The Great Eastern Japan Earthquake and Tsunami
Field observations on the coast of Tohoku six months later

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1. Introduction

The tsunami that hit the north pacific coast of Japan on March 11, 2011 has been characterized as a mega disaster. It inundated over 560 square kilometers of land, devastating a large number of coastal communities, causing over 20,000 casualties and huge economic damage in Tohoku region. As many catastrophic tsunamis have been recorded in the history of Tohoku and seismologists remarked the high probability of a major earthquake that could generate a big tsunami in Japan long time ago, the region was considered highly prepared against tsunami. However the event of March 11, exceeded most previous expectations. Following the disaster, a large group consisting of academics, engineers and governmental officials was assembled in order to survey the disaster by collecting data on tsunami inundation and run-up heights. In the meantime a massive effort to clean-up the devastated coastal zone and record fatalities and material damage has been taking place. An overview of the results of the tsunami surveys is presented in the following figure.

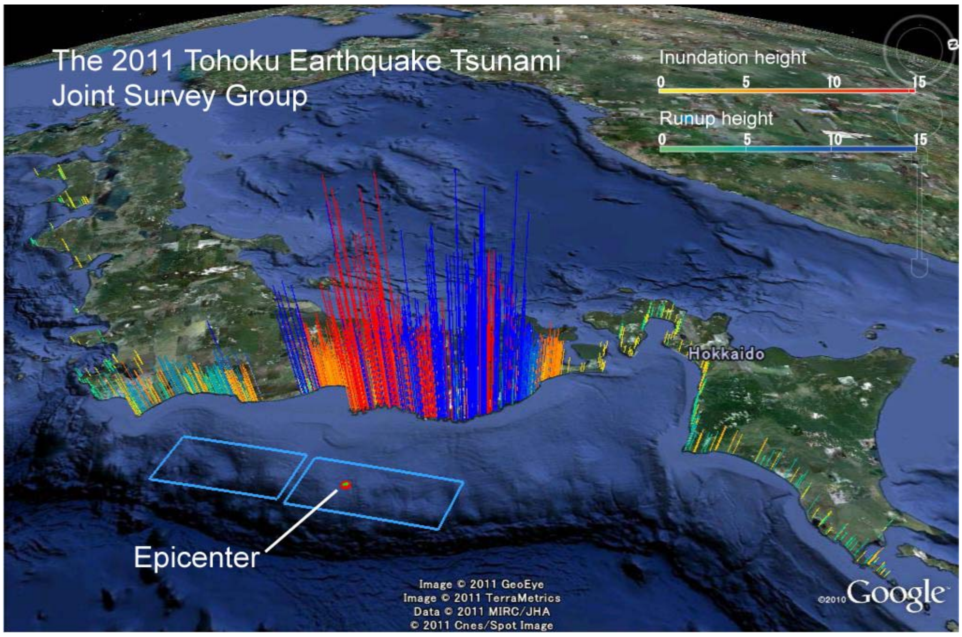

Figure 1: Overview of the tsunami survey results (The 2011 Tohoku Earthquake Tsunami Joint Survey Group; www.coastal.jp/tsunami2011)

Disaster Prevention Research Institute of Kyoto University have surveyed Tohoku area several times since April 2011. In September 2011 a small group of the same institute, including the author, visited the tsunami devastated coastal areas of Tohoku, for a new assessment of the disaster and survey of the recovering process six months after the tsunami, and following that some preliminary conclusions regarding the event had been drawn. The visited areas are presented in this report. The purpose of this report is to give insight into the magnitude of the disaster and the response of the Japanese tsunami countermeasures to it, based on which a number of questions can be formulated regarding in which direction research should go. In the beginning some background information is given regarding the affected coastline, which is useful in order for the local disaster patterns to be understood. The core content is a description of the visited areas, the local tsunami behaviour, and the damage that took place. The report ends up with some suggestions for future research.

2. Classification of affected areas

In order to analyse the occurred damage and comprehend the disaster patterns, the stricken areas can be roughly classified in three types based on their coastal morphology, which affects the local tsunami characteristics. The considered coastal types in Tohoku region are as follows: 1) Sanriku ria coasts, 2) Sendai flat plains, and 3) ports. Below a description of the three categories is presented.

2.1 Sanriku ria coasts

The northern part of the affected area, mainly along the coast of Iwate prefecture and the northern half of Miyagi prefecture, consists of rias, which are coastal inlets formed by the submergence of former river valleys, that can extend at a distance inland. Ria coasts can be extremely irregular and indented in places, forming narrow and steep bays. At this type of coast, due to resonant and refraction effects, the tsunami height usually increases. Moreover the intrusion of the water far inland is obstructed in the narrow areas, which, combined with the increased tsunami height, resulted in large inundation and run-up heights (figure X, left). Those narrow areas are bordered by high grounds facing the ocean with steep cliffs, and relatively deep sea in the front (figure X, right). At this piece of the coastline the tsunami did not break, but only elevated the water surface smoothly. A typical area where all mentioned characteristics could be observed is the coast of Sanriku region. As the coast of Sanriku has suffered several times in history tsunami devastation, a lot of tsunami protection structures can be found in the area, such as tsunami breakwaters and walls, even in small boat harbors.

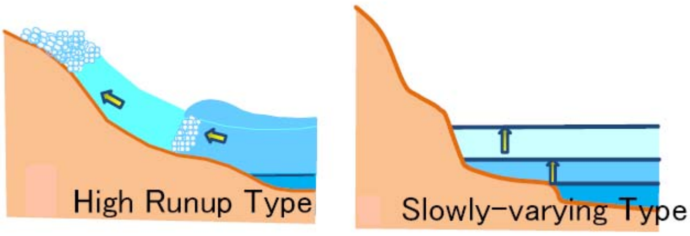

Figure 2: Typical cross sections of tsunami intrusion at ria coasts (PARI, 2011)

2.2 Sendai flat plains

The southern part of the affected area, starting from the coast of Sendai city in Miyagi prefecture, extending to Fukushima and further to the south, is characterized by large low-lying areas fronted by mild-sloped sandy beaches. Land-based coastal defences protect the inland area mainly against high storm waves. Around Sendai airport, which is a typical case of this type of coast, the tsunami broke near the shore, run-up the 5-10m high dunes, and propagated inland, inundating several square kilometers of flat land. The tsunami intrusion at this type of coast is shown in the following graph. Because of the sea dykes and dunes, fewer breakwaters can be found on the coast of flat plain areas.

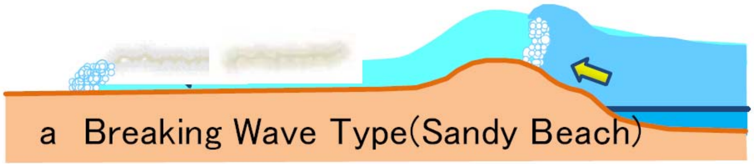

Figure 3: Typical cross section of tsunami intrusion at sandy beach flat land areas (PARI, 2011)

2.3 Ports

Ports constitute a special case of coastal areas, and their characteristics do not differ much along the entire affected coast. The water in front of ports is deep; hence in most cases the tsunami did not break, but reached the port facilities and intruded the land behind as a rapid bore, causing significant damage (figure 4). At Kamaishi port a current velocity of 10-30 km per hour was reported.

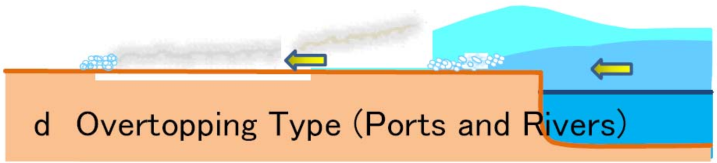

Figure 4: Typical cross section of tsunami intrusion at ports (PARI, 2011)

3. Field trip itinerary

The field trip was a three-day drive, starting on September 20, 2011. The team drove 300km from North to South along the most severely affected part of the coastal zone of Tohoku, which is the coastline of the South of Iwate and the entire Miyagi prefecture, and also along a small part of the northern coast of Fukushima prefecture. Further to the South access was prohibited because of the exclusion zone of excessive radiation after the nuclear accident at Fukushima Daiichi nuclear power station, caused by the tsunami of March 2011. Both urban and rural areas were visited, as well as the commercial port of Soma in Fukushima prefecture. Unfortunately the weather conditions did not allow the detailed observation of all visited areas, as the trip overlapped with the pass of Typhoon Roke over Tohoku, on the 21st of September.

The visited sites are presented below per prefecture, and from North to South.

A. Ryori
B. Ofunato
C. Rikuzentakata
D. Kesennuma
E. Minamisanriku
F. Onagawa
G. Arahama Wakabayashi-Ward
H. Watari
I. Yamamoto
J. Soma.

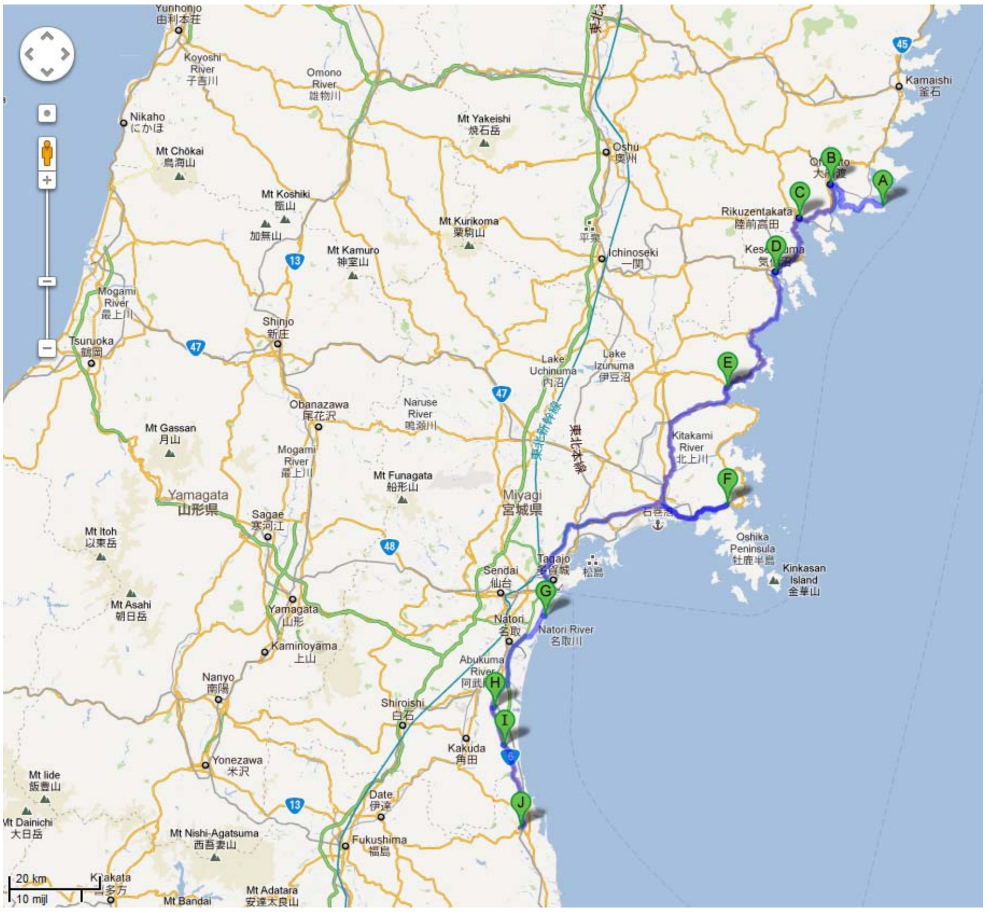

Figure 5: Field trip itinerary (Google maps; maps.google.com)

4. Field observations

The visited sites are presented below per prefecture, and in a sequence from North to South.

4.1 Iwate prefecture

Ofunato

Figure 6: Ofunato before and after the tsunami (Kokusai Kogyo Group; www.kk-grp.jp)

Ofunato is a city located in the narrow bay of a ria in Sanriku region. The city has a low lying part, which was inundated, and a part lying on higher grounds, which was not affected. The maximum reported inundation height is 8.3m. Most of the concrete buildings remained in place, but were seriously damaged. Windows and doors were missing from ground till the second or third floor, which is an evidence of the tsunami depth. Wooden houses were completely destroyed. Port infrastructure seemed to have remained in place, although a uniform subsidence of more than 0.5m was evident to the entire port area. Most of the debris had been cleaned and accumulated in certain spots. The volumes of trash were impressively large, forming hills of several meters height.

Figure 7: Left: Accumulations of debris in Ofunato port; Right: Damage of steel frame building. The height of the damage is indicative of the inundation height.

The bay of Ofunato used to be protected by an offshore tsunami breakwater, which after the tsunami of March 11, was completely disappeared. This breakwater was designed to withstand the attack of the Chilean tsunami that caused severe damage in the area in 1960, but still much smaller than the one of March 2011. It is still not clear what was the mechanism that caused this catastrophic structural failure.

Figure 8: Ofunato bay on March 12, 2011. The position of the completely destroyed tsunami breakwater is designated on the upper right corner (Kokusai Kogyo Group; www.kk-grp.jp)

It should be noted that the damage in Ofunato bay was less than other cities on the ria coasts, such as Rikuzentakata, which is located just 10km to the south-west of Ofunato. The only difference is that Rikuzentakata is not protected by a tsunami breakwater, which could mean that the structure, although totally destroyed, contributed in the mitigation of damage in the bay. Some research on this topic could give interesting outcomes.

Ryori tsunami wall

Ryori is a town 8km to the east of Ofunato in a smaller bay, protected by a caisson breakwater. On the east of the town there is another small bay with a sandy beach and a harbor. There is a tsunami wall on that beach that was overtopped, and seriously damaged, with a big breakage on its north end.

Figure 9: Left: Ryori bay after the tsunami. The severely damaged caisson breakwater and the sandy beach with the tsunami wall are designated; Right: Zoom in the tsunami wall bay. The large breakage on its north end, and the severe damage of the caisson breakwater are noted (Google Earth images, 2011)

The tsunami gates that were originally attached on the wall were displaced. It is notable that the gates were displaced towards the seaside, which shows that the cause of their failure was the run-down of the tsunami. At this area the maximum reported run-up height was more than 24m, in a distance of about 500m from the waterfront. As the land slope is quite steep in that area, a forceful run-down must have been induced. On the backside of the wall there were large accumulations of debris and stones, which can also be evidence of a forceful run-down. There were works taking place for the temporary strengthening of the structure with placement of sandbags. The caisson breakwater of the small harbor was seriously damaged as well.


Figure 10: Left: Large breakage of tsunami wall in Ryori; Right: Temporary protection measures against storm surges.


Figure 11: Left: Detached tsunami gate; Right: Severely damaged caisson breakwater. The armour unit was part of its outer side protection.

<u>*Rikuzentakata*</u>

Figure 12: Satellite image of Rikuzentakata before the tsunami (Kokusai Kogyo Group; www.kk-grp.jp)

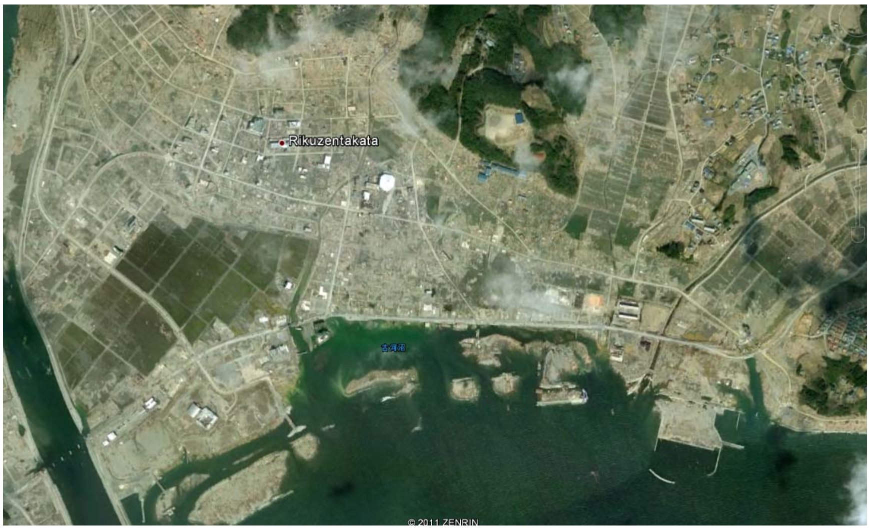

Figure 13: Satellite image of Rikuzentakata after the tsunami (Google Earth image, 2011)

Rikuzentakata is one of the most heavily damaged cities by the tsunami of March 11. It is located in a wide ria bay with a long natural sandy beach. On the top of the bay, in a zone of about 1.5km, the land slope is relatively mild. At this area, only concrete buildings of 3 floors or higher remained in place. In many of them, doors and windows of up to the fourth floor were missing, which shows that the water reached that height, and overtopped many of the buildings. The rest that was mainly wooden buildings, were washed away. As most of the debris has been cleaned and accumulated at certain spots, looking from above, the footprints of the foundations extending in several square kilometers could be seen, revealing the magnitude of the disaster.

Figure 14: Rikuzentakata as seen from higher grounds (Panoramio; www.panoramio.com)

Figure 15: Left: Concrete building that survived. It might have also been evacuation building. Right: Damage on steel frame building.

Figure 16: Left: Empty space that used to be a railway reaching a station. Both rails and station were devastated. Right: concrete building that was overtopped.

On the waterfront, there used to be a coastal forest of more than 70,000 pine trees, which was devastated. There is only one tree left standing in that area. The removal of trees can be used as an indicator of the tsunami drag forces. All over that place there was evidence of subsidence, which exceeded 1m near the waterfront. As the waterfront was so seriously damaged, the risk of further coastal erosion due to a storm or a typhoon is increased. Hence some urgent measures have been taken to prevent further erosion of the shoreline, with use of sandbags or rock armoring. The inundation depth near the shoreline reached the 15m. On the west side of the city there is a river reaching the coast, along which the tsunami run up several kilometers. Some of the river viaducts survived the tsunami, while others were seriously damaged with their slabs removed.

Figure 17: Left: Area of the former coastal forest of Rikuzentakata. On the right the only tree left can be seen. Right: The lone standing tree a few months earlier. On the background the corrosion of the first lines of woods is indicative of the inundation line, demarcated by the red line.

4.2 Miyagi prefecture

Kesennuma

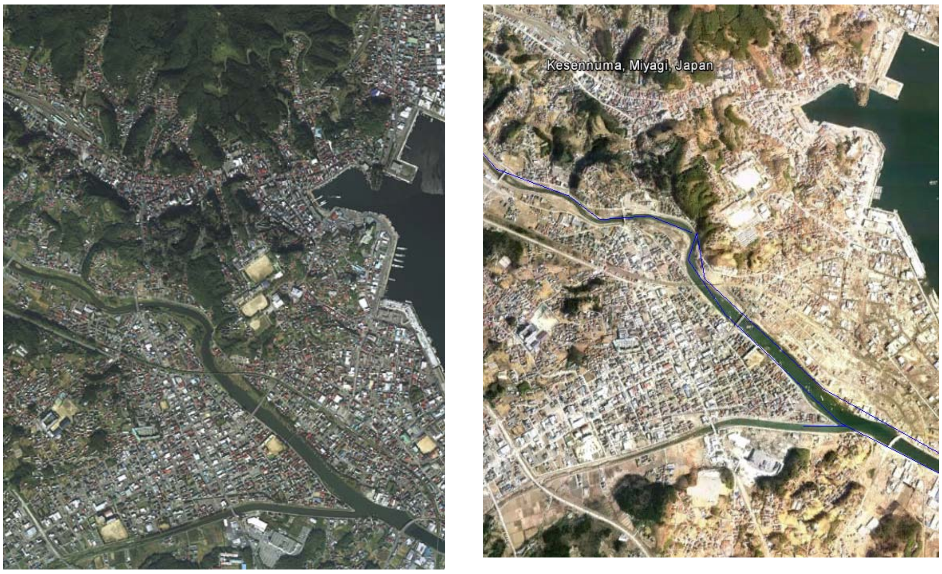

Figure 18: Kesennuma before and after the tsunami (Kokusai Kogyo Group; www.kk-grp.jp)

Kesennuma lays 12 kilometers to the south of Rikuzentakata, and was likewise severely damaged, with inundation reaching 15m in many spots on the waterfront. Apart from the tsunami, Kesennuma suffered some fire damages as well. Heavy oil was spilled and burnt during the tsunami attack. Important subsidence could be observed at the harbor infrastructure, which moved the waterline inland, towards the first roads. Some parts of the quay walls were completely inundated. Some temporary shore protection with sandbags was built to prevent expansion of the erosion further inland. Most of the rubble was already cleaned up, yet much work is still needed.

Figure 19: Damages in Kesennuma photographed one month after the tsunami (DPRI, 2011)

Figure 20: The waterfront of Kesennuma before and after the tsunami

Figure 21: Left: Temporary land protection, Right: Destructed warehouse on former quay wall

Figure 22: Left: Subsided land, Right: Retaining works at severely subsided land near Kesennuma

Minami-Sanriku

Minami-Sanriku is located in a quite narrow, fjord-like river valley. The town was almost entirely devastated. Like in Rikuzetakata, a tsunami run-up far inland along the river took place.

Figure 23: Minamisanriku after the tsunami (Left: Google Earth image)

Figure 24: View of Minamisanriku from evacuation point on higher grounds. Left: Indication of inundation line demarcated on the woods.

At this area the inundation line was clearly visible on the slopes of the mountains, where the inundated part of their forest was corroded, hence brown-colored, contrasting the green of the higher grounds. The inundation heights near the frontage exceeded 15m, while the maximum run-up exceeded the 35m. Only a few high concrete buildings remained standing in the town, while the rest was washed away. Serious subsidence and erosion can be seen near the waterfront, as well as damage of coastal roads. The transportation in that area was not fully recovered. The storm surge gates at the mouth of the river were also severely damaged, as well as parts of the river dikes. Some temporary protection measures have been attempted in the form of sandbags. On the northwest side of the town some temporary houses can be found on the mountain, were the local population is sheltered.


Figure 25: Left: Temporary houses for local population. Right: Staircase that served as evacuation route during the disaster


Figure 26: Left: Subsided land near the shoreline; Right: Evacuation building on the waterfront that was just overtopped, people sheltered on the top of it survived (The 2011 Tohoku Earthquake Tsunami Joint Survey Group; www.coastal.jp/tsunami2011)


Figure 27: Left: Severely damaged storm-surge gates (The 2011 Tohoku Earthquake Tsunami Joint Survey Group; www.coastal.jp/tsunami2011) Right: Temporary retaining measures on the riverbanks and lone standing bridge abutments. The slab was washed away.

Onagawa

Onagawa is located further to the south of Miyagi prefecture, yet still in the ria coast, almost south end of it. This town had a lot of attention from the media due to extensive damages. The bay of Onagawa was protected only against storm waves by a caisson breakwater, and not against tsunami. This breakwater was completely destroyed.

Figure 28: Onagawa after the tsunami(Google Earth image, 2011). Left: satellite picture where the position of the totally destroyed breakwater is indicated (Kokusai Kogyo Group; www.kk-grp.jp)

Figure 29: View of Onagawa from evacuation point in higher grounds

In the low-lying part of the city all wooden buildings were devastated, while it was interesting to see that many concrete buildings were overturned. It is believed that the cause of this special type of failure was the fact that those buildings had pile foundations that due to the earthquake were detached from the bottom of the building, and as a consequence the uplifting tsunami forces overturned the entire building. Liquefaction might have also played a role to this failure. Furthermore, some significant subsidence at the waterfront was evident, like in most areas in the rias. The inundation height near the shore was around 15m.

Figure 30: Devastated waterfront of Onagawa. Note the overturned building on the right picture.

Figure 31: Overturned buildings (Left: The 2011 Tohoku Earthquake Tsunami Joint Survey Group; www.coastal.jp/tsunami2011)

Arahama Wakabayashi-Ward of Sendai city

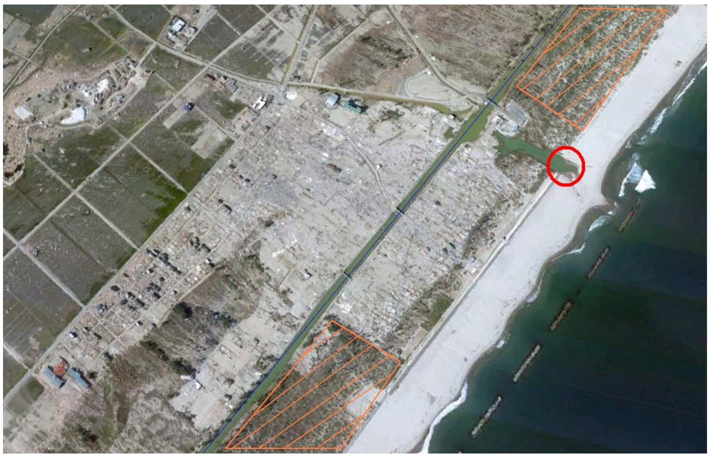

Figure 32: Arahama after the tsunami. The breakage on the sea levee is remarked with red, and the devastated forest zone is remarked with orange (Google earth image, 2011)

Arahama is a settlement at the waterfront of Sendai city. The landscape is totally different than a few kilometers to the north. From that spot and towards the south the flat plain coastal zone lies. The coastline of Arahama is straight with a long sandy beach. The inner land is protected against storm surges by a levee.

Figure 33: Sandy beach and sea dike at Arahama Wakabayashi-Ward

The levee was overtopped by the tsunami of March 11 and propagated to the flat land, inundating many square kilometers of rice paddies, and devastating a coastal pine tree forest and the settlement. A big breakage of the levee can be found on the northeast of the settlement. The inundation depths in Arahama were relatively lower than the ones recorded in the coastal cities in the rias. The watermarks and damage on concrete buildings that survived the tsunami were up to the second floor. It is notable that some concrete buildings behind the dike that were founded on sandy subsoil did remain in place, yet with significant scouring on their toe, which exceeded 2.5m. Scouring due to overtopping tsunami waves is considered to be the main cause of failure of the sea levees in that area.

Figure 34: Left: Devastated buildings behind the dike, Right: Scouring on the toe of concrete building (The 2011 Tohoku Earthquake Tsunami Joint Survey Group; www.coastal.jp/tsunami2011)

Based on the survey records, the maximum inundation height exceeded 19m. However there is an important scatter in the measurements of this region. It is possible that different teams that provided non-uniform information surveyed the area. A few kilometers to the south of Arahama, the airport of Sendai is located, which suffered serious damage. Apart from the damage caused directly by the tsunami, this area suffers also the effects of the intrusion of salt water far inland, which is expected to affect agriculture in the coming years.

<u>*Yamamoto elementary school*</u>

Yamamoto is a coastal town at the southern boarder of Miyagi prefecture, which was likewise heavily damaged by the tsunami. The team visited a still standing elementary school outside the town, and about 500 meters from the waterfront, consisting of two concrete buildings, the school and a gymnasium that was partly sheltered by the school. The school building is sufficiently aligned to minimize tsunami forces, although it is unknown if this was a design requirement or a random choice. This school was featured in the media for the successful vertical evacuation of all students on March 11, 2011. In the end the building was completely inundated. The recorded inundation heights in that spot were about 10m. From the first floor of the building the sea levee at the waterfront can be seen, on which also some breakages are visible, and large armor units scattered on its inland side.

Figure 35: Left: Gymnasium building, Right: Schoolyard used for storage of destroyed cars

Figure 36: Inside the school

Figure 37: View of waterfront from the first floor

Watari coastal levee

A few more parts of the coastal levees of Sendai plain were visited at the frontage of Watari, which is a town of 35,000 citizens. A lot of sections of the dike were destructed in that area, mainly due to significant erosion in the inner slope and toe. The core of this structure consisted of sand and gravel and was protected by non-reinforced concrete on the seaside slope, and armor units at places. According to local researchers, this part of the levee had no geotextile protection between the core and the encasing concrete layer, which might be the reason of their failure, as similar sections in the same area with a geotextile survived.

Figure 38: Retaining works as viewed from access point

Figure 39: Inundated land on the inner side of the levee

Figure 40: Left: Breakage of coastal levee, where the original cross section is displaced several meters inland and its core is exposed due to the lack of a geotextile; Right: Armor units of the original cross-section.

As the levee is meant to protect the inner land against high storm surges, which are quite common in the area, many temporary reconstruction works were taking place six months after the tsunami, with a lifetime of 5 to 6 years. The day of the visit was right after typhoon Roke hit the same coast on the 21st of September, inducing high storm surges that overloaded the already damaged levee and caused some important additional damage on the structure, while a part of the already devastated land was again flooded. This shows the necessity of temporary interventions in order to keep the inner land dry. Nevertheless it is unknown if those interventions are based on the results of an economic optimization.

Figure 41: Left: Plan for temporary retaining works, indicated with orange. The original cross section is indicated with grey; Right: Sandbags placed urgently the day of the visit (September 22, 2011), as the cross section was further destructed by typhoon Roke.

Figure 42: Left: Crest of the levee; Right: Sandy beach on the frontage

4.3 Fukushima prefecture

<u>Port of Soma</u>

The port of Soma is an important commercial port on the coast of Fukushima, 32km to the south of Sendai airport. As it is located on the straight coastline and not sheltered by natural barriers, it is protected against storm waves by a 2.6km long offshore caisson breakwater. The water depth on the outer side of the breakwater is 25m. The port infrastructure was severely damaged by the tsunami of March 11.

Figure 43: Port of Soma after the tsunami. The most severely damaged parts are indicated (Google Earth image, 2011)

Only 3 out of the 546 caissons of the breakwater remained in place, the ones at the toe of the structure that were well protected by armor units. The rest were displaced, and some totally inundated.

Figure 44: Damage of the caisson breakwater

Some significant subsidence of the quay walls that exceeded 1m in places was evident, and severe scouring at their foundation took place. It was notable that some concrete elements of the quay wall, with approximate dimensions 6x10x3 cubic meters were overturned and left standing with their foundation upwards, which shows the enormous uplifting forces caused by the tsunami and intensified by the scouring. Furthermore some severe damage of warehouses and cranes could be observed. Inundation heights of up to 10m were recorded in the port of Soma.

Figure 45: Damage of quay wall and fallen apart post-tsunami retaining measures

Figure 46: Subsidence of quay wall and under-flown liquefied sand

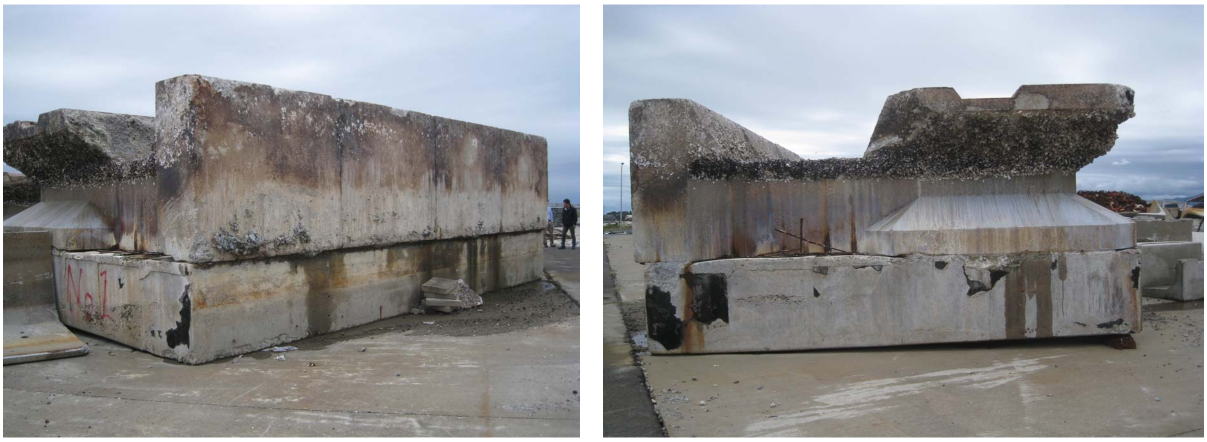

Figure 47: Overturned quay wall elements

Figure 48: Left: Ship wreck within the port; Right: Breakage of wharf

Figure 49: Left: Damage of cranes; Right: Destructed warehouse

Soma

Figure 50: Soma estuary before and after the tsunami (German Aerospace Centre; www.dlr.de)

On the South of Soma port the city of Soma can be found, with a population of 38,000 inhabitants. The biggest part of the city is located on higher grounds, therefore not seriously affected by the tsunami. However an estuary with flat agricultural land fronts it, which was subsided and inundated by the tsunami. The bad weather conditions during the visit, with high water levels that intruded the subsided land, did not allow access in many parts of that site. This was in fact the case in more areas, which shows how vulnerable this land is after the tsunami.

Figure 51: Inundated agricultural land on the frontage of Soma

Figure 52: Left: Water intrusion during storm, Right: Ship wreck within Soma estuary

5. Concluding remarks

Based on the field trip observations of September 2011, and on information provided by relevant scripts of Japanese universities and research institutes, a number of conclusions have been drawn regarding the disaster and the response of the Japanese countermeasures. Those conclusions are presented below with respect to various sub-issues.

5.1 Coastal tsunami characteristics

1. The coastal tsunami behavior varied, based on the local morphology of the coast. Two morphological patterns have been identified, the ria coasts of Sanriku region, and the flat plains of Sendai region. The ports can also be considered as a special case of coast.
2. Large inundation heights and long run-up distances along the river basins characterize the tsunami attack in the rias.
3. Large inundation areas with smaller inundation heights characterize the local tsunami attack in the flat plains of Sendai region.

4. In most ports the tsunami did not break before reaching the port facilities. As breaking took place within the ports, the tsunami intruded as a forceful bore.

5.2 Primary coastal defences

1. The primary defences in the ria coasts consisted mainly of offshore breakwaters and tsunami walls, whose design specifications were exceeded by the tsunami of March 2011. Most of them were completely destroyed or severely damaged.
2. The existence of primary defences in the rias might have played a role in the mitigation of the coastal damage, as lower inundation heights than expected were measured in places. Some further research on the topic might give interesting results.
3. The primary defences of the Sendai flat plains consisted mainly of sea levees along the sandy frontage. Those defences were overtopped by the tsunami, and large shear breakages are encountered in places. It is believed that this failure is correlated to the lack of geotextile that could protect the erosion of the core of the structure.
4. Some further research on the failure mechanisms of coastal defences both in the rias and the flat areas is necessary.

5.3 Buildings and infrastructure

1. Damage of buildings and infrastructure seemed to be more serious in the rias than in the flat plains, which was expected considering the much higher inundation heights in the rias.
2. Wooden buildings were completely washed away in the rias, while in the flat plains some of them remained in place, though severely damaged. Many concrete buildings, especially in the rias suffered severe damages as well, with a remarkable case the overturned buildings in Onagawa.
3. Some severe damages on transportation infrastructure, such as roads and railways, as also on storm surge gates, could be seen in Rikuzentakata, which is supposedly the most seriously destructed town.
4. Significant damages on coastal industries have been recorded, especially on fisheries in the rias.
5. A better picture of the damage on buildings and infrastructure can be obtained through damage maps, which require analysis of detailed damage records. This will allow some further research on the correlation of damage with local tsunami characteristics, which would be useful in the formulation of the local tsunami countermeasures.
6. The prevention of damage in buildings and infrastructure due to tsunami is technologically possible, yet its cost-effectiveness should be investigated in all cases. It could be possible that the most economical solution is to have only evacuation buildings strong enough to resist tsunamis of the same magnitude as the event of March 2011.
7. The decision of building any type of structures that can resist tsunami forces should be in the framework of a general disaster management strategy, and based on a cost-benefit analysis, where the loss of life should also be incorporated.

5.4 Coastal environment

1. A common characteristic of all visited areas was the significant subsidence along the waterfront, which in many places exceeded 1m. This subsidence is a cause of additional damage along the shoreline.
2. The areas of coastal forests encountered during the field trip were devastated. Especially in the case of Rikuzentakata, only one tree remained in place. In case of smaller tsunamis a coastal forest could mitigate the impact of the tsunami attack. However for events of the same magnitude as the one of March 2011, the impact of a coastal forest can be reversed, as the removal of trees induces a great amount of debris.
3. Some research on the impact of coastal forests on the tsunami forces and vice versa could be useful in order to have decisions made on the use of artificial coastal forests as tsunami defences. In case that an artificial forest is supposed to serve as tsunami defence, the type of its vegetation and how resistant this vegetation is to tsunami forces is important.
4. The intrusion of salt water inland increased the salinity of agricultural land, which is expected to have a negative impact to agriculture in the coming years.
5. Coastal erosion was evident in many places, especially where the coastal protection failed. The problem is intensified where land remains unprotected, and no temporary retaining measures have been taken to prevent further erosion.

5.5 Evacuation and casualties

1. The morphology of the rias allowed evacuation both to the top of high buildings and higher grounds, which could be reached in relatively short time.
2. In the ria coasts that very large inundation heights were recorded, the tsunami exceeded the expectations of the local emergency plans, as there were cases that evacuation buildings were overtopped. Such was the four storey-building on the waterfront of Minamisanriku, yet in that case all people on the top of the building survived, because the building was only just overtopped.
3. Due to the frequent tsunami attacks in Sanriku region, the local society was well prepared and willing to evacuate. Moreover the so-called “tendenco” local culture of mutual trust may have saved a lot of lives. The literal meaning of it is that people trust that their families will also be properly sheltered, and as a consequence, during a tsunami alarm, they shelter themselves immediately without looking for their family members first, which could take some precious time.
4. In the low-lying areas people could mostly evacuate to the top of high buildings, as higher grounds could not be reached in due time.
5. Although inundation heights were lower in low-lying areas, and therefore the height of evacuation buildings sufficed for the protection of evacuees, it has been recorded that many people did not succeed to evacuate in time, as there were only few evacuation spots covering too large areas.
6. The early warning system worked effectively, as the tsunami alarm was issued only three minutes after the earthquake. The inundation height expectations though, as issued by the Japan Meteorological Agency, were exceeded.

7. The evacuation project can only be substantially assessed after a site-specific analysis of facts. Although one could claim that evacuation was relatively effective, considering the total number of casualties compared to the magnitude of inundation, not all inundated land was urban or needed to be evacuated, while the number of casualties varies along the affected coast.
8. A site-specific analysis of facts concerning evacuation would contribute in the identification of needs in local, regional and national level, and therefore in the formulation of effective strategies for the future.

5.6 Disaster management advances

Following the Great Eastern Japan earthquake and tsunami and its devastating impact to Tohoku area, the Japanese scientific society intensified the effort to advance the tsunami and disaster management research. It has been realized that in order to protect the coastal zone against tsunami, it is absolutely necessary to combine effectively hard and soft countermeasures. The primary role of the former is to prevent the coastline being attacked by a tsunami, while the latter are meant to mitigate the damage and casualties in the coastal zone if the design specifications of the former are exceeded, as happened in March 2011.

In order to have the use of hard and soft measures organized in an effective way, a concept of tsunami classification is being adopted. Two tsunami levels are suggested, level-1 and level-2. A level-1 tsunami is supposed to have a return period of about 100 years. The primary defences should be designed to resist the forces of a level-1 tsunami and prevent any loss of life or material damage in the coastal zone. A level-2 tsunami is a higher scale event, with a return period of 1000 or more years. The event of March 2011 is indicative of this level. For level-2 events it is suggested to accept that the primary defences will fail and the tsunami waves will inundate the land, yet the degree of damage and casualties should be minimized. The primary defences should not fail catastrophically when a level-2 tsunami occurs, but they should prove to be sufficiently resilient, while the soft tsunami countermeasures of the coastal areas should prevent in the most efficient way any loss of life and should mitigate the material damage.

Another important concept that has been introduced is the classification of evacuation spots. Three categories are suggested, A, B and C. Category A includes higher terrains adjacent to the coast that are preferably part of higher mountains and have access to the hinterland and not isolated hills. Category B includes robust buildings of at least 6 floors that could shelter people even when a level-2 tsunami occurs. Category C includes robust buildings of 4 floors or higher, which would be efficient in the case of a level-1 tsunami. The already existing evacuation buildings fall in this category as well. In case of a level-2 tsunami there would be the risk that these buildings are overtopped, as happened in some cases in March 2011. When a higher event is expected during a tsunami alert, people should be directed to points A and B if possible. It is also suggested that no new evacuation buildings of category C are built, while the ones existing should be only used while no better evacuation points of higher categories are available.

The classification of tsunamis and evacuation points is undoubtedly a good step towards a new approach to tsunami risk management. However the concept should be extensively worked out, with most important point the clarification of the return period that every tsunami level and evacuation point category refers to. Some detailed recommendations for tsunami risk management in Japan are given in the following paragraphs.

6. Recommendations

Following the Great Eastern Japan earthquake and tsunami, the Japanese scientific society and authorities have been making an enormous effort to survey the event and to advance tsunami related research, which can be used for the formulation of effective strategies for the future. Comparing the Japanese case to the Netherlands as single point of common interest the need to protect their societies against flooding and its devastating impact can be mentioned. The type of flooding and its effects are considerably different. Based on the Dutch experience on flood risk management, and regarding the common point of interest, which is the safety against flooding, a few recommendations that could contribute in the effectiveness of disaster management in Japan are summarized. The recommended actions are meant to create a framework for an integrated risk-based approach to disaster management.

6.1 Determination of relevant return periods

One of the most important prerequisites in order to deal with potential disastrous events is to know their probability of occurrence, and to use it as a reference point for management. In the Japanese case tsunami is the top event that could induce a water disaster and whose return period has to be determined. The return period of particular events such as the Great Eastern Japan earthquake tsunami has to be determined carefully. This requires a thoughtful statistical analysis of tsunami records, and a probabilistic analysis of the tsunami generation mechanism, which should combine the knowledge and experience of hydraulic engineers and seismologists. As an overall indicator of the tsunami magnitude the deep-water tsunami characteristics need to be used, i.e. the tsunami height in deep waters, its period, and its total energy. The coastal tsunami characteristics can only be used locally, as they depend on the coastal morphology. Therefore a 1/1000 years event will usually mean a different tsunami magnitude in different coastal areas. Therefore a different tsunami return period should determine the hydraulic boundary conditions for the design of primary defences in different areas, as well as for secondary measures on the coastal zone and the emergency plans. It should be noted that the target probability of failure of the primary defences, which is proportional to the return period of a tsunami, should be the outcome of a cost optimization, in which the effect of damage mitigation measures and evacuation plans in the risk reduction should be taken into account. The risk reduction of both loss of life and material damage should be considered. In fact this optimization would determine the return periods of level-1 and leve-2 tsunamis, which cannot be generic, but will vary in different places.

6.2 Multi-layered safety approach

As the overload of tsunami defences is not uncommon in tsunami-prone areas, a variety of measures for the mitigation of damage and casualties, such as allocation of important community functions in higher grounds and emergency plans were combined with primary defences in Tohoku. This compound of measures that focus on both the reduction of risk probability and the mitigation of damage in case that a tsunami disaster happens, signifies a so-called multi-layered safety system. Looking at the system from a multi-layered safety perspective would create a rational framework for the assessment of the tsunami response in Tohoku to the event of March 2011. This would allow for a clear indication of risk correlations within the system and in the end would facilitate disaster management in all levels.

6.3 Communication and concretization of roles

The Great Eastern Japan earthquake and tsunami was one of the most devastating natural disasters ever recorded in Japan and worldwide. The record of such an event constitutes a unique opportunity for scientists to advance research on the topic and make important steps towards the water safety and therefore also the well being of coastal societies. It should be noted though that the success of such an effort depends greatly on the efficiency of communication among four different parties: the local communities, the decision-making bodies, the local scientists and the international scientific community. As the interactions and communication between those parties can be rather complicated, and often can involve conflicting interests, it is important that their role is well defined and understood. Hence the basic functions of the four parties are described below.

The role of the local communities is to share their experience of the disaster and to express their direct needs, as well as their vision for the future. This will help decision-makers to identify the short- and long-term needs of the devastated areas and to communicate them to the local scientific society. The role of the scientific community is to inform decision-making bodies about sustainable policy options, and their short and long-term impact. Due to the magnitude and the rarity of the disaster, it is important that the advice given by the local scientific community reflects the knowledge and experience on the topic on international level, where similar cases might have already been encountered and dealt, or different research approaches could be found and integrated. This would ensure an outcome of high quality, which could be used confidently by policy makers for the formulation of effective strategies that will advance safety and wealth. Another prerequisite in order to reach a realistic result is to have the formulated strategies validated through feasibility studies. This requires again the effective communication and cooperation of the local and international scientists with the policy makers who are supposedly the party that will implement the new strategies, and can confirm that the strategies reflect the needs of the local society.

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