Sliding and Falling of Caisson and etc.	8.5	T. F.
	Fujiwara	Settlement by seismic motion	―	―
	Kanbayashi	Sliding and Falling of Caisson and etc.	8.5	T. F.
	Fujiwara	Sliding and Falling of Caisson and etc.	8.5	T. F.
	Fujiwara	Settlement by seismic motion	―	―
	Fujiwara	Sliding and Falling of Caisson and etc.	8.5	T. F.
Soma	Honkou	Sliding and Falling of Caisson and etc.	14.38	T. F.

** HT means Tsunami Height. , OF means overflow, T.F. means Tsunami Force, H.B. means Head of Breakwater*

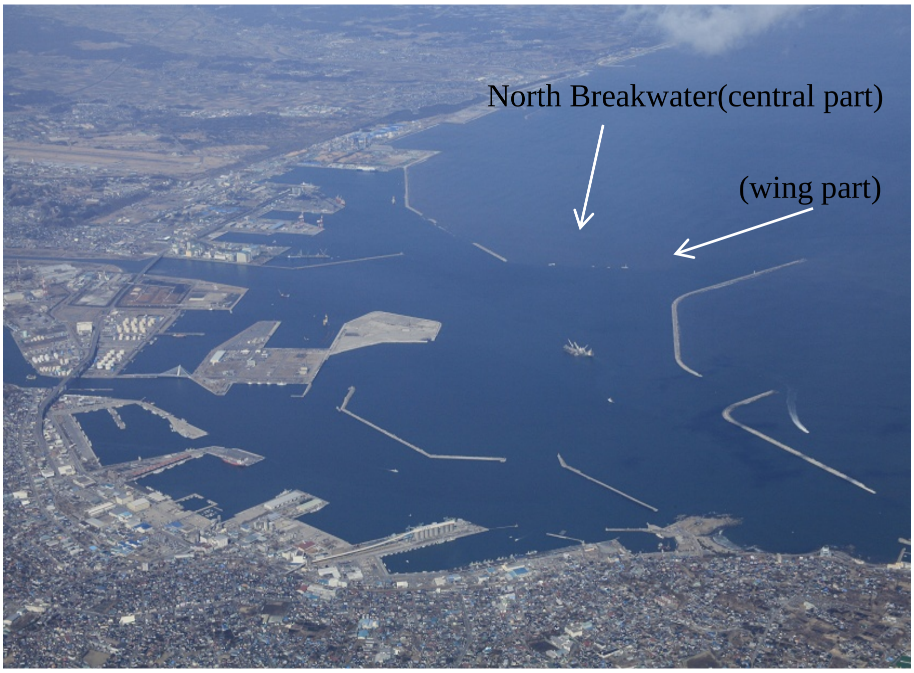


Fig. 2.13 State of damage at Hachinohe Port (courtesy by Tohoku Regional Bureau).

Fig. 2.14 shows the results of a tsunami simulation near the Northern Breakwater in Hachinohe Harbor, and Fig. 2.15 show photos of central part of the breakwater during the real tsunami event at times corresponding to [1] to [5] in the Fig. 2.14.

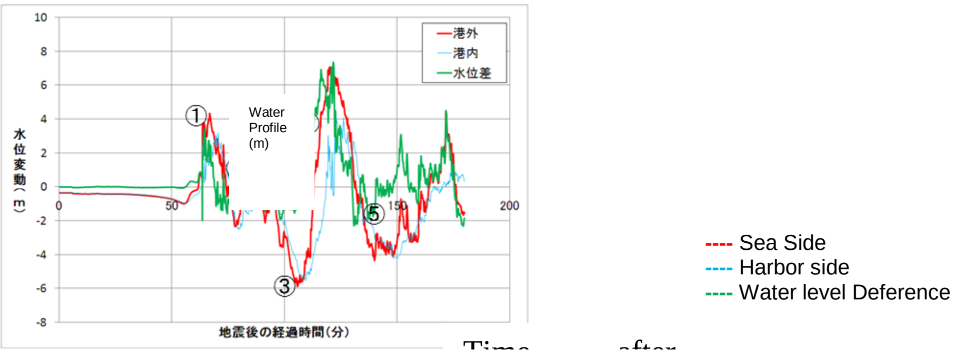


Fig. 2.14 Result of tsunami simulation at central part of North Breakwater.

Fig. 2.15 Photos of the central portion of the harbor at different time intervals.

Simulation results indicate that all breakwaters remained in good condition up to at least the first wave, but the caissons were damaged when the third wave overflowed at 16:35.

This example at Hachinohe illustrates that more effective countermeasures for overflow scouring are needed. The data show that scouring of the foundation mound is severe and a common type of damage. This damage is assumed to be a result of overflow of the breakwater. While not all caissons were displaced during the tsunami, this type of scouring behind breakwaters was found almost everywhere in the harbor. In turn, the bearing capacity of the mound was insufficient, and caissons were damaged by the water level difference between the inside and outside of the harbor. Many breakwater structures would not have toppled and failed had the overflow scouring occurred

2.2.3 Seawall and coastal dike

Kumagai et al. (2011) conducted a field survey on the damages of the 2011 Tohoku tsunami to the shore protection structures of 20 locations in 7 ports in Miyagi and Iwate prefecture. They summarized damaged to seawalls installed in 12 of these locations. Surface cracks, damage due to collision with debris, and the fractures along the joint surfaces were observed on these seawalls. Furthermore, upward waves of the tsunami did cause outflow of seawalls, the scattering of parapet, and the deformation of gates. The damages due to breaking waves or the convergence of waves was found in fishery ports. Scouring of the seabed in front and behind of the seawalls was also observed, but in none of the cases observed did the main body of the seawall collapse.

As shown in Fig. 2.16, scouring was observed in almost all the damaged cases, and sometimes sediment was flowing out from foundation due to piping. In Ofunato port, severe scouring would be observed, because drainage was concentrated where the facilities were collapsed due to the backrush.

Failure mode of seawalls have been summarized and discussed by several authors (e.g., Fraser et al., 2013; Mori et al., 2013; Jayaratne et al., 2013; Yeh et al., 2012). For details of these references, see also Chapter 4 in Deliverable D1 "*Report on existing tools, data, and literature on tsunami impact, loads on structures, failure modes and vulnerability assessment*"(Tarakcioglu et al., 2014a).

Damages to coastal dikes were also summarized by several authors (e.g., Watanabe et al., 2012; Kato et al., 2012; The Committee of Countermeasures along the Coast against Tsunami, 2011). Watanabe et al. (2012) surveyed the degree of damage, structure specifications, and tsunami height at 225 sections of coastal dikes with armored surfaces and analyzed the effective resilient structures. Kato et al. (2012) also investigated in detailed the failure mechanisms of coastal dikes (see also Deliverable D1). On determination of the design height of coastal dikes along the Pacific Coasts of Japan, see also Deliverable D4 "*Report on comparison of mitigation strategies in Europe and Japan*"(Tarakcioglu et al., 2014b).

(a*) Seawalls collapsed towards land*

(Chayamae district, coastal protection area in Ofunato port)(Crest height of walls: TP +3.40m, Observed tsunami height: TP +8.07m)

(b) Seawalls collapsed towards the sea

(Nagahama district, coastal protection area of Ofunato port)(Crown height of wall: TP +3.00m, Observed tsunami height: TP +10.02m)

(c) Severe scouring was observed on the seaside

(Suga district, coastal protection area of Kamaishi port)(Crown height of wall: TP +4.00m crown high parapet, Observed tsunami height: TP +8.64m)

Fig. 2.16 Damage to Seawalls

2.2.4 Land structures

Both houses and many concrete structures were damaged. Table 2.3 shows the relationship between tsunami height and damage proposed by Shuto (1992). Wooden housing in past examples was often damaged by tsunami 2m and deeper. In contrast, the effect of 5m to 16m on concrete buildings was unknown, showing that there have been few cases in the past.

A survey of buildings throughout the region struck by this tsunami (Building Research Institute, 2011) has shown that in districts where the inundation depth exceeded 2m, the percentage of totally destroyed buildings (including those washed away) was high. This survey did not distinguish between wooden or concrete, and steel frame buildings, but it provides reference information. Many buildings were washed away by the horizontal force or the buoyancy of the tsunami.

Table 2.3 The relationship between tsunami height and damage (Shuto, 1992).

Tsunami Height (m)	1	2	4	8 16 32
Wave Profile mild slope steep slope	rise in shallow like tide with fast speed	Like wall in offshore, 2nd wave breaking like tide with fast speed	Almost same profile as 2m, Possibility of breaking is increasing at toe of tsunami	Plunging breaker
Wooden Houses	Partially Destruction	Destruction（2m～）		
Stone Houses	Safe			Destruction（7m～）
Steel, Concrete Buildings	Safe（～5m）			Destruction
Community near shore		Partially	Damage ratio 50%	Damage ratio 100%

Fig. 2.17 shows a view of the land around Natori City in Miyagi Prefecture. The inundation depth of the tsunami (height of tsunami above the ground) was about 2 m, and while some houses survived, most were washed away. Of those which remained in place, many were damaged as shown in Fig. 2.18. This is interpreted as evidence of large impact force. In the hinterland near the coastline and on sand dunes in particular, breaking bores occur easily, raising the impetus of a tsunami and increasing its destructive force (Arikawa et al., 2006). If the impact force of the wave exceeds the strength of the front face of the house, the building will likely be destroyed by the leading edge of the tsunami before buoyancy begins to act.

Fig. 2.17 Damaged property around Natori City.

Fig. 2.18 Damaged property around Natori City.

In many steel frame buildings, the front walls are weaker than their columns. Often, the walls are first damaged by the tsunami, which dissipates the force of tsunami, allowing more building occupants to survive. The three-story steel frame building in Fig. 2.19 illustrates this point. While the tsunami reached the ceiling of the third story and the walls were severely damaged, the structure did not collapse.

However, if the impact force on the building is large enough, the columns may be broken. In the building shown in Fig. 2.20, the columns were almost all bent in the same direction. The force of tsunami on columns is reduced by their small surface areas, but in cases where they are covered by a large wall, they can all be broken in this way.

Fig. 2.19 Three-story steel frame building in the Rikuzentakada City, Iwate Prefecture.

Fig. 2.20 Damage of a steel frame structure in the Ohtsuchi City.

At places where the inundation depth exceeded approximately 8m, even concrete structures may be severely damaged. Walls of box-shaped buildings on the shoreline, refrigerated storage structures or purification plants for example, may be vulnerable. Fig. 2.21 is a view of a refrigerated ice making plant in Kamaishi with a wall pulled out. In this district, the inundation depth was about 8 m, and this was directly behind a revetment. Such buildings resisted the intrusion of tsunami, and there were no debris on the second story. Thus, it is presumed that it was destroyed by water pressure.

In Onagawa-cho in Miyagi Prefecture, many steel frame and concrete buildings were damaged. Fig. 2.22 shows a three-story apartment building thought to have stood near the quay wall but which was washed away. A collapsed two story police box to its right. Fig. 2.23 shows damage to buildings of three or more stories around Onogawa Fishing Harbor. Red circles denote the damaged buildings of three or higher stories and the black arrows show assumed washed-away directions of buildings. It is assumed that, as in the case of houses, buoyancy is one of the factors causing these buildings to be washed away, and that this occurred after submersion.

However, among regions where the inundation depth was similar, there are not very many where buildings were washed away. Ground conditions have been cited as a possible explanation of the difference. The ground reaction force was supposed to be smaller, and thus the frictional force against tsunami force was smaller in this area. Combination of the lesser frictional force and the buoyance force was attributed to the reason why concrete buildings were easily washed away. Therefore, it is thought to be possible that concrete buildings were more easily washed away than in other districts.

Fig. 2.21 View of a refrigerated ice making plant in Kamaishi with a wall pulled out.

Fig. 2.22 A three store apartment building that has been washed away (Takahashi et al., 2011).

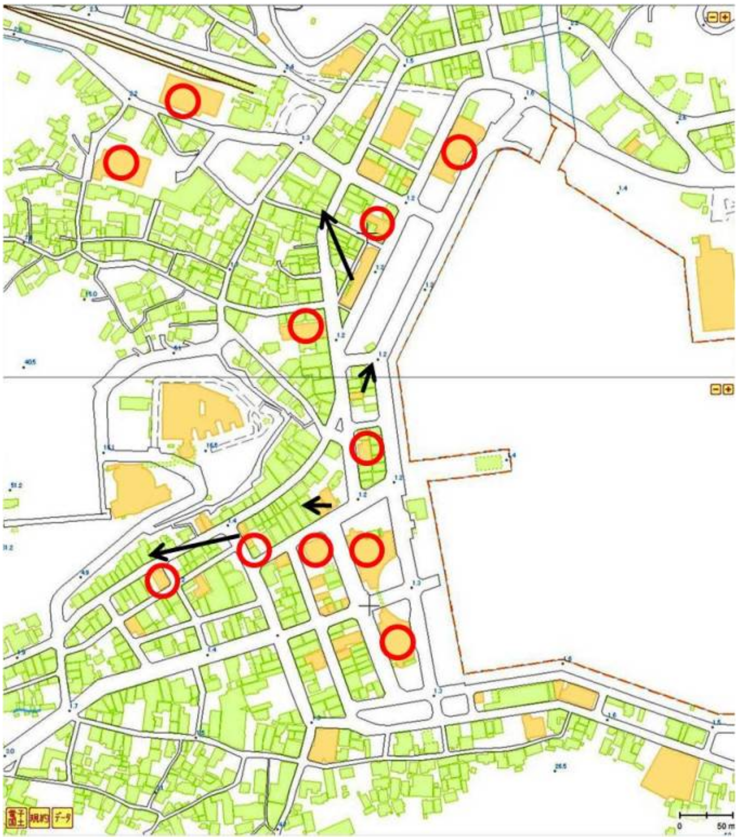


Fig. 2.23 Damage to buildings of three or more stories around Onagawa Fishing Harbor. Red circles denote the damaged buildings of three or more stories and the black arrows show assumed washed-away directions of buildings (Takahashi et al., 2011).

2.2.5 Human

The National Police Agency of Japan reported on 30 May, 2012 reported 15,859 fatalities and 3,021 people missing as a result of the 2011 Tohoku Earthquake (and proceeding tsunamis). Furthermore, 129,914 houses were reported as completely destroyed, and 258,591 houses were partially destroyed. Table 2.4 indicates the human losses and the house damage in different prefectures. The damage was most severe in Iwate Pref., Miyagi Pref. and Fukushima Pref. . The human losses were the highest in Miyagi Pref., with 9,517 fatalities and 1,581 missing. This was followed by Iwate Pref., with 4,671 fatalities and 1,222 missing, and finally Fukushima Pref., with 1,605 fatalities and 214 missing. Property damage was also the greatest in Miyagi Pref., where 84,940 houses were completely destroyed and 147,613 houses were partially destroyed. Fukushima Pref. followed, with 20,607 houses completely destroyed and 68,473 houses partially destroyed. Finally, in Iwate Pref., 20,189 houses were completely destroyed, and 4,688 houses were partially destroyed. Central Disaster Management Council (2011) analyzed the casualty rate in more detail. For example, age composition of fatalities was compared with that of damaged area. People who was 70 years or more occupied 18 % in the damaged residential area, whereas 47 % of dead people was comprised by the same category of the aged people. Actual behavior of evacuation just after the earthquake as well as peoples' awareness of tsunami were also analyzed.

Table 2.4 Human Losses and Building Damage in Different Prefectures.

Pref.	Casualties		Buildings Damage	
	Fatalities	Missing	Completely	Partially
Hokkaido	1	0	0	4
Aomori	3	1	306	701
Iwate	4,671	1,222	20,189	4,688
Miyagi	9,517	1,581	84,940	147,613
Yamagata	2	0	37	80
Fukushima	1,605	214	20,607	68,473
Tokyo	7	0	15	198
Ibaraki	24	1	2,738	24,506
Tochigi	4	0	260	2,103
Gunma	1	0	0	7
Chiba	20	2	798	9,985
Kanagawa	4	0	0	39
Total	15,859	3,021	129,914	258,591

2.3 *Fragility curve*

2.3.1 Breakwater

PIANC (2013) shows the relation between the design wave height-tsunami height ratio and the damage ratio (Fig. 2.24). The damage ratio is defined as the ratio of the length of damage-prone breakwaters (subject to damage assessment regardless of the degree of sustained damage) to the length of the front-line breakwaters in the harbors (i.e. = damage length/total length). The solid line represents the cumulative distribution function of the following logarithmic normal distribution:

$$F(\eta, H_{1/3}) = \Phi\left[\frac{\ln(\eta/H_{1/3}) - \mu}{\sigma}\right]$$

where $H_{1/3}$ is the design wave height, η is the tsunami height at the front side of the breakwater, and μ and σ are parameters (μ = 0.0386, σ = 0.279). This reveals that more severe damage occurs when a tsunami height at the front side of the breakwater is equal to or greater than the design wave height. This general result indicates that tsunami force acting on the breakwater was almost the same degree of that of the design wave height. On the contrary, in some limited cases such as Ishinomaki and Onagawa, nearly 100 % damage was observed even under relatively low tsunami height. This was supposed to be caused by the increased water level on the rear side of the breakwater and because the pressure caused by the tsunami was different from what is considered for regular high waves.

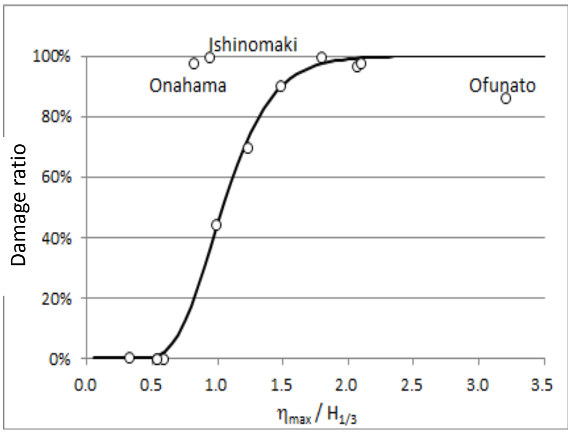


Fig. 2.24 Damage ratio of front-line breakwater and tsunami height of different port (PIANC, 2013).

2.3.2 Seawall

The relationship between the damage ratio and the relative height was investigated on each of the 60 seawall structures between Kuji City and Rikuzentakata City in Iwate Prefecture. Only seawalls where the cross-sectional shape of the structure was known was included in the analysis. The heights of the structures investigated are listed in Fig. 2.25. The damage ratios are given in Fig. 2.26 It is shown that about 20% of breast walls were damaged, including partially damaged ones.

Fig. 2.27 shows the relationship between the safety factors for sliding and overturning, calculated using the wall height paired with the damage ratio and with the crest water level. The relation reveals that the safety factor for sliding was generally lower than the safety factor for overturning and that the safety factor for sliding dropped below 1.0 around where the wall height exceeded 3 meters. The analysis further showed that that the damage ratio reached 1 around where the relative height exceeded 4.0 meters.

Fig. 2.28 shows the relation between the safety factor for sliding and the damage ratio, together with the cumulative distribution function curves of logarithmic normal distributions. The logarithmic variable is the inverse of the safety factor. One of the two curves is for the same parameters as for breakwaters and the other is for $\mu = 0.01$ and $\sigma = 0.1$. As far as the damaged breast walls are concerned, their values are generally on the curves, which appear sharper than those for the breakwaters. The implication is a nearly 100-percent probability of collapse for a given triggering event.

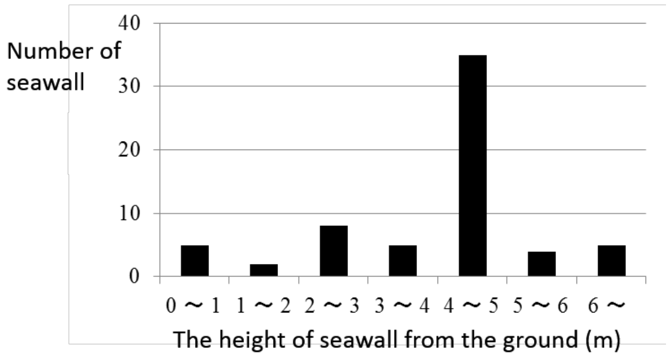


Fig. 2.25 Heights of seawall structures evaluated.

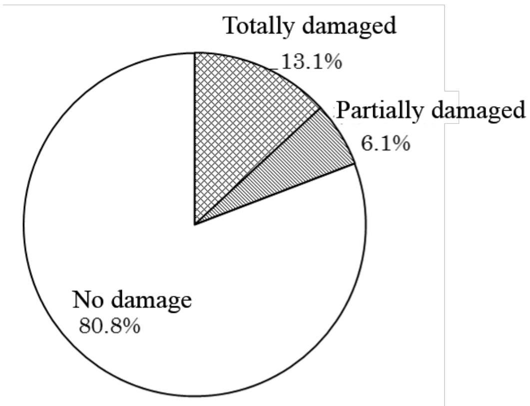


Fig. 2.26 Damage ratios of facilities evaluated.

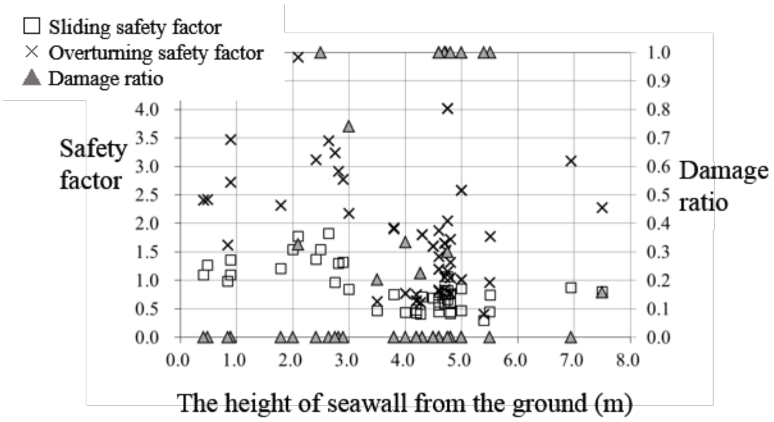


Fig. 2.27 Relations between various safety factors based on seawall heights, damage ratios, and crest water levels.

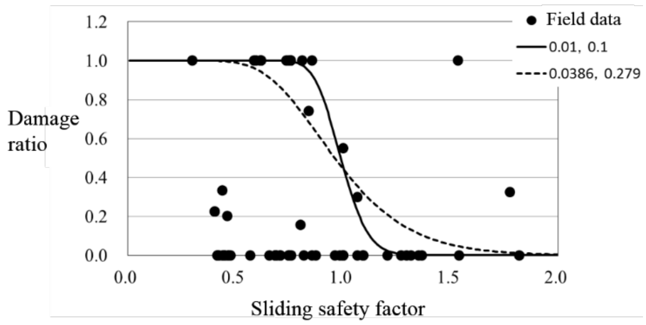


Fig. 2.28 Relations of safety factor for sliding to damage ratio.

2.3.3 Land Structure

The City Bureau of MLIT (2012) investigated the proportion of affected buildings in 6 prefectures: Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba. Their survey counted 250,000 affected buildings, of which approximately 140,000 were completely destroyed. Additionally, MLIT assessed the condition of all buildings located in the region flooded by tsunami. Seven categories were used: total loss (washed out), total loss, total loss (inundated beyond the 1st floor ceiling), large scale partially destroyed, partially destroyed (flood inundated), partially damaged (flooding below floor), and no damage based on field survey and damage certificate. (See Fig. 2.29 for full description of category criteria.) As for the proportion of affected buildings, wooden structures comprised 70% of the tally, reinforced concrete structure stood at 2%, steel frame structure at 4%, and others comprised 7% (light weight steel frame, soil structure, block structure) of all buildings as shown in Fig. 2.30.

Our analysis showed a significant relationship between inundation depth and the condition of a building after a disaster. The proportion of buildings completely destroyed in the case of inundation depth of 2 m or below tend to be significantly lower than above that value (Fig. 2.31). Building type also has a significant role, Fig. 2.32. The proportion of buildings completely destroyed was 5% in the case of reinforced concrete structures for inundation depth 1.5 m – 2m. In contrast, at least 20% of wooden structures were completely destroyed at this depth, which is not necessarily a low proportion.

Moreover, the following trends became clear as a result of analyzing inundation depth and disaster condition of buildings by structure and by number of floors.

1) In the case of reinforced concrete structures and steel frame structures, the proportion of buildings that were “Completely destroyed (washed out)” and “Completely destroyed” categories was low. Meanwhile, the proportion that were “Completely destroyed (inundated beyond the 1st floor ceiling) was high.

2) The number of stories floors (i.e. the building height) has an effect too. Reinforced concrete structures more than three stories high suffered a lower proportion of critical damages than shorter buildings. For instance, data showed that at inundation depths 2.5 m or below, the proportion of completely destroyed buildings is less than 10%.

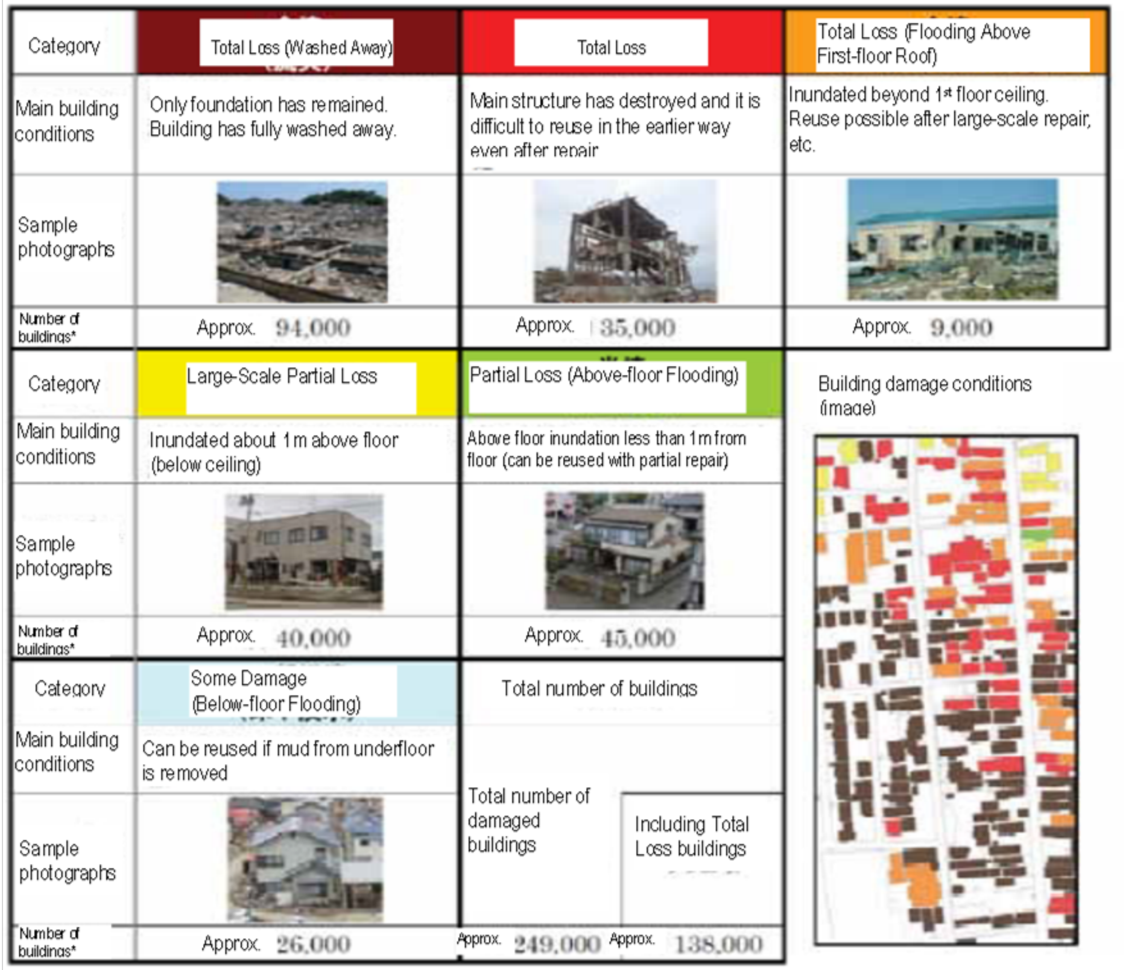


Fig. 2.29 Categories used to classify disaster condition of buildings (City Bureau, MLIT, 2012).

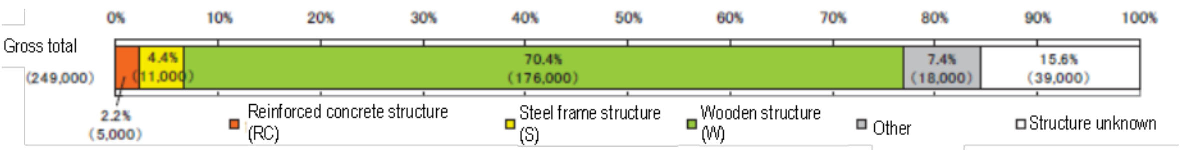


Fig. 2.30 Proportion of disaster condition of buildings by structure (City Bureau, MLIT, 2012).

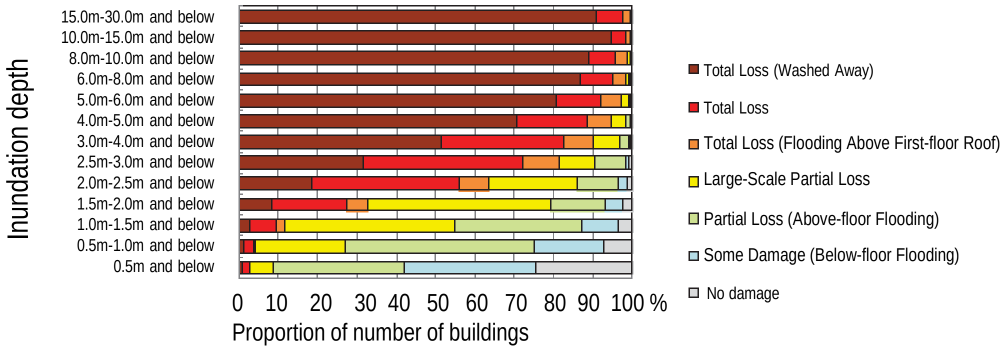
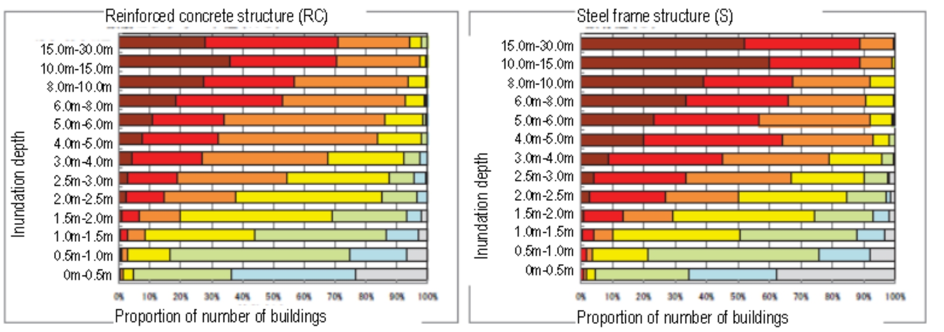
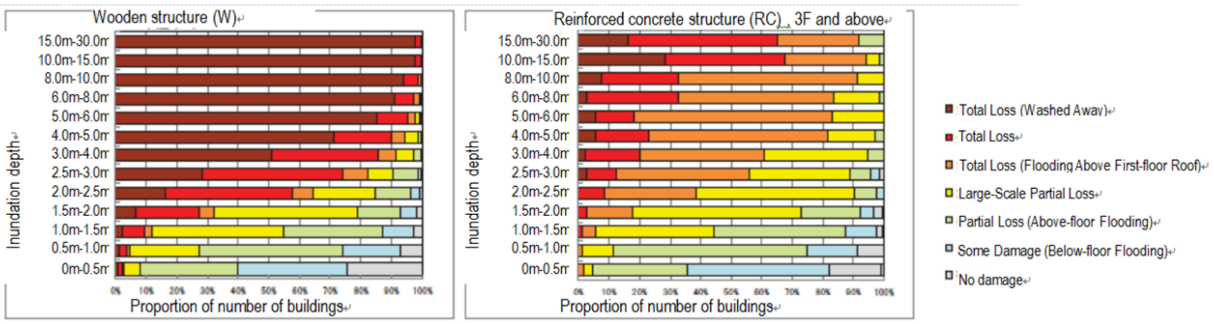


Fig. 2.31 Proportion of affected buildings with respect to inundation depth (City Bureau, MLIT, 2012).



(a) RC structure *(b) S structure*



(c) Wooden structure *(d) RC structure (3 stories or more)*

Fig. 2.32 Proportion of affected buildings by inundation depth, sorted by building type (City Bureau, MLIT, 2012).

2.3.4 Human

Table 2.5 shows the casualty rate in Iwate Pref., Miyagi Pref. and Fukushima Pref. These were calculated by dividing the total number of casualties (including both fatalities and missing persons) into the population of each inundated area. The casualty rate was highest in Iwate Pref. at 5.9%, followed by 3.5% in Miyagi Pref.

and 2.7% in Fukushima Pref. The higher the tsunami on coast is, the higher the casualty rate is.

Fig. 2.33 shows the relation between the tsunami height and casualty rate. These were calculated by dividing the total number of casualties (including both fatalities and missing persons) into the population of each inundated area. The data include not only 2011 tsunami but multiple previous tsunami events. This figure indicates that the casualty rate of Iwate prefecture is much smaller than the other cases. There, the tsunami preparedness education was more effective, and the hazard mapping was more in-depth and accurate. In comparison, the casualty rate in Miyagi prefecture was larger than that of Iwate prefecture. Some suggested explanations include differences in topography or hazard map accuracy. In Miyagi prefecture, the hazard map in many area underestimated inundation area. This comparison indicates that the preparedness of vulnerable populations is very important.

There have been several reports concerning socio-economical as well as environmental impacts. For environmental impacts, for example, a special report of JSWE (Japan Society on Water Environment, 2013) summarized impacts of tsunami on water environment including impacts of damages of sewage treatment system on water pollution in the receiving water. Large scale loss in natural habitat of seagrass beds in coastal area that was washed away by the attack of tsunami is well documented.

Table 2.5 Casualty Rate in Different Municipalities (Central Disaster Management Council, 2011).

Pref.	municipality	Population	Population in inundation area ①	Dead ②	Missing ③	Casualty rate (②+③)/①
Iwate		272,219	107,503	4,664	1,635	5.9%
	Hirono	17,823	2,733	0	0	0.0%
	Kuji	36,568	7,171	2	2	0.1%
	Noda	4,613	3,177	38	0	1.2%
	Fudai	3,071	1,115	0	1	0.1%
	Tanohata	3,831	1,582	14	16	1.9%
	Iwaizumi	10,597	1,137	7	0	0.6%
	Miyako	58,917	18,378	420	122	2.9%
	Yamada	18,634	11,418	604	214	7.2%
	Otsuchi	15,239	11,915	802	576	11.6%
	Kamaishi	39,119	13,164	884	198	8.2%
	Ofunato	40,643	19,073	339	112	2.4%
	Rikuzentakata	23,164	16,640	1,554	394	11.7%
Miyagi		1,708,692	331,902	9,411	2,088	3.5%
	Kesennuma	73,279	40,331	1,022	384	3.5%
	Minami-Sanriku	17,382	14,389	558	343	6.3%
	Ishinomaki	160,336	112,276	3,173	717	3.5%
	Onagawa	9,965	8,048	566	411	12.1%
	Higashi-Matsushima	42,859	34,014	1,044	94	3.3%
	Matsushima	15,017	4,053	2	0	0.0%
	Rifu	34,249	542	46	0	8.5%
	Shiogama	56,325	18,718	20	1	0.1%
	Shichigahama	20,377	9,149	66	5	0.8%
	Tagajo	62,881	17,144	188	1	1.1%
	Sendai	1,046,902	29,962	704	26	2.4%
	Natori	73,576	12,155	911	72	8.1%
	Iwanuma	44,138	8,051	183	1	2.3%
	Watari	34,773	14,080	257	13	1.9%
	Yamamoto	16,633	8,990	671	20	7.7%
Fukushima		526,813	71,292	1,802	119	2.7%
	Shinchi	8,176	4,666	109	1	2.4%
	Soma	37,738	10,436	455	4	4.4%
	Minami-Soma	70,834	13,377	640	23	5.0%
	Namie	20,861	3,356	146	38	5.5%
	Futaba	6,884	1,278	30	5	2.7%
	Okuma	11,574	1,127	80	1	7.2%
	Tomioka	15,959	1,401	19	6	1.8%
	Naraha	7,679	1,746	11	2	0.7%
	Hirono	5,397	1,385	2	1	0.2%
	Iwaki	341,711	32,520	310	38	1.1%

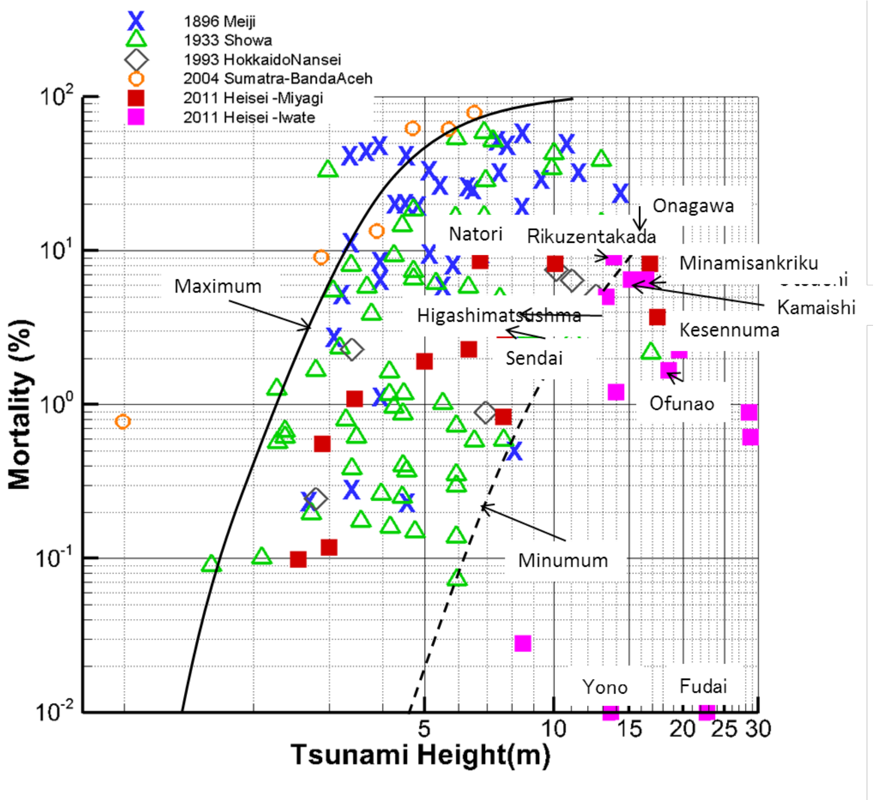


Fig. 2.33 Relationship between tsunami height and casualty rate.

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Appendix: Definitions of tsunami metrics used in Deliverable D2

In this report, inundation *height* is defined as the observed level of the water above the tide level at the time of the event at intermediate locations, and run-up height denotes the elevation above the tide level at the time of the event at the maximum distance from the shoreline. Note that inundation *depth* is defined as a height of tsunami above the ground. These definitions are commonly used among Japanese tsunami researchers and in Japanese literatures.

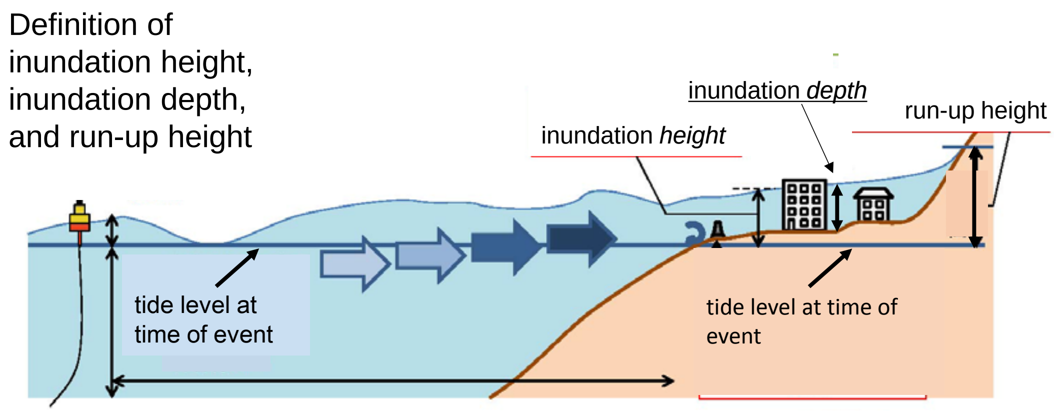

Fig. A1: Definition of inundation height, inundation depth, and run-up height used in Deliverable D2.

Review and reference page

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