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ACCEPTED MANUSCRIPT

A Survey of Impact on Industrial Parks Caused by the 2011 Great East Japan Earthquake and Tsunami

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A Survey of Impact on Industrial Parks Caused by the 2011 Great East Japan Earthquake and Tsunami

Abstract

During the 2011 Great East Japan Earthquake and Tsunami (GEJET), many industrial facilities were affected to different extents by the earthquake and/or tsunami. Damages and reasons for hazardous materials releases were reported by former studies. This paper provides further details concerning the impact of GEJET, by the data collected from a series of field visits, interviews and mail surveys. In this study, we report the facility damage and economic losses, the performance of safety and mitigation measures, the emergency preparedness and response to the chemical releases triggered by earthquake and/or tsunami, and changes to preparedness practices at the facilities after experiencing the GEJET. Recommendations are proposed at the end when compared to previous studies in the literature.

Key words: Industrial facility safety, earthquake, tsunami, hazardous materials

1. Introduction

The Great East Japan Earthquake and tsunami (GEJET) on March 11, 2011 affected industrial facilities and industrial parks, as well as port terminals in Iwate, Miyagi, Fukushima, Aomori, Chiba, Ibaraki, and Tokyo, along coastal areas on the Pacific Ocean in Japan. Earthquake damages extended beyond the coastal areas inland, and even to coastal facilities located on the Japan Sea. Zama et al. (2012) reported damage at 3,324 oil storage and hazmat facilities (out of 211,877 surveyed by the Japanese government) in the affected areas. 1,404 of these were damaged by the strong ground motion, 1,807 by the tsunami and the rest, 113, remain unknown. According to their report, fires occurred in 42 facilities, and oil leakage occurred in 122 facilities, representing about a 4.9% of the damaged industries. Zama et al. report the number of facilities that had releases, not the actual number of releases which is probably much higher.

Krausmann and Cruz (2013) investigated hazardous materials releases at industrial facilities impacted by the earthquake and tsunami based on a review of open sources such as company websites and newspaper articles, and interviews with fire department officials in Sendai and Chiba regarding. At the Sendai refinery, the authors reported several fires, and at least two large oil spills

(of 4400m^3 and 3900 m^3).

This paper provides further details regarding the impact of the Tohoku disaster on industrial installations at the Sendai, Kashima, and Chiba industrial parks in an effort to better understand the impact of the earthquake and tsunami in these areas. Although the sample is relatively small, the analysis complements the previous works by providing more details into the damage and losses, the performance of safety and mitigation measures, as well as the emergency management systems that were in place. Finally, the paper puts the Tohoku earthquake and tsunami impact on industry into perspective when compared to previous studies in the literature.

2. Methodology

Field visits, person-to-person interviews, and two mail surveys were undertaken in Miyagi, Iwate, Chiba and Ibaraki Prefectures, Japan. First, a series of interviews with fire department officials at the prefecture and city level were carried out in March and July 2014. Several follow-up visits by some of the authors were also carried out in 2015. The research partners worked together to prepare questions for the field visits, and the survey questionnaires. The Japanese team then prepared Japanese versions of the questionnaires, and went through several rounds of checks and reviews to insure the meaning of English and French questions were reflected in the Japanese translations. Survey questionnaires were used during the person-to-person visits at Cosmo Oil in Ichihara City (Chiba Prefecture), the JX Refinery and Zennoh in Sendai, and Nippon Steel in Kamaishi. Survey questionnaires were also prepared for person to person interviews with government and fire department officials.

We conducted two mail surveys of industrial facilities located in selected industrial areas affected by the GEJET in Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures, as shown in Figure 1. A first industrial survey was sent out through the Japan Industrial and Medical Gases Association (JIMGA)'s office in Sendai to member companies; this was very important because many companies had relocated or were still closed. JIMGA had the contact information of these companies and was able to contact their managers directly even if the facilities were not in operation. JIMGA recommended that the questionnaire be sent to 20 of its member companies that were located in areas affected by the earthquake and tsunami. Eighteen completed questionnaires were received

from JIMGA member companies. Another three surveys questionnaires were filled out during field visits.

After tabulation and analysis of the first set of completed questionnaires we found that there were several questions that were left unanswered. Thus, further reviewing and testing of the questionnaire was done and a new version was prepared and translated hoping to get better results in the second mailing to all the companies at the Chiba and Kashima industrial parks located in Chiba and Ibaraki Prefectures, respectively. A total of 351 questionnaires were mailed out. The questionnaires were written in both Japanese and English. A cover letter with instructions, and a pre-addressed return envelope were mailed to the entire sample. There were no follow up mails or phones to the investigated facilities.

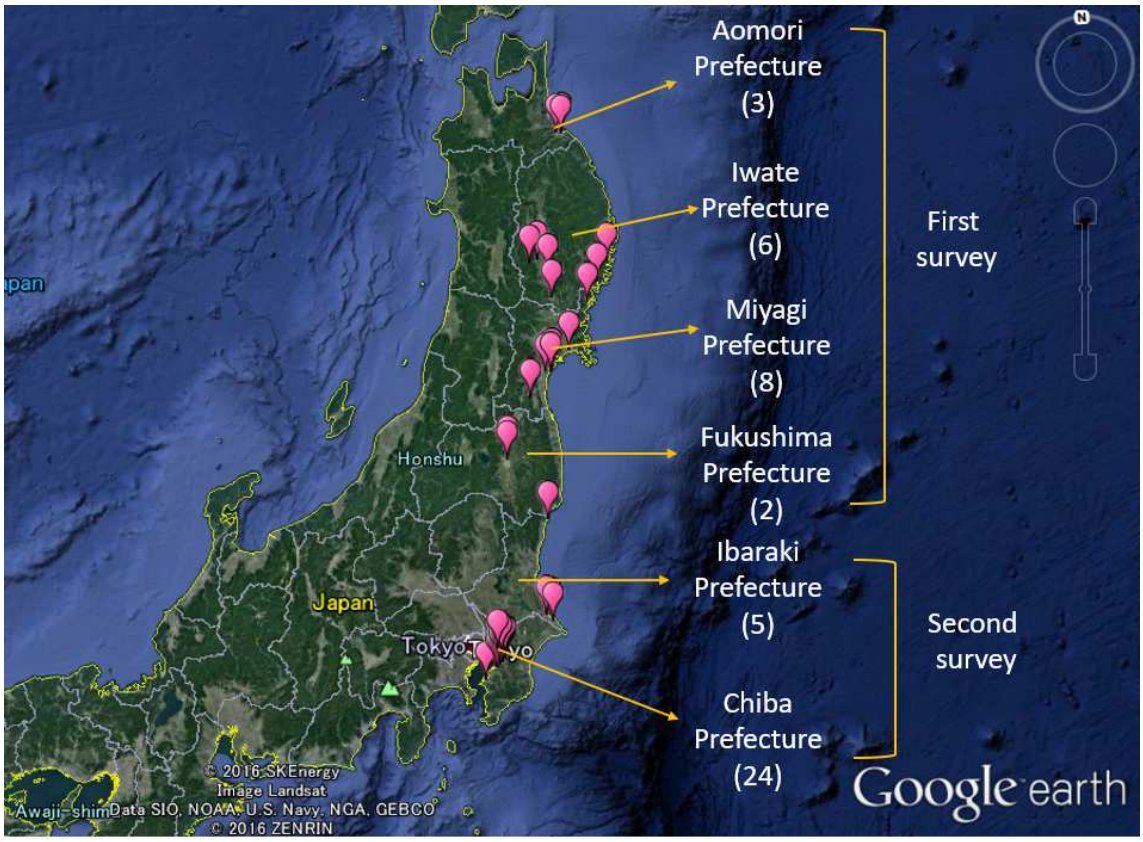

Figure.1 Map showing the location of industrial facilities for which a completed questionnaire was received (the number of respondents of each area is shown in the brackets)

The questionnaire was divided into ten sections. As listed in Table 1, Section A provided an introduction to the questionnaire survey. Section B asked questions that identified each industrial facility, including company name, size, number of employees, year of construction and type of industry. Section C asked questions

regarding the earthquake (e.g., peak ground acceleration (pga) or Gal, Shindo scale intensity) and the tsunami (e.g., water depth, duration of submersion, water flow velocity) hazard event if known, and their impact.

We were interested in learning about damages and losses to the facility as well as the performance of safety and mitigation, and emergency response systems. Thus, Section D inquired about the overall damages and economic losses at the facility from the earthquake, tsunami and aftershocks. Specifically, we asked if the plant was directly or indirectly damaged by the earthquake, tsunami or aftershock; the causes of total or partial plant shutdown; and the monetary losses suffered by the companies. In Section E, we asked whether the units or system handling hazardous materials were damaged by the earthquake or tsunami, and whether these damages involved hazmat releases. In the case of a hazmat release, the responder was further asked to indicate if these releases had resulted in, or posed a threat of fire, explosion, etc. In this section, we also asked about the performance of safety and mitigation measures in place when the earthquake and/or tsunami occurred. In addition, we asked the respondents to tell us about any other problems or failures that occurred during the earthquake and/or tsunami, such as, building collapse, debris impact, etc. Section F asked questions concerning damage to emergency response facilities and resources by the earthquake and/or tsunami.

Questions regarding the preparedness and emergency response actions taken were also included. Section G inquired about the emergency preparedness actions taken to prevent casualties, and the effectiveness of emergency plans for the earthquake and/or tsunami triggered chemical accident. In Section H, we asked about the actions taken to control the releases triggered by earthquake and /or tsunami during the GEJET.

Questions concerning the possible impact of the chemical releases on nearby residents and the environment were included in Section I. Finally, Section J investigated changes to regulations, preparedness practices, and recommendations for future practices based on the experience of the GEJET.

Table 1. Contents of the survey questionnaire

Section	Topic
Section A	Introduction to the questionnaire survey

Section B	General information of surveyed companies
Section C	Hazard information
Section D	Overall damage and economic losses at the facility from the earthquake and tsunami
Section E	Performance of units and systems handling high pressure gases and other hazardous chemicals during the earthquake and tsunami
Section F	Performance of emergency response systems (facilities and resources)
Section G	Emergency preparedness
Section H	Actions taken to control the earthquake/ tsunami caused chemical accidents
Section I	Consequences of the chemical releases
Section J	Changes and recommendations

3. Results

3.1 Response rate and general characteristics of the facilities

In total, we have received 48 completed questionnaires from the two mail surveys and field visits, resulting in a response rate of 13.3%. The response rate is low for this kind of survey. Past surveys reported response rates of 23-26% (Cruz and Steinberg 2005; Lindell and Perry 1998, Webb et al. 2000). Nonetheless, given the general difficulty to access information from industrial installations, we believe the results here presented provide some interesting insights as to the impacts of the GEJET on the chemical industry.

The characteristics of respondents are shown in Table 2. Among the 48 facilities surveyed, only 5 were part of a multinational company. We used two measures of company size including self-identification as small, medium, or large; and selection of the number of employees from among three categories as shown in table 2. A relatively large group of facilities (63 %) were small-size companies, and 65% of the facilities had 0-50 employees. A little less than 20% of the facilities had more than 200 employees. Half of the facilities were chemical companies, 15% were petrochemical, 8% were metallurgical, and 4% were oil refineries.

We asked respondents to indicate the date of construction of the facilities. Unfortunately, almost half (23) of the respondents did not answer this question.

Ten respondents indicated their facilities were built between 1970 and 1980, six said the facilities were built in1969 or before, and nine were built after 1980.

Table 2. Industrial facility characteristics

	No. of facilities	Percent
Multinational		
Yes	5	10%
No	43	90%
Company size		
Small	30	63%
Medium	12	25%
Large	4	8%
No answer	2	4%
No. of employees		
(0-50)	31	65%
(51-200)	8	17%
(201+)	9	19%
Type of industry		
Chemical	24	50%
Petrochemical	7	15%
Oil refinery	2	4%
Metallurgical	4	8%
Other	10	21%
No answer	1	2%
Age of industrial facilities		
⩽1969	6	13%
⩾1970＜1980	10	21%
≥1981＜1990	4	8%
≥1991	5	10%
No answer	23	48%
Total	48	100%

3.2 Damage and economic losses

3.2.1 Overall damages

In the questionnaire, we asked respondents to indicate whether the industrial facility was damaged by the earthquake, tsunami, and earthquake aftershocks directly (e.g. due to ground shaking, liquefaction, inundation) or indirectly (e.g. debris impact, collapse of support structure, earthquake/tsunami triggered fires at other facilities). As indicated in table 3, of the 48 facilities, 22 were damaged by the earthquake and/or its aftershocks. 11 of these, were located at the Chiba industrial park in Chiba Prefecture. Only 3 facilities from Chiba prefecture indicated being affect by the tsunami or the combined effect from both the earthquake and tsunami. Two of the facilities surveyed through JIMGA were located inland in Fukushima prefecture and were thus not affected by the

tsunami. Most of companies located along the coastline reported damage due to both the earthquake and the tsunami (27%), and by the tsunami alone (6%). Moreover, among the companies surveyed, 60% were directly damaged by the earthquake, and 29% directly damaged by the tsunami. 63% were indirectly impacted by the earthquake, and 25% indirectly damaged by the tsunami. The earthquake aftershock also caused direct damage to 33% and indirect impacts to 25% of the surveyed companies.

Table 3 Overall damages by impact hazards

Hazards / Locations	Only earthquake or aftershock	Only Tsunami	Both earthquake and tsunami	No damage	Total
Aomori	0	0	3	0	3
Iwate	4	0	2	0	6
Miyagi	2	2	4	0	8
Fukushima	2	0	0	0	2
Kashima	3	0	2	0	5
Chiba	11	1	2	10	24
Total	22	3	13	10	48

In addition, the earthquake and/or tsunami caused total shut down in 48% (23 out of 48) of surveyed facilities; and partial shutdown in 6% (3out of 48). 19% (9 out of 48) said they experienced both total and partial shutdown of different parts of their plants; and 21% (10 out of 48) did not shut down. On average, the earthquake and/or tsunami impacts cost surveyed companies to shut down totally for 61 days, and partially for 63 days. The main causes of shutdown are listed in Table 4, which shows that the most common cause for shutdown was direct (e.g., direct damage due to ground shaking, submersion) or indirect damage (e.g., debris impact, collapse of neighboring structure) due to the earthquake and/or tsunami (58%). Loss of electricity was the second most common cause, resulting in shutdown at 44% of surveyed companies. Other causes such as “blocked transportation routes” and “supplier company was damaged”, etc. were also reported by respondents.

Table 4 Main cause of total or partial plant shutdown

	No. of facilities	Percent of facilities reporting

Direct/Indirect damage	28	58%
Blocked transportation routes	8	17%
Loss of electricity	21	44%
Lack of workers	3	6%
No/loss of backup power generation	4	8%
Lack of supply of prime materials	3	6%
Loss of water	3	6%
Supplier company was damaged	3	6%
Lack of fuel supply	2	4%
Total	48	

Multiple answers are possible

3.2.2 Damage to the facilities handling hazardous materials

In the questionnaire, we asked if there was any damage caused by the earthquake and/or tsunami on process units, vessels, storage tanks or other equipment that handle high pressure gases, flammable liquids or toxic chemicals. As indicated in Table 5, 21 of the surveyed companies handling high pressure gases, in which 12 of them were damaged by the earthquake, while nine were damaged by the tsunami. Furthermore, 2 companies handling toxic chemicals, and three that handle flammable liquids were damaged by the earthquake and/or tsunami.

Table 5 Damage to the facilities handling hazardous materials by impact hazards

Hazards / Units and systems	Earthquake	Tsunami	Total
High pressure gases	12	9	21
Flammable liquids	2	1	3
Toxic chemicals	1	1	2

Two facilities reported fires, and one facility reported explosions and fires during the earthquake and tsunami disaster. Six of the surveyed facilities reported hazardous materials releases. Although these facilities did not suffer fires or explosions, they did report concern that the released materials posed a fire or explosion hazard. Furthermore, the releases resulted in resident evacuation in two surveyed cases. Furthermore, 2 facilities indicated that the hazardous material releases caused environmental consequences such as air or water

pollution. Four employees in one industry were killed by the tsunami. No domino effect was reported by the respondents despite the fact that in one of the facilities surveyed there were several domino chemical accidents. As reported by Krausmann and Cruz (2013), during the GEJET, the strong ground motion at the Chiba refinery caused the support braces of an LPG tank to buckle which led to complete tank collapse during an aftershock. The collapse of the tank, which contained water at the time of the earthquake due to a maintenance check, ruptured connected LPG pipes and eventually degenerated into a major refinery fire and series of explosions. The associated explosions destroyed all 17 LPG tanks in the tank farm, and damaged nearby asphalt tanks due to debris impact, causing asphalt to leak into the ocean. The reason for no report about domino accidents in this survey by the Chiba refinery may have been due to a misunderstanding of the concept of “domino” effects.

In our survey we asked about the types of problems or failures that occurred at: (a) Atmospheric storage tanks; (b) Pressure tanks/ vessels; (c) Process units/ equipment; and (d) Pipeline systems as presented in Table 6. The selection of failures and/or problems used in this survey was based on a similar list used by Cruz and Steinberg (2005) and typical failures reported by ABAG (1990). Loss of electricity was the most often reported problem affecting operation at four atmospheric storage tanks, five pressure tanks/ vessels, six process units/ equipment, and two pipeline systems. Water intrusion affected 10 facilities causing total damage or malfunction. Furthermore, failure of support structures (6 facilities), building collapse (6 facilities) and debris impact (6 facilities) were also reported. Process units/ equipment (28 facilities) and atmospheric storage tanks (16 facilities) appear to be the most vulnerable in our study. Even though no respondents reported any problems or failures due to human error in the survey, the interview with Cosmo oil refinery revealed that human error and design were the major contributors to the hazmat release and fires that resulted.

Table 6 Types of problems or failures that occurred at (a) Atmospheric storage tanks; (b) Pressure tanks/ vessels; (c) Process units/ equipment; (d) Pipelines

Problem or failure	Number of facilities				
	a	b	c	d	Total
Failure of support structure (leg braces, steel frame, etc.)	4	0	1	1	6
Building collapse	1	1	2	0	4
Debris impact	2	1	2	1	6

Damage to connections	0	0	0	1	1
Failure of control mechanisms	1	0	1	0	2
Loss of electricity	4	5	6	2	17
Loss of water or water pressure	1	1	3	1	6
Loss of cooling/Cooling tower failure	0	0	4	0	4
Loss of heating/Boiler failure	0	0	2	0	2
Over pressurization	0	0	0	0	0
Human error	0	0	0	0	0
Corrosion	0	0	0	0	0
Overtopping of facility sea wall by flood waters	0	2	2	1	5
Overtopping of containment dike by flood waters	0	0	1	0	1
Water intrusion or flooding of low lying equipment	2	3	4	1	10
Domino Effects	0	0	0	0	0
Displacement of storage tanks	1	0	0	0	1
Total	16	13	28	8	65

3.2.3 Damage to emergency equipment and resources

We were also interested in collecting information concerning the damage to emergency equipment and resources by the earthquake and/or tsunami. The results show that the emergency response resources of 6 (13%) surveyed facilities were damaged by the earthquake, while 7 (15%) were damaged by the tsunami. One respondent reported that their emergency team members were unable to reach the plant during the earthquake and/or tsunami. Fortunately, no emergency team members were reported to be injured or killed by the earthquake and/or tsunami.

In more detail, we asked respondents about damage to the emergency operations center, and on-site fire station building (if present in the installation). The results are shown in Table 7. Ten facilities lost utilities at the emergency operation's center during the earthquake and/or tsunami. Furthermore, 7 and 8 respondents reported damage to their IT equipment and communications equipment at the emergency operation center, respectively. For the on-site fire station building, the earthquake and/or tsunami damaged the IT equipment in 6 of the surveyed facilities. Other issues such as loss of utility, damage to fire suppression and hazmat response equipment were also reported by some respondents.

Table 7 Damage to emergency response systems

	No. of facilities
Emergency Operations Center	
Loss of utility	10
Damage to IT equipment	7
Damage to communication equipment	8
On-site fire station building	
Loss of utility	3
Damage to IT equipment	6
Damage to fire suppression equipment	2
Damage to hazmat response equipment	1
Damage to emergency medical care equipment	0
Damage to personal protective equipment	0
Total	48

3.2.4 Economic losses

15% (7 out of 48) an4d 38% (2 out of 48) of respondents at the surveyed facilities reported direct and indirect economic losses, respectively. 38% (18 out of 48) of them reported both direct and indirect losses. 44% (21 out of 48) of respondents did not provide information about their economic losses or indicated that such information had not been published. As shown in Table 8, direct and indirect economic losses were on average, 2,144 million and 843 million Japanese yen, respectively, due to the earthquake and/ or tsunami impact. Only 6 (13%) industries indicated that their losses were covered by insurance, while 27 (56%) were not. In the questionnaire, we also asked what percentage of the total losses was covered by the insurance. Only 3 respondents answered this question, by providing the amount of money they received from insurance instead of percentage. The average losses covered by the insurance was 1800 million Japanese yen.

Table 8 Economic losses at industrial facilities surveyed

Economic losses (million)	Mean	Minimum	Maximum
Estimated cost of total direct losses	2144	1	50000
Estimated cost of total indirect losses	843	0.6	7500
Losses covered by the insurance	1800	100	5000

Note: Direct losses refer to the estimated cost of property damage losses caused by the

earthquake and/or tsunami. Indirect losses refer to the estimated cost of other losses such as loss if production, business interruption, etc.

3.3 Industry preparedness for hazmat releases during the earthquake and tsunami

3.3.1 Available and damaged mitigation measures

In the questionnaire, we asked respondents to indicate the mitigation measures that were available and whether they were damaged by the earthquake and/or tsunami. According to results shown in Table 9, 21% of facilities had adopted structural design/ retrofitting for earthquake at the facility level, followed by anchoring of storage tanks and other equipment (19%). 17% and 19% of respondents said that atmospheric storage tanks and pressure tanks/vessels were designed or retrofitting for earthquake respectively. Emergency shut off/ safety valves were available for these two types of equipment at 13% and 15% of facilities, respectively. The damage rate of these types of mitigation measures was quite low, less than 4% according to our survey.

Table 9 Available and damaged mitigation measures adopted by industrial facilities

Mitigation measures in place at the time of the earthquake and tsunami	**Percent of (a) available and (b) damaged mitigation measures**									
	Facility level		Atmospheric storage tanks		Pressure tanks/vessels		Process units/other equipment		Pipelines	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Sea wall to protect facility from storm surge or tsunami	10%	4%	8%	0%	6%	0%	6%	0%	6%	0%
Structural design for earthquakes/ retrofitting for earthquakes	21%	2%	17%	4%	19%	2%	13%	2%	6%	0%
Containment dikes or walls	8%	2%	8%	0%	6%	0%	6%	2%	6%	0%
Anchoring mechanisms for storage tanks and other equipment	19%	0%	8%	2%	13%	2%	15%	4%	10%	0%
Bracing of pipes and connections	10%	2%	4%	0%	8%	0%	6%	0%	6%	2%
Flexible connections for pipes	10%	2%	4%	0%	8%	0%	4%	0%	4%	0%
Restraining straps or chains for barrels or pressure vessels	8%	2%	4%	0%	13%	0%	4%	0%	2%	0%
Strapping and anchoring of emergency equipment	6%	2%	4%	0%	4%	0%	4%	0%	2%	0%
Emergency shut off/safety valves	17%	0%	13%	0%	15%	0%	8%	0%	6%	0%
Emergency water systems and foam spraying systems	8%	2%	6%	0%	6%	0%	6%	2%	6%	0%
Alarm systems	10%	4%	10%	2%	10%	2%	8%	2%	4%	0%
Emergency power generators	4%	0%	0%	0%	0%	0%	2%	2%	0%	0%
Water proofing equipment	2%	0%	2%	0%	2%	0%	2%	0%	2%	0%
Fire protection walls	2%	0%	4%	0%	4%	0%	4%	0%	2%	0%
Water curtain/water spraying system	2%	0%	4%	0%	4%	0%	4%	0%	2%	0%
N	48									

3.3.2 Emergency preparedness adopted by industrial facilities

54% of surveyed industries reported that they had emergency response plan

that took into account the response to earthquake and/ or tsunami triggered chemical accidents. However, 21% of respondents indicated that they think the procedures in the emergency response plan were not well designed for the chemical accidents triggered by earthquake and/or tsunami (35% said the procedures were well designed). In comparison, 63% of the respondents thought the procedures were well designed to cope with the earthquake. Only 31% of industries thought their emergency plans were adequately designed for the tsunami.

Concerning to the emergency teams, 33 (69%) industries had an on-site fire teams, while 18(33%) had an on-site Hazmat team at the time of the earthquake and tsunami. Comparatively fewer industries had on-site incident support services (e.g., excavator, bull dozer, and crane) (15 (31%)), and on-site emergency medical teams (13 (27%)). 31(65%) surveyed facilities had an evacuation plan for employees at the time of the earthquake, while only 12 (25%) of them did not have one. This may be because 63% of respondents were small-size companies. Six facilities reported that they now have an evacuation plan. 40% of facilities had an established program for training their workers for the handling of chemicals safely at the time of the earthquake, while 42% of them did not have such program.

In addition to asking about the on-site emergency preparedness, we were also interested in the off-site plans adopted by the industries. We asked respondents to indicate if they had established procedures to notify local authorities in the event of a chemical accident at the time of the earthquake. A relatively high percentage (60%) of respondents said they had such plan in place. However, for the program for enhancing residents' risk awareness and/or disseminating knowledge about hazardous materials, 65% of industries did not have one.

3.4 Emergency actions during the earthquake and/or tsunami

Among the 48 respondents, 67% (32) of them indicated that they did not receive the tsunami evacuation warning from local authorities. However, 46% (22) of them did evacuate for the tsunami. 15% (7) of them evacuated before receiving the official evacuation warning, while 27% (13) of them evacuated after receiving the warning. Most facilities evacuated all the staff (67%), while only 5 (10%) of them left a crew to deal with later emergencies.

The facilities that experienced releases of hazardous materials, fires, explosions, or oil spills, were further asked about their emergency actions. As indicated in section 3.2.2, six facilities reported hazardous materials releases, fires or explosions. Furthermore, another two facilities indicated that releases almost occurred at their plants (near misses). Among the 8 respondents, only 3 of them indicated that they were able to control the accident or release once it began. The emergency shut down procedure worked effectively which prevented further releases. The emergency response to contain the accidents in 6 out of 8 facilities involved the facilities' fire teams, while 1 facility reported the involvement of the facility hazmat team, and 1 facility reported the involvement of government fire team support. 3 out of 8 respondents indicated that there were sufficient numbers of personnel to respond to the release, while 3 industries did not have enough personnel. In the questionnaire, we asked if the respondents were able to clean up or recover the released materials. 4 respondents said yes, while 2 of them said no.

In order to understand more details about the emergency response actions, we asked respondents to indicate the timing when they: 1. Activated the emergency plan; 2. Manage to respond effectively; 3. Communicated with outside agencies/authorities; 4. Secured the facility, 5. Accessed the accident scene; and Respondents were given five "time periods" to choose from: a. immediately after the earthquake, before the tsunami warning; b. after tsunami warning, before the tsunami; c. sometime after the tsunami attack (one or two days after); d. several days after the tsunami attack (three days or more); and e. it was not able to take actions. The results are shown in Fig.2. 50% of respondents successfully activated the emergency plan immediately after the earthquake (1 involved earthquake, and 3 involved both earthquake and tsunami). However, only 25% of them managed to respond effectively in the same time period (1 involved earthquake, and 1 involved earthquake and tsunami). 38% of respondents secured the facility immediately (1 involved earthquake, and 2 involved earthquake and tsunami), but, only 25% of them were able to access to the emergency equipment or respond to the accident (1 involved earthquake, and 1 involved earthquake and tsunami). Moreover, 38% of respondents indicated that they were unable to communicate with outside agencies/authorities (1 involved earthquake, 1 involved tsunami, and 1 involved earthquake and tsunami).

Fig.2 Timing of emergency actions

3.5 Changes in industry preparedness for hazmat releases after the GEJET

After experiencing the GEJET, many industrial facilities had changed their regulations or practices to better respond to the next earthquake and tsunami. Table 10 shows that 65% of surveyed industries have added or modified their emergency response plans after the GEJET. Furthermore, 44% of industries indicated that they have changed the company's external relations policies to improve public safety around the facility, such as the dissemination of information concerning self-protective knowledge, etc. Other measures taken include improving the way to obtain disaster information and warnings (40%), improving the way to communicate disaster information and warnings to their employees (35%), earthquake retrofitting of existing buildings, storage tanks or process units (33%), and adopting specific measures for tsunami impacts (23%). Fewer respondents indicated that they have taken measures to

improve communication, coordination, and cooperation with local authorities.

Table 10. Changes to regulations or practices after the GEJET

Changes and improvements	No. of facilities (%)
Earthquake retrofitting of existing buildings, storage tanks, etc.	16 (33%)
Adopted specific prevention and mitigation measures for tsunami	11 (23%)
Making efforts to improve public safety around the facility	21(44%)
Modified emergency response plans	31(65%)
Improved the way to collect disaster information	19 (40%)
Improved the way to communicate disaster information	17(35%)
Improved the way to coordinate and cooperate with local Designated Government Organizations	2(4%)
Improved the way to communicate with external responders of municipal office	7(15%)
Total	48

4. Discussion and Conclusion

This study provided detailed information regarding the impact of the Tohoku earthquake and tsunami on 48 industrial facilities. Of these, six facilities reported hazardous materials releases. Three of these releases resulted in fires and/ or explosions. No injuries or deaths of residents were reported due to the Natech. However, four workers at one refinery were killed due to the tsunami, and injuries were reported during release control, fire-fighting and evacuation among staff in another refinery. Three facilities reported slight environmental pollution of air, water and soil. Residents near two of the affected facilities were forced to evacuate.

This study shows that the investigated industrial facilities suffered substantial damages and economic losses during the GEJET. More than 60% of the responding industrial facilities suffered damages due to the earthquake, and around 30% of them were damaged by the tsunami or by aftershocks. Almost 70% of surveyed companies were shut down. Over 50% of responding facilities reported economic losses, and 56% of them indicated their losses were not covered by insurance. Direct/ indirect damages caused by the earthquake and/or tsunami and loss of electricity were the main reasons for facility shutdowns.

In fact, loss of electricity was reported as a problem affecting operations at 17 storage tanks and vessels, and pipeline systems. 11 of these facilities were impacted by the tsunami or by the conjoint effect of the earthquake and tsunami. 10 of these facilities reported damage due to water intrusion. Onsite power generation plants or back up power generators if available (only 4% indicated they had them) were most likely flooded, and those that were not, may have been available only for lighting purposes, not to operate process equipment. Our results show that facilities were less likely to take tsunami protection countermeasures. Thus, to prepare for any future disaster, measures should be conducted to prevent or mitigate the direct/ indirect impact by natural events (such as earthquake and tsunami), and to avoid losing electricity, especially for critical facilities.

About 44% of facilities handling high pressure gases were damaged by the earthquake and/or tsunami. The high percentage may be a sample bias because 35% (17 out of 48) of the respondents were from high pressure gas facilities. Hazmat releases occurred in 13% of hazmat-handling industrial facilities in our survey. This is higher than that reported for the Kocaeli earthquake (8%) by Cruz and Steinberg (2005), but lower than 18.5% reported by Lindell and Perry (1996). Besides the fact that our sample was small, the difference may due to the fact that the GEJET was a much more powerful earthquake in addition to the large tsunami and series of earthquake aftershocks. Our results show that process units and atmospheric storage tanks were more vulnerable than other types of equipment. Earthquake retrofitting, elevating the equipment or improving waterproofness may help facilities to increase their ability to cope with next earthquake and tsunami impact. Furthermore, the higher number of facilities reporting loss of electricity as a “failure mode”, indicates that adequate planning of backup power requirements is needed, including ways to insure their integrity during future earthquakes and tsunami.

Even though over 50% of respondents reported that they had response plan considering the hazmat releases during earthquake and/or tsunami, 21% of them indicated that the plans were not well designed. An important issue revealed by this study is that 65% of the facilities surveyed had no programs or activities to communicate with the public regarding preparedness for hazardous materials accidents.

About a third of the surveyed facilities reported that they have retrofitted existing buildings, storage tanks, etc. for the next earthquake, and about a quarter have adopted specific prevention and mitigation measures for tsunami. Most surveyed facilities have made some changes to improve disaster preparedness after the GEJET. Improvements were reported regarding emergency response plans and risk communication to residents living close to the facilities. However, more needs to be done to reduce Natech risks based on the lessons from this survey. For example, the domino accidents that occurred at the Chiba refinery suggests that strict regulations should be adopted to ensure that sufficient separation distances are kept between storage tanks, as well as between storage tank farms and other facilities. Following the GEJET, the Chiba refinery increased the distance between the new LPG tanks to 25-30m, and improved water sprinkler systems on each tank. At other existing tanks and neighboring facilities that cannot be moved, risk assessments should be performed to ensure that Natech risks are identified and adequate prevention and preparedness measures are put in place. Furthermore, emergency planning that considers the potential loss of onsite and offsite utilities required for mitigating the consequences of a Natech accident should be introduced (Krausmann and Cruz 2013).

This study provides detailed information concerning the impact of earthquake and tsunami on industrial facilities as well as their emergency system during the GEJET. Even though, the samples for this study is relatively small and has potential bias, it provide some insights in the management of risks resulting from earthquake and tsunami triggered chemical accidents. First, comprehensive loss estimation caused by potential natural hazard impact should be conducted for the existing industrial facilities in areas subject to high earthquake and tsunami hazards such as Osaka Bay in Japan. Second, particular attention should be given to the facilities or equipment that are more vulnerable (e.g. process units and atmospheric storage tanks found in this study). Finally, effective emergency plans to deal with the conjoint impact by natural events and chemical accident should be discussed.

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- The earthquake and /or tsunami during the GEJET had caused substantial damages and economic losses to the industries investigated.
- The investigated industries were less prepared for the tsunami impact
- Loss of electricity was reported as a major problem affecting operations at storage tanks and vessels, and pipeline systems.
- Process units and atmospheric storage tanks were more vulnerable than other types of equipment
- 65% of the facilities surveyed had no programs or activities to communicate with the public regarding preparedness for hazardous materials accidents