# Tsunami-induced Debris of Freight Containers due to the 2011 off the Pacific Coast of Tohoku Earthquake

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Key Facts

- Hazard type: Earthquake and Tsunami
- Date of the disaster: 5:46 UTC, March 11, 2011
- Location of the survey: Hokkaido, Aomori, Iwate, Miyagi, Fukushima and Ibaraki Prefectures of Japan
- Date of the field survey: June 2012 – April 2013
- Survey tools: Field survey and hearing survey
- Key findings: 3,018 freight containers were lost from ports because of the Tohoku tsunami. It was determined that the container loss rate was zero for inundation depth less than 1.6 m and 0.4 or more for inundation depth of above 3.5 m.

***Key Words:*** *The 2011 off the coast of Tohoku earthquake, tsunami-induced debris, freight container*

## 1. INTRODUCTION

The 2011 off the Pacific coast of Tohoku earthquake tsunami hit Japan coastlines on March 11, 2011. Several container ports were affected and many freight containers were lost from wharfs of the ports as a result of the tsunami.

With the exception of the Talcahuano port of Chile which was affected by 2010 Chilean tsunami [1)], few studies have reported the extensive damages of freight containers debris in modern ports. Therefore, a detailed survey of tsunami-induced debris of freight containers is meaningful for planning tsunami mitigation.

Japan's Ministry of Environment (MOE) estimated the mass of freight container debris resulting from the Tohoku tsunami to be approximately 30,000 t in Iwate, Miyagi and Fukushima prefecture [2)], which are the closest prefectures to the epicenter (**Fig. 1**).

Although no official number of lost containers was announced by MOE, the Cargo Press Co. Ltd. interviewed MOE and reported the result of the interview that 1,995 containers were lost from the three prefectures [3)].

MOE's estimation did not include information for ports located at Hokkaido, Aomori, and Ibaraki Prefectures. Thus, the reported estimate of tsunami-induced debris of freight containers due to the Tohoku tsunami is incomplete, and we have little knowledge about a complete view of tsunami-induced debris of containers due to the tsunami.

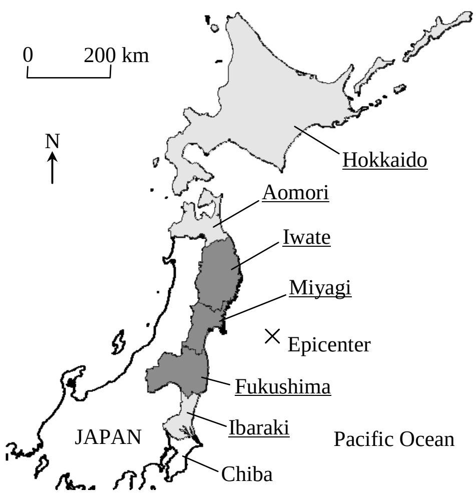



**Fig. 1** Prefectures along the Pacific coast of northern Japan

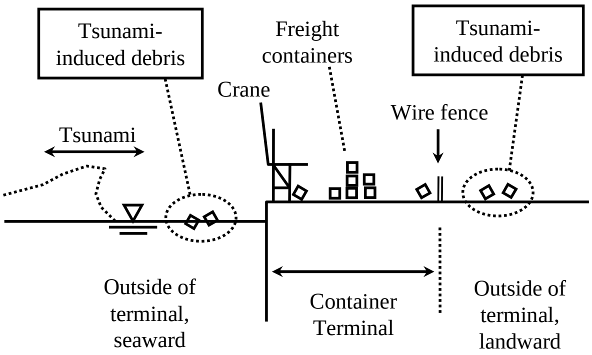



**Fig. 2** Diagram of container terminal

In this study, field and hearing surveys were conducted to collect fundamental information and a complete view of tsunami-induced debris of freight containers from ports due to the 2011 off the Pacific coast of Tohoku earthquake. The survey result showed damages from the 2011 Tohoku tsunami, and are expected to be utilized for tsunami mitigation.

**Fig. 2** shows a diagram of a container terminal. If a tsunami runs up onto a container terminal, containers are scattered. Some of them are pushed landward to the outside of the terminal, and others drift seaward because of the back current of tsunami and lost to the sea. The rest remain in the terminal area. Thus, various drifting phenomena are included in the phrase, "tsunami-induced debris." In this survey, we use the definition to describe only containers pushed landward to the outside of the terminal and those lost to sea. The ones which were scattered but remain in the terminal area are not regarded as tsunami-induced debris in this survey.

## 2. METHOD OF SURVEY

### (1) Objective Ports

The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) publishes an annual statistical report concerning container port rankings in Japan. According to the report of 2010 [4)], 14 container ports were situated along the Pacific coasts from Hokkaido to Ibaraki Prefecture. Therefore, this survey focuses on these 14 container ports. The Pacific coast of Chiba Prefecture was also inundated by the Tohoku tsunami, but has no container port in the area. Thus, no port in Chiba Prefecture is included in this survey.

**Fig. 3** shows the locations of the 14 container ports. Nos. 1–3 are located in Hokkaido, Nos. 4 and 5 are located in Aomori, Nos. 6–8 are located in Iwate, Nos. 9 and 10 are located in Miyagi, Nos. 11 and 12 are located in Fukushima, and Nos. 13 and 14 are located in Ibaraki Prefecture.

### (2) Surveillance Period and Participants

The author conducted field and hearing surveys for the 14 ports.

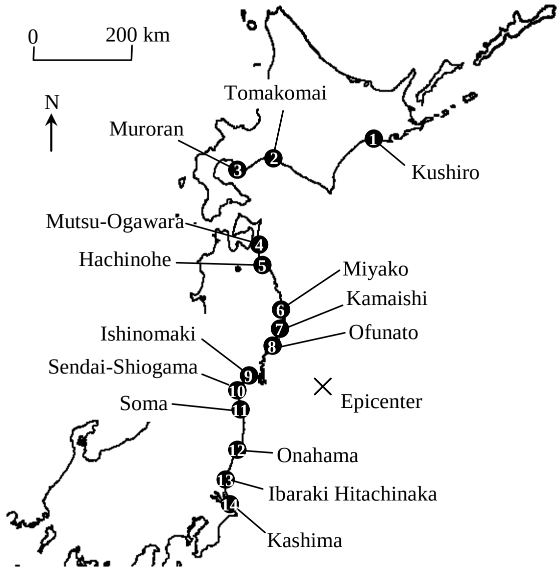



**Fig. 3** Objective ports in this survey

**Table 1** Items of Questionnaire

| Category | Subcategory |
|---|---|
| 1 General information | 1-1 The number of freight container stored on container terminal at earthquake |
| | 1-2 The number of tsunami-induced debris of freight container |
| 2 Characteristics of containers, cargo and cargo handling operation | 2-1 Container size |
| | 2-2 Mass of cargo |
| | 2-3 Location of storage area |
| | 2-4 The number of stacked containers in vertical direction |
| 3 Damage of fence | 3-1 Damage of SOLAS wire fence * |
| 4 Behavior of container debris | 4-1 Spatial limits of container drifting |
| | 4-2 the Number of salvaged container |

* Wire fence installed around container terminal on the request of the International Convention for the Safety of Life at Sea of 2002

The field survey was conducted at four ports by the author and participants. At Port No. 5, Miss Rumiko SHIMIZU, engineering official of Hachinohe Port and Airport Construction Office of MLIT, participated in the survey on February 5, 2013. At Port No. 10, Mr. Osamu OKAMOTO, senior researcher of PARI, participated in the survey on March 25, 2013, and Mr. Itaru EHIRO, research engineer of NILIM, participated in the survey on April 22, 2013. At Port No. 13, Mr. Akio TAGUCHI, assistant manager of Ibaraki Port Authority Co., Ltd., participated in the survey on June 13, 2012. And at Port No. 14, Mr. Hidenori ENDO, engineering official of Kashima Port and Airport Construction Office of MLIT, participated in the survey on September 25, 2012.

The hearing survey was conducted for the other 10 ports from May 2012 to March 2013 by the author.

**(3) Questionnaire Items**

**Table 1** shows items included in the questionnaire used in the surveys. The first category is a questionnaire on general damages, such as the number of freight containers stored in the container terminal at the time of the earthquake and the amount of tsunami-induced debris of containers according to the definition used in this study. The second category is about the characteristics of container size, loading mass of cargo, and cargo handling operations. The third category is about the wire fence that surrounds container terminals. If the tsunami height is low enough to keep the wire fence from destruction, the fence is useful to some extent containing the drifted containers. The forth category is about the behavior of container debris, and is intended to gather information on the spatial limits of the container drifting and locations of sunken freight containers.

**(4) Inundation Depth**

The Tohoku Earthquake Tsunami Joint Survey Group (TTJT), consisted of approximately 300 tsunami, coastal engineering, seismology and geology researchers, measured the tsunami height at approximately 5,900 points by the group, and the group released the survey results on its website [5)].

In this study, maximum tsunami heights at container terminals are extracted from the survey results of TTJT, if not stated otherwise specified. The values are extracted from neighborhood points or are estimated from several points from the neighborhood to the terminal to obtain an averaged value.

**(5) Dimension and Mass of Container**

20 foot and 40 foot containers are popular sizes for shipping cargo. **Fig. 4** shows dimensions of dry freight containers of 20 foot, 40 foot and 40 foot high cube type, defined by ISO standards [6)]. Height and width are common for 20 and 40 foot containers, which are 2.591 m high and 2.438 m wide. They differ in length, however, at 6.058 m and 12.192 m, respectively, for the 20 and 40 foot containers.

The base of a freight container is buoyancy free structure because a gooseneck tunnel and spaces between floor bearers are easily inundated if the container sinks in water (**Fig. 5**). It is satisfactory to consider height of the buoyancy-free base structure as approximately 0.14 m (**Fig. 6**).

No regulation exists for the mass of empty containers, and it varies among products of container manufactures. In general, according to the sample survey at the Sendai-Shiogama Port, the average masses of 20 foot, 40 foot and 40 foot high cube empty dry containers are 2,240 kg, 3,740 kg and 3,860 kg, respectively. **Appendix A** provides results of the sample survey of masses of empty containers at the Sendai-Shiogama Port.

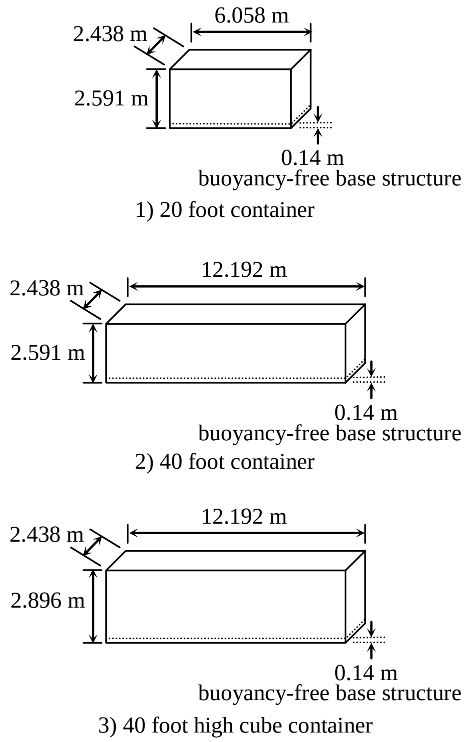



**Fig. 4** Dimensions of normal freight containers

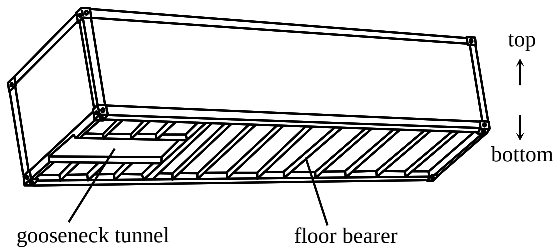



**Fig. 5** Base structure of freight container
*This figure is quoted from JIS Z 1613-1994 of JSA and modified by NILIM

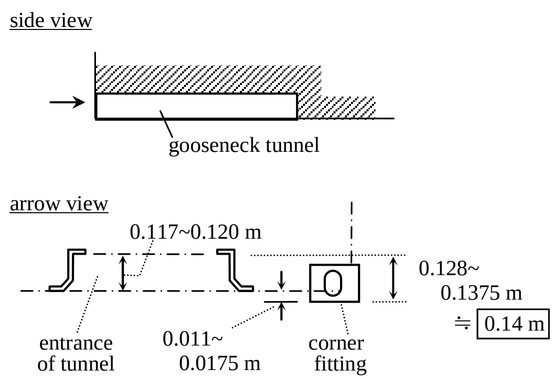



**Fig. 6** Dimensions of gooseneck tunnel
*This figure is quoted from JIS Z 1618-1994 of JSA and modified by NILIM

For container handling, maximum mass is more important than the deadweight. According to the regulations in Japan, the maximum mass is 24,000 kg for a 20 foot container, and 30,480 kg for 40 foot container and 40 foot high cube containers [7)].

**Table 2** The number of tsunami-induced debris of freight containers due to the Tohoku tsunami

| No. | Name of Port | The number of containers handled during 2010 (TEU *1) | The number of containers stored on terminal [ A ] | The number of tsunami-induced debris of freight containers [ B ] | Container loss rate [ B/A ] | Tsunami inundation height above T.P. (m) *2 [ C ] | Ground elevation at terminal above T.P. (m) [ D ] | Tsunami inundation depth (m) [ C-D ] |
|---|---|---|---|---|---|---|---|---|
| 1 | Kushiro | 31,731 | 788 *3 | 0 | 0.000 | 2.85 | 1.8 | 1.1 |
| 2 | Tomakomai | 322,128 | 7,400 | 0 | 0.000 | 2.79 | 2.41 | 0.38 |
| 3 | Muroran | 5,482 | 136 *3 | 0 | 0.000 | 1.16 | 2.61 | - |
| 4 | Mutsu-Ogawara | 245 | 0 | 0 | 0.000 | 3.30 | 2.63 | 0.67 |
| 5 | Hachinohe | 45,430 | 1,159 | 701 | 0.605 | 5.95 | 2.50 | 3.45 |
| 6 | Miyako | 100 | 7 | 7 | 1.000 | 8.94 | 1.99 | 6.95 |
| 7 | Kamaishi | 119 | 0 | 0 | 0.000 | 8.93 | 0.44 | 8.49 |
| 8 | Ofunato | 2,839 | 73 | 72 | 0.986 | 8.71 | 0.50 | 8.21 |
| 9 | Ishinomaki | 4,024 | 100 *3 | 40 | 0.400 | 6.67 | 1.33 | 5.34 |
| 10 | Sendai-Shiogama | 155,611 | 4,318 | 1,724 | 0.399 | 6.49 | 2.95 | 3.54 |
| 11 | Soma | 622 | 6 | 6 | 1.000 | 9.73 | 2.08 | 7.65 |
| 12 | Onahama | 22,352 | 555 *3 | 0 | 0.000 | 3.56 | 2.04 | 1.52 |
| 13 | Ibaraki Hitachinaka | 21,261 | 639 | 12 | 0.019 | 4.32 | 2.20 | 2.12 |
| 14 | Kashima | 6,189 | 809 | 456 | 0.564 | 4.31 | 2.43 | 1.88 |
| | Total | 618,133 | | 3,018 | | | | |

*1 TEU stands for Twenty-foot equivalent unit, one of the measurement unit for freight container. *2 T.P. stands for Tokyo Peil, the vertical datum of Japan. *3 This value is an estimate value, obtained from calculation based on the method of 'Technical Standards and Commentaries for Port and Harbour Facilities in Japan' (PHAJ, 2007).

### (6) Quantity of Container

A common method used in port logistics is to count the number of containers in units of twenty foot equivalent unit (TEU), because mass and volume are both important barometers of port activity. By definition, a single 40 foot container is equivalent to two TEU under the rule of counting.

In this survey, however, no distinction was made in counting the number of 20 foot and 40 foot containers because survey aimed to collect fundamental information on tsunami-induced freight container debris. In this survey, the quantity of containers indicates the actual number of containers or debris.

## 3. RESULTS OF SURVEY

### (1) General Overview

**Table 2** presents a general overview of the results of this survey. Details of the damage of each port are described in the following subsection (2).

The third column of the table shows the number of fright containers handled in 2010 at the 14 ports shown in Fig. 3. The values of the column were extracted from the annual statistical report of container handling in Japan published by MLIT [4]. The values are in TEU. Port Nos. 2 and 10 are the largest two ports in the table, each handling more than 100,000 containers in one year.

The fourth and the fifth columns of the table are the key findings in this survey. The value of the fourth column, Column A, represents the number of containers stored on a terminal at the time of the earthquake. Note that the value followed by an asterisk and three (*3) is an estimated value obtained by calculating the values of the third column, cargo handling time, seasonal peak factor, coefficient of extra container stock in consideration of empty containers, and other parameters. **Appendix B** provides details of such estimation. Values of Column A with no symbol are actual values obtained from the hearing survey.

Values in the fifth column, Column B, represent the number of tsunami-induced debris of freight containers from container terminals due to the Tohoku tsunami. The maximum number in the column is 1,724 from the Sendai-Shiogama Port. Port Nos. 1–4, 7 and 12, in contrast, had no damage. The numbers of the other ports are within the range of values from 6 to 701. As a result, it is found that 3,018 freight containers were lost from eight ports due to the Tohoku tsunami.

As stated in Chapter 1, 1,995 containers were lost from the ports of three prefectures, Iwate, Miyagi and Fukushima Prefecture, as estimated by MOE and reported by the news company. Table 2 shows that the total number of container debris from Port Nos. 6 –12, located at the three prefectures, is 1,849. This result is in satisfactory agreement with the MOE report.

### (2) Individual Report

#### a) Kushiro Port

**Fig. 7** shows a plain view of the Kushiro Port.

The container terminal is located at the West Port area.

According to the TTJT report, tsunami inundation height was 2.85 m above T.P. —the fundamental metric datum of Japan, at survey point JMAS-0084.

**Fig. 8** is a cross sectional view of the container terminal, showing relationships among tsunami inundation height, inundation depth, and ground elevation. Ground elevation of the container terminal is approximately T.P. +1.8 m in the port. Inundation depth, the difference between the inundation height and ground elevation, was estimated at approximately 1.1 m at the terminal, although the container terminal is approximately 3 km from the survey point of TTJT. Unfortunately, no data of inundation height was obtained at the West Port area.

According to the hearing survey, no tsunami-induced debris of freight containers was detected in the Kushiro Port.

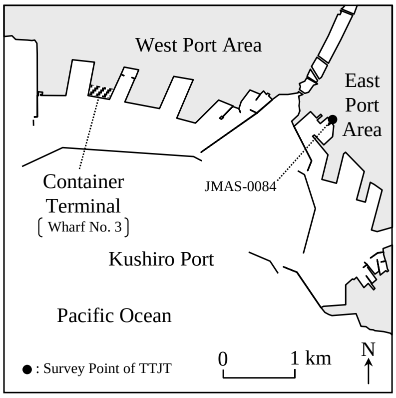



**Fig. 7** Kushiro Port

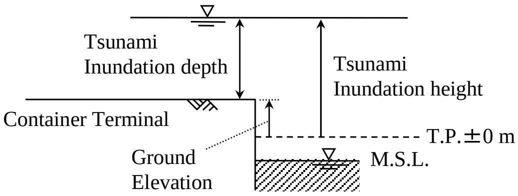



**Fig. 8** Relationships among inundation height, inundation depth, and ground elevation

**b) Tomakomai Port**

**Fig. 9** shows a plain view of the Tomakomai Port. Container terminals are located at three areas, Benten, Yufutsu and Honko. Approximately 7,000, 300 and 100 containers were stored at these container terminals, respectively.

According to the TTJT report, the tsunami inundation height was T.P. +2.79 m, based on an average of six survey points. Locations and identification numbers of the six points are shown in the figure. Ground elevation was T.P. +2.41 m at all container terminals. The average tsunami inundation depth was, therefore, estimated to be 0.38 m at the port.

According to the hearing data, no tsunami-induced debris of containers was detected at the Tomakomai Port.

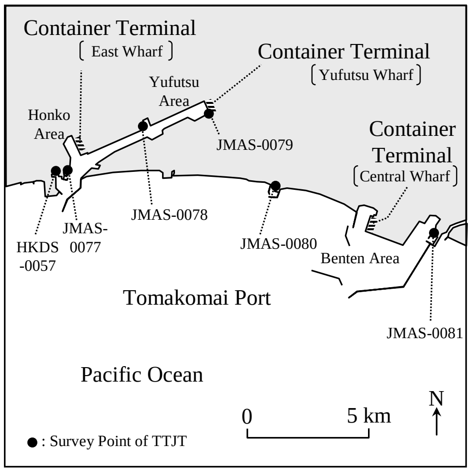



**Fig. 9** Tomakomai Port

**c) Muroran Port**

**Fig. 10** shows a plain view of the Muroran Port.

According to the TTJT report, the inundation height was T.P. +1.16 m, based on the average of three survey points. Ground elevation at the container terminal was T.P. +2.61 m. The tsunami height was lower than the ground elevation of the container terminal.

No tsunami-induced debris of containers was detected at the Muroran Port, because the tsunami was too small to have inundated the terminal.

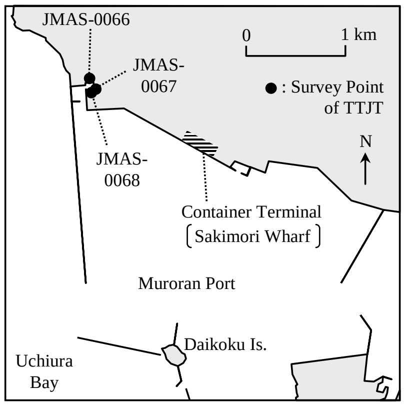



**Fig. 10** Muroran Port

**d) Mutsu–Ogawara Port**

**Fig. 11** shows a plain view of the Mutsu–Ogawara Port. No tsunami-induced debris of freight containers was detected at the Mutsu–Ogawara Port because no regular shipping lines used this port in 2011. Therefore, no container was stored in the port.

According to the TTJT report, inundation height is T.P. +3.30 m at survey point HKDS-0082. Ground elevation at the wharf is T.P. +2.63 m. Inundation depth is, therefore, estimated at 0.67 m on the wharf.

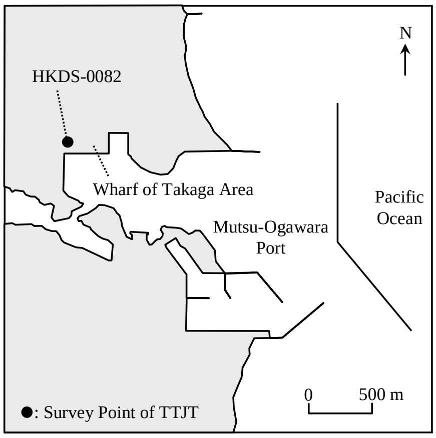



**Fig. 11** Mutsu-Ogawara Port

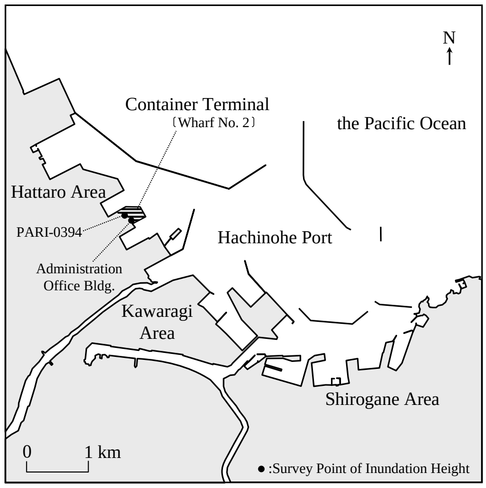



**Fig. 12** Hachinohe Port


**Photo 1** Memorial board displayed at the administration office building

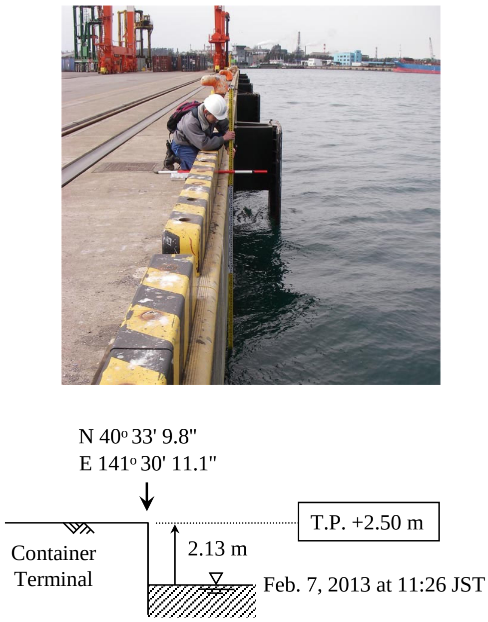



**Fig. 13** Ground elevation measurement

## e) Hachinohe Port

**Fig. 12** shows a plain view of the Hachinohe Port. The container terminal is located at the Hattaro area.

Tsunami inundation height was T.P. +5.74 m at the administration office building of the terminal company, Hachinohe Kowan Unso Kaisha Ltd.. **Photo 1** shows a tsunami memorial board displayed inside the building. According to the survey conducted by TTJT, the inundation height was T.P. +6.16 m at survey point PARI-0394. In this study, the average value of the two, T.P. +5.95m was adopted.

Ground elevation was measured through field survey. **Fig. 13** shows a snapshot of measurement work and a cross sectional view of the terminal. Ground elevation of wharf was T.P. +2.50 m at the survey point, and the inundation depth was estimated at 3.45 m.

**Fig. 14** shows a plain view of the terminal. In the figure, a marshaling yard is partitioned into small zones distinguished by dotted lines. In the terminal, 1,159 containers were stored at the time of the earthquake. Containers in area A consisted mainly of 20 and 40 foot containers with cargo in triple stacks, and 20 foot empty containers in triple stacks. In area B, the number of container was approximately 150, mainly consisting of 40 foot empty containers in double stacks.

**Photos 2** a) and b) show satellite views of the terminal on June 6, 2010 and March 13, 2011, respectively. Many containers were scattered over a wide area of the terminal because of the repeated inflow and backflow of the tsunami. Some containers were concentrated around a warehouse. According to the hearing, 458 containers were located at the terminal after the tsunami, and 701 containers were lost from the terminal. **Photo 3** shows that wire fences were also damaged and broken.

Although many containers were lost from the terminal, some triple stack containers remained. **Photo 4** shows the terminal immediately after the tsunami. Some 20 foot triple stacked containers are in their original positions. The cargo of these containers was ferronickel with a mass of approximately 20 t for each container. According to the hearing survey, it was observed that the bottom and middle containers in the triple stack were wet due to the tsunami. The container at the top remained dry. Although the triple stacked containers remained at their original positions after the tsunami, double stacked containers drifted even if loaded with ferronickel.

As we will discuss later in Section (1) of Chapter 4, when the inundation depth is 3.45 m, the buoyant force acting on a 20 foot container is estimated to be $4.71 \times 10^5$ N. **Fig. 43** shows that when the inundation depth is 3.45 m, it is equivalent to the magnitude of gravitational force of 48.0 t in mass. The buoyant force is not enough to drift the triple stacked containers, because the mass of triple stacked 20 foot containers filled with ferronickel is approximately 67 t. On the other hand, the mass of double stacked 20 foot container with ferronickel is only 44 t. Therefore, the buoyant force is enough to drift these containers. This result agrees with the observed fact through Photo 4.

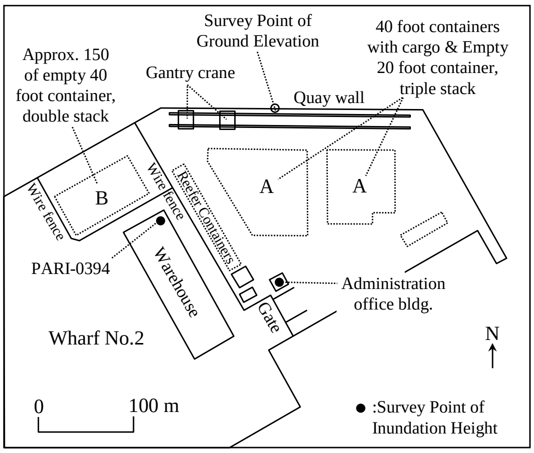
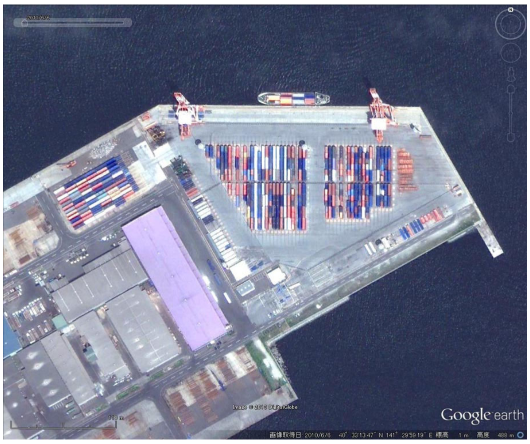



**Fig. 14** Plain view of the Container Terminal

**Fig. 15** shows beaches upon which containers from the Hachinohe Port were washed ashore. The northern boundary is the coast of Onbetsu, Kushiro City, Hokkaido, and the southern boundary is the coast of Oarai Town, Ibaraki Prefecture. Onbetsu and Oarai are 330 km and 480 km from the port in linear distance, respectively. Both containers washed up on the beaches are reefer containers. Although insufficient knowledge exists on the floating behavior of containers, reefer containers may show relatively high waterproof quality, which may have enabled them to travel far from the port.

As shown in **Fig. 15** b), many containers were found near the Hachinohe port. **Photo 5** shows container debris that washed up on a reef 5 km from the terminal, at Shimomatsu-naeba, Same, Hachinohe City. According to the figure, containers also washed ashore at upstream areas of the river. It is estimated that containers drifted along the river from the river mouth to the upstream areas by the force of the tsunami.



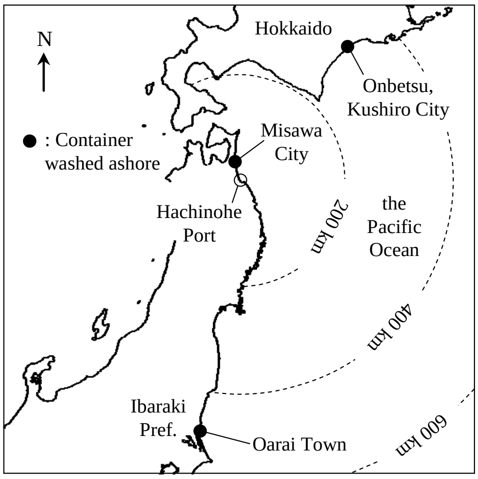

a) Pre-tsunami at June 6, 2010. Photo by Google Earth


b) Post-tsunami at March 13, 2011. Photo by Google Earth

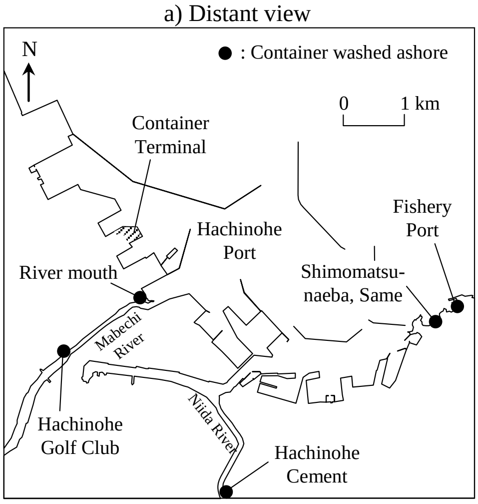
**Photo 2** Satellite View of Container terminal

**Photo 3** Damaged wire fence on March 16, 2011.
Photo courtesy of Mr. Yuji WATANABE


**Photo 4** Container terminal of the Hachinohe Port.
Photo courtesy of Hachinohe Kowan Unso Kaisha, Ltd.




a) Distant view




b) Close-up view

**Fig. 15** Beaches upon which containers washed ashore

**Photo 5** Container debris on reef of Shimomatsu-naeba, Same, Hachinohe City on March 16, 2011

## f) Miyako Port

**Fig. 16** shows a plain view of the Miyako Port. The container terminal lies behind Berth No. 8 in the Fujiwara area. Seven containers including five 20 foot and two 40 foot containers were stored at the terminal in a single stack. Both of the two 40 foot containers held the cargo of pasture grass. The 20 foot containers were empty.

According to the TTJT report, the tsunami inundation height was T.P. +8.94 m at PARI-0401. Ground elevation was T.P. +1.99 m according to the field survey conducted by Takahashi et al. 2011[8]. The inundation depth was then estimated at 6.95 m on the wharf.

All seven containers were lost into the sea at the Miyako Port. Unfortunately, no information exists on their final destinations. The wire fence surrounding the terminal was damaged by the tsunami.

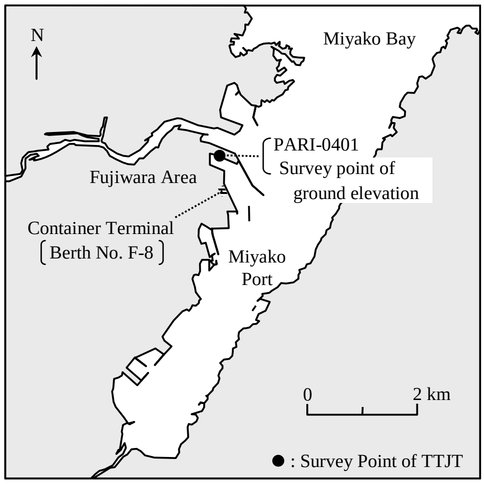



**Fig. 16** Miyako Port

## g) Kamaishi Port

**Fig. 17** shows a plain view of the Kamaishi Port. The container terminal is located at the tip of Suka Public Wharf. No containers were stored in the terminal at the time of the earthquake, because there is no regular container shipping service. According to the TTJT report, the tsunami inundation height was T.P. +8.93 m, based on an average of six survey points. Locations and identification numbers of these points are shown in the figure. Ground elevation was T.P. +0.44 m at a survey point, and a cross sectional view of the point is shown in **Fig. 18**. The inundation depth was estimated at 8.49 m on the terminal. According to the hearing, the wire fence surrounding the terminal was damaged due to tsunami.

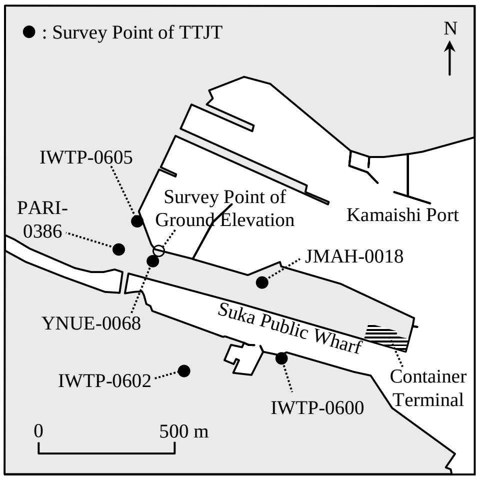



**Fig. 17** Kamaishi Port

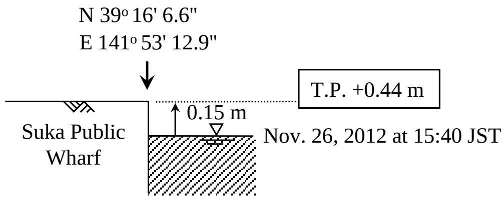



**Fig. 18** Ground elevation of wharf of Kamaishi Port

### h) Ofunato Port

**Fig. 19** shows a plain view of the Ofunato Port. The container terminal is located at the Nonoda area. **Photo 6** shows an aerial view of the area in May 2010. 73 containers were stored in double stacks at the time of the earthquake. 35 containers are with cargo, and the other 38 were empty containers. No information was available on container size in length.

According to the TTJT report, the tsunami inundation height was T.P. +8.71 m at survey point, YNUE-0042. Ground elevation was T.P. +0.50 m according to a result of a field survey, as shown in **Fig. 20**. The survey point is located at the Chayamae area, which is a neighboring area of the terminal. Although the survey point of ground elevation is approximately 700 m from the terminal, inundation depth was estimated at 8.21 m on the terminal.

72 containers were lost from the container terminal of the the Ofunato Port. Only one container was left on the terminal following the tsunami. The container held cargo. Nearly all wire fences surrounding the terminal were damaged.

32 containers were found following the tsunami and were scattered in a widespread area around the Ofunato Bay. **Fig. 21** shows locations in which 25 of the 32 containers landed. The location data for this figure were determined on the basis of a survey regarding tsunami-induced debris conducted by MIIT, which was provided by the Ofunato City Office. The inundation area drawn in the figure is the result of a survey conducted by Haraguchi and Iwamatsu (2011) [9]. According to Fig. 21, 25 containers were found in the northern half of the Ofunato Bay area. Unfortunately, the author has no information data on the location of the remaining seven containers.

41 of the 72 containers remain unaccounted for.

### i) Ishinomaki Port

**Fig. 22** shows a plain view of the Ishinomaki Port. The container terminal is located at the Hibarino area. According to the TTJT report, the tsunami inundation height was T.P. +6.67 m at the survey point, MLIT-0345. Ground elevation was T.P. +1.33 m, based on the averaged value of the two points [10]. The inundation depth was then estimated at 5.34 m on the container terminal. According to the hearing survey, 40 containers were lost from the terminal.

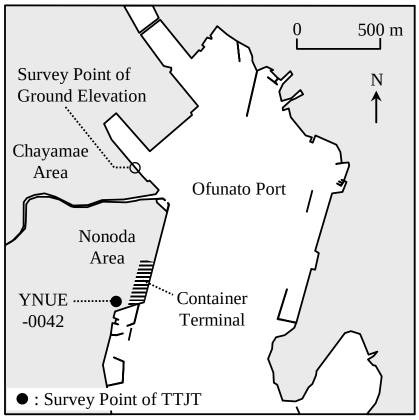



**Fig. 19** Ofunato Port

**Photo 6** Aerial view of container terminal in May 2010, Photo courtesy of Iwate Prefecture

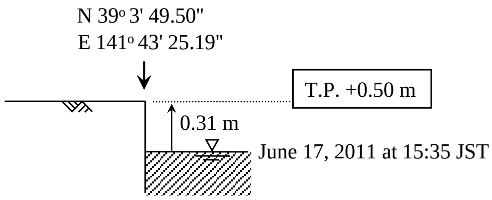



**Fig. 20** Ground elevation of the wharf at Ofunato Port

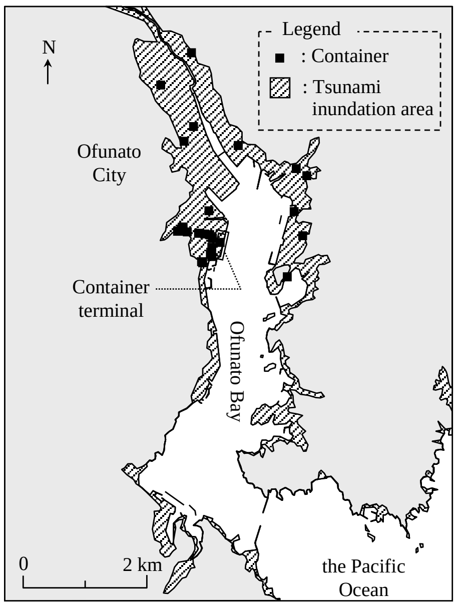



**Fig. 21** Containers found around Ofunato Bay after the tsunami

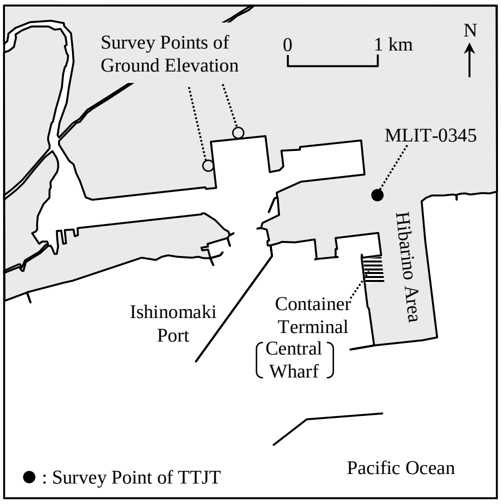



**Fig. 22** Ishinomaki Port

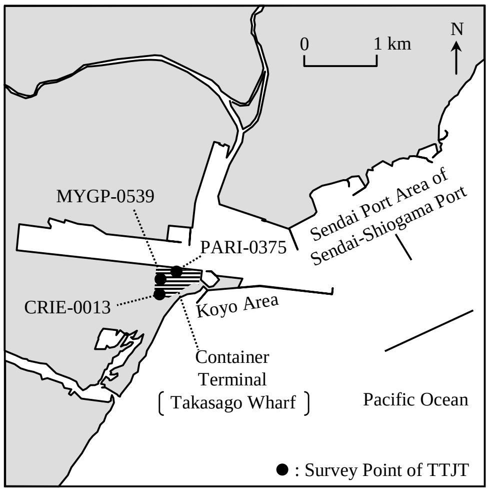



**Fig. 23** Sendai Port area of Sendai–Shiogama Port

## j) Sendai–Shiogama Port

The Sendai–Shiogama Port consists of two port areas including the Sendai Port area and the Shiogama Port area. The container terminal is located at the Koyo area of the Sendai Port area. **Fig. 23** shows a plain view of the area.

**Fig. 24** shows a close-up of the container terminal. The tsunami inundation height was T.P. +6.49 m, based on the average of three survey points of the survey conducted by TTJT. The three survey points are shown in the figure. The author conducted a ground elevation survey. **Fig. 25** shows results of the survey in a cross sectional view of the wharf. Ground elevation was T.P. +2.95 m at the survey point, and the inundation depth on the terminal was then estimated at 3.54 m.

At the time of the earthquake, 4,318 containers were stored in the terminal. **Table 3** shows the number and characteristics of these containers. 614 were 20 foot containers with cargo, and 1,254 were 40 foot container with cargo. The number of empty 20 foot container is 866, and empty 40 foot container is 1,584.

The marshaling yard on the terminal was partitioned into 10 small zones, distinguished in **Fig. 24** from neighboring areas by dotted lines and marked with characters A–J.

Containers stored in area A in **Fig. 24** were triple stacked containers with cargo. 60 % are 20 foot containers and 40 % are 40 foot containers.

In area B, containers with cargo were double stacked.

In areas C and D, containers with cargo were triple stacked. No information was obtained on the size of the containers in these areas.

In area E, containers with cargo were triple stacked. 60 % are 20 foot containers and 40 % are 40 foot containers.

Containers were also stored in areas F and H.

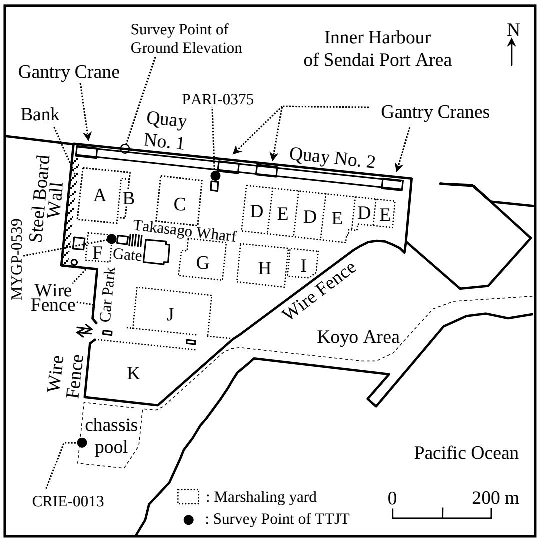



**Fig. 24** Container terminal of Sendai–Shiogama Port

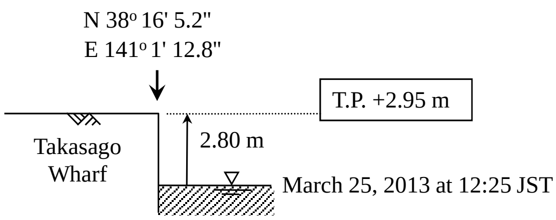



**Fig. 25** Ground elevation of Sendai-Shiogama Port

However, no information on their sizes or cargo conditions was available.

In area G, empty containers and containers with cargo were double stacked.

In areas I, J and K, empty containers were quadruple stacked. In area I, 60 % of the containers are 20 foot and 40 % are 40 foot containers. In area J, no information on container size was available. In area K, 40 % of the containers are 20 foot and 60 % are 40 foot containers.

Items of export cargo include tires, roll paper and pulp. The mass of tires for each 40 foot container is approximately 6 to 8 tonnages. The mass of roll paper for each 20 foot container is approximately 16 tonnages.

**Photo 7** shows a terminal that immediately followed the earthquake, prior to the arrival of the tsunami. It is found that a container has fallen to the ground from the top of the triple stacked containers because of the strong seismic motion. According to the hearing survey, several containers had fallen. It should be noted that this photo was slightly altered to conceal the name of the shipping company on the fallen container.

**Photos 8** a) and b) show aerial views of the terminal on March 31, 2009 and March 12, 2011, respectively. As a result of the tsunami, many containers were concentrated at the west end of the terminal. Some were scattered around the terminal, and others were moved eastward and were washed onto the shallow reef located next to the container terminal.

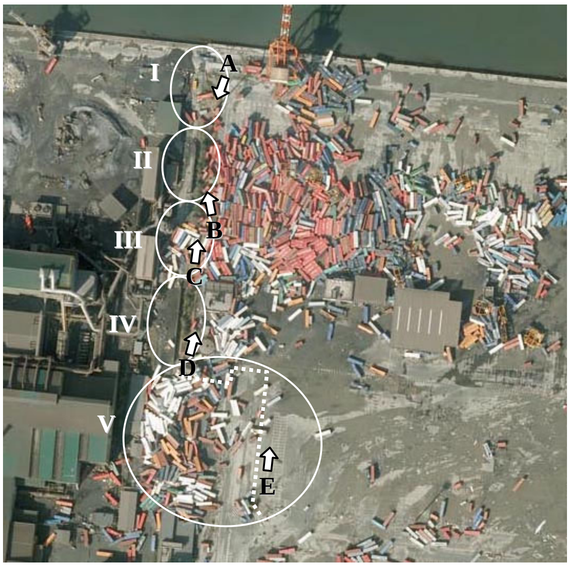
**Table 3** Characteristics of Container stores on Terminal

| | 20 foot Container | 40 foot Container | Total |
|---|---|---|---|
| Container with Cargo | 614 | 1,254 | 1,868 |
| Empty Container | 866 | 1,584 | 2,450 |
| Total | 1,480 | 2,838 | 4,318 |

**Photo 7** Displacement and Fallen Container in Triple stack due to the seismic effect,
Photo by courtesy of Shiogama-kowan Unso Co.Ltd.
*This photo was altered to conceal the name of the shipping company written on the fallen container.

a) Pre-tsunami conditions on March 31, 2009.
Photo by Google Earth

b) Post-tsunami conditions on March 12, 2011.
Photo by GSI




**c)** Close-up of zones I–V, Photo by GSI
**Photo 8** Aerial view of the container terminal at Sendai-Shiogama Port

According to the hearing survey, 2,594 containers were found on the terminal after the tsunami. 1,528 were empty containers and 1,066 were containers with cargo. On the other hand, 1,724 containers were lost from the terminal.

**Photo 8** c) shows a close-up view of **Photo 8** b) focusing on the boundary, where the containers are concentrated. Zones I to IV include a steel board wall and a bank parallel to the wall. Zone V includes a wire fence on the boundary, and no bank.

Although the role of the bank for blocking containers remains unclear, a description of its physical conditions may be useful. **Fig. 26** shows the field survey results of the elevation of the bank on April 22, 2013. According to the survey, the length, width and height of the bank is approximately 210 m, 14 m and 1.0–1.6 m above the ground level of the quay, respectively.

**Photo 8** c) shows that, in zones I and III, the steel board wall on the boundary had broken, and containers drifted westward beyond the boundary and to reach to the outside area of the terminal. **Photos 9** a) and c) show zones I and III in April 2013. The wall had been restored already at that time. Both zones are in a treeless area, and containers were driven beyond the bank without interruption of vegetation. The wall was previously broken by the tsunami flow or by collision with containers.

In zone II, in contrast, the wall remained in its original condition despite the tsunami inundation. **Photo 8** c) shows that the vegetations on the bank dammed the tsunami debris and prevented the wall from collapsing. **Photo 9** b) shows the vegetation in the zone. The differences between zone II and zones I and III imply that the bank and trees on the bank have some effect for blocking the containers in this terminal.

In zone IV, containers were trapped behind the fumigation warehouse, water supply tank, and other small buildings, as shown in **Fig. 26**. No containers drifted beyond the bank in this zone.

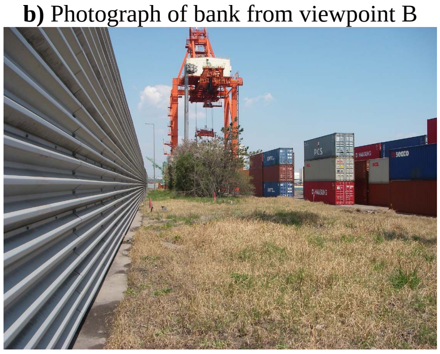
There is no bank in zone V. A wire fence separates the terminal area from the outside of the terminal, as shown in **Photo 9** e). Containers drifted to westward beyond the boundary and reached the outside area of the terminal. The wire fence was broken due to the tsunami.

**Photo 10** shows an aerial view of Sendai Bay following the tsunami, in which many containers are floating on the sea surface. No information on the date of this photo is available.

In the main channel and its surrounding area, many containers sank to the seabed. Salvage operations were implemented until May 2011 to resume safe shipping navigation connecting the outer sea and

**a)** Photograph of bank from viewpoint A

**b)** Photograph of bank from viewpoint B



**c)** Photograph of bank from viewpoint C

**d)** Photograph of bank from viewpoint D

**e)** Photograph of wire fence from viewpoint E

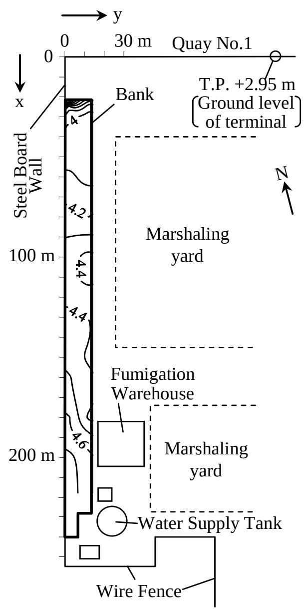
**Photo 9** West end of the terminal

the inner port area. **Fig. 27** shows salvage points in this operation, in which 324 containers were removed. The location data for the figure were provided by Marine environment and Engineering Division of Tohoku Regional Development Bureau of MLIT.

**Fig. 28** shows beaches around the Sendai Bay upon which containers washed ashore from Sendai Shiogama Port. The eastern boundary is the coast of Higashihama Beach of Makinohama, Ishinomaki City, and the southern boundary is the coast of Iwanuma City. Higashihama Beach and Iwanuma City are 37 km and 20 km from the port in linear distance, respectively.

A newspaper article printed in the Asahi Shimbun on August 23, 2011, stated that approximately 200 freight containers washed ashore on the beaches along coasts from Ishinomaki City to Iwanuma City [11]. The article also stated that approximately 30 freight containers washed ashore on Shobuta Beach in Shichigahama Town.

**Photo 10** Aerial view of containers on sea surface of Sendai Bay, Photo courtesy of the Japan Coast Guard




Elevation of tha Bank on the Terminal

| No. | x | y | height above T.P. (m) |
|---|---|---|---|
| 1 | 0 | 2 | 2.94 |
| 2 | 22.6 | 2 | 3.19 |
| 3 | 24.85 | 2 | 3.85 |
| 4 | 30 | 2 | 3.96 |
| 5 | 40 | 2 | 3.96 |
| 6 | 50 | 2 | 4.06 |
| 7 | 60 | 2 | 4.13 |
| 8 | 70 | 2 | 4.19 |
| 9 | 80 | 2 | 4.22 |
| 10 | 100 | 2 | 4.37 |
| 11 | 120 | 2 | 4.38 |
| 12 | 140 | 2 | 4.46 |
| 13 | 160 | 2 | 4.51 |
| 14 | 180 | 2 | 4.61 |
| 15 | 200 | 2 | 4.73 |
| 16 | 24.85 | 12 | 3.96 |
| 17 | 40 | 12 | 4.06 |
| 18 | 60 | 12 | 4.03 |
| 19 | 70 | 12 | 4.18 |
| 20 | 80 | 12 | 4.20 |
| 21 | 100 | 12 | 4.43 |
| 22 | 150 | 12 | 4.38 |
| 23 | 180 | 12 | 4.38 |

**Fig. 26** Elevation of Bank

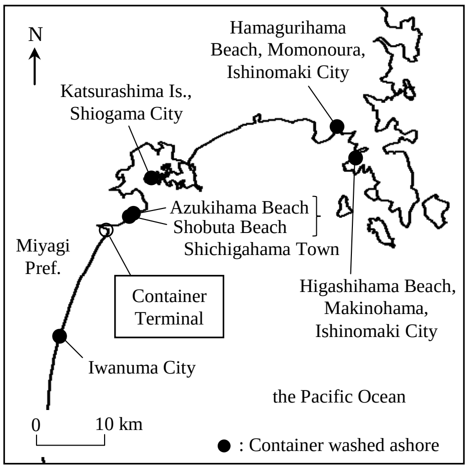



**Fig. 28** Beaches upon which container were washed ashore

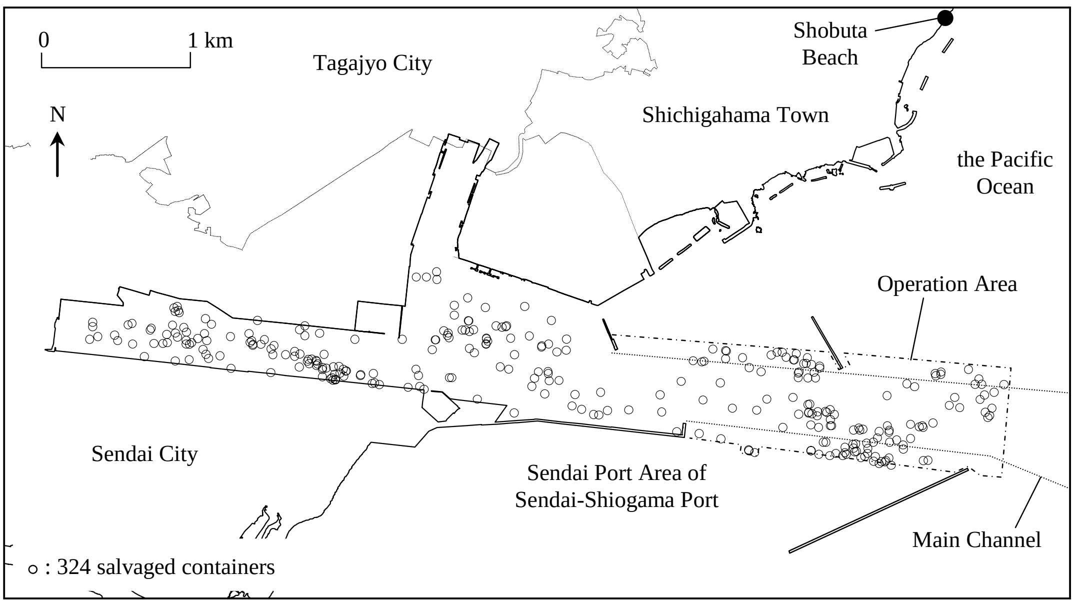



**Fig. 27** Containers Salvaged in Main channel and its surrounding area of Sendai-Shiogama Port

## k) Soma Port

**Fig. 29** shows a plain view of the Soma Port. The container handling area is located at Wharf No. 2.

**Photo 11** shows the container handling area on September 8, 2009. When the Tohoku earthquake occurred, six freight containers were stored in the area in a single stack. One is a container with cargo, and the other five are empty containers. All containers are 40 foot in length.

According to the TTJT report, the tsunami inundation height was T.P. +9.73 m at survey point, PARI-0414. Ground elevation was T.P. +2.08 m, according to a survey conducted by the Soma Branch Office of Onahama Port Office, MLIT. The inundation depth was therefore estimated at 7.65 m on Wharf No. 2.

All of the six freight containers were lost from container handling area of the Soma Port. Five of the six were found on land areas. The other was lost into the sea and was salvaged from the sea bottom. **Fig. 30** shows the locations at which the containers arrived. The five containers were driven westward from the container handling area by the tsunami. One of the five containers was driven to the west approximately 1,100 m from the terminal, and was cast to the front side of an industrial plant.

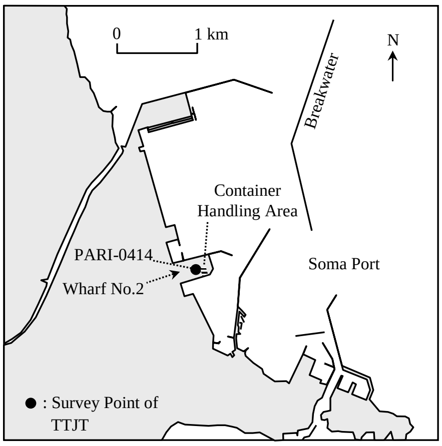



**Fig. 29** Soma Port

**Photo 11** Container handling area on September 8, 2009, Photo courtesy of the Soma Branch of Onahama Port Office, MLIT

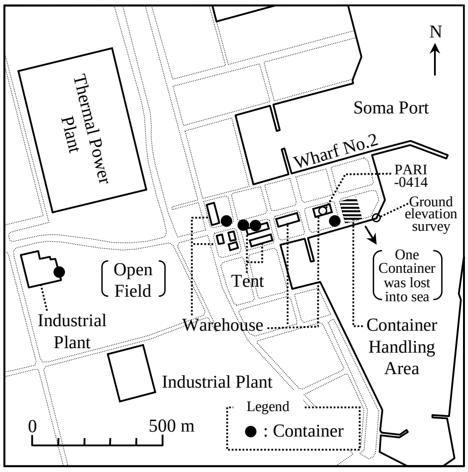



**Fig. 30** Containers located around Soma Port after the tsunami

## l) Onahama Port

**Fig. 31** shows a plain view of the Onahama Port. The container terminal is located at the Ohtsurugi area.

**Fig. 32** shows a close up view of the terminal. According to the TTJT report, the tsunami inundation height was T.P. +3.56 m, based on the average of two survey points PARI-0419 and FKSP-0094. Ground elevation was T.P. +2.04 m, according to a survey conducted by the Onahama Port Office of MLIT. The inundation depth was, therefore, estimated at 1.52 m on the terminal.

Area A of **Fig. 32** included containers with cargo in a triple stack. Approximately half of the containers are 20 foot, and the rest are 40 foot. According to the hearing, the average gross weight of a 20 foot container in this area is approximately 18,000 kg. Because the mass of the empty container is approximately 2,200 kg, by reference of **Appendix A**, the mass of the cargo is approximately 15,800 kg. The average gross weight of a 40 foot container in this area is estimated at approximately 20,000 kg.

In area B, 40 foot containers with cargo were triple stacked. The gross weight of each container is approximately 23,000 kg to 24,000 kg.

In area C, 20 and 40 foot empty containers were triple stacked. The bottom and middle containers in 20 foot triple stack were connected by fittings. The 40 foot containers had no such connection. In this area, horizontal gaps between container rows were very narrow and in close contact with each other, because the containers were stacked by a top-lifter forklift. In areas A and B, in contrast, a relatively wide gap was present between rows, because containers were stacked by a straddle-carrier truck.

In area D, empty containers were stored in usual. But, at the Tohoku earthquake, the containers with cargo were triple stacked. No information is available on the sizes of the containers in this area.

**Photo 12** shows displacement of a triple stacked container due to the earthquake. According to the hearing, no containers fell from the top position of the triple stack to the ground.

According to hearing, no container was driven to the outside of the terminal, and no containers were lost from the container terminal. **Photo 13** shows an aerial view of the container terminal on March 13, 2011, following the tsunami. All containers remained inside the terminal. However, one empty 40 foot container in a single stack was moved by the tsunami and remained at the center of the terminal.

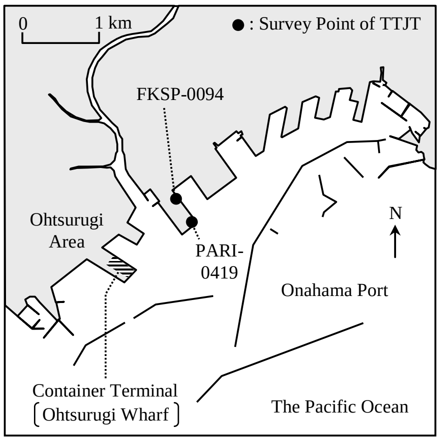



**Fig. 31** Onahama Port

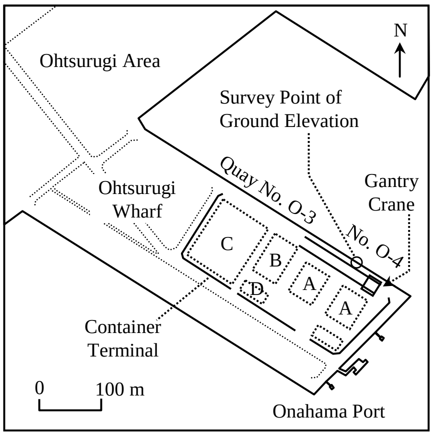



**Fig. 32** Container Terminal of Onahama Port

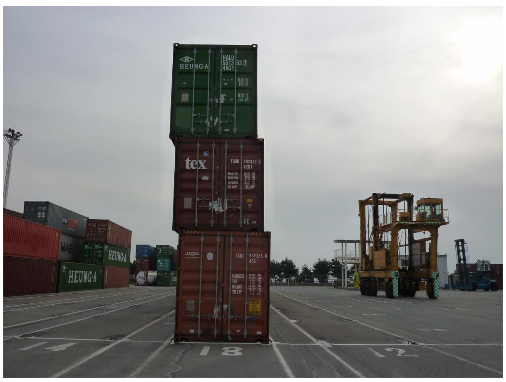


**Photo 12** Displacement of triple stack container due to the earthquake at Onahama Port, Photo by courtesy of Onahama Port Office of MLIT

## m) Ibaraki–Hitachinaka Port

**Fig. 33** shows a plain view of the Ibaraki –Hitachinaka Port. The container terminal is located at the North Wharf.

According to the TTJT report, the tsunami inundation height is T.P. +4.32 m at PARI-0435. **Fig. 34** shows a close-up view of the terminal. The author conducted ground elevation survey at the point shown in the figure. **Fig. 35** shows a result of the survey in a cross sectional view of the terminal. The ground elevation was T.P. +2.20 m at the survey point. The inundation depth, therefore, was estimated at 2.12 m on the terminal.

In areas A, B, and C in **Fig. 34**, 639 containers were quadruple stacked. According to the results in April 2011, approximately 40 % of the containers stored on the terminal were 20 foot and approximately 60 % of them were 40 foot.

The tsunami entered the inner harbor through the north and south openings of the breakwater. According to a worker at the terminal, containers were swept by the tsunami, which entered the inner harbor through the south opening. **Photo 14** b) and **Fig. 36** show an aerial view and a sketch of the terminal after the tsunami, respectively. Many containers were swept and were concentrated at the northern end of the terminal. If the movement was caused by the tsunami through the south opening of the breakwater, the containers should have been swept from the south to the north. This fact coincides with the eyewitness report from the worker.

Most of the containers were trapped by the wire fence. However, eight containers drifted through the boundary beyond the wire fence or through the section where the fence was broken, and finally caught into the windbreak fence located in the area of thermal power plant, next to the container terminal. **Fig. 37** and **Photo 15** show the damaged wire fence. The fence was broken into two sections of 23.8 m and 30.5 m in length.

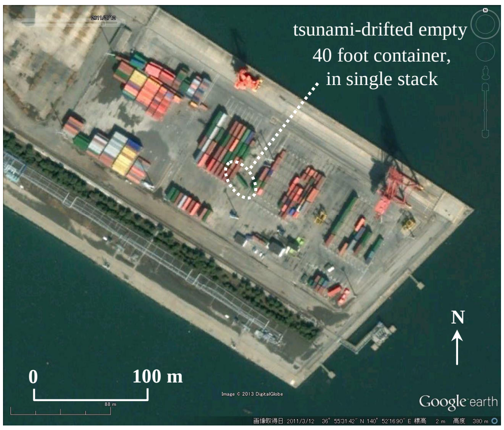



**Photo 13** Container terminal of Onahama Port on March 13, 2011. Photo by Google Earth

Because of the tsunami, containers were also scattered at the central area of the terminal and in the area near the gantry cranes. It should be noted that some containers remained in their original positions.

Four containers were swept to sea. **Photo 16** shows a 40 foot container floating on the sea surface of the inner port along the breakwater. Two of the four were empty 40 foot containers. The third was a 40 foot container with cargo, and the fourth one was an empty 20 foot container.

The two empty 40 foot containers swept to sea were once found at Isozaki and Hiraiso beaches, as shown in **Fig. 38**. The beaches are at the south of the container terminal, approximately 6 km and 8 km away from the terminal, respectively. Both containers arrived at the two beaches and were again swept by waves on the beach to be completely lost into the sea. The 40 foot container with cargo was found at Kujihama Beach, approximately 8 km away from the container terminal to the north. The 20 foot container was not found and was lost into the sea.

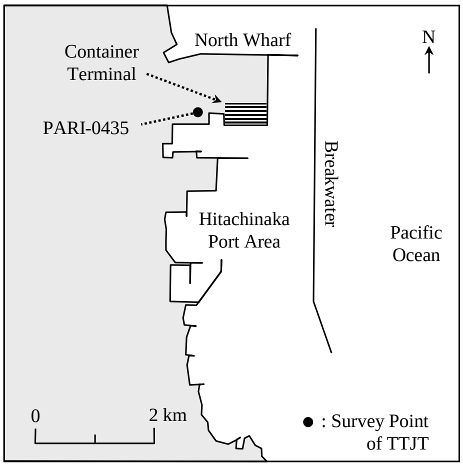



**Fig. 33** Ibaraki–Hitachinaka Port

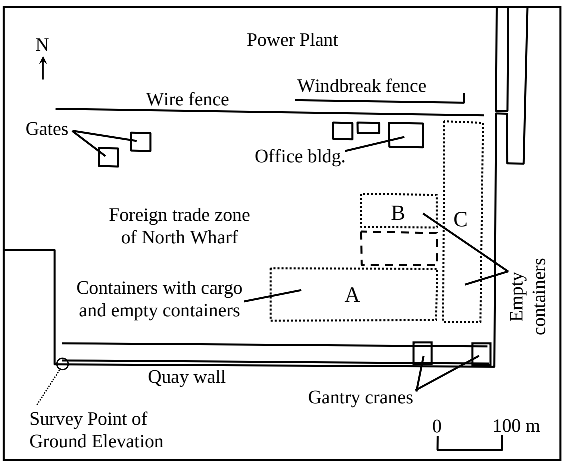



**Fig. 34** Pre-tsunami conditions of container terminal of Ibaraki–Hitachinaka Port

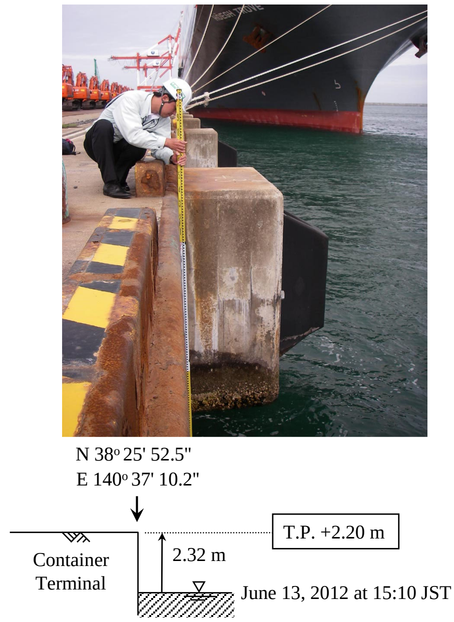
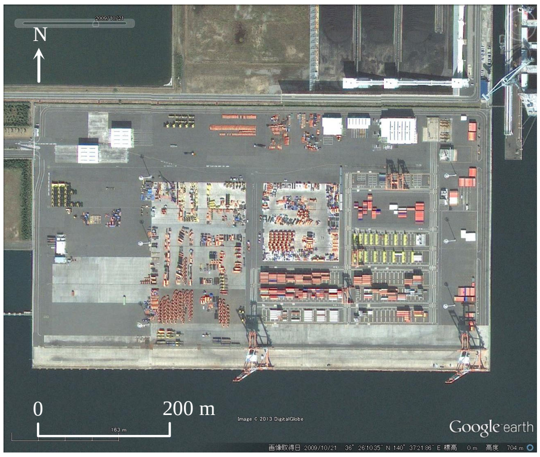
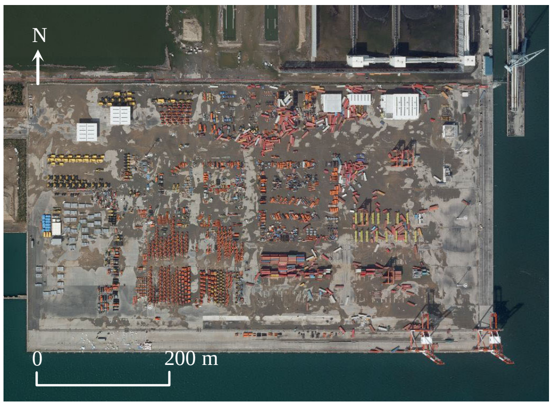



**Fig. 35** Ground elevation of Ibaraki–Hitachinaka Port




a) Pre-tsunami conditions on Oct. 21, 2009.
Photo by Google Earth




b) Post-tsunami conditions on March 12, 2011.
Photo by GSI

**Photo 14** Aerial view of container terminal of Ibaraki–Hitachinaka Port

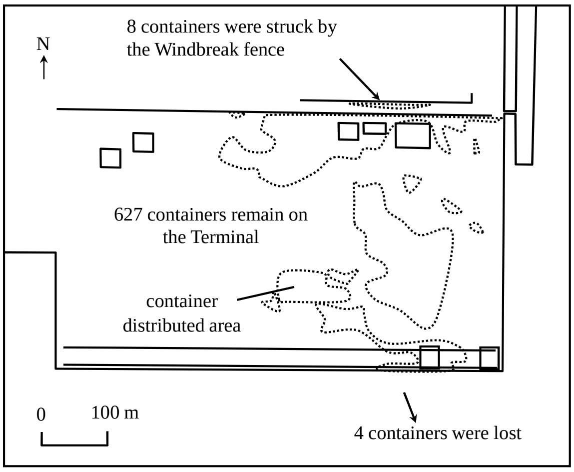



**Fig. 36** Post-tsunami view of scattered containers

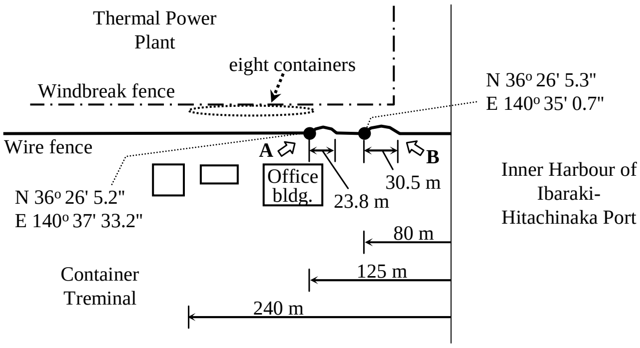



**Fig. 37** Damages to wire fence

a) Snapshot from view point A

b) Snapshot from view point B

**Photo 15** Snapshots of wire fence

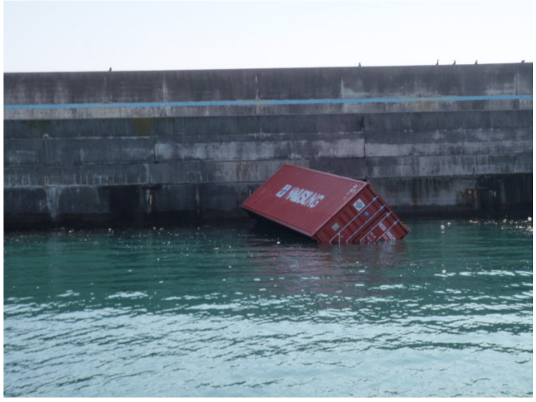


**Photo 16** Container floating on the sea surface of the inner port along the breakwater of Ibaraki–Hitachinaka Port on March 13, 2011, Photo courtesy of the Hitachnaka Branch Office of Kashima Port and Airport Construction Office, MLIT

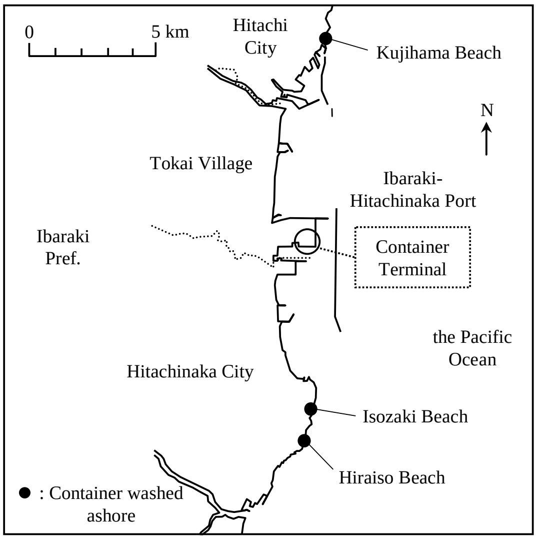



**Fig. 38** Beaches upon which containers were washed ashore

## n) Kashima Port

**Fig. 39** shows a plain view of Kashima Port. The container terminal is located at the North Public Wharf area.

**Fig. 40** shows a close up view of the container terminal. According to the TTJT report, the tsunami inundation height was T.P. +4.31 m at PARI-0424. The author conducted a ground elevation survey, whose results are shown in **Fig. 41** as a cross sectional view of the terminal. Ground elevation was T.P. +2.43 m at the survey point. The inundation depth, therefore, was estimated at 1.88 m on the terminal.

In the container terminal, 809 containers were stored at the time of the earthquake, including three hundred and sixty three 20 foot containers with cargo, fifteen 40 foot containers with cargo, 370 empty 20 foot containers, and 61empty 40 foot containers (**Table 4**). The average mass of the cargo in the 20 foot containers was approximately 16,000 kg. That of the 40 foot container is approximately 16,000 kg to 26,000 kg.

According to the hearing, 353 containers remained on the terminal following the tsunami. All were 20 foot containers with cargo. The 20 foot empty containers and all of 40 foot containers drifted beyond the boundary and reached the outside area of the terminal. 456 containers were lost from the terminal, all of which were found on land areas behind the terminal. No containers were lost to the sea.

In area A of **Fig. 40**, three 20 foot containers with cargo were stored in a single stack. All were swept by the tsunami, and reached the outside area of the container terminal.

In area B, empty containers were stored in a single stack. No information on the numbers and sizes of containers was available in this area.

In area C, thirty-one 40 foot containers and ten 20 foot containers were stored, and all of them were containers with cargo. Three 20 foot containers and ten 40 foot containers were lost by the tsunami, and twenty-eight 20 foot containers remained on the terminal.

In area D, two 20 foot containers and five 40 foot containers were stored in a single stack, and all of them were containers with cargo. All containers in this area were lost by the tsunami.

In area E, empty containers were stored in a single stack. No information on the numbers and sizes of containers was available in this area.

In area F, empty containers were stored in double stack. No information on the numbers and sizes of containers was available in this area.

In area G, three hundred and twenty seven 20 foot containers with cargo were stored in a double stack. Two 20 foot containers were lost by the tsunami, and the rest remained on the terminal. **Photo 17** shows the containers in area G in September 2012. Horizontal gaps between container rows are very narrow and in close contact with each other in an orthogonal direction to the container's long axis because the containers were stacked by a top-lifter forklift.

**Photo 18** shows an aerial view of container scattered area behind the terminal. It can be seen that containers were scattered in a wide area behind the terminal. Koyama (2011) developed a distribution map of the scattered containers on the basis of his field survey and photo image analysis research [12]. According to Koyama's research and an additional photo image analysis conducted by the author, the area in which containers arrived from the terminal due to the tsunami was determined, as indicated by the dotted line in **Photo 18**. The size of the area is approximately 1.2 km in an east-west direction, and approximately 1.1 km in a north-south direction.

**Photo 19** shows the wire fence at the container terminal, which was broken by the tsunami, from the viewpoint of X in **Fig. 40**. According to the photo, the wire fence was severely damaged and fell toward the outside of the container terminal.

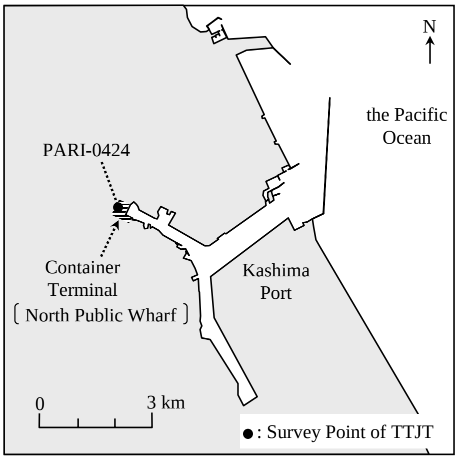



**Fig. 39** Kashima Port

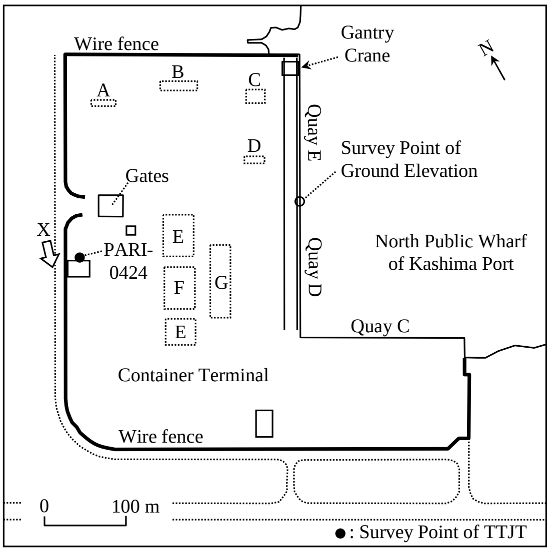



**Fig. 40** Container terminal of Kashima Port

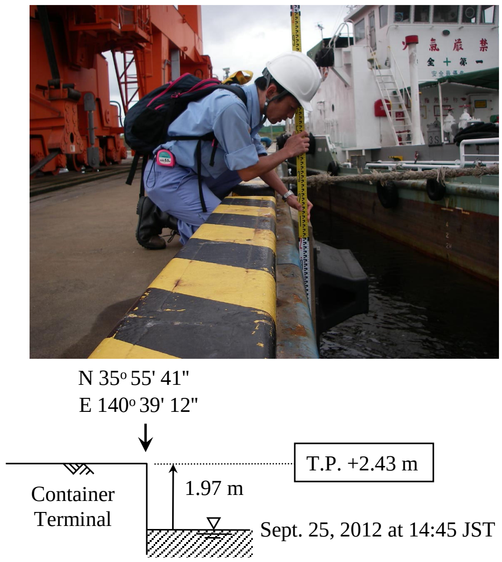



**Fig. 41** Ground elevation of Kashima Port

**Table 4** The number of containers at Kashima Port *

| | 20 foot Container | 40 foot Container | Total |
|---|---|---|---|
| Container with Cargo | 363 (353) | 15 (0) | 378 (353) |
| Empty Container | 370 (0) | 61 (0) | 431 (0) |
| Total | 733 (353) | 76 (0) | 809 (353) |

*The upper figure in each field of matrix are the number of container stored at the Tohoku earthquake, and the lower figure in parentheses are the number of container which remained on the container terminal after the tsunami.

**Photo 17** 20 foot containers with cargo in area G on September 25, 2012


**Photo 18** Aerial view of area around the container terminal on March 12, 2011, Photo by Google Earth

**Photo 19** Broken wire fence of container terminal in Kashima Port, Photo courtesy of Ibaraki Prefectural Office

## 4. DISCUSSION

### (1) Inundation Depth and Container Mass

Buoyant force acts on containers inundated by the tsunami. **Fig. 42** shows the vertical forces acting on a body of double stacked containers. Gravitational force $F$, buoyant force $B$, and restitution force $R$ act on the body in the vertical direction. $F$ is determined by the mass of the container $M$ and acceleration of gravity $g$. $B$ is determined by tsunami inundation depth $h_i$, width of the container $W$, length of the container $L$, height of the buoyancy-free base structure $h_b$, density of seawater $\sigma$, and $g$. Buoyant force $B$ is defined by the following formulae:

$$
\begin{array}{lll}
B = const. = 0 & 0 & < h_i \leqq h_b \\
B = (h_i - h_b)WL\sigma \cdot g & h_b & < h_i \leqq h_c \\
B = const. & h_c & < h_i \leqq h_c + h_b \\
B = (h_i - 2h_b)WL\sigma \cdot g & h_c + h_b & < h_i \leqq 2h_c \\
B = const. & 2h_c & < h_i \leqq 2h_c + h_b \\
B = (h_i - 3h_b)WL\sigma \cdot g & 2h_c + h_b & < h_i \leqq 3h_c \\
B = const. & 3h_c & < h_i \leqq 3h_c + h_b \\
B = (h_i - 4h_b)WL\sigma \cdot g & 3h_c + h_b & < h_i \leqq 4h_c
\end{array}
\qquad (1)
$$

For all container types, $W$ equals 2.44 m. For 20 foot, 40 foot and 40 foot high cube containers, $L$ equals 6.06 m, 12.19 m and 12.19 m, respectively. As stated in Section (5) of Chapter 2, $h_b$ equals 0.14 m. $\sigma$ equals 1,030 kg/m$^3$ and $g$ equals 9.81 m/s$^2$.

**Figs. 43–45** show relationships between $h_i$ and $B/g$ for 20 foot, 40 foot and 40 foot high cube container, respectively.

$R$ equals $M$ minus $B$. When the value of $R$ is negative, the container floats. When the value of $R$ is zero or positive, container stability depends on the balance between the static frictional force and drag force in the horizontal direction. To estimate the static frictional force, the report by Honda and Hori (1980) helps us to know the value of the maximum

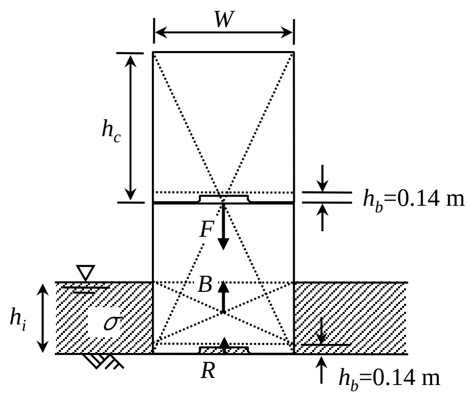



**Fig. 42** Vertical forces acting on double Stacked container

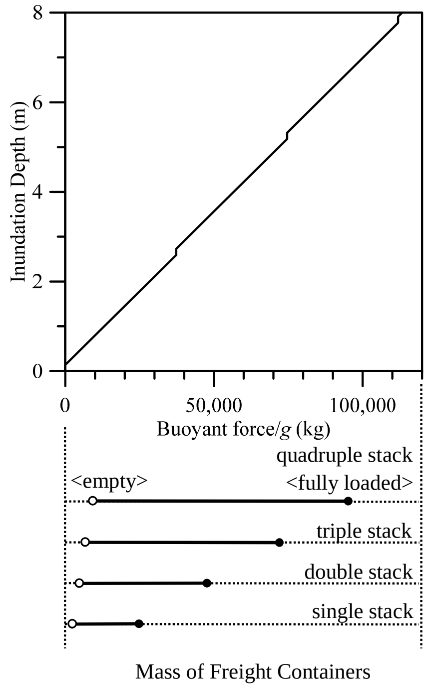



**Fig. 43** Relationship between inundation depth and buoyant force on 20 foot container

coefficient of static frictional force μ [13]. In their report, they noted μ=0.56 at dry condition and μ =0.53 at wet condition between the 20 foot container and asphalt pavement from the result of the full-scale container tensile test.

Case examples of the container with cargo of Ports No. 5, 10, 12 and 14 were analyzed in this study because detailed conditions of cargo and damages due to the tsunami are available in these ports, as reported in the previous section.

**Table 5** shows verification data in the four ports for correlation between tsunami inundation depth and tsunami damage. The information was extracted from the previous descriptions of e), j), l) and n) in Section (2) of Chapter 3.

For example, in Port No. 5, Hachinohe Port, 20 foot containers with ferronickel cargo were triple stacked, in reference to (2) e) of Chapter 3. The mass of the ferronickel was 20 × $10^3$ kg for each contaner. Because the average tare mass of the empty container is 2.2 × $10^3$ kg, the mass of a single container with

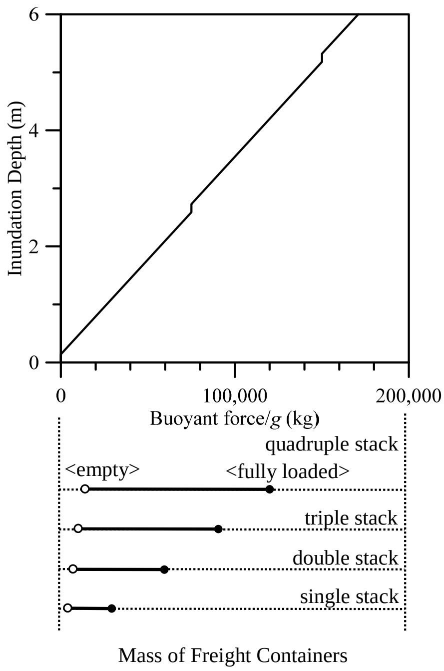



**Fig. 44** Relationship between inundation depth and buoyant force on 40 foot container

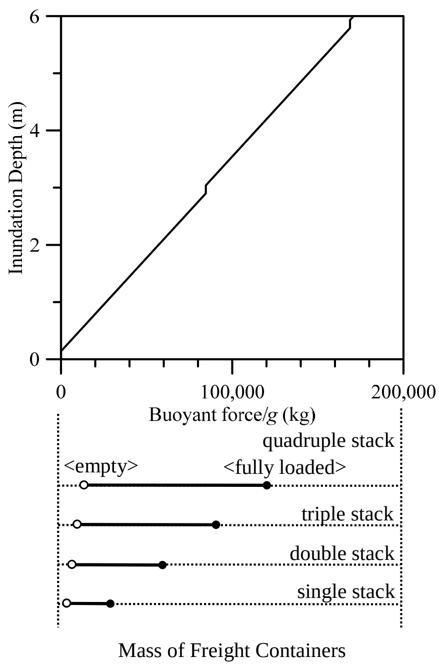



**Fig. 45** Relationship between inundation depth and buoyant force on 40 foot high cube container

**Table 5** Verification Data for Correlation between Inundation Depth, Mass of Container and Tsunami Damage

| No. | Name of Port | Tsunami Inundation Depth (m) | Mass of a single container with cargo (x $10^3$ kg) | Container size in length | Condition of storage | Mass of containers at ground level (x $10^3$ kg) | Remained at its original position after tsunami or Shifted | Reference to |
|---|---|---|---|---|---|---|---|---|
| 5 | Hachinohe | 3.45 | 22.2 | 20 foot | Triple stack | 67 | Remained | (2) e) of Chapter 3 |
| 10-1 | Sendai-Shiogama | 3.54 | 18.2 | 20 foot | Triple stack | 55 | Shifted | (2) j) of Chapter 3 |
| 10-2 | | | 9.7 to 11.7 | 40 foot | Triple stack | 29 to 35 | Shifted | |
| 12-1 | Onahama | 1.52 | 18 | 20 foot | Triple stack | 54 | Remained | (2) l) of Chapter 3 |
| 12-2 | | | 20 | 40 foot | Triple stack | 60 | Remained | |
| 14-1 | Kashima | 1.88 | 18.2 | 20 foot | Double stack | 36 | Remained | (2) n) of Chapter 3 |
| 14-2 | | | 19.7 to 29.7 | 40 foot | Double stack | 39 to 59 | Partially-shifted | |

ferronickel cargo is 22.2 × $10^3$ kg. The containers were stored in triple stacks, mass of three containers at ground level is equivalent to approximately 67 × $10^3$ kg in mass.

In **Table 5**, Nos.5, 10-1, 12-1 and 14-1 are examples of a 20 foot container, which are plotted in **Fig. 46**. All points were plotted in the area in which the buoyant force acting on group of containers was less than the gravitational force. According to **Table 5**, container Nos. 5, 12-1 and 14-1 remained in their original position against the tsunami. For these examples, the plot result in the figure coincides with this fact. On the other hand, containers of No. 10-1 were forced to shift from their original position due to the tsunami. Although the magnitude of the buoyant force was less than that of the gravitational force, the difference in magnitude between the two forces was very small. It may be considered that the horizontal force due to the flow or wave of the tsunami affected the positions of the containers in combination with the effect of gravitational force reduction caused by the buoyant force.

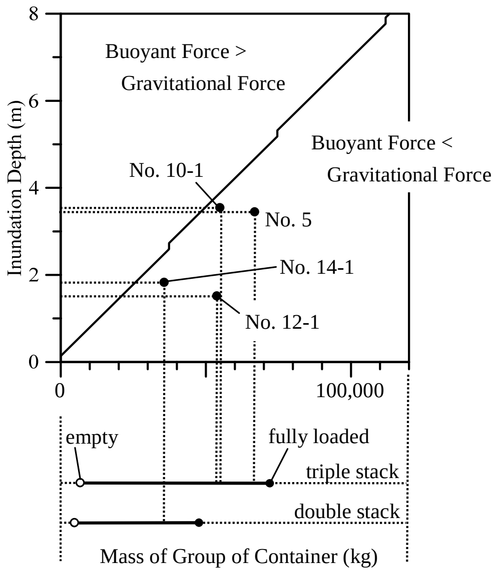



**Fig. 46** Verification of correlation between tsunami inundation depth and tsunami damage for 20 foot container

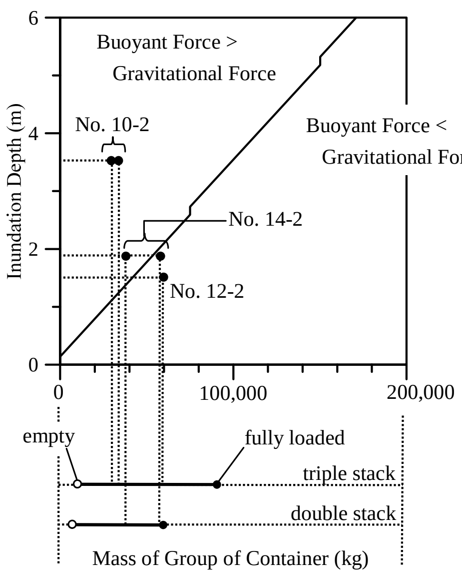



**Fig. 47** Verification of correlation between tsunami inundation depth and tsunami damage for 40 foot container

The two types of 40 foot containers include a high cube type and a non high cube type. A comparison of **Figs. 44 and 45** reveals that these differences have no bearing on the discussion in this section. Thus, only 40 foot non high cube containers are considered in this discussion. In **Table 5**, Nos. 10-2, 12-2 and 14-2 are examples of a 40 foot container and are plotted in **Fig. 47**. No. 10-2 is plotted in the area in which the magnitude of the buoyant force is greater than that of the gravitational force. No. 12-2 is plotted in the area in which the buoyant force is less than the gravitational force, and No. 14-2 is located in the middle. According to **Table 5**, containers of No. 10-2 were forced to shift from their original positions, and those of No.12-2 remained unchanged by the tsunami. In No. 14-2, some containers were forced to shift whereas others remained in their original positions. The plotting results agree well with the facts.

In this section, the effect of buoyant force due to tsunami inundation on the displacement of containers is discussed. As a result of the discussion, it was confirmed that containers with cargo remained in their original positions when the magnitude of the buoyant force due to tsunami inundation was less than that of the gravitational force acting on the containers, with the exception of one case in which the difference in magnitude between the two forces was negligible.

**(2) Inundation Depth and Container Loss Rate**

In this survey, container loss rate is defined as the number of tsunami-induced debris containers against the number of containers stored on the container terminal at the time of the earthquake. In column 6 of **Table 2**, the container loss rate was calculated, and is shown for each container port.

**Fig. 48** shows a correlation chart between the container loss rate and inundation depth due to the Tohoku tsunami on the container terminal of each port. The Arabic number in the figure indicates the serial number of the port, also shown in column 1 of **Table 2**. Because no containers were in Port Nos. 4 and 7 at the time of the earthquake, the two ports were eliminated from plotting.

The container loss rate is zero when the tsunami inundation depth is less than 1.6 m. However, the rate is approximately 0.4 or more when the inundation depth is above 3.5 m. If the inundation depth is at least 1.6 m and less than 3.5 m, the container loss rate varies widely, as indicated by the port with little damage and that with loss rate of approximately 0.6.

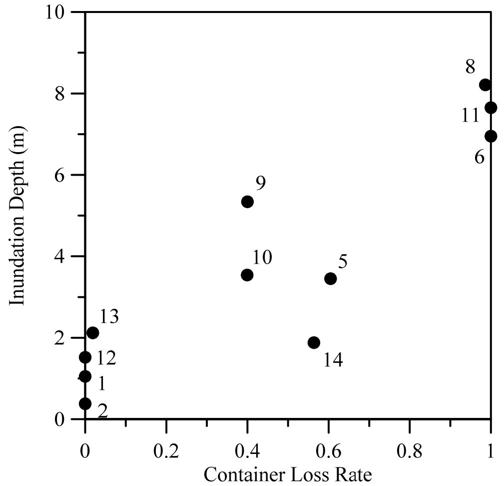


**Fig. 48** Correlation chart between container loss rate and inundation depth

## 5. CONCLUSIONS

In this study, field and hearing surveys were conducted to collect fundamental information on tsunami-induced debris of freight containers from ports due to the 2011 off the Pacific coast of Tohoku earthquake.

It was determined that 3,018 freight containers were lost from eight ports due to the Tohoku tsunami.

Container loss rate is defined as the number of tsunami-induced debris containers against the number of containers that were stored on the container terminal at the time of the earthquake. The rate is zero when the tsunami inundation depth is less than 1.6 m. On the other hand, the rate is approximately 0.4 or more when the inundation depth is above 3.5 m. If the inundation depth is at least 1.6 m and less than 3.5 m, the container loss rate varies widely, as evidenced by two ports including one in which very few containers were lost and that in which the container loss rate was approximately 0.6.

And it was confirmed that containers with cargo remained in their original positions when the magnitude of the buoyant force due to tsunami inundation was less than that of the gravitational force acting on the containers, with the exception of one case in which the difference in magnitude between the two forces was negligible.

The survey results include basic data of the damages caused by the 2011 Tohoku tsunami, and are expected to be utilized for tsunami mitigation planning.

**ACKNOWLEDGMENT:** The author would like to acknowledge the following agencies for providing information and assistance to conduct the field and hearing surveys: the Water Environment Division of Environmental Management Bureau of Ministry of Environment, Kushiro Port Office of Hokkaido Regional Development Bureau of MLIT (HRDB), Tomakomai Port Office of HRDB, Muroran Port Office of HRDB, Hachinohe Kowan Unso Kaisha, Ltd., Hachinohe Harbors and Airport Construction Office of Tohoku Regional Development Bureau of MLIT (TRDB), Miyako City Office, Iwate Prefectural Government, Kamaishi City Office, Kamaishi Port Office of TRDB, Ofunato City Office, Ishinomaki Mill of Nippon Paper Industries Co., Ltd., Shiogamako Unso Co., Ltd., Sanriku Unyu Co., Ltd., Sendai–Shiogama Port Office of Miyagi Prefecture, Marine environment and Engineering Divition of Port and Airport Department of TRDB, Shiogama Port and Airport Construction Office of TRDB, Iwaki Onahama Container Service Co., Ltd., Onahama Port Office and Soma Branch Office of TRDB, Ibaraki Port Authority Corporation, Hitachinaka Container Terminal Corporation, UNI-X Corporation, Ports and Harbors Division of Ibaraki Prefectural Government, Kashima Port and Airport Construction Office and Hitachinaka Branch Office of Kanto Regional Development Bureau of MLIT and Kashima Futo Co., Ltd. The author would like to express appreciation to Dr. T. Tomita and Mr. K. Honda, Asia Pacific Center for Coastal Disaster Research of Port and Airport Research Institute, and Dr. T. Okada, Marine Environmental Division of NILIM, for providing information and considerable advice.

## APPENDIX A: Masses of Empty Containers

(1) Surveillance Date: March 25, 2013
(2) Objective port: Takasago container terminal, Sendai–Shiogama Port
(3) Researcher: Kumagai, K., NILIM
(4) Survey Method: Recording tare mass of freight containers with random sampling.
(5) Result of survey:

**Figs. A-1** – **A-3** show the survey results for empty 20 foot, empty 40 foot, and empty 40 foot high cube containers, respectively, where *N* is the number of freight container sample, *M* is tare mass of the container, and *M* bar is the average value of *M*.

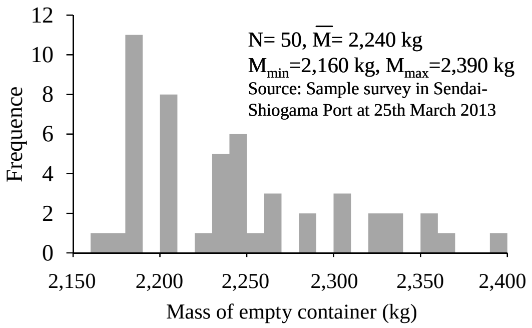



**Fig. A-1** Frequency distribution chart of mass of empty 20 foot container

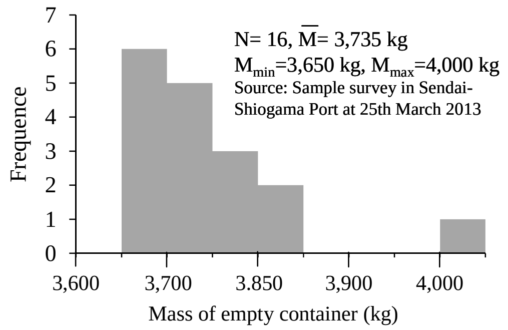



**Fig. A-2** Frequency distribution chart of mass of empty 40 foot container

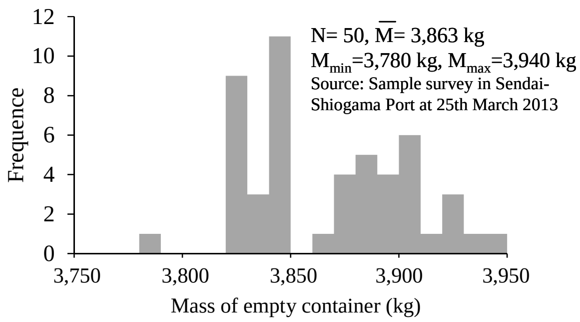



**Fig. A-3** Frequency distribution chart of mass of empty 40 foot high cube container

## APPENDIX B: Estimation Method of the Number of Freight Containers stored on Container Terminal at time of Earthquake

For Port Nos.1, 3, 9 and 12 in **Table 2**, the value of column 4, which is the number of containers stored on the container terminal at the time of the Tohoku earthquake, was estimated from the number of containers that were handled during 2010. The estimation method is described in the following paragraphs.

In port planning of Japan, the capacity of a container in a container terminal are estimated using a method defined in the book for the Technical Standard and Commentaries for Port and Harbour facilities*. This method is applied to estimate the number of freight containers at the time of the earthquake for Port Nos.1, 3, 9 and 12. The method is described below:

The number of containers stored on a terminal on a specific day is estimated by the following equation:

$$V_1 = f\left(\frac{V_0}{e}\right) \tag{B-1}$$

where $V_1$ is the number of containers stored on the terminal at a specific day, $f$ is the peak factor, $V_0$ is the number of containers handled during 2010, and $e$ is the annual rotation frequency of container handling.

The value of the peak factor $f$ is 1.2–1.3 in the book of technical standard*. **Fig. B-1** shows monthly change in the number of containers handled during 2010 at the major three container ports of Japan**. It appears that March is a peak period in a year for container handling. Then, $f$ is assumed to be 1.25, the average value between 1.2 and 1.3.

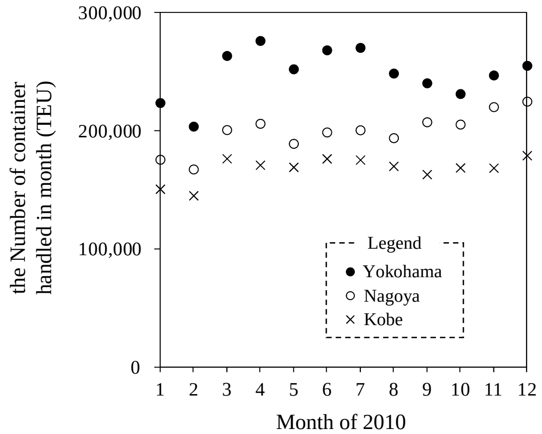



**Fig. B-1** Monthly change of the number of containers handled during 2010 at major container ports

The annual rotation frequency of container handling, $e$, is defined by the following equation:

$$e = D_y / D_t \tag{B-2}$$

where $D_y$ is the operation days of a container terminal in a year, and $D_t$ is the an average period in which a container was stored on the terminal. In this study, $D_y$ is assumed to be 364 days because the typical container terminal in Japan is opened every day of a year with the exception of the new year's day, January 1. $D_t$ is assumed to be 7 days. Then $e$ becomes 52 according to equation B-2.

In equation B-1, the units of $V_0$ and $V_1$ are in TEU. On contrary, the value of column 4 in **Table 2** shows the actual number. The equation, therefore, must be revised to change the unit of $V_1$ to the actual number rather than TEU. Shibasaki (2004) reported that approximately half of the containers handled in the major ports of Japan are 20 foot containers and the other half are 40 foot containers***.

By definition, one 40 foot container is counted as two TEU containers. Then the equations are modified to

$$V_2 = x_1 \times f\left(\frac{V_0}{e}\right) \qquad \text{(B-3)}$$

$$x_1 = 0.67 \qquad \text{(B-4)}$$

where $V_2$ is the modified number of containers stored on the terminal on a specific day, and $x_1$ is a constant number, and is a conversion factor between the actual number of containers and TEU.

**Table B-1** shows the relationship between the estimated value $V_2$ and the observed value. Generally, $V_2$ is smaller than the observed value. The reason why the estimated value $V_2$ is smaller than the observed value may be that extra empty containers were stored in the terminal area. The observed value of Port No. 11 is very small. This port is the only one; hence, $V_2$ is larger than the observed value. Moreover, the estimated value $V_2$ of Port No. 14 is significantly smaller than the observed value. With elimination of the values of Port Nos. 11 and 14, an averaged ratio of $V_2$ to the observed value becomes 0.65.

**Table B-1** Estimated value of $V_2$ and observed value

| No. | The number of containers handled in year 2010 (TEU) | Estimated value, $V_2$ [A] | Observed value [B] | [A/B] |
|---|---|---|---|---|
| 2 | 322,128 | 5,188 | 7,400 | 0.71 |
| 5 | 45,430 | 732 | 1,159 | 0.63 |
| 6 | 100 | 2 | 7 | 0.29 |
| 8 | 2,839 | 46 | 73 | 0.63 |
| 10 | 155,611 | 2,506 | 4,318 | 0.58 |
| (11) | (622) | (10) | (6) | (1.67) |
| 13 | 21,261 | 342 | 639 | 0.54 |
| (14) | (6,189) | (100) | (809) | (0.12) |
| Total | 547,369 | 8,816 | 13,596 | 0.65 |

Note: The values with parentheses, No. 11 & 14, are eliminated from 'Total' in the last line of the table.

Equations B-3 and B-4 are further modified:

$$V_3 = \frac{x_1}{x_2} \times f\left(\frac{V_0}{e}\right) \qquad \text{(B-5)}$$

$$x_1 = 0.67 \qquad \text{(B-6)}$$

$$x_2 = 0.65 \qquad \text{(B-7)}$$

where $V_3$ is the modified number of containers stored on the terminal at the Tohoku earthquake, and $x_2$ is constant number for an effect of extra empty containers stored on the port.

**Table B-2** shows the relations between the estimated value $V_3$ and the observed value. The distributions of a value A/B is 0.82 to 1.08 with an exception of No. 6. As a result, although there is an exception, it may be quite all right to adopt the equations B-5 to B-7 for estimation of the number of containers stored on container terminal.

**Table B-2** Estimated value of $V_3$ and observed value

| No. | The number of containers handled in year 2010 (TEU) | Estimated value, $V_3$ [A] | Observed value [B] | [A/B] |
|---|---|---|---|---|
| 2 | 322,128 | 8,001 | 7,400 | 1.08 |
| 5 | 45,430 | 1,129 | 1,159 | 0.97 |
| 6 | 100 | 3 | 7 | 0.43 |
| 8 | 2,839 | 71 | 73 | 0.97 |
| 10 | 155,611 | 3,856 | 4,318 | 0.90 |
| 13 | 21,261 | 527 | 639 | 0.82 |

**Table B-3** shows the result of the estimation of the number of containers stored on the terminals of Port Nos. 1, 3, 9 and 12 at the time of the Tohoku earthquake with application of equations B-5 to B-7.

**Table B-3** Estimated value of $V_3$

| No. | The number of containers handled in year 2010 (TEU) | Estimated value, $V_3$ |
|---|---|---|
| 1 | 31,731 | 788 |
| 3 | 5,482 | 136 |
| 9 | 4,024 | 100 |
| 12 | 22,352 | 555 |

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* The Ports and Harbours Association of Japan: Technical Standard and Commentaries for Port and harbour facilities, pp.1346-1358, 2007.

** The Ports and Harbours Association of Japan: Monthly "Ports and Harbours", pp.54-55 of Issue 5 and pp.56-57 of Issue 6, Vol.88, 2012.

*** Shibasaki R., Watanabe T. and Kadono T. : An Analysis of Economic Loss due to Bottlenecks in Domestic Land, Research Report of National Institute for Land and Infrastructure Management, No.18, pp.1-4, 2004.

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**(Received August 9, 2013)**