

# DESTRUCTION MECHANISM OF COASTAL STRUCTURES DUE TO THE 2011 TOHOKU TSUNAMI IN THE SOUTH OF FUKUSHIMA

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Destruction mechanisms of coastal structures due to the 2011 Tohoku Tsunami were investigated on the basis of intensive field surveys in the southern part of Fukushima Prefecture. Numerical tsunami simulation was utilized to estimate the tsunami force exerted to the structure. The large difference in water pressure due to overflowing tsunami is found to be the essential mechanism of overturning destruction of coastal structures. The destruction was enhanced by the generation of large impulsive force due to a turbulent bore and the local scour of the foundation. The seaside slope of the seawalls was found to be essential as more significant damage was observed for upright seawalls than gentle slope ones. Inland topography also exerted dominant influences on the destruction of seawalls due to receding tsunami. The joint between the parapet and the seawall basement was considered to be a weak point unless it was appropriately reinforced by steel bars.

*Keywords: tsunami; coastal structures; disaster mitigation*

## INTRODUCTION

Many coastal structures were destroyed by the massive Tohoku Tsunami generated on March 11, 2011. Although many studies were reported on catastrophic damages in the Sanriku area located in Iwate and Miyagi Prefectures, studies in Fukushima Prefecture were limited owing to the evacuation from high radiation caused by the Fukushima Dai-ichi Nuclear Power Plant accident. Sato *et al.* (2013) described their survey on coastal tsunami watermark heights in the 20 km radius evacuation zone. Their survey was the first scientific survey after the nuclear power plant accident. The highest watermark height was 21.1 m T.P. (T.P. stands for Tokyo Peil which is the standard datum for topography in Japan) found on a coastal cliff in Tomioka, 7 km south of the Fukushima Dai-ichi Power Plant. Sato *et al.* (2013) found that the distribution of coastal tsunami heights in Fukushima Prefecture was strongly affected by complex offshore bathymetry. Several follow-up surveys were conducted in Minami-Soma, north of the Fukushima Dai-ichi Power Plant (Sato *et al.*, 2014) and in Nakoso and Naraha, south of the power plant (Sato *et al.*, 2012; Sanuki *et al.*, 2013).

Understanding the destruction mechanism of coastal structures in the southern part of Fukushima is considered to be important in the future design of tenacious structure against tsunami overflow. The tsunami heights there were several meters higher than the top height of structures, thus providing a clear contrast between collapsed and survived structures. This study aims to describe the damage and analyze destruction mechanism of coastal structures on the basis of intensive field surveys combined with numerical tsunami computations.

## FIELD SURVEY

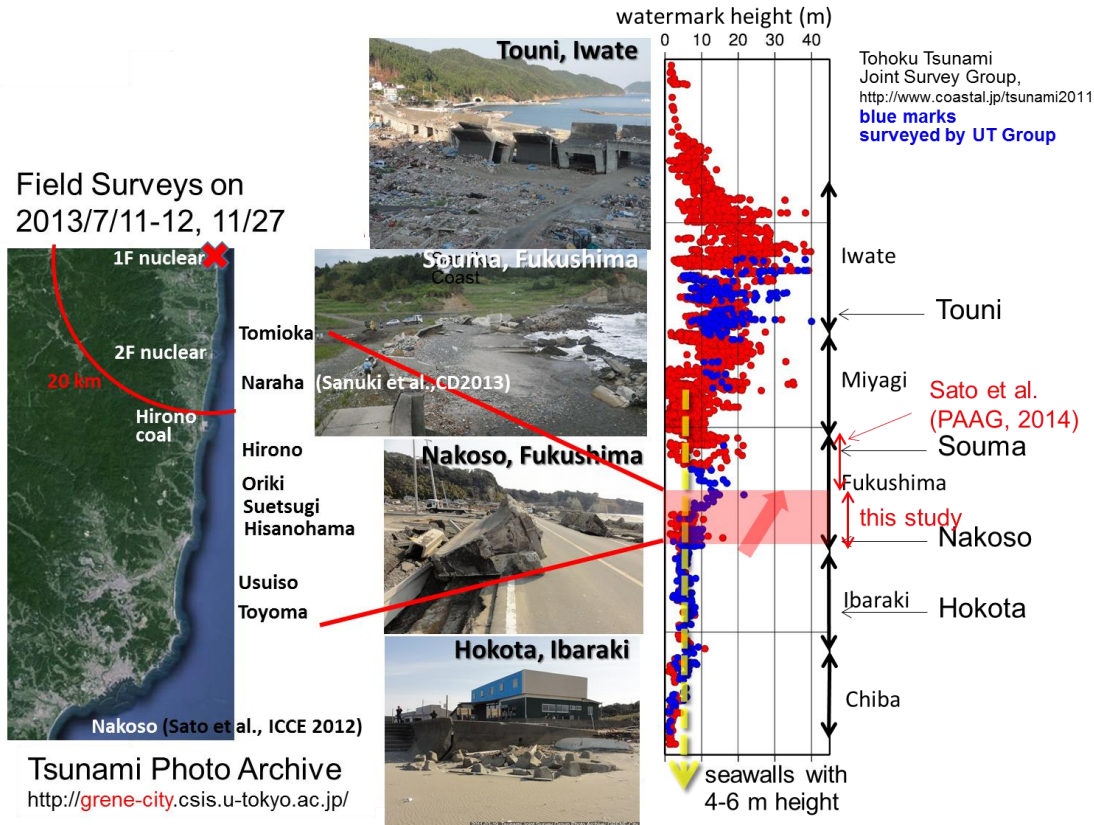
Field surveys were conducted on July 11-12 and November 27, 2013. Damage of coastal structures, such as seawalls, revetments and breakwaters was investigated in the southern part of Fukushima Prefecture, from Tomioka to Nakoso (**Figure 1**). According to the dataset provided by the Joint Tsunami Survey Group (2011), the watermark height is about 15 m in Tomioka and about 8 m in Nakoso, indicating that tsunami heights were basically larger in the north than in the south. The coast is protected by seawalls with height 5 to 6 m above sea level, except for coastal cliff with height 10 to 20 m. Tsunami overflowed the seawalls on many coasts and destroyed many seawalls and breakwaters.

Seawalls showed different performance depending on their relative height to tsunami. In Iwate Prefecture, many large seawalls were broken including those in Touni shown in **Figure 1**. Such complete destruction of seawalls was also observed in Miyagi Prefecture and in the north part of Fukushima Prefecture. **Figure 2** also displays broken seawalls in Soma, north part of Fukushima Prefecture, where 5 m tall seawalls were completely broken from the bottom. In these areas, it was difficult to conjecture the destruction mechanisms since even debris of seawalls were sometimes washed away. In the southern part of Fukushima Prefecture, on the other hand, although many seawalls were broken as observed in Nakoso in **Figure 2**, the contrast between broken and survived structures can be observed. Lessons learned from such observations will help us to design tenacious structures for tsunami overflow (*e.g.*, Sato *et al.*, 2012). Seawalls further south exhibited different performance in

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Ibaraki and Chiba Prefectures. The details are described in Shimozono *et al.* (2011). It is noted here that all photos taken in tsunami surveys including those in **Figure 2** are archived and freely available in Tsunami Joint Survey Group Photo Archive (2013).



**Figure 1.** Study sites with watermark height distribution compiled by the Tohoku Tsunami Joint Survey Group (2011). Tsunami survey photographs are freely available in the Tohoku Tsunami Joint Survey Group Photo Archive (2013).

#### NUMERICAL SIMULATION OF TSUNAMI PROPAGATION

The propagation of tsunami was simulated on the basis of the linear long wave equation in the large area including the whole source zone. Tsunami source proposed by Satake *et al.* (2012) was assumed. The computation was then connected with detailed tsunami computation areas based on the nonlinear shallow water equation in the nearshore areas with a fine grid size. The detailed computation areas were situated in two areas, one in Tomioka and the other in Oriki and Suetsugi. The cross-shore distance of the detailed computation area was 5 km while the alongshore distance was 9 km for Tomioka and 10 km for Oriki and Suetsugi. The grid size was 2 m for Tomioka and 5 m for Oriki and Suetsugi. The validity of the computation was verified with time histories of water surface elevation recorded by GPS buoys.

#### DAMAGE OF BREAKWATERS AND SEAWALLS IN TOMIOKA

**Figure 2** shows the damage of structures in Tomioka located 7 km south of the Fukushima Dai-ichi Power Plant and 3 km north of the Fukushima Dai-ni Power Plant. Damage of breakwater caissons and seawalls was observed at the Tomioka Harbor. Damage of seawalls was also found 1 km south of the harbor. In the Tomioka Harbor, several caissons of the breakwater were overturned to the harbor side and seawalls were broken at the entrance to the harbor where a gate was installed at the seawall gap as shown in **Figure 3**. The gate was completely destroyed by the tsunami. The entrance road to the harbor was connected to an underpass running through the shore-parallel road embankment.

**Figure 4** illustrates collapse of the breakwater caissons at Tomioka Fishery Harbor. The breakwater caissons, 5 m tall and 4 m wide, were considered to be overturned to the harbor side by water pressure

difference due to large tsunami. Assuming the axis of rotation is at the bottom corner of the harbor side, the critical tsunami height for the overturning was calculated as 7.1 m. The water pressure due to tsunami was assumed to be static on the sea side while the water pressure on the harbor side was assumed to be zero since the vertically downward acceleration was large for the flow on the harbor side. The maximum tsunami height computed in the numerical model was 10.4 m. It is therefore confirmed that the difference in water pressure due to overflowing tsunami was large enough to overturn the caissons.

The seawalls located behind the Tomioka Harbor were destroyed by the scour on the landside slope. **Figure 5** illustrates the concentration of tsunami flow near the seawall gap and the underpass. The concentration of tsunami flow is especially significant for receding tsunami. Strong current velocity due to receding tsunami is considered to be the reason for the scour of the landside slope of the seawall. Most of the seawalls located further south from the seawall gap were found intact. A road embankment in parallel to the seawall located 30 m landside appeared to be efficient in weakening the overflowed tsunami as a two-line embankment.

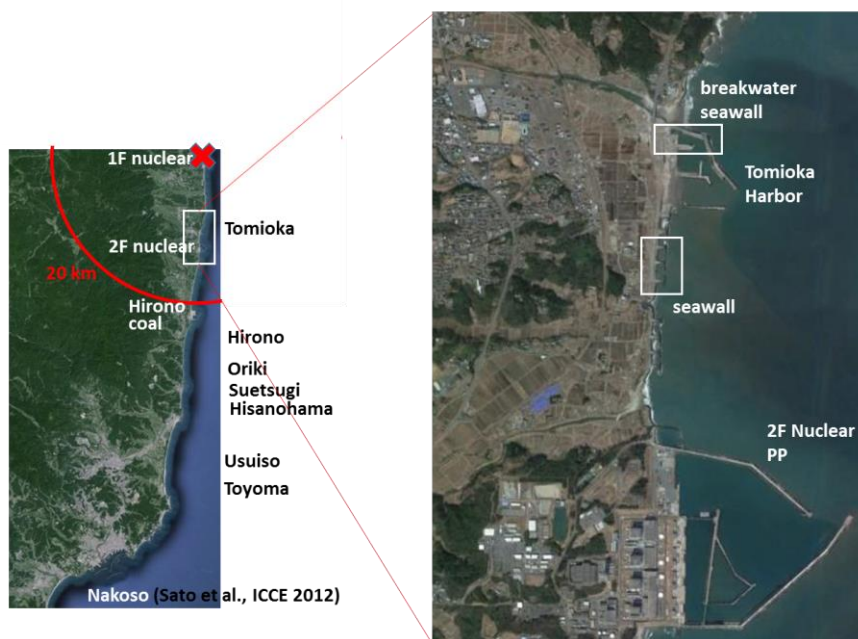


Figure 2. Damage of seawalls and breakwaters in Tomioka. The Tomioka Harbor is located 7 km south of the Fukushima Dai-ich NPP and 3 km north of the Fukushima Dai-ni NPP.



Figure 3. Damage of breakwater caissons in the Tomioka Harbor. Damage of seawalls was significant near the seawall gap connected with an underpass of a shore-parallel road embankment. The embankment appeared to be effective in reducing the tsunami force.

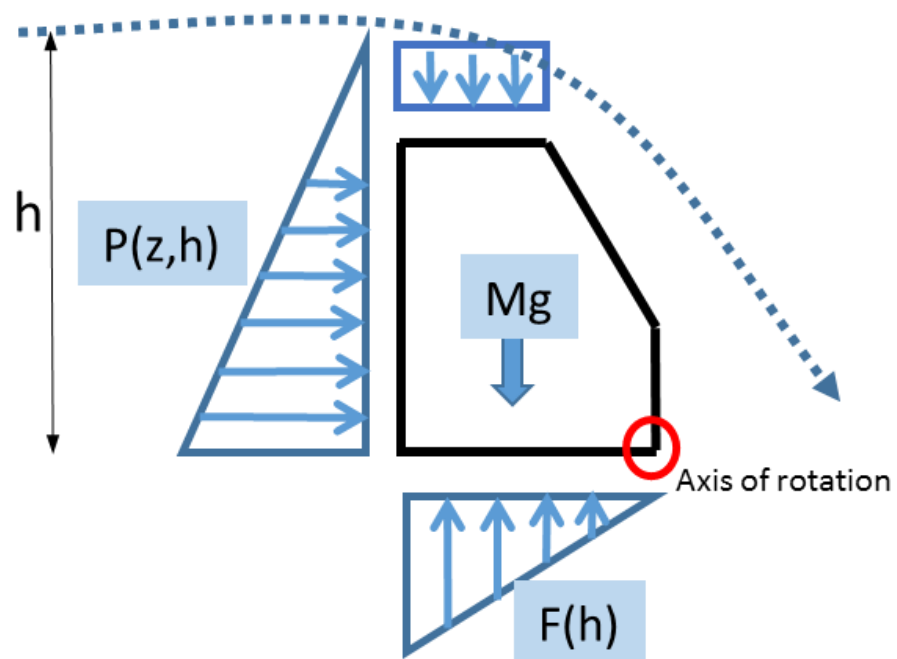
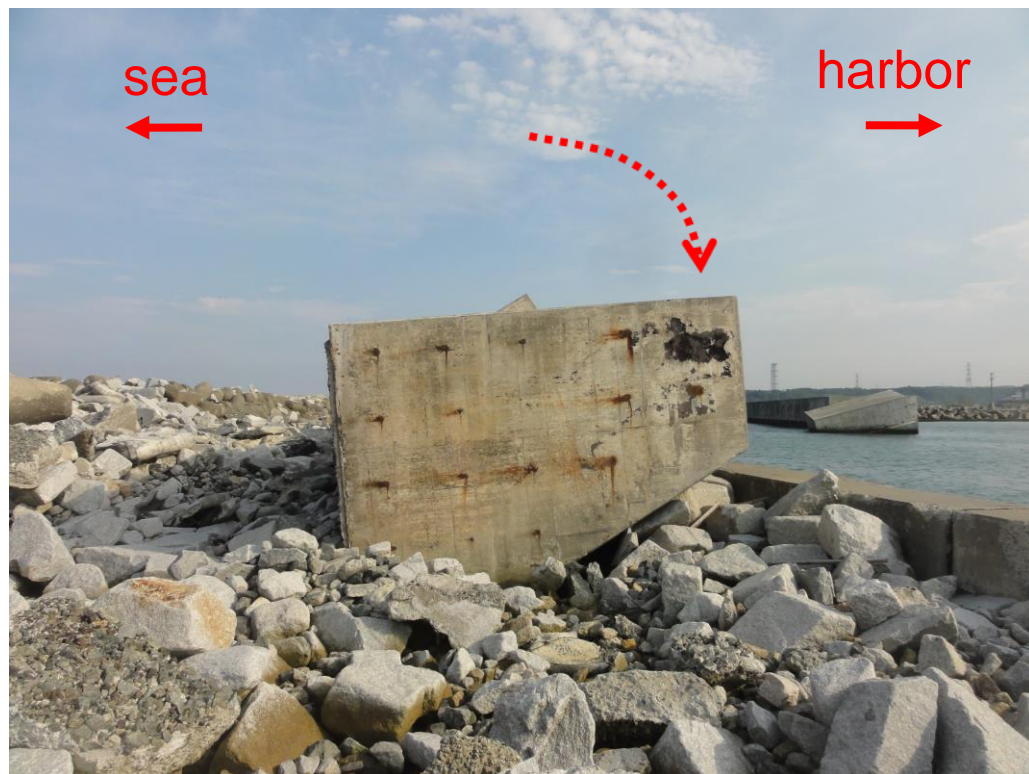


Figure 4. Collapse of a breakwater caisson in the Tomioka Harbor. Several 5 m tall caissons were overturned to the harbor side. The large static water pressure due to large tsunami appeared to rotate the caisson body.



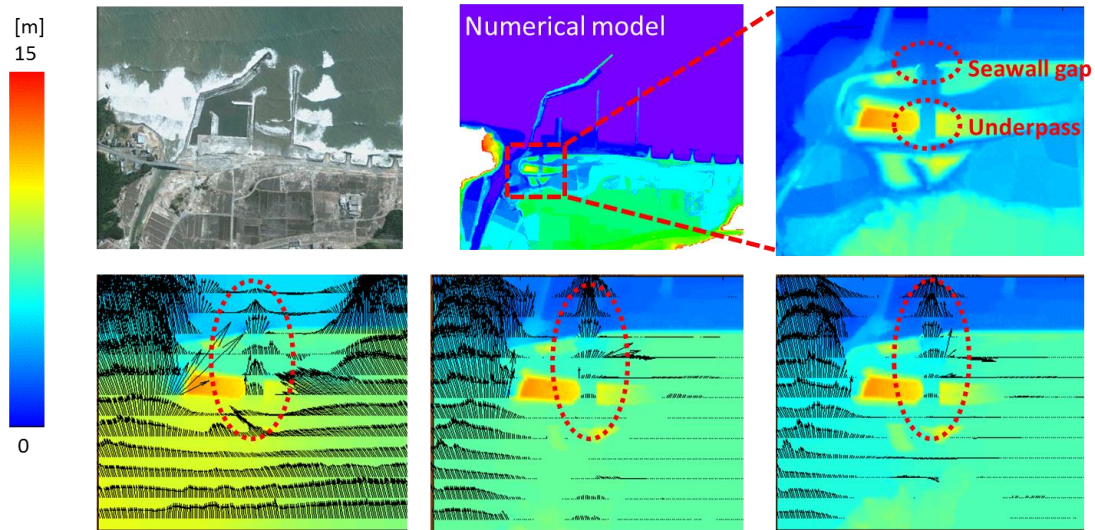


Figure 5. Concentration of tsunami to the seawall gap and the underpass simulated near the Tomioka Harbor. The figures on the bottom display the concentration of receding tsunami flow at the gap/underpass location.

The coast located 1 km south of the Tomioka Harbor was protected by a series of detached breakwaters and seawalls. Most of the detached breakwaters appeared to be intact while seawalls were partially destroyed by the tsunami. **Figure 6** illustrates the damage of seawalls. The damage appeared to be significant at the gap of detached breakwaters. The computed tsunami demonstrated the concentration of incoming tsunami to the gap location in a similar way to **Figure 5**. These examples showed that the gap of structures must be considered as a weak point for the tsunami.

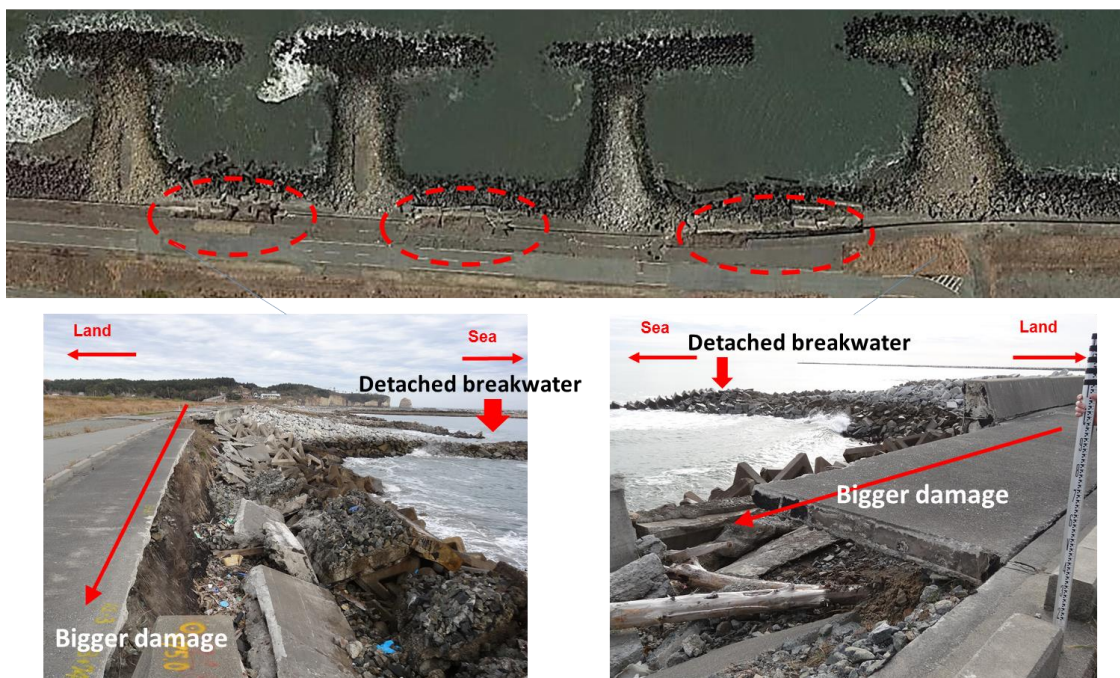
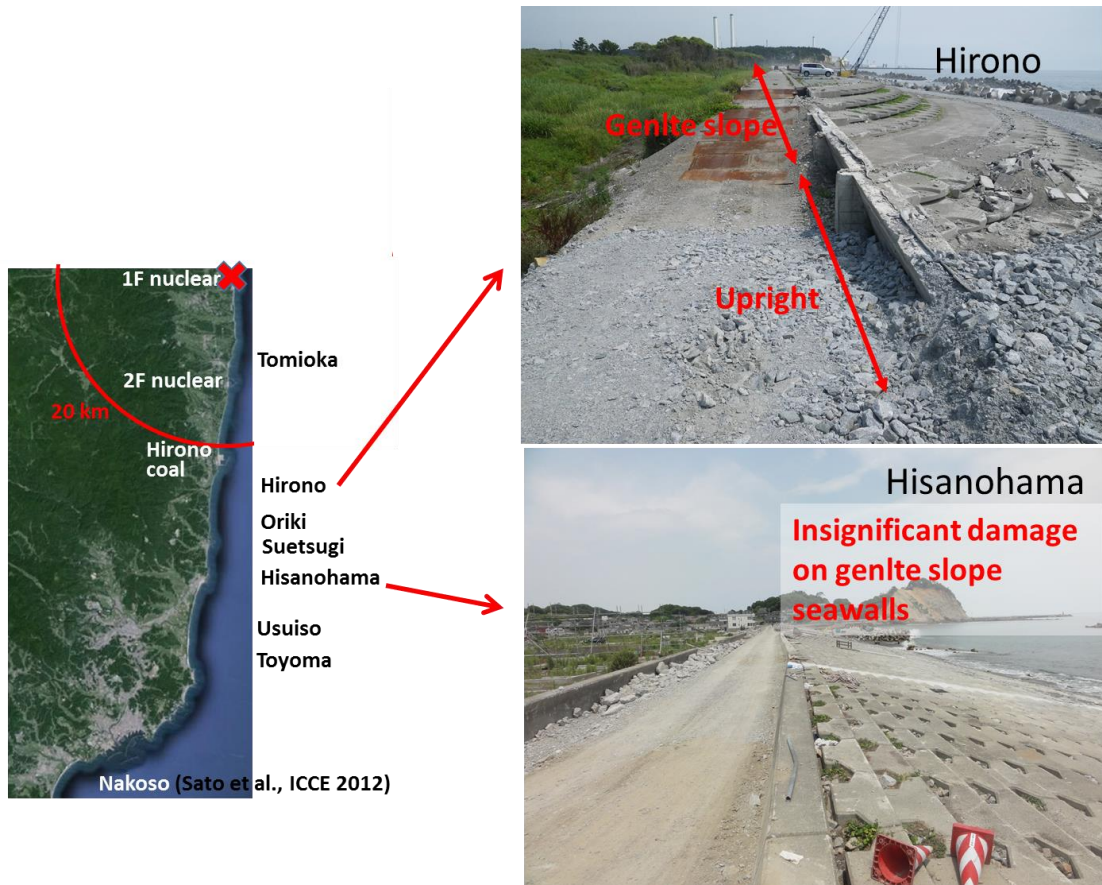


Figure 6. Damage of seawalls south of the Tomioka Harbor. The damage was significant at the gap of detached breakwaters.

### DAMAGE OF SEAWALLS IN HIRONO, ORIKI, SUETSUGI AND HISANOHAMA

The seaside slope of seawalls were found to be essential in the destruction mechanism. Seawalls in Hirono are composed of upright dikes in the north part and gentle slope seawalls in the south part. **Figure 7** shows the damage of seawalls in Hirono and Hisanohama. In Hirono, gentle slope seawalls were connected to upright seawalls. **Figure 7** demonstrates that the damage of the upright seawalls was serious while the damage of the gentle slope seawalls was very small. Gentle slope seawalls were also found mostly intact in Hisanohama. This is considered to be due to the larger wave force exerted to upright seawalls than to gentle slope seawalls. Although many upright seawalls were broken in this area, some of upright seawalls in Hirono and Naraha were found survived in case they were supported by inner partition walls. The partition walls were placed every 10 m section. Seawalls without partition walls were mostly collapsed after the scour of filled sand as explained in the Tomioka Harbor. Seawalls with inner partition walls are therefore considered to be one of tenacious structures for overflowing tsunami.



**Figure 7.** Damage of seawalls in Hirono and Hisanohama. The damage of seawall was smaller for gentle slope seawalls.





**Figure 8. Damage of seawall in Oriki. The parapets with 1.5 m height were broken and transported about 50 m inland. A large scour hole is observed behind the seawall.**

Collapsed seawalls in Oriki and Suetsugi, Iwaki City, displayed another contrast in terms of destruction mechanisms. The upright seawalls in Oriki were found to be collapsed at the joint between the parapet and the basement although they were connected with steel bars with 19 mm diameter (**Figure 8**). The height of the parapet was about 1.5 m. The broken parapet was transported inland with maximum distance of about 50 m. On the other hand, sloping seawalls in Suetsugi were found to be overturned to seaside (**Figure 9**). The destruction mechanisms of these two seawalls were investigated by using computed tsunami properties.

In Oriki, the seawall parapet was found to be destroyed when the tsunami was larger than 11.4 m. The maximum tsunami height at Oriki computed by the numerical model was 8.2 m. Therefore, the static water pressure alone was insufficient to cause the destruction. Asakura *et al.* (2000) demonstrated by hydraulic experiments that the maximum impulsive pressure due to broken bores was three times as large as the pressure due to unbroken bores with the same height. If the incoming tsunami formed a broken bore at Oriki, the wave force due to the broken bore with height of 8.2 m must have been large enough to destroy the structure. It is noted that the tsunami attacked in the form of a broken bore in Naraha, 3 km north of Hirono (Sanuki *et al.*, 2013). In Suetsugi, on the other hand, the maximum tsunami height was computed as 5.9 m and the sloping seawalls were found stable to the onshore force due to the incoming tsunami even in case the impulsive force of broken bores was applied. However, it could be turned over to seaside if the water level of the receding tsunami at the land side was higher than 5.9 m. It was considered that the receding tsunami flow concentrated to the damaged section of seawalls since they were found near the mouth of a small stream.

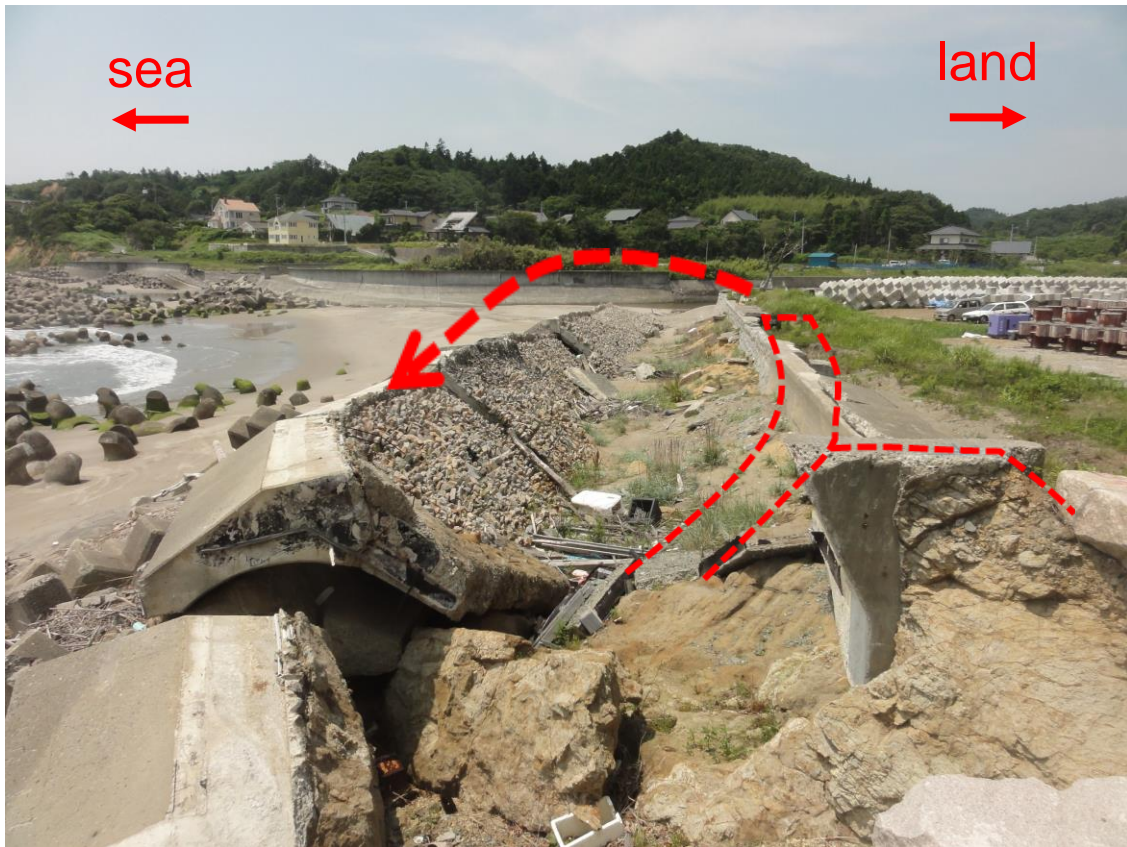


Figure 9. Damage of seawall in Suetsugi. The concrete plate on the seaside slope with parapet was overturned to the sea side. The original location of the concrete plate is illustrated by the red dashed line.

#### DAMAGE OF PARAPETS IN AREAS FURTHER SOUTH

In the southern part of the study sites, Usuiso, Toyoma and Nakoso, damage of seawalls was concentrated to the parapet. **Figure 10** shows broken parapets in Usuiso and **Figure 11** shows those in Toyoma. Although the seawalls in Toyoma were broken in the middle of the parapet as shown in **Figure 11**, most of the seawalls were broken at the joint between the parapet and the basement. The location of the failure appeared to be dependent on the ground level on the land side. The collapse of seawalls at the joint is also reported in Nakoso by Sato *et al.* (2012). The enforcement of the joint is considered to be another key point in strengthening the structure.





Figure 10. Damage of seawall parapet in Usuiso. The height of the parapet is about 2 m. The seawall was broken at the joint between the parapet and the basement. Black sand bags were placed as temporal recovery.



Figure 11. Damage of seawall parapet in Toyoma. The seawall was broken in the middle of the parapet. Broken parapets were transported inland. Black sand bags were placed for temporal recovery.

## CONCLUSIONS

Intensive field surveys were conducted in the southern part of Fukushima Prefecture where various destruction mechanisms of coastal structures were observed. Numerical tsunami computation was utilized to estimate the fluid force due to tsunami. Main conclusions are summarized as follows:

- (1) The large difference in water pressure due to overflowing tsunami is considered to be the essential mechanism of overturning destruction of coastal structures. The scour of the seawall foundation was also greatly influenced by the behavior of flooded tsunami on the land side of the structure.
- (2) The seaside slope of the seawalls was found to be essential in the destruction mechanism of seawalls. The generation of a turbulent bore must have increased the impact wave force.
- (3) The joint between the parapet and the basement of the seawall was considered to be a weak point unless it was appropriately reinforced by steel bars.

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