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Paper:

Damage in Ports due to the 2011 off the Pacific Coast of Tohoku Earthquake Tsunami

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The tsunami following the 2011 off the Pacific Coast of Tohoku Earthquake devastated ports in the Tohoku and Kanto regions of Japan. Even Iwate Prefecture in Tohoku, which had experienced many tsunami disasters and prepared tsunami disaster mitigation measures, incurred great devastation because the tsunami was both higher than any historically recorded tsunamis and than any estimated tsunamis for disaster management. The tsunami-induced inundation destroyed many of wooden houses widely found in the area. Many ships and boats at sea were displaced by the tsunami, with some vessels colliding with others and port facilities such as cargo handling equipment and quay walls being damaged. Much debris was generated and disrupted rescue and restoration activities in the disaster aftermath. Port devastation caused stagnation in logistics and industrial operations, negatively impacting on residents' lives and industrial activities in the disaster aftermath. There was a positive lesson that breakwaters and seawalls damaged by the tsunami reduced tsunami impacts behind them. Ports should be robust and resilient against possible tsunami hazards, considering measures for worst-case earthquake and tsunami scenarios.

Keywords: tsunami damage, The 2011 off the Pacific Coast of Tohoku Earthquake, breakwater, debris, resiliency

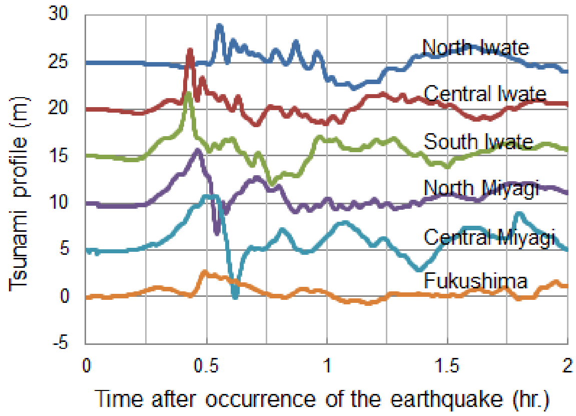


Fig. 1. Tsunami profiles observed with GPS-equipped buoys.

Photo courtesy of the Japan Coast Guard

Fig. 2. Tsunami overflowing the breakwater of Kamaishi Bay.

1. Introduction

Japan's coastal areas facing the Pacific Ocean, especially the Sanriku coast, have been well prepared for tsunamis in their structural and nonstructural measures, because they have experienced many tsunami disasters. The tsunami following the 2011 off the Pacific Coast of Tohoku Earthquake, however, was beyond all historical and scientific considerations – hence the unexpectedly devastating results.

The highest inundation and runup heights above sea level, according to the 2011 Tohoku Earthquake Tsunami Joint Survey Group [1], had been 33.0 m in Minami-Sanriku Town, Miyagi Prefecture, and 40.0 m in Ryori area of Ofunato City, Iwate Prefecture. The tsunami was also observed offshore by GPS-equipped buoys [2] moored in seas with depths of 100-400 m at distances of 10-20 km off the Tohoku coast (**Fig. 1**). Each of tsunami profiles in **Fig. 1** includes an apparent rise in sea level reflecting tectonic subsidence of a corresponding land station to each GBS-equipped buoy that gave reference altitude for calculating the vertical buoy displacement accurately. The tsunami height observed off Kamaishi Bay was 6.1 m after correction for tectonic subsidence. The tsunami was considerably high even in deep water areas 200 m deep at the site. Based on Green's Law, tsunami height is expected to increase to 11.0 m in shallow wa-

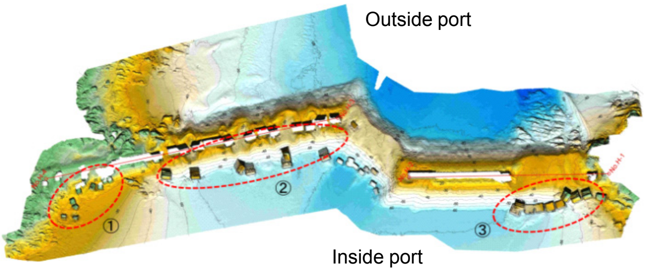


Fig. 3. Tsunami-distributed caissons of the breakwaters in Kamaishi Port, ①: Shallow water section of the north breakwater, ②: Deep water section of the north breakwater, and ③ Part of the south breakwater.

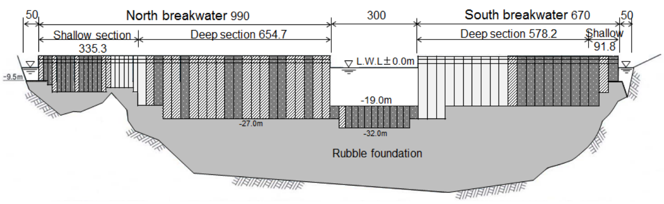


Fig. 4. Damaged caissons of the breakwaters in Kamaishi Port. White: No sever damage, Light gray: Inclined, and Dark gray: Displaced.

Fig. 5. Damaged north breakwater in Kamaishi Port.

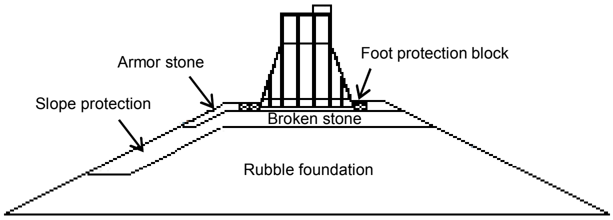


Fig. 6. Standard cross section in the deep water section of the north breakwater in Kamaishi Port.

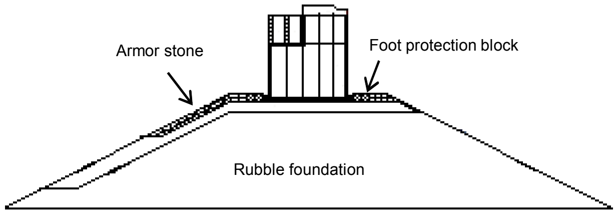


Fig. 7. Standard cross section in the deep water section of the south breakwater in Kamaishi Port.

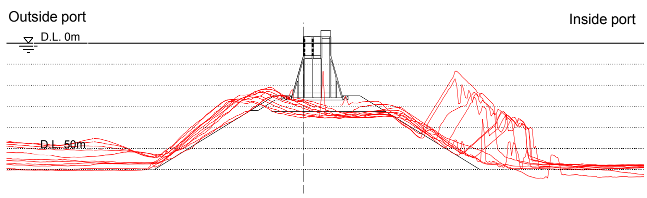


Fig. 8. Example of damaged section of breakwater in Kamaishi Port.

ters 20 m deep. At the mouth of Kamaishi Bay, in fact, the tsunami exceeded 11.8 m in height estimated from an analysis of **Fig. 2**. Note that tsunami profiles observed by GPS-equipped buoys and open-sea seabed pressure gauges were also used to estimate the tsunami source inversely [3].

Port devastation caused logistics and industrial operations to stagnate, negatively impacting on residents' lives and industrial activities in the disaster aftermath. Stagnating logistics, in turn, caused shortages in various goods, including the gasoline and heavy oil vital to residents' daily lives in the short run and prompt recovery work in the long run. Stagnating industrial work depressed industrial activities from local to national economic levels, resulting in the loss of employment in damaged areas. Importantly, of course, the resiliency of ports is vital in ensuring national and international cargo distribution networks and residents' lives and economic activities.

2. Tsunami Damage to Ports

2.1. Breakwater Damage

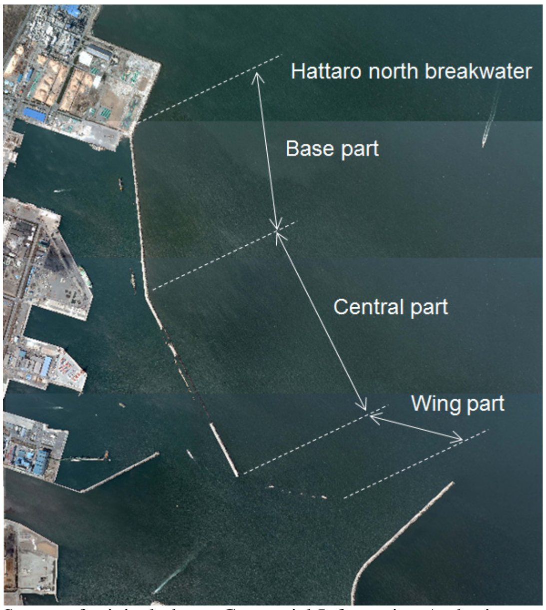
2.1.1. Kamaishi Port Breakwaters

The tsunami damaged breakwaters at the mouth of Kamaishi Bay, where the maximum water depth was 63 m, as shown in **Figs. 3**, **4** and **5**. Because the bay coast had been severely damage by the 1933 Showa Sanriku tsunami and the 1960 Chilean tsunami, the tsunami breakwater had been built to reduce maximum tsunami inundation depth to less than 0.5 m, based on the highest tsunami recorded in the area following the 1896 Mw 8.5 Meiji Sanriku Earthquake. The design tsunami height was 5.0 m and the difference in water level between the front and back of the breakwater was considered to be 2.8 m. The 2011 tsunami, however, was over 11.8 m high and the water level difference between the front and back of the breakwater was over 6 m, resulting in heavy damage of the breakwater.

The 990 m north breakwater in Kamaishi consisted of trapezoidal caissons (**Fig. 6**) of about 36,000 tons in the deep water section and rectangular caissons in the shallow water section. Among caissons in the 670 m south breakwater, three caissons were the trapezoidal caissons and the rest were rectangular caissons of about 32,000 tons (**Fig. 7**). The height of the breakwater crest was D.L. +6.0 m (T.P. +5.14 m). Along a 300 m long opening between the north and south breakwaters, a submerged breakwater was installed that consisted of caissons whose crown height was D.L. −19.0 m.

Photo courtesy of Hachinohe Harbors and Airport Office of MLIT

(a) Breakwater arrangement



Source of original photo: Geospatial Information Authority of Japan

(b) Damaged Hattaro north breakwater

Fig. 9. Damaged breakwater in Hachinohe Port.

According to the Tohoku Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), seven caissons had slid, 14 were tilted and one was undamaged among 22 in the deep section of the north breakwater. In the shallow water of the north breakwater, 11 caissons dropped from the rubble foundation, five were tilted and six were undamaged. Of the remaining six caissons, five were on scour protection mats increasing friction. At the south breakwater, eight caissons had slid, one had tilted and 10 were undamaged in the deep water section. In shallow water, two caissons had slid and one had tilted. At the submerged breakwater, 12 caissons had slid and one remained. As shown in **Fig. 8**, for example, rubble foundation at neither the north nor south breakwaters were not seriously deformed whereas caissons were slid on the foundation. This suggests that damaged caissons had been pushed toward the inside of the port on the less-deformed foundation mainly by fluid force of the tsunami – a suggestion supported by hydraulic model experiments [4].

Photo courtesy of Tohoku Grain Terminals, Co. Ltd.

Fig. 10. Tsunami overflowing the central part of Hattaro north breakwater

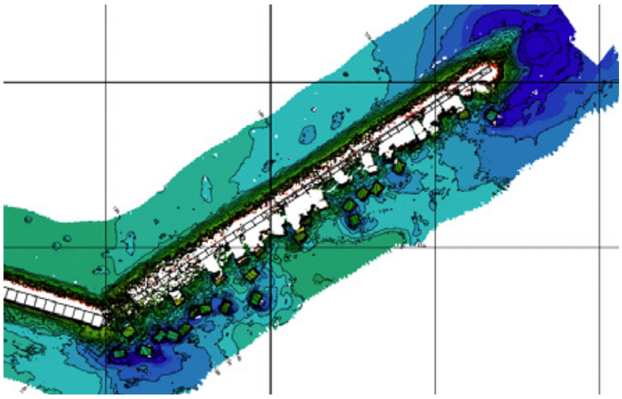


Fig. 11. Damaged wing part of Hattaro north breakwater.

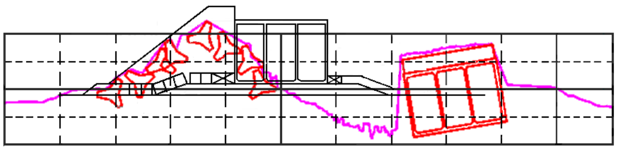


Fig. 12. Damaged central part of Hattaro north breakwater.

2.1.2. Hachinohe Port Breakwater

Breakwaters at Hachinohe Port had been installed to ensure calm water when loading and unloading cargo, so breakwater resistance to tsunamis was not considered regarding its design. In the 2011 event, a tsunami approximately 8 m in height struck Hachinohe Port, according to tsunami water mark heights listed by the 2011 Tohoku Earthquake Tsunami Joint Survey Group [1]. All breakwaters suffered under the tsunami's impact. Breakwaters in the most offshore areas had almost no damage, because they were designed against high storm waves. Some of caissons at heads of the breakwaters had slid. In contrast, the wing and central parts of the Hattaro north breakwater were severely damaged, as shown in **Fig. 9**. It was confirmed that the tsunami overflowed the Hattaro north breakwater (**Fig. 10**) and other breakwaters inside the port.

At the 700 m long wing, caissons, wave absorbing blocks and rubble foundation had been destroyed. Many of the caissons had fallen over inside the port, as shown in **Fig. 11**, where a bathymetry survey had been conducted by the Tohoku Regional Bureau, MLIT, using narrow multibeam echo sounding. The maximum displaced

(a) Seawalls collapsed toward the landside

(b) Seawalls collapsed towards the seaside

Fig. 13. Seawalls damaged in Ofunato Port.

distance of the caisson was approximately 90 m.

Many of the caissons were leaning in a portion of the central part of the 750 m long breakwater. **Fig. 12** indicates a typical example of the damaged central section. The rubble foundation had been severely scoured at the back of the caisson, which had also been displaced. According to numerical simulation of tsunami propagation from a tsunami source [3] inversely analyzed with the offshore tsunami waveform observed with GPS-equipped buoys and seabed pressure gauges, all of caissons in the center had been stable against the tsunami force to have hit the breakwater. In addition to tsunami's horizontal force pushing caissons, therefore, there is another failure mechanism, e.g., probably the reduction in the bearing capacity of the rubble foundation resulting from scouring by overflowing water (**Fig. 10**). This failure mechanism indicates the importance of taking measures against massive scouring due to tsunami overflow.

According to the multibeam echo sounder seabed survey, seabed scouring occurred around damaged head caissons beside opening sections of breakwaters and damaged caisson had been displaced toward scoured areas. Damage thus probably resulted from seabed scouring.

2.1.3. Failure Mechanisms of Breakwaters

Three types of breakwater failure mechanisms were found from damaged breakwaters in Kamaishi and Hachinohe ports that the tsunami overflowed severely: i) strong horizontal force due to water surface level differences between the front and back of breakwater caissons, ii) reduced rubble foundation bearing capacity due to scouring by overflowing water, and iii) reduced rubble foundation bearing capacity around the breakwater head due to the strong tsunami current. Breakwater failures in other ports are explained by these failure mechanisms, as is also supported by experimental analysis and calculation of damaged caisson stability by the Tohoku Regional Bureau of MLIT against the tsunami impact [5].

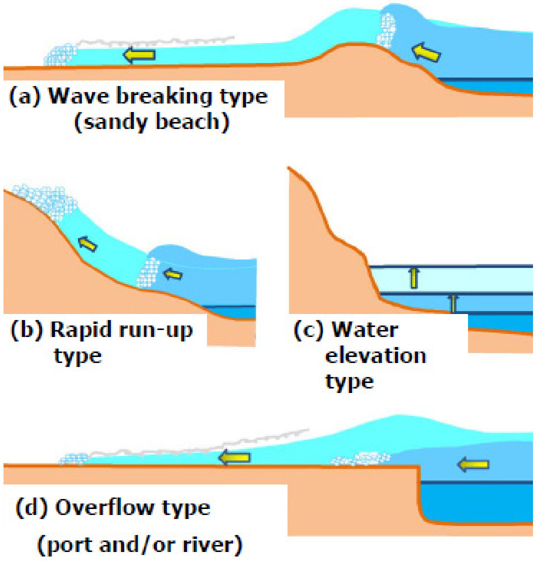


Fig. 14. States of the tsunami overflowing.

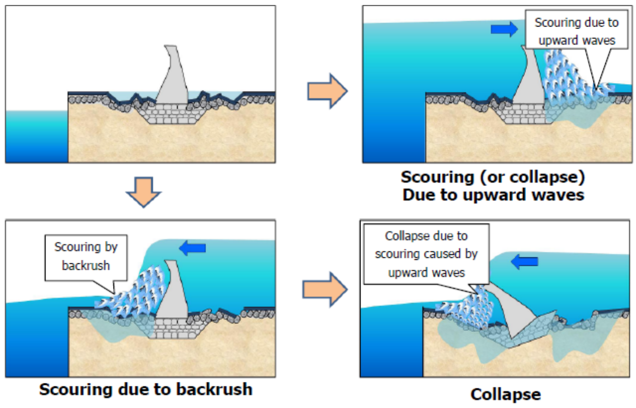


Fig. 15. Failure mechanism of seawall in ports.

2.2. Seawall Damage

Types of seawall damage in ports and harbors were as follows: i) seawall breaching, ii) seawall parapet scattering, iii) seawall surface cracks, iv) local damage due to tsunami debris collision, and v) breakage along seawall surface joints [6]. Scoured foundations were found at the front or back of many breached seawalls (**Fig. 13**). No seawall breakdowns were found in ports, but scouring occurred around damaged seawalls. Typical tsunami damage at ports is shown in **Figs. 14(c)** and **(d)**. Although no wave breaking of tsunamis occurred in sea areas because of the water depth, tsunamis overflowed rapidly onto quays at 10-30 km/h with or without breaking. These

Fig. 16. Kamaishi City in the disaster aftermath.

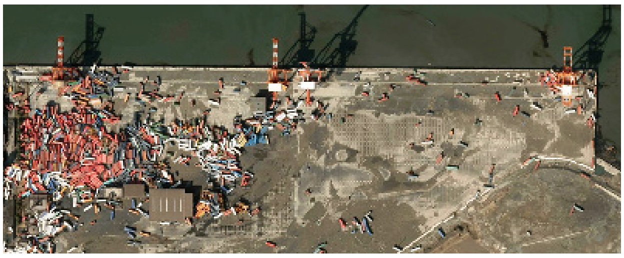


Photo courtesy of MLIT

Fig. 17. Containers displaced by the tsunami in Sendai-Shiogama Port.

(a) After the first positive tsunami

(b) After the second positive tsunami

Photo courtesy of Tohoku Grain Terminal Co. Ltd.

Fig. 18. Containers displaced by the tsunami in Hachinohe Port.

Photo courtesy of MLIT

Fig. 19. Fire accident in Kesennuma Port.

rapid tsunami waves caused no breakdown in main seawalls, which they overflowed, causing scouring failures at seawalls. Failures occurred both during the rushing tsunami phase and during the receding tsunami phase, as shown in **Fig. 15.**

2.3. Tsunami-Induced Debris

The tsunami destroyed houses, which resulted in debris. In addition, many cars floated along both on land and at sea. At the time that the tsunami hit, residents said that traffic jams occurred on roads in Sendai City and Ishinomaki City. **Fig. 16** shows the state of Kamaishi City in the disaster aftermath.

Containers in ports were displaced, especially in Sendai-Shiogama Port, where approximately 2,000 floated (**Fig. 17**). In Hachinohe Port, 700 containers were displaced as shown in **Fig. 18**. The first positive tsunami was 2.3 high in observed water level records at the port tide station of Hachinohe and caused enough inundation for a container chassis to be soaked at approximately 1 m in depth, and therefore some containers were knocked down and displaced. The second tsunami wave, which was the highest in Hachinohe Port, carried many containers out to sea. The observed height of the second tsunami wave was 4.5 m at the port tide station, and watermark height measured at the container wharf in the posttsunami field survey was 2.9 m above the ground surface.

From some of the oil tanks carried away by the tsunami, oil leaked and caused fires in flammable debris. **Fig. 19** shows burned-out Kesennuma Port, including displaced oil tanks.

Many ships and boats were also displaced by the tsunami. A cargo carrier landed in Kamaishi Port (**Fig. 20(a)**) because the inundation depth was 8 m and deeper than the ship's 7.2 m draft. If the inundation depth had been shallower than this draft, the vessel would have collided with the quay wall and other obstructions. **Fig. 20(b)** shows the collision of a chemical tanker whose draft was 8.7 m in Hachinohe Port, where the inundation depth was 3 m. Some vessels were displaced with carrying cargo handling equipment such as buckets because electrical power failures due to seismic motion prevented equipment from being removed from vessels that were being unloaded. **Fig. 21** shows unloading equipment damaged when carried away by a ship displaced by the tsunami. Equipment was also damaged by tsunami wave forces and collisions with tsunami debris, such as tsunami-displaced vessels.

(a) Cargo carrier with the draft of 7.2 m
(Inundation depth of 8 m)

Photo courtesy of Hachinohe City

(b) Chemical tanker with the draft of 8.7 m
(Inundation depth of 3 m)

Fig. 20. Damaged vessels by the tsunami.

Fig. 21. Damaged loading and unloading equipment in Soma Port.

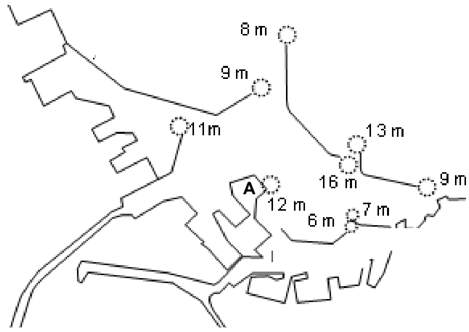
2.4. Bathymetric Changes in Ports

Figure 22 shows the locations of scouring and its depth, which is the difference in water depth surveyed by multibeam echo sounding after the tsunami from that of navigation chart. Since scouring occurred at the tips of breakwaters and quays, especially in openings between breakwaters, tsunami-induced currents and eddies probably generated it. **Fig. 23** shows missing caissons at a corner of a port island (Point A). Three caissons forming the corner were moved to a hole due to scouring whose depth was 12 m. Scouring around the structure is responsible for damage of the structure.

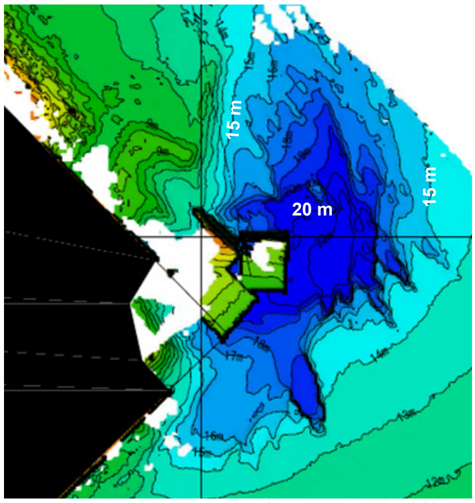
3. Reducing Tsunami Inundation Through Breakwaters and Seawalls

3.1. Breakwaters in Kamaishi

Numerical simulation of the propagation and inundation of the 2011 tsunami indicated a reduction in tsunami impact by bay-mouth breakwaters in Kamaishi Port. In numerical simulation, the tsunami numerical model, STOC-ML, with assumption of hydrostatic pressure [7] was used. A nested grid system was applied to reduce calculation time and memory. The smallest calculation grid, 5 m × 5 m, was applied to the whole port area where airborne LIDAR topographic data was used to make topography and structure data, and nautical charts and a port planning map were used to make bathymetry data. The tsunami source area was calculated using the modified



(a) Locations of scouring and depth



(b) Bathymetry surveyed using narrow multibeam
echo sounding at Point A

Fig. 22. Tsunami-induced scouring in Hachinohe Port.

Fig. 23. Missing caisson corners at a port island due to scouring.

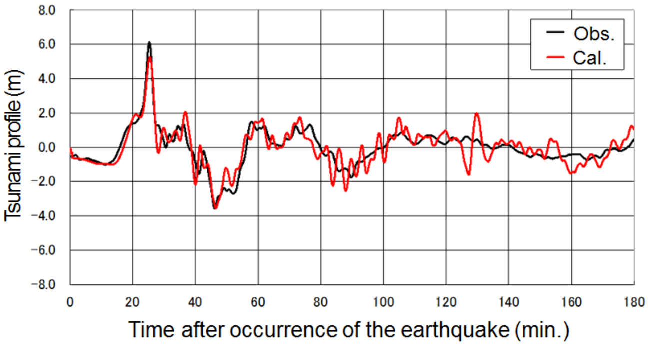


Fig. 24. Tsunami profiles observed with the GPS-mounted buoy located off Kamaishi Bay (black line) and calculated profile (red(gray) line).

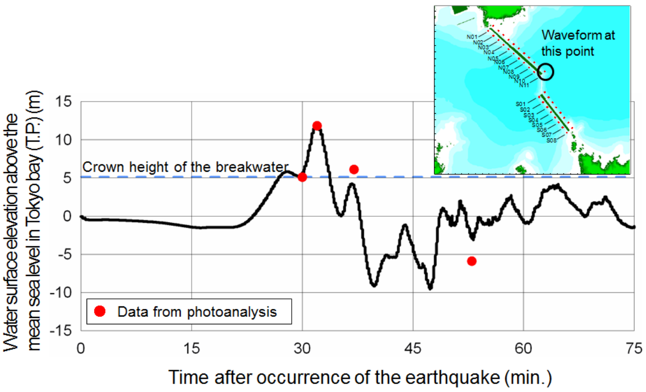
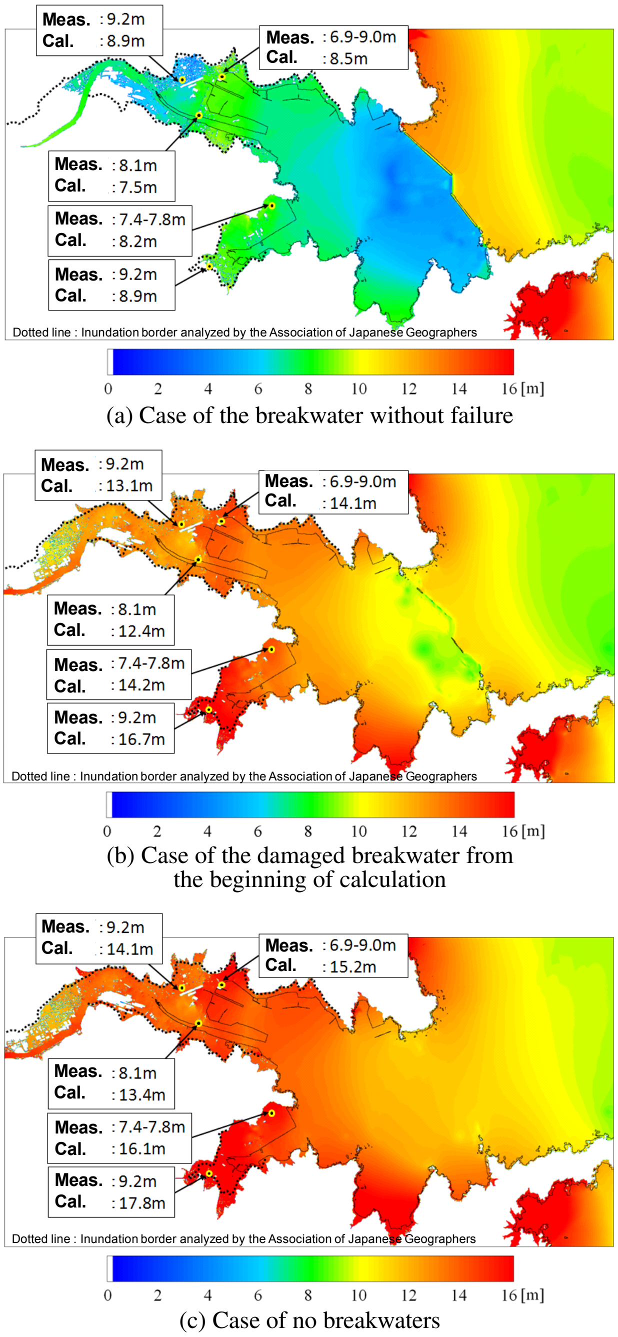


Fig. 25. Calculated tsunami profile (line) and water surface elevation analyzed from photos (circles) at the head of the North Breakwater in Kamaishi Bay.

fault parameters of Fujii and Satake's version 1.0 (more advanced model [8]) to fit the calculated height of the first positive tsunami wave to that observed by GPS-equipped buoys moored off Kamaishi Bay.

Figures 24 and **25** show the tsunami profiles calculated at GPS-equipped buoys off Kamaishi Bay and the seaward point of the north breakwater head. Circles in **Fig. 25** indicate water surface elevation analyzed using photos and video footage. Calculated results agree well with the results of photoanalysis. Based on calculation in the case where there was no breakwater, the tsunami height was approximately 12 m along the north breakwater. This height exceeds the crown of the breakwater by about 7 m, as shown in **Fig. 2**. The breakwater was not designed to withstand the force of such a high tsunami, resulting in the failure of the breakwater.

Figure 26 shows the spatial distribution of the calculated maximum tsunami height at sea and inundation height on land with tsunami watermark heights measured in posttsunami field surveys. In case (a) of breakwaters without failures, calculated inundation heights are 30-60 cm lower than heights of watermarks measured. This reduction could be because the breakwater failure that occurred when the first tsunami wave struck the breakwater was not introduced into calculation. In case (b), where broken breakwaters were set as the initial calculation condition, crown height distribution was determined from



(a) Case of the breakwater without failure

(b) Case of the damaged breakwater from the beginning of calculation

(c) Case of no breakwaters

Fig. 26. Distribution of the maximum tsunami height in the sea and inundation height on land, depending on the situation of the breakwaters.

measurements of actual damaged breakwaters. Calculated inundation heights are 4 m or higher than measured watermark heights. Indeed, **Fig. 2** shows the tsunami around the peak of the first positive wave, which is the highest tsunami wave in Kamaishi Bay, where the tsunami overflowed the breakwater has a long crest line of the same height. This indicates that no serious breakwater failure occurred until this moment, so measured tsunami inundation heights lie between cases (a) and (b) and comparably near case (a). This indicates that the breakwater probably resisted the force of the tsunami until the peak of the first tsunami wave, resulting in the reduction of tsunami

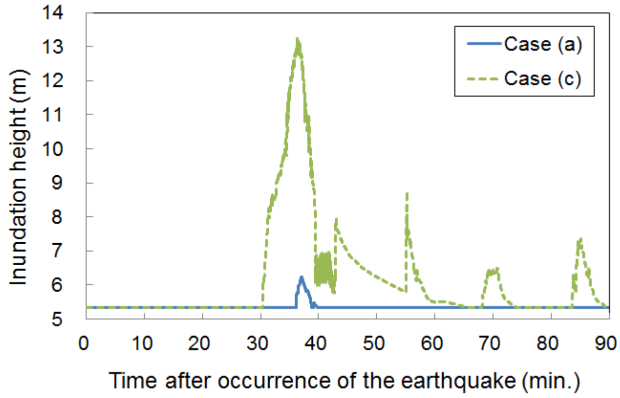


Fig. 27. Time of the start of inundation around the point where the inundation heights of 6.9-9.0 m were measured.

Fig. 28. Arrangement of seawalls in Kamaishi Port.

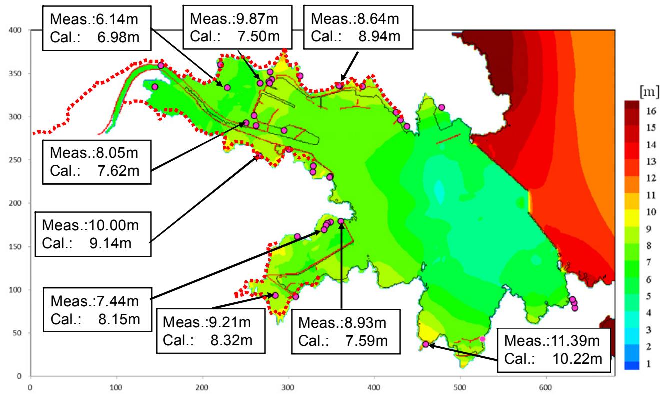
intrusion flux and impact on the port. Note that the damaged breakwater reduced tsunami inundation height by 40% around the coast inside the port because the calculated inundation height is about 14 m in case (c), which was calculated under the condition of no breakwaters, and measured watermark heights are about 8 m. According to calculation, inundation areas are 3.38 km^2, i.e., areas with an inundation depth of 2 m or deeper are 76% of the total inundation area in case (a), 4.57 km^2 (90%) in case (b), and 4.87 km^2 (90%) in case (c), confirming that breakwaters reduced the area of inundation.

Figure 27 shows the time inundation started around the point where inundation heights of 6.9-9.0 m were measured in **Fig. 26**. In case (a) of breakwaters without failure, the tsunami overtopped the seawall along the coast and inundation started 36 minutes after the earthquake occurred. If, however, there were no breakwaters, i.e., case (c), inundation started 30 minutes after the earthquake, so breakwaters had an effect on the time delay in the start of inundation and on the reduction of tsunami height.

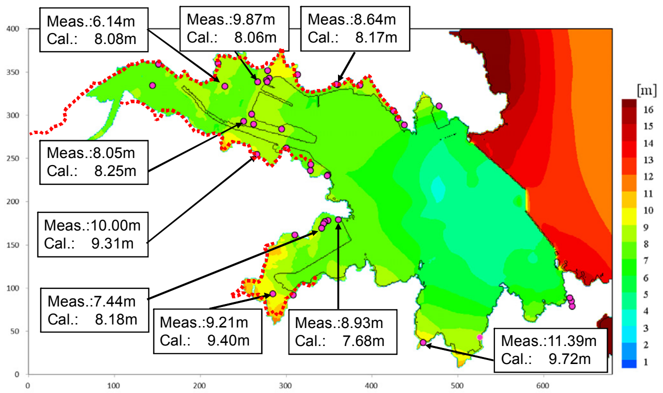
3.2. Kamaishi Seawalls

Numerical simulation of seawalls in Kamaishi Port is presented as an example of tsunami impact reduction by seawalls. Case (a) is discussed here because calculated inundation heights are similar to heights measured in posttsunami field surveys. Two other conditions of seawalls are compared: case (a-1) of an actual arrangement of 4 m high seawalls along the coastline (black thick lines in **Fig. 28**) and case (a-2) with no seawalls. The calculation area is constructed with nested 5.4 km, 1.8 km, 600 m, 200 m, 100 m, 50 m, 25 m, and 12.5 m grids.

Figure 29 indicates the spatial distribution of maximum tsunami height at sea and inundation height on land and the inundation heights measured in posttsunami field surveys. Both tsunami and inundation heights for case (a-2), i.e., no seawalls, are several tens of cm to 1 m higher than those for case (a-1) with the actual seawall arrangement. Calculated areas of inundation are 3.26 km^2 (inundation area with an inundation depth of 2 m or more: 2.55 km^2) in case (a-1) and 3.33 km^2 (2.62 km^2) in



(a) Case (a-1) of actual seawall arrangement



(b) Case (a-2) of no seawalls

Fig. 29. Distribution of the maximum tsunami height in the sea and inundation height on land depending on the seawalls along the coast.

case (a-2). The seawall has a limited effect on reducing tsunami inundation because a tsunami 8 m in height struck the coast, overtopped the seawall by 4 m and inundated a narrow low-lying flat area.

4. Toward Tsunami-Resiliant Port

4.1. Worst-Case Scenario

People living on areas devastated by the 2011 Tohoku tsunami had taken precautions against tsunamis since the devastating experience of past tsunami disasters, includ-

Fig. 30. Tsunami evacuation terrace at Aonae Fishing Port, Okushiri Island.

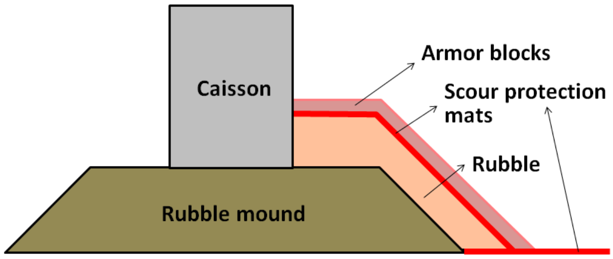


Fig. 31. Example of tsunami-resilient breakwater.

Fig. 32. Scattered tsunami-induced debris on the seabed at Sendai-Shiogama Port.

ing the 1896 Meiji-Sanriku Tsunami. The 2011 tsunami was significantly larger than that predicted by scientists, however, more than twice the predicted height on some coasts. The tsunami thus inundated wider areas than inundation area expected before the event, costing lives. From this lesson, the committee of the Central Disaster Management Council of Japan [9] has reported tsunami disaster management importance for two levels of tsunami. On the first level (Level 2) are the largest-possible tsunamis for developing comprehensive disaster management measures, especially for saving lives and reducing economic loss. On the second level (Level 1) are tsunamis lower but occurring with higher possibility than Level 2 tsunamis. Protection structures are constructed to prevent inundation that is estimated to be caused by Level 1 tsunami. In ports there are low-lying flat areas vulnerable even to Level 1 tsunamis. Measures to save lives, therefore, should be considered for Level 1 tsunamis in ports, for example, in the arrangement of tsunami shelters. **Fig. 30** is an example of an evacuation facility built at Aonae Fishing Port, Okushiri Island, after the 1993 Okushiri tsunami. This terrace is built as an emergency shelter in tsunamis and is usually used for drying marine products. If people recognize a dangerously high tsunami coming, they can move safely from the shelter to higher places via the high connecting road.

4.2. Tsunami-Resilient Breakwaters

Even if breakwaters are damaged by a tsunami, it may reduce tsunami impact if many parts of it interrupt tsunami intrusion as was the case for the Kamaishi Port breakwater. Breakwaters and seawalls built to resist huge storm waves can probably withstand Level 2 tsunamis if scouring of their foundations and sand sucked out from around foundations are prevented. If the main structure is not strong enough against Level 2 tsunamis, especially foundation scouring and sand being sucked out from around foundation, reinforcement of the structure is recommended with scouring protection implemented for the foundation. This reinforcement is an important measure in adding resilience to tsunami defenses.

An example of a structure with adequate resistance to tsunamis is a breakwater with extra fill on the shore side of caissons, as shown in **Fig. 31**. This widened riprap increases resistance to sliding and foundation capacity against scouring. Hydraulic model experiments confirmed that this type of reinforcement increased resistance to both sliding and scouring [4].

4.3. Measures Against Tsunami-Induced Debris

In Sendai-Shiogama Port, various kinds of debris were caused by the tsunami impact. Some of these were carried out to sea by the tsunami, sank and were scattered on port sea beds of the port. Dots in **Fig. 32** indicate locations where debris was collected from the seabed in Sendai area of Sendai-Shiogama Port. The number of locations was 531, including 335 containers and 26 cars. They were obstacles to navigation in the transport of emergency supplies and in ensuring national and global supply chains in the disaster aftermath. It took about 80 days to collect most debris from the seabed. In addition to developing methods for collecting debris, measures to minimize the debris carried out to sea are also needed to increase port resiliency. Guardrails and wind shelters were effective in trapping cars and boats going out to sea in the 2011 event.

5. Conclusions

Port devastation due to the 2011 Tohoku tsunami stagnated logistics and industrial operations, negatively impacting on residents' lives and industrial activities in the disaster aftermath. The tsunami higher than expected tsunamis for disaster management in damaged areas caused various damage: inundation, the destruction of cities and infrastructures, the generation of debris including large vessels, the deformation of topography and seabeds, and the leakage and spreading of oil and dangerous materials. Breakwaters damaged by the tsunami, however, had at least an effect in reducing tsunami impact.

Based on lessons from the 2011 tsunami disaster for saving lives and mitigating economic loss, Level 1 tsunamis are considered in tsunami disaster prevention and Level 2 tsunamis are considered for tsunami disaster mitigation and for the protection of lives. Measures to protect lives should be considered in ports even for Level 1 tsunamis, because these will probably inundate low-lying flat port areas. In addition, ports should be resilient enough against tsunamis to ensure national and worldwide logistic networks and residents' lives and economic activity in damaged areas. To make ports resilient, structural and nonstructural measures should be developed and integrated.

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