Quantifying tsunami impact on industrial facilities and production capacity in ports: An application to Sendai Port, Japan

Abstract. The 2011 Great East Japan earthquake and subsequent tsunami is one of the costliest natural hazards to date. Losses were not only from physical damage alone. Indirect losses due to business interruptions and their consequential impacts on the rest of the economy and supply chain account for most losses. In this study, 12 companies across five industrial sectors in Miyagi Prefecture were interviewed to gain a better understanding about the damage that were sustained by their factories during the 2011 Great East Japan earthquake and tsunami as well as subsequent earthquake and tsunami events. The study investigates (i) the vulnerability of mechanical structures to tsunami impacts, and (ii) the recovery rates of production capacity for various industrial sectors through interviews with companies from various industrial sectors. In addition, tsunami risk assessment is performed for future tsunami scenarios using Sendai Port as a case study. Results from this study indicate that only 1-2 m of flow depth is enough to cause damage to mechanical structures in most industries, which disrupts operations. In addition, recovery rates of production capacity vary at different tsunami inundation levels. Full recovery of production capacity can occur as quickly as 1-2 months later and as late as 10-12 months later depending on the situation. Tsunami risk assessment demonstrates that using structural fragility functions alone might underestimate the actual loss of industries and that most industries in Sendai Port are potentially capable of recovering within eight months after large future tsunami.

1 Introduction

Since the 2011 Great East Japan earthquake and its subsequent tsunami, an extensive body of work has been dedicated to studying the structural damage to buildings [1, 2, 3] and, more recently, the structural damage to port industries [4] due to tsunami impacts. However, even when buildings remain structurally intact, industrial facilities may lose their functions due to nonstructural damage. Here, nonstructural damage refers to damage to mechanical structures within an industrial facility, including installations, equipment, machineries, vehicles and power distribution systems. Nonstructural damage can cause significant disruption to production processes and adversely affect business continuity. Indirect losses, such as losses from business interruptions due to major disaster events, can be far greater than losses from physical damage alone [5].

Until recently, few studies [4,6] have considered the vulnerability of industrial facilities to tsunami impacts. This gap in research can be due to the infrequency of large tsunami events that result in limited observations. However, the vulnerability of industrial operations needs to be assessed to minimize disruption time and losses for the company as well as functions that depend on them. In this study, the objective is to assess the vulnerability of industrial operations to tsunami impacts, using port industries affected by the 2011 tsunami as case studies. To achieve this overarching aim, this study sets out to investigate (i) the vulnerability of mechanical structures to tsunami impacts, and (ii) the recovery rates of production capacity for various industrial sectors through interviews with companies from various industrial sectors. Production capacity refers to the maximum production level of the industry if all originally available resources are employed [6]. In this study, the production capacity of a company is set at pre-earthquake production levels. Findings from interviews conducted and additional reported information were used to perform a risk assessment for future tsunami scenarios for the Sendai Port – a major port in the Tohoku region.

The following events were considered as case studies to illustrate the objectives of the study: The 2011 Great East Japan earthquake and its subsequent tsunami; 2016 November and 2021 February earthquakes and subsequent tsunamis; 2021 March and May earthquakes (Table 1). Many industrial facilities, including critical infrastructure, were reported to be affected and/or badly damaged by the 2011 event [7]. A post-2011 tsunami survey carried out by the Tohoku Regional Development Bureau [8] found only 13% of the 233 companies in ports along the eastern coastline of the Tohoku region to be unaffected by the earthquake and tsunami. Various types of industrial facilities are located in the ports along the coast of Tohoku region [8] and their recovery rates varied between industries and events [4]. Therefore, case studies from the Tohoku region provides an excellent opportunity to quantify the vulnerability of sector-specific operations to tsunami impacts. It is hoped that the findings of this study will assist in mitigation and business continuity plans for industrial facilities located along the coast, as well as prepare Sendai Port against future tsunami events.

2 Background & methods

2.1 Recent earthquakes and tsunami in the study area

In this study, twelve companies from five industrial sectors in Miyagi Prefecture were interviewed to assess the extent of damage sustained in the different events, and establish their vulnerabilities and recovery capabilities. The Miyagi Prefecture was one of the most badly affected prefectures (along with Iwate and Fukushima) during the 2011 event. The companies interviewed in this study are located in Ishinomaki city, Shiogama city, Sendai city (Sendai port), Natori city and Iwanuma city, as shown in Fig. 1. These areas were also affected by more recent earthquakes [9], 22 November 2016 (Mw 6.9), 13 February 2021 (Mw 7.1), 20 March 2021 (Mw 7.0) and 1 May 2021 (Mw 6.8); however, they were not affected by the tsunami (Table 1).

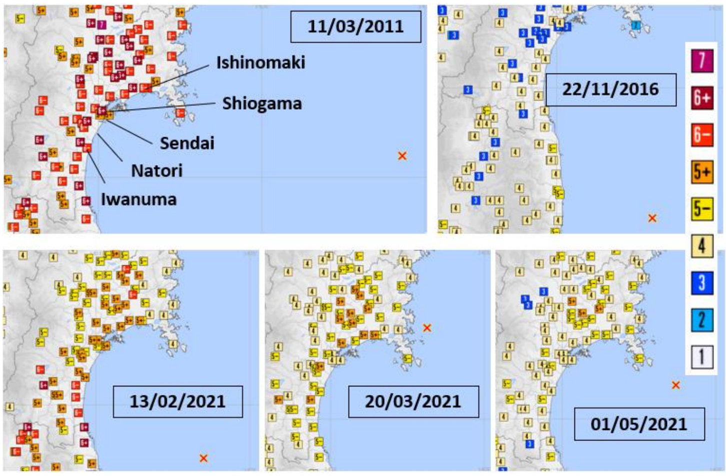

Fig. 1. Locations of study areas, earthquake epicenters and distributions of earthquake intensities [9].

Table 1. Earthquake (and subsequent tsunami) events in the Tohoku region since the 2011 Great East Japan earthquake derived from [9]

Date	Earthquake magnitude (Mw)	Maximum seismic intensity (JMA)	Maximum tsunami height (m)
11 Mar 2011	9.0	7	40.1
22 Nov 2016	7.4	5-	1.44
13 Feb 2021	7.3	6+	0.20
20 Mar 2021	6.9	5+	-
01 May 2021	6.8	5+	-

2.2 Data collection through interviews

Both in-person and online interviews were conducted with input from owners or company representatives from 12 companies. The interviews were conducted between April and June 2021. In some instances when in-person interviews were conducted, the authors were invited to visit the facilities. The interviews were semistructured and centered around three core themes, which are described as follows:

(i) Damage to installations and mechanical structures (e.g., equipment and vehicles)
(ii) Business disruption and recovery of production capacity
(iii) Lessons learned and mitigation measures adopted against future events

In line with the key research objectives of this study, the interview consisted of five broad questions covering the following topics:

1) Damage sustained by the facility by ground shaking
2) Damage sustained by the facility by tsunami inundation
3) Criteria for damage to facility components in an earthquake and/or tsunami
4) Time required for damage repair and restoration
5) Period of disruption and recovery of productivity

2.3 Numerical simulation of future tsunami scenarios

To assess potential tsunami risk for Sendai port, four main earthquake sources in the Tohoku region [10] were considered in this study (Fig. 2). One of the sources recently identified is an M9 large earthquake along the Japan Trench. It was estimated based on new information from tsunami deposits along the Tohoku and Hokkaido coasts [11]. A frequent source of earthquake in Miyagi and Iwate Prefectures is an M8 earthquake off the coast of Miyagi, which has relatively shorter recurrence intervals [12]. Another source of earthquake is an M7.7 earthquake off Fukushima – a local source for the Fukushima Prefecture [13]. Lastly, M8.7 outer-rise earthquakes along the eastern part of the Japan Trench have also been proposed as possible sources of earthquakes [14]. Tsunami inundation in the Sendai Port is modelled for each of these proposed scenarios. Initial water level for tsunami generation was calculated based on [15], which assumes that the water level change is equal to the change in the seafloor due to the earthquake as calculated by the proposed fault parameters. Fault parameters for each earthquake scenario were obtained from [11-14]. The TUNAMI-N2 model was used to numerically simulate the tsunami [16]. The TUNAMI-N2 model was first developed at Tohoku University to model tsunami propagation and inundation on land by applying the nonlinear theory of the shallow water equation, which is solved using a leap-frog scheme. The nonlinear shallow water equation is presented in equations (1)-(3), wherein the finite difference method is applied to the nonlinear equation and surface friction is represented by Manning's roughness coefficient:

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gn^2}{D^{\frac{7}{3}}} M\sqrt{M^2 + N^2} = 0 \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{NM}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gn^2}{D^{\frac{7}{3}}} N\sqrt{M^2 + N^2} = 0 \tag{3}$$

where η is the water level, M and N are the fluxes of water in the x and y directions, D is the total depth, g is the gravitational acceleration and n is Manning's roughness coefficient. An equivalent roughness coefficient of 0.025 was used in this study. The simulation was performed on a nested grid system from the largest computational region (region 1 = 1,215 m resolution) to the smallest computational region (region 6 = 5 m resolution). A seawall of 4 m in Sendai Port was also added to the topography data when simulating future tsunami but was not included when reproducing the 2011 tsunami. The simulation time is 6 hours, and the simulation time step is 1 second. The tide level (-0.4 m) at the time of the 2011 Great East Japan Earthquake [17] is considered in the simulation. Simulation results produced under these conditions were compared to observational data to validate the tsunami simulation model. However, the damage might be larger if an earthquake occurs during high tide. Therefore, the tide level of +0.7 m is selected as the high tide level [18] in other tsunami case scenarios for hazard and risk assessment in sections 5 and 6.

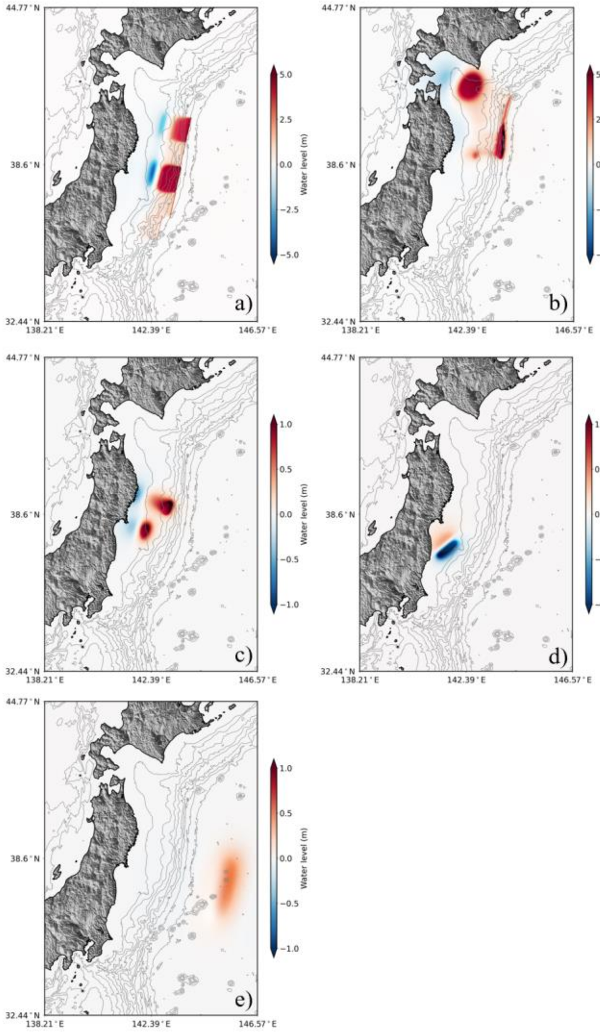

Fig. 2 Initial water level displaced by different tsunami sources

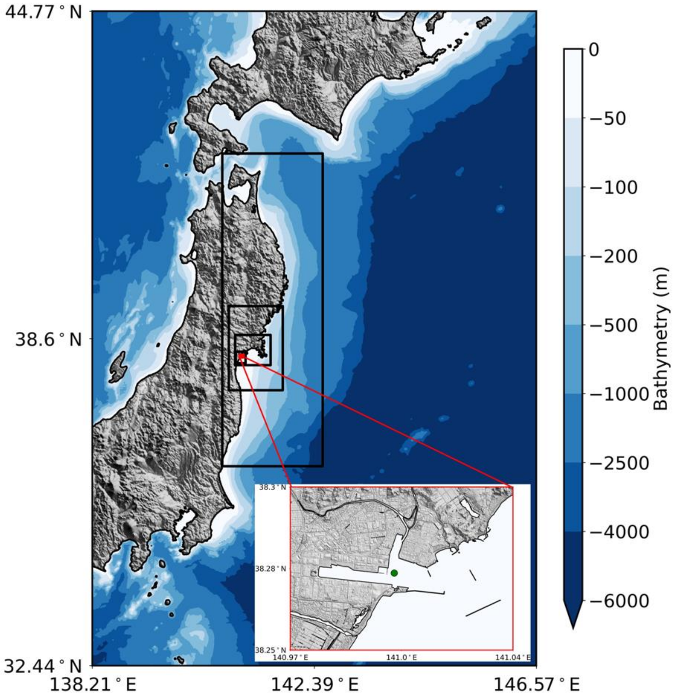

Fig. 3 Topography and bathymetry data. The green circle indicates the location of the simulated waveforms in Sendai Port.

3 Damage to industries by the 2011, 2016 and 2021 earthquakes

In a previous study [4], eight common port industries were identified in the Tohoku region based on their occupancies. The participants in this study could be classified into five of those industries as follows:

1. Cargo handling industry: Container terminals, stacking and transport facilities
2. Warehousing and distribution: Warehouse, cold storage and logistic support
3. Food industry: Food processing
4. Manufacturing industry: Metal and alloy products, feed manufacturing, etc.
5. Petrochemical industry: Oil depots, reserves and refineries

This section summarizes the interview outcomes for each of the companies interviewed (Table 2). The names of the companies are not disclosed in this manuscript to ensure confidentiality.

3.1 Cargo handling industry

Two companies from the cargo handling industry participated in the interviews. Aside from cargo handling services, both companies also offer logistic services (warehousing and distribution industry).

3.1.1 Company A

Company A has several offices, and its industrial facilities occupy several areas within Sendai Port. Company A was unaffected by recent earthquakes, one occurring in 2016 and three in 2021. During the 2011 Great East Japan earthquake, most of the damage sustained to its offices and facilities was from the consequent tsunami. Ground shaking had a relatively limited impact on the offices and facilities. Most of its offices were inundated by approximately 2–3 m, and the main container terminal was inundated up to 6.2 m. When asked about the threshold inundation depths for damage to occur, Company A explained that damage to smaller equipment, such as automobiles and forklifts, can start at a 1 m inundation depth. On the other hand, damage to heavy equipment, such as top lifters and cranes, starts at 2–3 m, which is the height of their engines. Company A was able to resume some of its operations a few months after tsunami debris removal and restoration occurred. However, recovery only reached 70–80% one year after the tsunami, and two years were required to return to the normal production capacity of pre-earthquake levels.

3.1.2 Company B

Similar to Company A, Company B also has several offices and facilities within Sendai Port. Likewise, Company B was unaffected by the recent earthquakes occurring in 2016 and 2021. The 2011 event resulted in approximately 1-2 m of tsunami inundation in most of its offices, except one that had experienced inundation up to 3.2 m. Damage caused by ground shaking to its offices was considered minor and was limited to wall cracks. Company B commented that considerable damage can be expected for heavy equipment, such as cranes, at inundation depths of approximately 2 m and less than 2 m for smaller equipment and vehicles, consistent with the remarks made by Company A. An inundation depth of 0.2–0.3 m generally only requires cleaning and drying of the equipment. Company B was able to resume some of its operations 3 months after the tsunami, and one year was required to recover production capacity.

3.2 Warehousing and distribution

3.2.1 Company A

Company A also provides logistic services. Its container warehouses sustained little damage from ground shaking during the 2011 earthquake or the recent earthquakes. Most of the damage sustained during the 2011 event was due to the tsunami. The tsunami resulted in water intrusion into the containers as well as the uplift and collision of containers. The company's warehouses also sustained structural damage, which prompted the elevation of warehouses above ground level after the 2011 event.

3.2.2 Company B

For this company, empty containers that were stacked fell because of ground shaking from the 2011 Great East Japan earthquake. The tsunami destroyed all of its warehouses.

3.3 Food industry

3.3.1 Company C

This company produces cold seafood products. According to its representatives, ground shaking during the 2011 Great East Japan earthquake resulted in the slipping of its installations from their fixed locations, but this slippage was repaired in a matter of days. However, the factory was destroyed by the tsunami that was 5.7 m deep at its facility, which consequently led to the relocation of its business to another site, a factory that had not been in use for an extended period. Production in the relocated factory returned to one-third of its pre-earthquake levels after 2 months and fully recovered within a year. The interview revealed that shaking with a seismic intensity of less than 5+ on the JMA (Japan Meteorological Agency) scale is unlikely to cause significant damage to its equipment. The critical threshold depth for damage is approximately 0.7 m, as this is the height of its production line systems.

3.3.2 Company D

Company D produces dried seafood products. Its facility was not inundated during the 2011 Great East Japan tsunami; however, ground shaking from the earthquake resulted in the inclination of the factory building (> 3 degrees). The owner of Company D believed that the foundation of the building was weak, as it was built on a former rice field. The factory was relocated to another site with better ground conditions away from the coast. Production in the relocated factory restarted after 3-4 months, and production capacity was restored after 13 months. Company D explained that, like Company C, a seismic intensity of < 5+ is unlikely to cause significant damage to its equipment. On the other hand, the threshold depth for damage is 1 m, which is the height of its production line systems (Fig. 2). An inundation depth of 0.2–0.3 m generally only requires cleaning and drying of the equipment.

3.3.3 Company E

Company E is a producer of retort foods (retort packaging). The size of its factory is much larger than those of companies C and D. The seismic intensity recorded around the factory during the 2011 Great East Japan earthquake was approximately 6-, but ground shaking did not result in significant damage. In anticipation of flash floods, the factory was built 1 m above road level. Therefore, with the exception of damage to pumps and air ventilation systems, the factory was relatively unaffected by the 2011 tsunami, which was 1 m in depth. Company E was able to resume one-third of its production capacity in one and a half months and return to pre-earthquake levels within two months following the earthquake. Company E believes that the critical depth for damage to its equipment is 0.1 m, which differs slightly from the estimations provided by Companies C and D.

3.3.4 Company F

Company F produces cold seafood products and has three factories. The seismic intensity recorded around its factories during the 2011 Great East Japan earthquake was 6-. The ground shaking caused some equipment to fall from their positions, but this equipment was fixed within two days. The tsunami affected the main factory and a secondary factory. The flow depths at these two locations were approximately 6 m. On the other hand, at the headquarters factory, the tsunami overtopped a nearby river, which resulted in an inundation of 0.8 m. Most equipment in its factories was badly damaged by the tsunami. However, the structural integrity of the buildings remained intact, which allowed them to restart their production after one month. Company F was able to achieve production capacity within two months. Currently, the main factory is raised 2 m above road level. Contrary to the opinions expressed by other companies, Company F believes that a flow depth of 1 m is unlikely to cause significant damage. This finding shows that damage is likely to start at 1.5 m, which is the height of the company's equipment, and complete damage will occur when the inundation depth reaches 3 m.

3.4 Manufacturing industry

3.4.1 Company G

This company produces ice for fishing boats and other fishery-related activities. The seismic intensity observed around its factory during the 2011 Great East Japan earthquake was 6+, and tsunami inundation was 1.9 m. Ground shaking resulted in moderate damage to nonstructural components of the building, e.g., wall cracks and fallen ceilings and lights. Some damage to the equipment was also observed. Ice-making machines are installed on the second and third floors of the factory, and ice is loaded directly from the upper floors into refrigerated trucks on ground level for shipment. Therefore, damage from the tsunami was mostly limited to vehicles parked on ground level. Company G was able to resume business 10 days after the tsunami and return to production capacity within a month. Recent earthquakes, i.e., 2016 and 2021, in which the seismic intensities were approximately 4 around the factory, caused minor damage, including wall cracks, to the building.

3.4.2 Company H

Company H is a precision engineering company. Recent earthquakes (intensities of 6-) resulted in only minor damage. The seismic intensity observed around its factory during the 2011 Great East Japan earthquake was also 6-, but the tsunami inundation was 2.5 m. Ground shaking did not cause observable damage, but the tsunami damaged some of the factory equipment. While half of them could be repaired, the other half had to be replaced. Company H resumed business within a month at 40% of its production capacity, and production capacity returned to pre-earthquake levels after seven months. In anticipation of flash floods, the factory building, like Company E, was elevated 1 m above road level. The factory's switchboard was also raised 1 m higher. Company H mostly operates mechanical press machineries. The main engines of these machineries are approximately 1.5 to 2.0 m above ground, which makes them less vulnerable to flood impacts than food processing equipment.

3.4.3 Company I

Company I is a feed manufacturer. As the recorded seismic intensity was 6+, the company reported damage from the 2011 Great East Japan earthquake. Ground shaking resulted in the buckling and failure of some equipment as well as the deformation of tanks. Company I believes that such damage could be repaired within a week. However, most of the damage sustained by the factory did not originate from the ground shaking itself but rather from the tsunami that followed. Tsunami inundation was 3 m, completely submerging the ground floor of the factory. Most equipment and content, including feed ingredients on the first floor, were completely damaged. Company I was able to resume business six months after the 2011 event and was operating at 80% of its production capacity. Experiences from recent earthquakes in 2016 and 2021 have led Company I to believe that a seismic intensity of 5 or less is unlikely to cause damage to its factory due to ground shaking. However, contrary to the opinions expressed by most of the interviewed companies, Company I explains that a 0.2–0.3 m tsunami inundation depth can easily cause damage to equipment found in the building basement and content on the ground floor. A 1–2 m flow depth can damage to equipment located on the ground floor, while equipment installed on upper floors will be relatively safe.

3.4.4 Company J

Company J is a steel manufacturer. The seismic intensity recorded around its factory during the 2011 Great East Japan earthquake is approximately 6+. Ground shaking caused some nonstructural damage, including damage to ceilings and walls as well as equipment that hung from the ceiling. The company also experienced a blackout because of the earthquake. Tsunami inundation was 3.8 m and caused damage to the structure of the building as well as the equipment and electrical system. Most of the damage was to the basement and ground floor of the building, while damage to the second floor was relatively minor. Production was disrupted for 4 to 6 months because of tsunami damage, and production capacity only recovered after 10 months. Company J believed that production would resume quickly because most of its equipment was stored on higher floors. Other unintentional measures also reduced the impact of tsunami floods, including having a back-up generator and not having paper-based documents stored in the basement or ground floor. The seismic intensities recorded in the recent earthquakes in February and March 2021 were approximately 5+. In both events, ground shaking caused blackouts and minor structural damage to the factory. Production in the factory was disrupted for 7 to 10 days during the February 2021 event and 3–5 days during the March 2021 event.

3.4.5 Company K

Company K is a metal recycling company. It did not sustain any damage in the recent earthquakes in 2021. During the 2011 Great East Japan earthquake, the seismic intensity recorded around its factory was 6-. No damage was sustained through ground shaking. Most of the damage came from the tsunami, where the maximum depth was 2.1 m at Company K. This company is located behind a pine forest. Therefore, in addition to tsunami waves, the factory was also impacted by debris generated by broken trees. Within the factory, all equipment and vehicles were damaged by the tsunami. The company was able to resume operations by June 2011. Power outlets were raised 1 m higher after the 2011 event. Company K believes that a flow depth of 0.5 m can start causing damage to vehicles, equipment and the building structure.

3.5 Petrochemical industry

3.5.1 Company L

This company is an oil refinery company. The seismic intensities observed around the oil facility were 6+ in the 2011 earthquake and 5+ in the recent earthquakes in February and May 2021. Ground shaking in these events triggered the automatic shutdowns of systems in the facility. A shutdown can take a few weeks to a few months for the company to resume production. The 2011 earthquake and tsunami also triggered fires in its facilities. Damage from the 2011 event was so severe that the company was only able to resume production after a year. In the oil refining industry, industrial fire trucks (or emergency vehicles) are adopted to reduce fire risk. However, during the 2011 event, these trucks were badly damaged by the tsunami, affecting firefighting efforts. After the 2011 event, the ground was elevated within the facility to improve the movement of trucks in the case of a tsunami. A new seawall was also constructed by the Miyagi Prefecture along the coastlines of the facility to reduce tsunami risk. In addition, tanker trucks used for oil transportation were relocated to higher ground above the inundation height of the 2011 tsunami and away from the inundation zone.

Table 2 Summary of the damage and recovery conditions in each of the interviewed companies.

Industry	**Distance from the sea (km)**	**Surrounding conditions at the time of the 2011 tsunami**	**Damage conditions**	**Recovery conditions**
Company A	0.4	No seawall	Most of its offices were inundated by approximately 2–3 m. The tsunami resulted in water intrusion into the containers as well as the uplift and collision of containers.	Able to resume some of its operations a few months after tsunami but recovery only reached 70–80% one year after the tsunami and required two years for fully recover.
Company B	0.5	No seawall	About 1-2 m of tsunami inundation in most of its offices.	Able to resume some of its operations 3 months after the tsunami, and one year was required to recover production capacity
Company C	0.8	T.P. 6.2 m seawall	Destroyed by the tsunami that was 5.7 m deep at its facility, which consequently led to the relocation of its business to another site.	Production in the relocated factory returned to one-third of its pre-earthquake levels after 2 months and fully recovered within a year.
Company D	Not inundated by the 2011 tsunami		Inclination of the factory building (> 3 degrees) caused by ground shaking led to relocation.	Production in the relocated factory restarted after 3-4 months and fully restored after 13 months.
Company E	2.4	T.P. 6.2 m seawall	With the exception of damage to pumps and air ventilation systems, the factory was relatively unaffected by the 2011 tsunami at 1 m in depth.	Able to resume one-third of its production capacity in one and a half months and return to pre-earthquake levels within two months
Company F	1.0	T.P. 6.2 m seawall	Most equipment in its factories was badly damaged by 6 m tsunami.	Able to achieve production capacity within two months as structural integrity of the buildings remained intact.
Company G	0.05	T.P. 2.1 m seawall	Damage from 1.9 m tsunami was mostly limited to vehicles parked on ground level as machines are installed on the second and third floors of the factory.	Able to resume business 10 days after the tsunami and return to production capacity within a month.
Company H	2.0	T.P. 6.2 m seawall	Tsunami of 2.5 m depth damaged equipment that half of them could be repaired, the other half had to be replaced.	Able to resume business within a month at 40% of its production capacity, and production capacity fully returned after seven months.

Company I	0.1	No seawall	Tsunami inundation of 3 m completely damaged all equipment and content on the ground floor.	Able to resume business six months after the 2011 event and was operating at 80% of its production capacity.
Company J	0.1	No seawall	Tsunami inundation was 3.8 m and caused damage to the structure of the building as well as the equipment and electrical system.	Production was disrupted for 4 to 6 months because of tsunami damage, and production capacity only recovered after 10 months.
Company K	1.6	T.P. 6.2 m seawall	All equipment and vehicles were damaged by 2.1 m tsunami and debris generated by broken trees.	Able to fully resume operations after three months.
Company L	0.1	No seawall	Not only 7.1 m tsunami but also fires caused completely damage to facilities and vehicles.	Able to resume production after a year in case of the 2011 tsunami.

4 Threshold for non-structural damage and production capacity of industries

4.1 Tsunami depth threshold for non-structural damage to industries

Damage ratios (as replacement cost against the whole facilities in each factory) were calculated for each industry surveyed where the number of data points is sufficient. Findings from the cargo handling industry and warehouse and distribution industry were aggregated to develop the damage ratios – the companies interviewed were the same for both industries. The results are summarized in Fig. 4(a). Linear regression analysis with normal distribution is a classic method for fitting tsunami damage data, the same as that used in [19] for buildings and in [20] for marine vessels. The damage ratio is calculated as a function of the standardized normal (or lognormal) distribution function using the flow depth (or its natural logarithm) as well as their mean and standard deviation. Parameters for developing vulnerability functions are shown in Table 2. For the cargo handling (and warehousing) industry, the rate of damage increases at a slower rate below a depth of 2 m. However, complete damage to the industry occurs at 2 to 3 m. On the other hand, the rate of damage increase varies for the food industry. The facility producing dried seafood appears to be the most vulnerable to tsunami inundation – complete damage occurs at 1 m. Cold food facilities are less vulnerable to tsunami inundation – the rate of damage only increases rapidly after 1 m in depth, and total damage occurs between 2 m and 3 m. These are mainly because the cold food facilities we interviewed were partially located in higher positions. For the manufacturing industry, minor damage starts at 0.5 m, while complete damage occurs at 2 m. In general, the threshold for complete damage across all industries is approximately 2 m. Fig. 4(b) is our proposed upper line (company E), average line (company C) and lower line (company A).

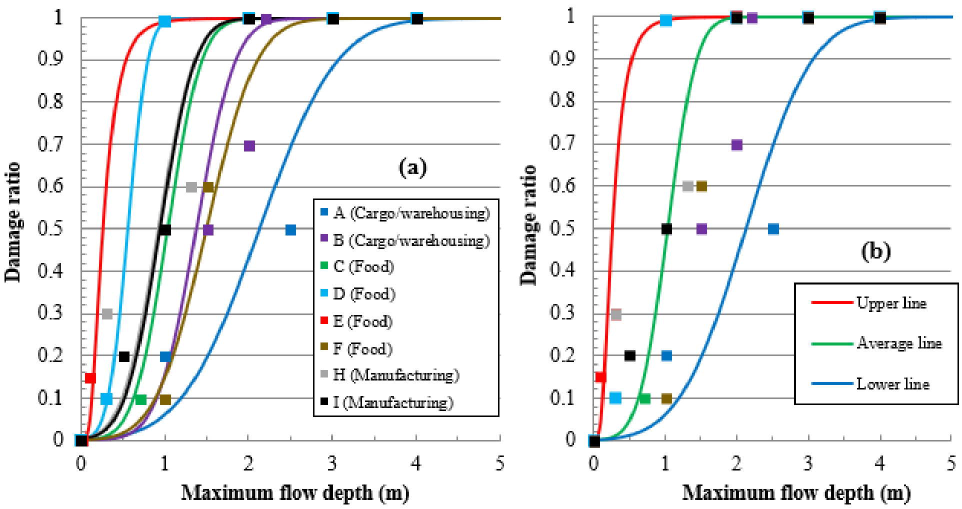

Fig. 4 Tsunami depth threshold for non-structural damage to industries

Table 3 Regression parameters of vulnerability functions of non-structural damage for each of the interviewed companies using normally or lognormally distributed linear regression

Industry	Distribution	Mean	Standard deviation
Company A	Normal	2.1283	0.7337
Company B	Normal	1.3768	0.3678
Company C	Normal	1.0362	0.3187
Company D	Normal	0.5601	0.186
Company E	Lognormal	-1.34	0.5591
Company F	Normal	1.4974	0.4763
Company H	Normal	0.923	0.3397
Company I	Normal	0.9446	0.3309

4.2 Recovery of production capacity after a tsunami

The production capacity of a company is considered to be recovered when production has returned to its maximum or pre-earthquake levels. The recovery rates of production capacity after the 2011 Great East Japan tsunami for each industry are summarized in Fig. 5 and their upper lines, average lines and lower lines in Fig. 6. Parameters for developing vulnerability functions are shown in Tables 3-6. The rates of recovery are modeled under the tsunami conditions (maximum flow depth) that each company was found in during the 2011 tsunami. Additional data from 20 companies all over the 2011 tsunami-affected areas for the interruption period after the 2011 disaster were collected from [21], and the maximum tsunami flow depth was taken from [22]. The recovery of production is plotted for three cases: 1) companies having no tsunami inundation, 2) companies damaged by tsunami flow depths of 3 m and below and 3) companies damaged by tsunami flow depths above 3 m. Fig. 5(a) shows that production capacity was interrupted even though there was no tsunami inundation. Some reasons include power shortages, a lack of staff who were impacted by the tsunami and a shortage of supply from other companies in the tsunami-inundated zone. Nevertheless, most of the companies could fully recover within 1-2 months. There are two companies that took approximately six months to reach full recovery. One company is an electronic equipment manufacturing company, and the other company is a petrochemical company. Figs. 5(b) and 5(c) show that the earliest fully recovered production capacity for a flow depth of 3 m or less is two months, whereas it is 3 months for a flow depth higher than 3 m. The general trend of both cases shows that full recovery can be expected after one year.

In terms of industry types, the rate of recovery is much slower for the cargo handling industry than for other industries. At flow depths of 1-2 m, the industry takes 10 months to return to production capacity, while at flow depths of 2-3 m, the recovery period can be much longer. The rate of recovery for the food industry is the fastest among all industries. At a 1 m flow depth, the industry is able to return to production capacity in two months. At higher flow depths, recovery rates can vary depending on the usability of its facilities after the tsunami. A doubling of tsunami inundation depths can increase the recovery period by up to 9 months. However, manufacturing industries encompass a wider range of industrial occupancies, e.g., feed manufacturing versus steel manufacturing, and this factor could influence the differences in companies' vulnerabilities within the same industry. The recovery process of the petrochemical industry is unlike that of other industries, as recovery is a staggered process. The business closure period is similar to the production recovery period for the petrochemical industry.

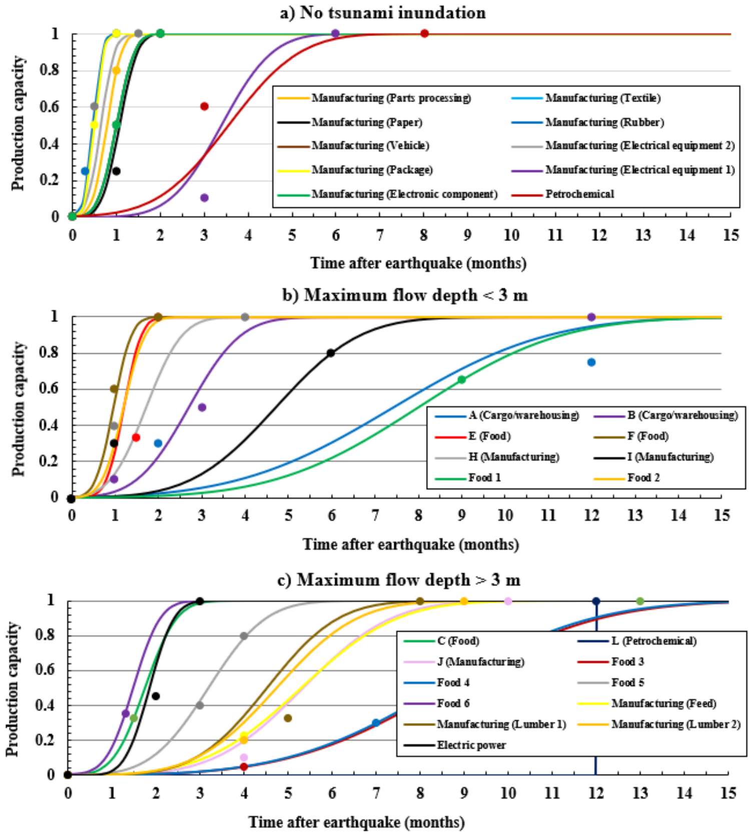

Fig. 5 Recovery potential for industries with different tsunami inundation situations

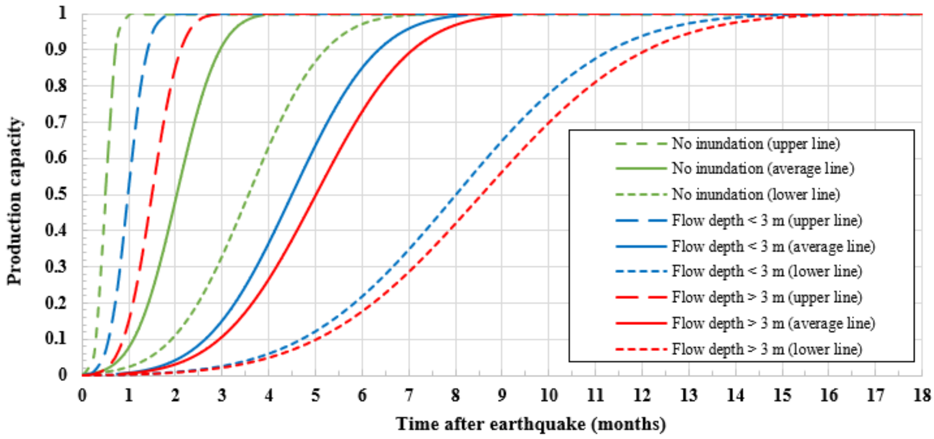

Fig. 6 Recovery potential for industries with different tsunami inundation situations (upper lines, average lines and lower lines)

Table 4 Regression parameters of vulnerability functions of non-structural damage where there is no tsunami inundation using normally distributed linear regression

Industry	Mean	Standard deviation
Manufacturing (Parts processing)	0.7859	0.2543
Manufacturing (Textile)	1.0000	0.3236
Manufacturing (Paper)	1.0716	0.3185
Manufacturing (Rubber)	0.4702	0.1639
Manufacturing (Vehicle)	1.0000	0.3236
Manufacturing (Package)	0.5000	0.1618
Manufacturing (Electrical equipment 1)	3.3922	0.9182
Manufacturing (Electrical equipment 2)	0.6464	0.2400
Manufacturing (Electronic component)	1.0000	0.3236
Manufacturing (Petrochemical)	3.5583	1.2827

Table 5 Regression parameters of vulnerability functions of non-structural damage at maximum flow depth of less than 3 m using normally distributed linear regression

Industry	Mean	Standard deviation
Company A (Cargo handling/warehousing and distribution)	7.4176	2.8069
Company B (Cargo handling/warehousing and distribution)	2.7079	0.9433
Company E (Food)	1.2127	0.3138
Company F (Food)	0.9727	0.3229
Company H (Manufacturing)	1.7219	0.6546
Company I (Manufacturing)	4.7157	1.5260
Food 1	8.0022	2.5895
Food 2	1.2044	0.3897

Table 6 Regression parameters of vulnerability functions of non-structural damage at maximum flow depth of more than 3 m using normally distributed linear regression

Industry	Mean	Standard deviation
Company C (Food)	1.749	0.5660
Company L (Petrochemical)	-	-
Company J (Manufacturing)	5.3384	1.5726
Food 3	8.5520	2.7674
Food 4	8.4306	2.7282
Food 5	3.1885	1.0254
Food 6	1.4852	0.4806
Manufacturing (Lumber 1)	4.5196	1.2705
Manufacturing (Lumber 2)	4.736	1.4354
Electric power	1.8537	0.4379

Table 7 Vulnerability functions for the upper lines and lower lines for each tsunami inundation condition (Fig. 6). The average lines are taken as an average of the upper line and the lower line.

Tsunami inundation condition	Selected vulnerability functions
No tsunami inundation (Upper line)	Manufacturing (Package)
No tsunami inundation (Lower line)	Petrochemical
Maximum flow depth of less than 3 m (Upper line)	Company F
Maximum flow depth of less than 3 m (Lower line)	Food 1
Maximum flow depth of more than 3 m (Upper line)	Manufacturing (Lumber 1)
Maximum flow depth of more than 3 m (Lower line)	Food 3

5 Tsunami numerical simulation results

The numerical tsunami model was calibrated using a performance indicator – Aida's geometric mean K or geometric standard deviation κ proposed by [23] following equations (4) to (6). Aida's K and κ values were used to check the accuracy of the modeled flow depths in Sendai Port by comparing them with observational data. The K value is the ratio between simulated and observed flow depth and κ value is its corresponding standard deviations. Observational data used in this study is from the 2011 tsunami survey data collected by [24] and tsunami trace data from Sendai Port was used for comparison with the simulated results (Fig. 7). The Japan Society of Civil Engineering (JSCE) recommends values of $0.95<K<1.05$ and $k<1.45$ for modelled results to be in "good agreement" with observational data when evaluating tsunami source and propagation models [25]. Based on the distribution of the surveyed data and the simulation results shown in Fig. 8, the computed K is 1.01, and k is 1.25, which indicates a good agreement between the modelled results and observational data. The reproducibility of the 2011 tsunami event indicates that the bathymetry and topography data used in this study are suitable for the simulation of future tsunami in the same area.

$$log\, K = \frac{1}{n}\sum_{i=1}^{n} log\, K_i \qquad (4)$$

$$\log k = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\log K_i)^2 - (\log K)^2} \quad (5)$$

$$K_i = \frac{x_i}{y_i} \quad (6)$$

where x_i and y_i are the observed and simulated data, respectively, at point i.

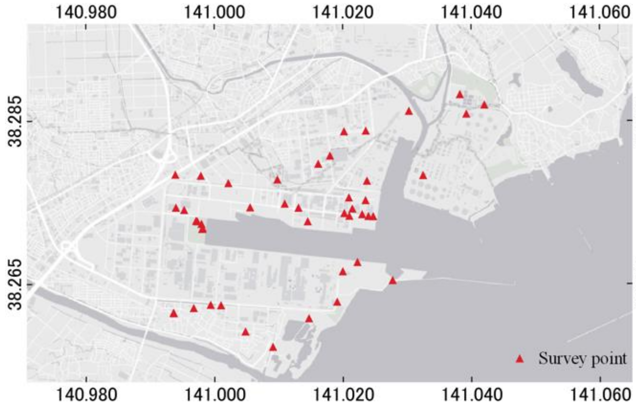

Fig. 7 Locations of the tsunami trace heights (surveyed data) used for evaluating the reproduction of the 2011 tsunami in this study

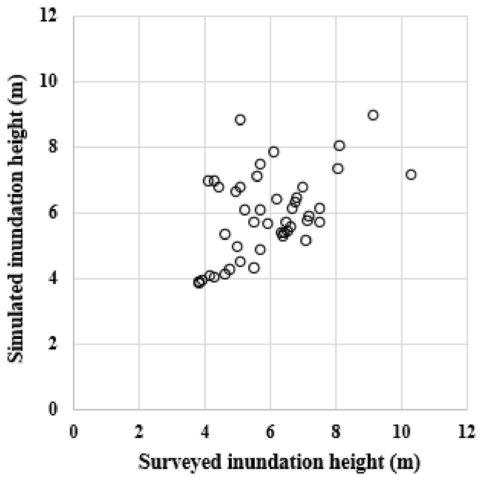

Fig. 8 Comparison of the surveyed inundation height and the simulated inundation height in Sendai Port

Simulated tsunami inundation maps from each tsunami source are shown in Fig. 9. The 2011 tsunami creates the largest tsunami flow depth (3-6 m in Sendai Port), which can reach up to the second floor compared to the other four sources (3 m or less), which may only inundate the first floor. Simulated tsunami flow depths from each of the case scenarios are calculated as a ratio of the simulated flow depths from the 2011 tsunami. The spatial distribution of the ratios is illustrated as maps (Fig. 10). A ratio of less than 100% means that the simulated flow depth is smaller than the 2011 tsunami. Maximum flow depths from other case scenarios are approximately 70% of the 2011 tsunami or approximately 40-50% more or less on average. Simulated waveforms from each case scenario are shown in Fig. 11. In the case of the 2011 tsunami, maximum wave height is the first wave of 8 m, which arrives after 70 min. For the Japan Trench earthquake, the first wave of 4.5 m arrives after 80 min, and a series of tsunami waves of more than 4 m arrive after three hours. For the off-Miyagi earthquake, the first wave of 4 m arrives after one hour, but the maximum wave of 5 m arrives after three hours. For the off-Fukushima earthquake, the first wave may not overtop the seawall, but the maximum wave of 5 m arrives after three hours. For the outer-rise earthquake, more than 4.5 m of the first wave arrives 100 min after the earthquake, as this is the longest distance from the tsunami source to Sendai Port. However, the maximum wave of 5.5 m arrives after three hours. Although there is a case (the off-Fukushima earthquake) in which the first wave might not overtop the seawall, which would allow a longer time for emergency operations, all the interviewed companies said that they would evacuate as soon as possible.

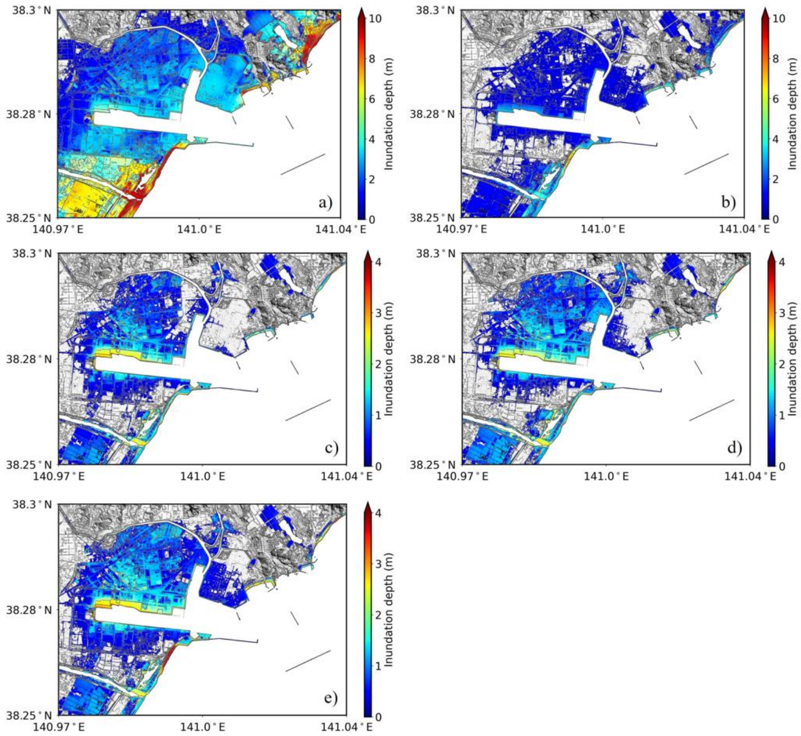

Fig. 9 Simulated tsunami inundation maps from each tsunami source for a) the 2011 tsunami with high tide, b) the Japan Trench earthquake tsunami, c) the off-Miyagi earthquake tsunami, d) the off-Fukushima earthquake tsunami and e) the outer-rise earthquake tsunami.

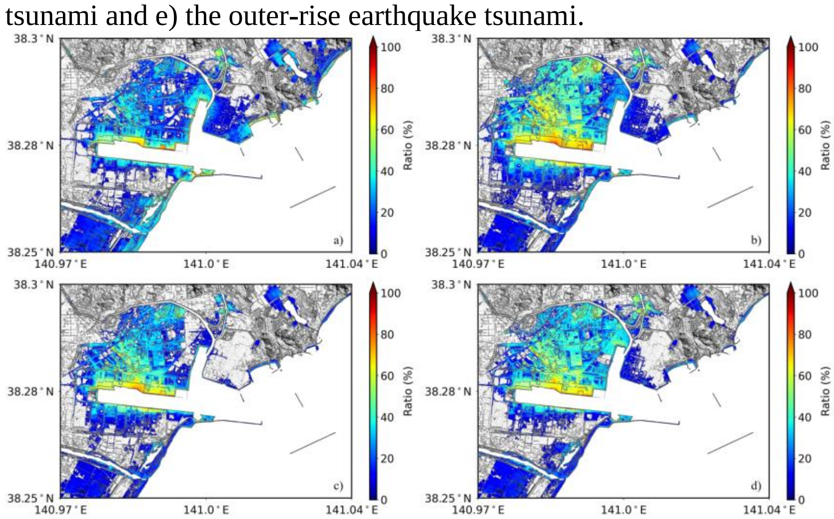

Fig. 10 Simulated tsunami inundation from each tsunami source as a ratio of the 2011 tsunami for a) the Japan Trench earthquake tsunami, b) the outer-rise earthquake tsunami, c) the off-Miyagi earthquake tsunami and d) the off-Fukushima earthquake tsunami

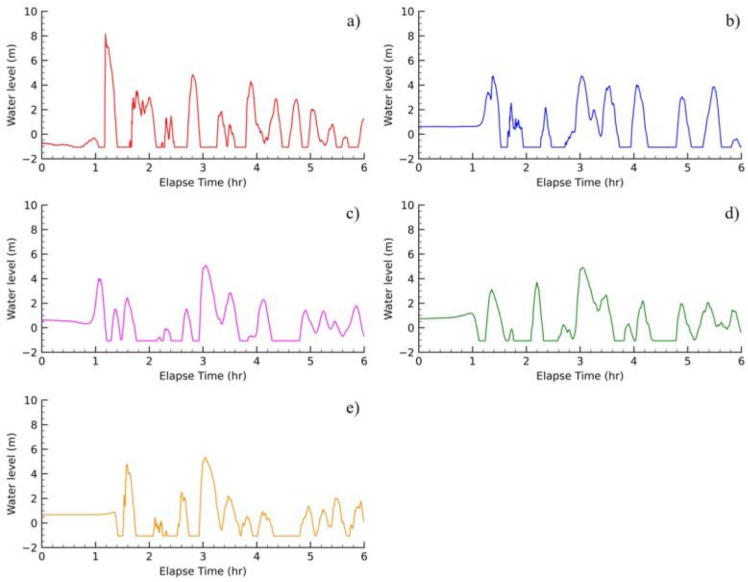

Fig. 11 Waveforms of the simulated tsunami from each source for a) the 2011 tsunami with high tide, b) the Japan Trench earthquake tsunami, c) the off-Miyagi earthquake tsunami, d) the off-Fukushima earthquake tsunami and e) the outer-rise earthquake tsunami.

6 Tsunami risk assessment in Sendai Port

Tsunami risk assessment in Sendai Port using the tsunami simulation results and the developed threshold for non-structural damage and production capacity are used and explained in this section. Fig. 12 shows the factory damage maps when applying structural fragility functions (Damage State 2 = Operational only after repairs) [4] to all five large tsunami scenarios. Similar to the inundation maps (Figs. 9 and 10), the 2011 tsunami with high tide generates the highest damage probability (Fig. 12 a)), varying between 0.1-1.0, while damage from other large tsunamis (Figs. 12b - e) are mostly 0.1 or less but can go up to as high as 0.4-0.5 in some areas. Fig. 13 shows damage probability of each factory building when considering the developed threshold for non-structural damage using the average line (Fig. 4 b)), under different case scenarios. In contrast to the structural damage, probability of non-structural damage from the 2011 tsunami with high tide is almost 1.0 for most factories, especially for factories located around the center of Sendai Port. This result demonstrates that using only structural damage underestimates the actual damage when considering damage to facilities. Finally, examples of production capacity maps for the 2011 tsunami with high tide and the Japan Trench earthquake tsunami using the average production capacity (Fig. 6) are shown in Fig. 14. The production capacity of both tsunami scenarios is 0.1 or lower two months after the tsunami. The production capacity increases to approximately 0.4 at four months after the tsunami and gradually increases to almost 1.0 eight months after the tsunami.

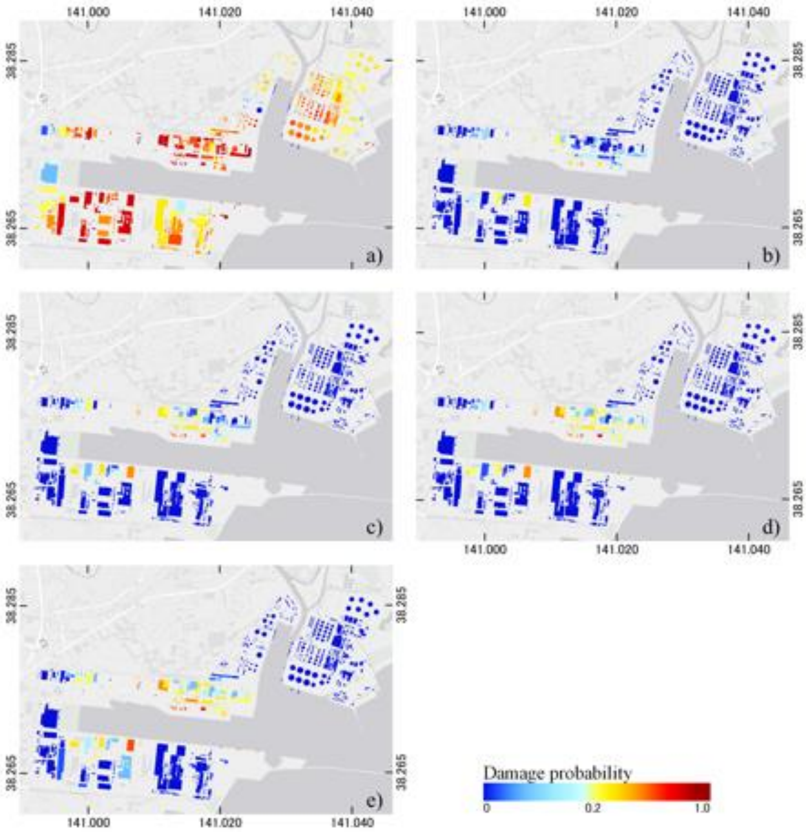

Fig. 12 Factory damage maps based on the structural fragility functions [4] for a) the 2011 tsunami with high tide, b) Japan Trench earthquake tsunami, c) off-Miyagi earthquake tsunami, d) off-Fukushima earthquake tsunami and e) outer-rise earthquake tsunami.

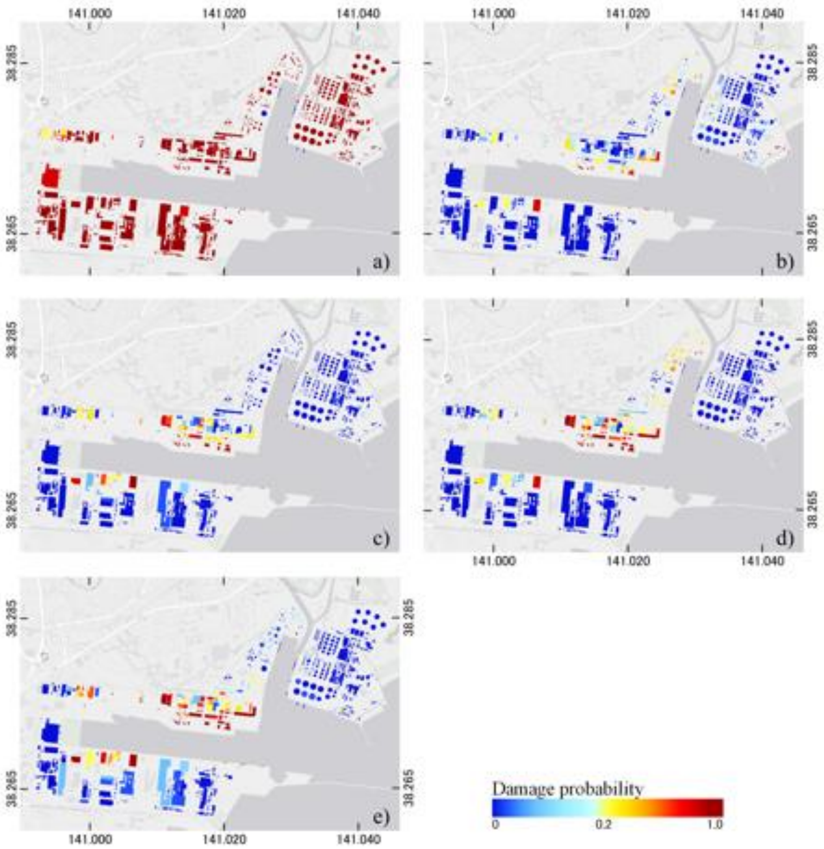

Fig. 13 Factory damage maps based on the developed threshold for non-structural damage (average line) for a) the 2011 tsunami with high tide, b) Japan Trench earthquake tsunami, c) off-Miyagi earthquake tsunami, d) off-Fukushima earthquake tsunami and e) outer-rise earthquake tsunami.

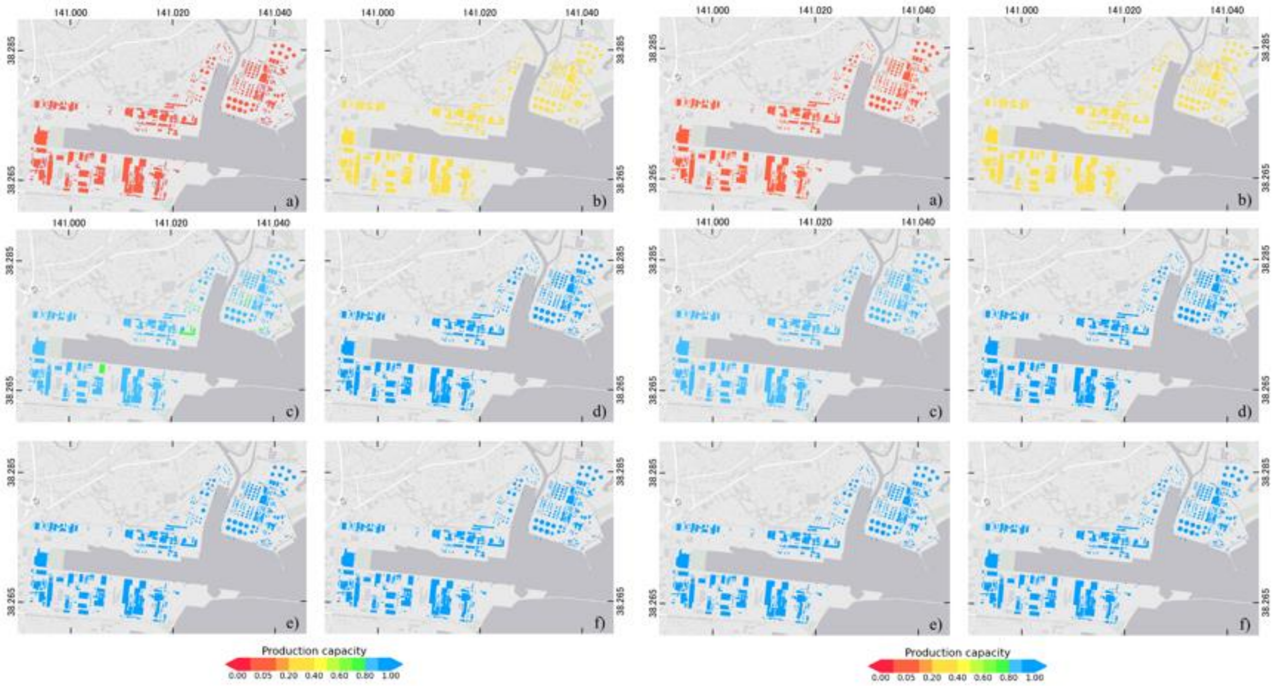

Fig. 14 Production capacity maps based on the developed threshold for recovery potential (average line) for the 2011 tsunami with high tide (left) and Japan Trench earthquake tsunami (right) after a) two months, b) four months, c) six months, d) eight months, e) ten months and f) twelve months.

7 Conclusions

In this study, interviews were conducted to quantify the vulnerability of industrial facilities to tsunami impacts as well as to estimate the recovery rates of production capacity for each industry in a tsunami event using the 2011 Great East Japan earthquake and tsunami as a case study. In general, a tsunami inundation depth of 2 m can result in total damage to most industries. However, a lower depth can cause damage if the facilities have mechanical structures, such as switchboards and equipment, stored in basements. The interviews also included questions on recovery rates of production capacity after earthquake impacts using the 2011, 2016 and 2021 earthquakes as case studies. Industrial facilities, with the exception of the petrochemical industry, are generally less vulnerable to earthquakes, especially where seismic intensities are less than 6 on the JMA scale. Protocols mandate the automatic shutdown of operations in petrochemical facilities in the event of earthquakes, which would require a long time to restart production. Therefore, the petrochemical industry is much more vulnerable to disruptive events, such as tsunamis and earthquakes. It also illustrates that business interruption can be triggered even where no damage occurs. Based on the interviews and additional data related to recovery conditions after the 2011 tsunami, new thresholds for quantifying non-structural damage and production capacity after the tsunami for different tsunami inundation conditions are developed.

This study also simulated hazards from future large tsunamis from earthquake sources in the Tohoku region. Although the 2011 tsunami was likely the largest tsunami affecting Sendai Port, other potential tsunamis are still large enough to overtop the new seawall in Sendai Port and arrive in one hour. The results from a risk assessment illustrated that using the classical structural fragility functions alone might underestimate the actual loss of industries. In terms of production capacity, most industries in Sendai Port are potentially capable of recovering within eight months after large tsunamis in the future.

This work provides a preliminary understanding of the effects of earthquakes and tsunamis on the operations of industrial facilities. It can support the development of business continuity plans for industries, especially those located along the coast and in port areas, and adaptation plans that can reduce or prevent economic recess can be developed. Nevertheless, both new thresholds for non-structural damage and production capacity are developed using limited numbers of data. More data enable vulnerability functions for different types of industry and tsunami inundation situations.

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