An English Abstract of the Technical Note of Port and Air Port Research Institute, No. 1231, April 28, 2011

Urgent Survey for 2011 Great East Japan Earthquake and Tsunami Disaster in Ports and Coasts – Part I (Tsunami)

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The Great East Japan Earthquake, which occurred at 14:46JST on March 11, 2011 with the magnitude M9.0 generated a huge tsunami and caused devastating disasters in the coastal towns facing the Pacific Ocean. It is very sad and horrible that the number of casualties and missing persons is more than 25 thousands.

The Port and Airport Research Institute is conducting investigations including field surveys just after the earthquake, for recover the ports and coasts in the regions for the Ministry of Land, Infrastructure, Transport, and Tourism (MLITT) .

The tsunami attacked all the Pacific coasts in Japan impacting the coastal towns from Hokkaido to Chiba Prefecture. Especially devastating disasters occurred in Iwate, Miyagi, and Fukushima Prefectures. Damages due to the earthquake are significant especially in the southern areas of Miyagi Prefecture. In this report the tsunami disasters in Iwate, Miyagi and Fukushima Prefectures are described.

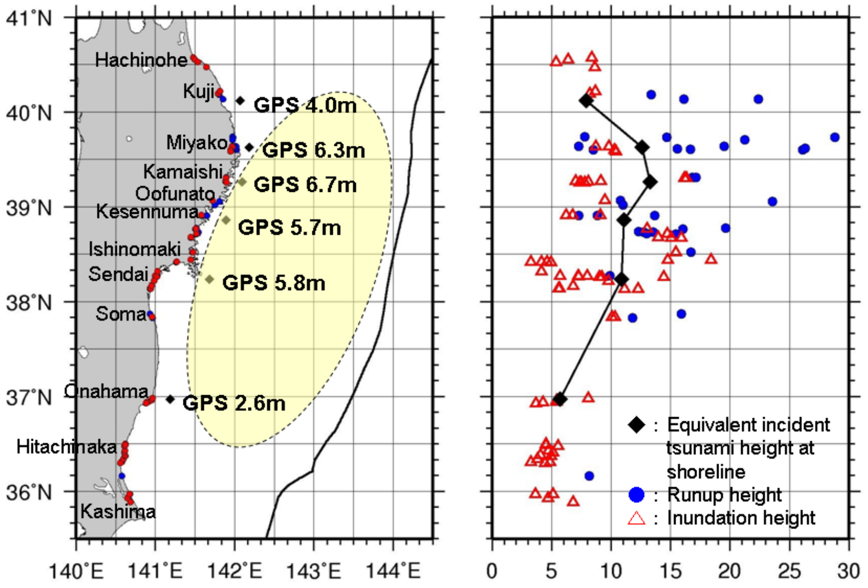

Fig.1 Source region and GPS wave meters(left)
and Estimated Incident Tsunami and Measured Tsunami water marks(right)

１． Offshore tsunami observed by GPS wave meters and 10-m tsunami warning

Huge tsunami waves were generated by the M9.0 earthquake. The left figure of Fig. 1 shows the source region, which ranges 400km from north to south and 200km from east to west. The sea bottom of the region rose and dropped, causing the initial tsunami. The Port and Harbour Bureau of the Ministry of Land, Infrastructure, Transport and Tourism had installed a number of GPS wave meters (GPS mounted buoy) along the Japanese coast, that measured the tsunami directly. For example a GPS wave meter 18km off the coast of Kamaishi at a depth of 204m measured a 6.7m high tsunami at 15:12. Another GPS wave meter off the coast of

Rikuzen-Takada recorded a 5.7m high tsunami at 15:14.

The measured values of tsunami were incredible since the tsunami was expected to be more than 10m (2 or 3 times) on shore if the simple shoaling effect was considered. At 14;49 the Japan Meteorological Agency had issued a Major tsunami warning of more than 6m and changed it to that of more than 10m accordingly

２． Huge tsunami attacking the coast

The GPS data are very important for the disaster analysis. For example the incident tsunami can be estimated from the GPS data. The right figure of Fig.1 shows 'Equivalent Incident Tsunami Height at Shore' which is evaluated considering shoaling coefficient assuming perpendicular incidence and parallel contours. The estimated tsunami height at shore η (defined here as equivalent incident tsunami height at shore) is evaluated by $\eta = (h_G \eta_G{}^4)^{0.2}$ where the water depth h_G and the GPS tsunami height η_G. As mentioned above the equivalent incident tsunami height at shore is two or three times the GPS values -- 7.9m at Kuji, 12.6m at Miyako, 13.3m at Kamaishi, 11.1m at Hirota Bay (Rikuzen-Takada), 10.9m at Kinkazan, and 5.7m at Onahama.

The right figure of Fig.1 shows the measured water mark heights. Although the teams of Japan Society of Civil Engineers also measured the water marks, the figure shows only the authors' data due to the urgency of this report. The water mark heights are the heights above the sea level when the tsunami arrived and include those of inundation heights and run-up heights. The data scatters significantly. The run-up heights exceed 15m and the inundation heights vary from 5 to 15m approximately. The equivalent incident tsunami height at shore agrees with the average of the measured inundation heights which exceed 10m in Miyagi and Iwate Prefectures.

It is well-known that the tsunami height increases at sawtooth coastlines with decreasing width and resonant effects and the heights increases with refraction effects, while the heights decrease with the sheltering effects due to natural islands, artificial breakwaters, and seawalls. These are the reasons of the wide scattering of the measured data in Fig.1. It should be noted that the tsunami ran up rivers and overflowed from the rivers.

Tsunami height changes significantly due to the shore profile. Figure 2 shows a schematic diagram of typical cross sections of the shores to explain the intrusion of tsunami more than 10m. Videos and photos that were taken during the tsunami attacks will be analyzed further to reveal the tsunami behaviors at shore.

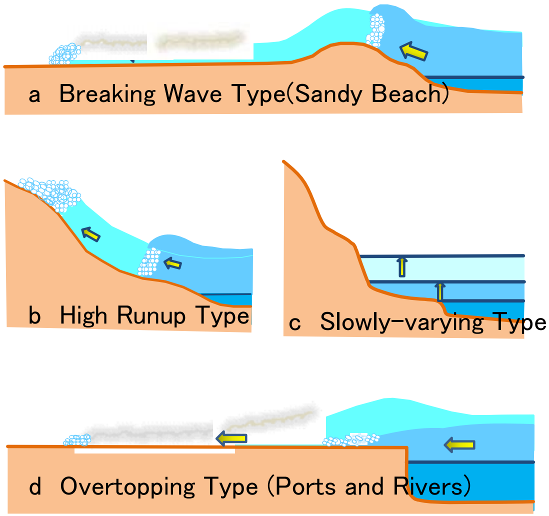

Fig.2 Typical cross sections of shores and intrusion of a huge tsunami

(a) Ordinary Sandy Beaches:

The coast near Sendai Airport is a typical mild-sloped sandy beach with a sand dune. Tsunami broke near the shore and run up 5- 10 m high sand dune. The tsunami ran down from the dunes to a lowlying rice field and inundated several km in the paddy field. The sea bottom slope in the coast is 1/200 to 1/500 at a depth from 10 to 100m. Videos showed the tsunami front breaking with solitons. A 15m high tsunami waves of this type were also seen in the beach at Rikuzen-Takada of Hirota Bay.

(b) Steep slope shore:

Tsunami fronts break and run up rapidly on a relatively steep slope. This type of rapid runup with breaking waves was seen at Omoe Peninshula and Ryori-Shirahama Bay where the runup heights were more than 20m. The sea bottom slope at Ryori-Shirahama is 1/100 at a depth of 10m and 1/10 on land. The tsunami runup heights are high at this type of shore in Fig. 1.

(c) Steep cliff with deep front sea:

Nagasaki district of Ohfunato has a very steep cliff facing the Pacific Ocean and relatively deep sea in front, and therefore the tsunami did not break and the water surface moved up and down relatively smoothly.

(d) Ports and rivers:

Since ports have a relatively large water depth and tsunami does not break. In Kamaishi port the tsunami overtopped the quaywalls and seawalls and intruded into the town with a very rapid current of 10 to 30 km/h. It should be noted that the tsunami heights exceeded those of 1896 Maiji-Sanriku Tsunami and the tsunami heights were more than two times higher in the southern areas from the border of Iwate and Miyagi Prefecture.

３． Various devastating damages due to huge tsunami

Table 1 Damages due to tsunami more than 10m

General	Destruction and washed-away of houses
	Drift and crash of cars
	Fires
	Destruction of tanks and oil spill
	Destruction of Railways, roads and bridges
	subsidance of ground
	Inundation of rice paddles
Ports and Coasts	Drifting and collision of ships
	Destruction and inundation of port faciliteis
	Drifting and collision of timbers and containers
	Debris deposit in ports
	Scouring and deposit in ports
	Scouring of sandy beaches and destruction of green belts
	Destruction of acuaculture facilities
Coastal Defenses	Scouring and sliding of Breakwaters and quaywalls
	Destruction of jetties and detached breakwaters
	Destruction (scouring) of Dykes and Seawalls
	Destruction of water gates

The tsunami caused significant damages on all the coastal towns along the Pacific Oceanfrom Hokkaido to Chiba. Especially more than 10m tsunami caused all the kinds of tsunami damages to the coastal towns of Iwate, Miyagi and Fukushima Prefectures. Devastating damages due to huge tsunamis were observed in many places by 2004 Indian Ocean Tsunami and Aonae District of Okushiri Island by 1993 Hokkaido Nansei-oki Tsunami in Japan.

Table 1 summarizes the tsunami damages due to more than 10m tsunamis except for casualties. Most typical damage is complete destruction of wooden houses. Almost all the coastal towns in the three prefectures were flattened by tsunami.

Wooden houses are destroyed by even 2m tsunamis and it was obvious that more than 10 tsunami caused fatal damages to wooden houses (Photo 1 and 2). It is said that some concrete buildings collapsed although the concrete buildings are said to be safe against tsunamis. The impulsive force due to collision of breaking wave front might be a reason for the collapse of concrete buildings as shown in (a) and (b) in Fig.2.

Photo 1(a) Flattened wooden houses and remaining concrete buildings(Minami-Sanriku)

Photo1(b) Flattened wooden houses and remaining concrete buildings(Rikuzen-Kakada)

Photo 1 (c) Burnt houses (Ishinomaki)

Photo 2 debris and cars piled in a road(Kamaishi)

Cars floated everywhere and were found even in houses and under the debris (Photo 2). Some were found on the roof of concrete buildings. Fires broke out in the debris and spread due to drifting of the debris. Spilled oil spread due to tsunami and caused large-scale fires. Damages to railways and roads were also significant including the damages to bridges (i.e. Minamisanriku-Utatsu). Sendai Airport which is located 1.5 km from the coastal line was inundated and airplanes floated just like cars.

It should be noted that the land subsidence due to crustal movement by the earthquake was from 0.5 to 1m, which cause secondary inundation due to spring tide in the lowlying coastal areas like Ishinomaki.

４． Damages in Ports and Coasts

Various damages occurred in ports areas including typical port damages as shown in the middle of Table 1. For example, many ships broke their moorings and collided with port facilities and one was washed on a wharf (Photo 3). According to Maritime News Paper a total of 6 vessels (1 at Ishinomaki, 2 at Souma, 1 at Haramachi, 1 at Onahama, 1 at Kamaishi) of 20 to 200 thousand tons were stranded or caused oil spill within ports. 31 passenger ships were severely damaged including 2 partially damaged according to Tohoku-disrict passenger ship association. Also small boats including fishing boats were carried far inland areas and it is estimated that more than 17,000 boats were damaged. The severe damage to warehouses and factories in the port industry areas caused the secondary impact on industry in the world. The container terminals suffered from inundation. More than 4000 containers in Sendai Port floated from their foundations and 1000 of them went into the sea.

Scouring and deposit occurred in ports and navigation channels. At some breakwater mouths the scouring depth was more than 10m. Much debris sunk in port areas and removal operations are in progress. The operations were started just after the damages and some ports opened just one week after the earthquake with limited quays to contribute recovery of the neighbor areas.

It should be noted that utterly damages occurred to aquaculture facilities and that sandy beaches and beach forests disappeared, as in Rikuzen-takada.

Photo 3 Ship landed on a quay

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Photo 4　Fishing boats landed on quay and burnt in a fire

Photo 5 Scattered containers (Sendai Port)

５．　Effect of Tsunami Breakwater and its Damge

Tsunami breakwaters were constructed in the baymouth of Kamaishi and Ofunato. The tsunami breakwater at Kamaishi Bay was designed to protect the port against not only the tsunami of 1896 Meiji-Sanriku Earthquake but also the large storm waves. Although the tsunami was very high, exceeding significantly the design tsunami height, the breakwater was relatively strong and tough since the stability design was determined by a large storm wave. According to the video, the breakwater was relatively safe until the peak of the first tsunami wave.

Figure 3 shows a result of numerical simulation for the tsunami at Kamaishi. The tsunami measured by the GPS wave meter 18km off the Kamaishi coast was used as the boundary condition. The figure compares the effect of tsunami breakwater by the two time series of tsunami heights at a tide gauge station of Kamaishi Port with and without the breakwater. The tsunami height is 13.7m without breakwater while 8m with breakwater, reduced to 60 % by the breakwater. The measure value at Kamaishi was around 8 m which agrees with the calculation with the breakwater. It can be said that the breakwater maintained its function until the peak. However, the caissons of the breakwater gradually sunk down and slipped from the breakwater mound due to scouring by the strong current and due to the pressure difference between the front and back walls of the breakwater caissons (Photos 6 and 7)

It should be noted that the tsunami breakwater at Ofunato was designed against Chilean Tsunami and the caissons of that breakwater shifted before the first peak of the tsunami

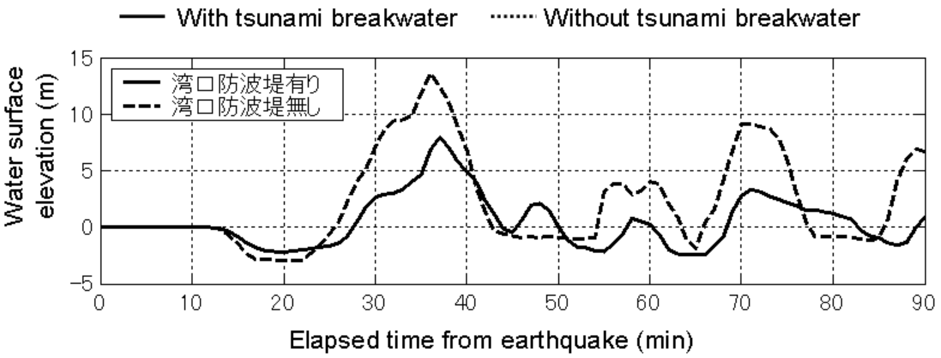

Fig. 3 Calculation results of tsunami profile at Suga in Kamaishi Port

Photo 6 Overtopping from Kamaishi Breakwater
(Courtesy of Tohoku Bureau of MLIT)

Photo 7 Damaged caissons of Kamaishi Breakwater

６． Damage to other coastal facilities

Many breakwaters and seawalls were also damaged by the tsunami. For example, the north breakwater of the Hattaro-district in Hachinohe Port (Photo 8), the marina breakwater of the Fujiwar-Kanbayashi district in Miyako Port and the offshore breakwater of Souma Port were damaged significantly. However, they were designed against severe storm waves and therefore relatively strong and tough against the huge tsunami. The breakwaters damages due to the 1983 Nihonkai-Chubu Earthquake Tsunami and 1993 Hokkaido-Nansei-oki Earthquake and Tsunami were limited to inner breakwaters and the parts near breakwater mouths. The more than 10m tsunami caused extensive damage to offshore breakwaters but still was limited to those that have a relatively small width of the caisson.

It should be noted that many seawalls and dykes were constructed to protect the coastal towns from tsunamis , using the 1896 Meiji-Sanriku Tsunamis for design conditions. The more than 10m tsunami overtopped the tsunami defenses and damaged them significantly (Photo 9). Even for huge tsunamis the tsunami defenses should exist and work to reduce the tsunami. The tough stability of the structures should be investigated further.

Photo 8　Caisson sliding at Hattaro Breakwater in Hachinohe

Photo 9 Seawall at Ryoishi in Kamaishi

７．　Tsunami Forces and Damages

Table 2 shows the major tsunami forces to damage the coastal structures and Figure 4 shows the typical failures of the coastal defenses:

1. The force due to the pressure difference between the front and back walls broke the breakwaters and seawalls. The pressure is almost static especially when the water depth is large enough. Uplift forces should also be considered to check the stability.
2. Impulsive breaking wave forces hit the seawalls. Tsunami wave front breaks due to shallow water in the shore and collides into seawalls. Also rapid current due to breaking causes dynamic wave pressures on the seawalls.
3. Drag forces due to strong current causes the scattering of armor stones and blocks. However comparing the very rapid currents induced by tsunami the damages to concrete blocks for detached breakwaters to dissipate the wave energy are limited.
4. Strong current caused scouring damages in navigation channels, around seawalls and breakwaters in addition to beaches and rivers. Scouring is the most typical failure of coastal structures by tsunamis.

It should be noted that the tsunami force can be evaluated by the accumulated knowledge of coastal engineering　using the current velocity and height of the incident tsunami by proper numerical simulations.

Table 2　Tsunami forces on coastal structures

Tsunami Force	Force due to the Pressure Difference between the front and back walls
	Impulsive Breaking Wave Force
	Drag Force due to Strong Current
	Scouring due to Strong Current

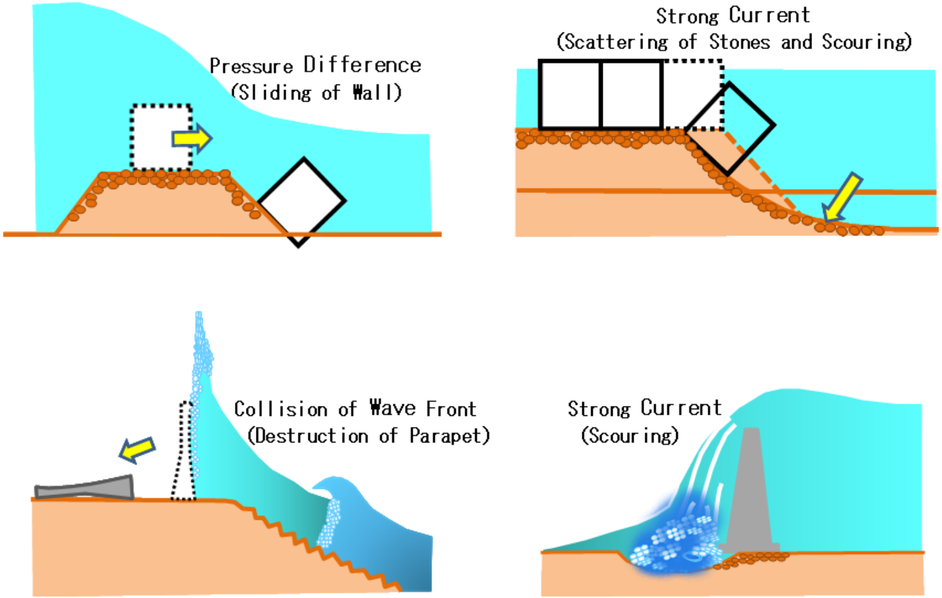

Figure 4 Typical Failures of Coastal Defenses

８．　Preparedness for the worst case (Level II-　Performance Design)

As you remember we had recently devastating disasters like Indian Ocean Tsunami and Hurricane Katrina. The most important lessen we learnt was to prepare for the worst case. The Port and Airport Research Institute considered that to prepare for the worst case we need to have performance design concept for the design of coastal defenses.

Table 2 shows the concept to prepare for the worst case tsunami using the performance design. For the ordinary design tsunami (Level-I) we have to save all the lives and to protect all the properties and economic activities. For the extraordinary tsunami (Level II) we have at least to save all the lives. In addition, we have to reduce the economic loss and to prevent the severe secondary disasters and to prepare for early recovery. In the figure the worst case is Level II and the present tsunami is the worst case tsunami. If necessary we have to consider a higher tsunami as the Level III.

In the design of tsunami defenses the function performance and stability performance should be determined according to the required performance for the Level I and II scenarios. For the Level II we need to use structural and non-structural countermeasures to save lives. To reduce the economic loss for the Level II it is important to have the structural countermeasures. If we construct a seawall to stop the Level II tsunami it might be a huge structure and economically not feasible. The height should be determined by considering the cost and the inundation reduction performance.

Table 3 Preparedness for the worst case (performance design)

	Design tsunami	Required performance
Level 1	Largest tsunami in modern times (return period: around 100 years)	• To protect human lives • To protect properties • To protect economic activities
Level 2	One of the largest tsunamis in history (return period: around 1000 years)	• To protect human lives • To reduce economic loss, especially by preventing the occurrence of severe secondary disasters and by enabling prompt recovery

It should be noted that the tsunami defenses should be stable against the Level II tsunami, at least tough and strong to deform not largely and maintain the functional performance. It should be repeated that the tsunami defenses should be tough and strong enough. The performance design concept was already employed in the design standard for port facilities and for coastal defenses in Japan. However, the level II tsunami should be considered in the next version of the standards. The stability performance should be investigated further.

It is said that the most effective way to save the people's lives is not to live in the inundation areas. It is important and useful countermeasure to move to high lands. However the economic activities near ports and coasts are very high and it is very important to protect the economic activities in the areas. High residential and business buildings are very useful countermeasures in addition to the high grand level of reclaimed land. Comprehensive measures should consider the lives of the people in the coastal areas

Acknowledgement

We would like to express our sincere gratitude to all the supports for the urgent survey. Especially we would like to thank the people of the Tohoku District Bureau of MLIT for their cooperations.

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