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ORIGINAL PAPER

# Impact of the 11 March 2011, Great East Japan earthquake and tsunami on the chemical industry

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**Abstract** The Great East Japan earthquake and tsunami damaged or destroyed many industrial facilities housing or processing hazardous substances, such as refineries, petrochemical facilities and other types of chemical industry. This showed that also generally well prepared countries are at risk of suffering natural hazard triggered technological (Natech) accidents. An analysis of data collected from open sources and through interviews with authorities was performed to understand the main reasons for the industrial damage and downtime as well as the extent of hazardous-materials releases and the associated impact on society. The analysis of the data set confirmed the findings from other studies with respect to main damage and failure modes, as well as hazardous-materials release paths. In addition, gaps in Natech risk management were identified. Based on the data analysis and interviews lessons learned in support of a more far-reaching Natech risk management are presented.

**Keywords** Industrial safety · Natech · Earthquake · Tsunami · Fire · Hazardous material

## 1 Introduction

A massive earthquake of magnitude 9.0 occurred off the northeast coast of Honshu Island, Japan, on 11 March 2011, at 14:46:24 Japan Standard Time (USGS 2011). This earthquake, which is known as the Great East Japan or Tohoku earthquake, caused a tsunami 130 km off the coast of Miyagi Prefecture which inundated over 400 $km^2$ of land

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(Mori et al. 2012). Both the earthquake and the tsunami reached unexpected magnitudes of severity and affected a wide swath of land, leaving a trail of devastation behind. The death toll has reached almost 16,000 with over 3,000 people still missing as of September 2012 (NPAJ 2012). With the total economic damages exceeding US$ 210 billion (not considering the Fukushima nuclear power plant accident), the Tohoku disaster is the most destructive on record (CRED 2011). Figure 1 gives an overview of the areas affected by the earthquake.

A large number of chemical installations with major accident potential are located in the disaster-hit areas, and many of these facilities were damaged or destroyed by the earthquake and/or tsunami. This resulted in many instances in the release of toxic or flammable materials, as well as fires and explosions which posed an additional risk to the disaster-stricken population, as well as to emergency responders. These secondary effects of natural disasters, also called Natech (natural hazard triggered technological) accidents (Krausmann et al. 2011a; Showalter and Myers 1994), frequently occur in the wake of a natural disaster and have often caused injuries and fatalities, environmental pollution and economic damage but also supply disruptions (e.g. Girgin 2011; Krausmann et al. 2010; Cozzani et al. 2010; Cruz and Krausmann 2009; Steinberg and Cruz 2004; Young et al. 2004, Lindell and Perry 1997).

Although the Tohoku earthquake generated very strong ground motion, most damage to non-industrial buildings was caused by tsunami impact, which highlights the effectiveness of Japan's earthquake risk mitigation system. However, hazardous installations might require specific protection measures, and the Tohoku disaster showed that even countries with high levels of earthquake preparedness are at risk of major Natech accidents. It therefore offers an opportunity to assess the performance of existing Natech prevention and mitigation measures and to learn lessons for a more far-reaching management of Natech risk to make the chemical industry more resilient. In order to understand how chemical facilities performed during the Tohoku earthquake and to highlight potential shortcomings in the

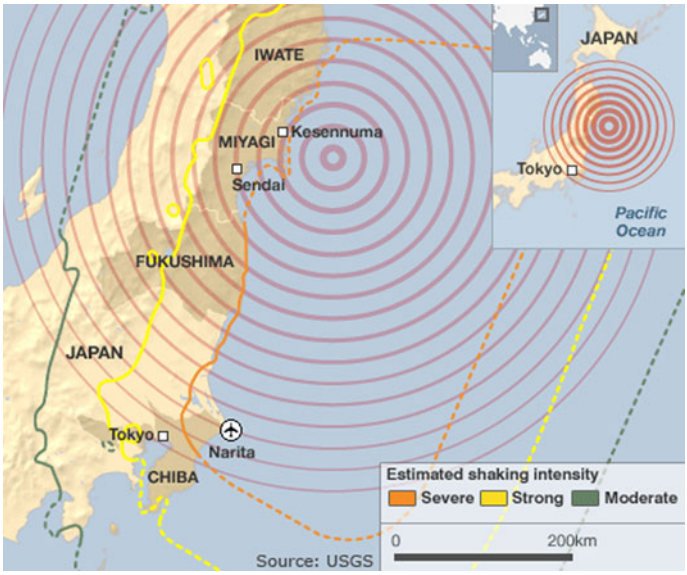



**Fig. 1** Areas affected by the Tohoku earthquake (*Source*: USGS)

disaster management process, an analysis of selected data sets collected from companies and authorities was performed. The results of this analysis including preliminary lessons learned are presented.

## 2 Data collection methodology

Shortly after the world learned about the Great East Japan earthquake and the associated tsunami, we started the collection of data on industry impact with a focus on possible Natech accidents. In this context, we were only interested in chemical facilities with a potential for fires, explosions and the release of hazardous substances, including oil- or gas-fired power plants that store these substances in high quantities. The nuclear disaster at Fukushima Daiichi was beyond the scope of this study.

In order to understand how industrial facilities performed during the March 11 earthquake and tsunami, data on the Natech accident trigger, the accident dynamics and its consequences were collected. This included information on the affected industrial activity and its location, the type of major event that occurred (fire, explosion, toxic release), the kind of substance(s) involved in the accident and the severity of structural damage suffered. Where available, data on health and business impact and emergency response were also analysed.

The initial data collection was limited to accident information accessible from open sources such as chemical company websites, newspapers and commercial chemical industry business news (e.g. ICIS, Argus Media, Chemical Week, etc.). This was supplemented for some major facilities with information from experts and competent authorities from Chiba, Ibaraki and Miyagi Prefectures interviewed during two field visits in October and November/December 2011. Overall, data on 46 damaged chemical establishments in Chiba, Miyagi, Ibaraki, Fukushima, Tochigi and Iwate Prefectures were collected and analysed (Table 1). These facilities, which are listed per activity category in Table 2, were on the one hand selected based on the media attention they got and on the other hand on whether at least some data was publicly available in English. While we are aware that 46 records constitute only a small subset of the chemical accidents triggered by the Great East Japan earthquake and tsunami, we are confident that the findings of this study can also be extrapolated to other facilities not captured by the analysis.

## 3 Analysis and results

### 3.1 Regulations and general preparedness activities

In Japan, the prevention and management of severe chemical accidents are regulated by various laws. The petrochemical industry with a major accident potential is regulated by the Law on the Prevention of Disasters in Petroleum Industrial Complexes and Other Petroleum Facilities (or Petroleum Complex Disaster Prevention Law) passed in 1975 (CAO 2012). Following the Tokaichi-oki earthquake in September 2003, in which a large-scale tank fire broke out at a refinery, this law and related regulations were updated to include anti-earthquake safety measures for floating roof tanks and fire-fighting tactics in case a full-scale fire involving such a tank would occur (PAJ 2011; CAO 2012). The storage, handling and use of high pressure gases and liquefied pressurised gases are controlled by the amended High Pressure Gas Safety Law (HPGSIJ 2005). Non-pressurised

**Table 1** Affected company sites per Prefecture considered in the analysis and associated damage trigger

| Name of company | Damage trigger |
|---|---|
| *Chiba Prefecture* | |
| Chiba Polyol Corp. | Earthquake |
| Chisso Corp. | *Domino* |
| Cosmo Oil Co., Ltd. | Earthquake |
| JFE Chemical Corp. | Earthquake |
| Maruzen Petrochemical Co., Ltd. | *Domino* |
| *Fukushima Prefecture* | |
| ADEKA Corp. | Tsunami |
| Dow Chemicals | Tsunami |
| Kureha Corp. | Tsunami |
| Sakai Chemical Industry Co., Ltd. (3 factories) | Earthquake |
| Shin-Etsu Handotai Co., Ltd. | Earthquake |
| Sumitomo Rubber Industries, Ltd. | Earthquake |
| TEPCO (Hirono power plant) | Tsunami |
| Tohoku Electric Power Co. (Haramachi power plant) | Tsunami |
| Tohoku Shannon Co., Ltd. | Tsunami |
| *Ibaraki Prefecture* | |
| Asahi Kasei Construction Materials Corp. (2 factories) | Earthquake |
| Asahi Kasei Metals Ltd. | Earthquake |
| Asahi Glass Co., Ltd. | Earthquake/tsunami |
| JSR Corp. | Earthquake |
| JX Nippon Mining and Metals | Earthquake |
| Kashima Oil Co., Ltd. | Earthquake/tsunami |
| Kashima Chlorine and Alkali | Earthquake/tsunami |
| Mitsubishi Chemical Corp. | Earthquake/tsunami |
| Mitsui Chemicals, Inc. | Earthquake/tsunami |
| Mitsui Chemicals Tohcello, Inc. (3 factories) | Earthquake |
| Shin-Etsu Chemical Co., Ltd. | Earthquake |
| Sumitomo Metal Industry Ltd. | Earthquake |
| Teijin-DuPont Films Ltd. | Earthquake |
| Tosoh Plas-tech Corp. | Earthquake |
| *Iwate Prefecture* | |
| Nippon Steel | Tsunami |
| Shionogi & Co., Ltd. | Earthquake |
| *Miyagi Prefecture* | |
| Asahi Kasei Power Devices Corp. | Earthquake |
| JX Nippon Mining and Metals | Earthquake |
| JX Nippon Oil and Energy | Earthquake/tsunami |
| Mitsui Chemicals Agro, Inc. | Earthquake |
| Sendai Gas | Earthquake/tsunami |
| Tokai Carbon Co., Ltd. | Earthquake/tsunami |
| Tohoku Tosoh Chemical Co., Ltd. | Tsunami |

**Table 1** continued

| Name of company | Damage trigger |
|---|---|
| Zen-noh | Tsunami |
| *Tochigi Prefecture* | |
| DuPont | Earthquake |
| Mitsui Chemicals Tohcello, Inc. | Earthquake |
| Teijin-DuPont Films Ltd. | Earthquake |

**Table 2** Categories of industrial activities and number of associated analysed accident records

| Type of industrial activity | Number of data records |
|---|---|
| Energy-related (oil refining, LNG terminal, oil-fired power plants, etc.) | 7 |
| Petrochemical (plastics, polymers, rubber, etc.) | 19 |
| Fine chemicals (pharmaceuticals, agrochemicals, etc.) | 7 |
| Metallurgy, electrochemistry and mining (steel mills, semiconductors, tailings impoundment, etc.) | 9 |
| Other (construction materials, etc.) | 4 |

toxic materials and flammables are regulated by the amended Fire Service Law (FSL 2008). The only regulation explicitly addressing Natech risk is the amended High Pressure Gas Safety Law which requires industrial establishments to take all additional measures necessary to reduce the accident risk from earthquakes and tsunamis (Cruz and Okada 2008). It is likely that there will be an amendment to regulations after the accident at the Chiba oil refinery (Chiba Prefecture Fire Department, personal communication).

Competent authorities perform inspections in high-risk chemical industries to ensure that safety standards are respected. In addition, companies have to prepare for the eventuality of an accident in compliance with the legislation in force that covers their industrial activity. Structural safety measures for minimising the risk of an accident due to earthquakes, for example, interlocks triggered by ground motion, exist. At the Kashima industrial complex, shutdown was triggered at a peak ground acceleration (PGA) of 0.15 g (Kamisu City Policy and Planning Division 2011), while at the Sendai refinery safe shutdown occurred at 0.25 g (Shiogama City Fire Department, personal communication). Wada and Wakakura (2011) report shutdown criteria of 0.05–0.25 g in 158 chemical plants surveyed after the earthquake.

## 3.2 Accident characteristics

### *3.2.1 Accident trigger*

Many areas in Eastern Japan were subjected to severe earthquake shaking and record tsunami wave impact. The maximum PGA of 2.7 g was recorded in Miyagi Prefecture (USGS 2012). The Japan Meteorological Agency observed tsunami heights of 7.3 m or higher in Fukushima Prefecture (JMA 2011). JMA's tsunami bulletin included, however, the caveat that tsunamis higher than those recorded at the observation sites could have

occurred along the coast. In fact, in situ observations after the disaster indicate that in some coastal zones tsunami heights were significantly higher (PARI 2011; ERI 2012). Mori et al. (2012) report mean inundation heights of 10–15 m in the southern Sanriku region just north of Sendai, as well as several peaks of inundation along the coast from the northern to middle part of Sanriku.

At the site of the major refinery fire in Sendai in Miyagi Prefecture, the earthquake sensors stopped measuring at 0.45 g; it is believed that the actual shaking forces exceeded this value. The tsunami inundation height was between 2.5 and 3.5 m (Shiogama City Fire Department, personal communication). At the Kashima industrial complex, the PGA values are assumed to have exceeded 0.36 g which is the upper limit of the PGA metres on site. The height of the tsunami waves inundating the complex was estimated at "the height of an adult human" (Kamisu City Policy and Planning Division 2011). In Tokyo Bay, where the earthquake caused a major fire in a refinery's liquefied petroleum gas (LPG) storage tank farm, PGA values of 0.114 g were measured during the main shock and 0.099 g during the aftershock (Chiba Prefecture Fire Department, personal communication; Wada and Wakakura 2011). The tsunami height did not exceed 0.9 m which indicates that the facility perimeter was not overtopped.

Overall, in the 46 installations analysed in this study, a total of 57 minor or severe events were observed due to earthquake and/or tsunami impact (6 fires, $\geq$5 explosions, 46 cases of damage to equipment with possible releases of hazardous materials). Hence, in some installations, more than one Natech event occurred simultaneously. For the events analysed in this study, the earthquake forces were the main accident trigger, causing damage in 28 cases and three fires. One of these fires resulted in at least five major explosions at Chiba refinery, the biggest of which generated a fireball of over 600 m diameter and height (Nishi 2012). The tsunami or a combination of earthquake and tsunami triggered 16 cases of damage and one fire (in some cases, the company bulletins did not distinguish between earthquake and tsunami as trigger but listed both). Another two installations suffered damage and fires due to a cascading effect from a nearby burning facility. While the earthquake was the dominant accident trigger in this study, it caused mostly incidents of minor severity in contrast to the tsunami impact which was severe (see Sect. 3.3.1).

### *3.2.2 Accident dynamics*

In agreement with the findings of several studies on earthquake-triggered damage in chemical facilities (e.g. Krausmann et al. 2010, 2011b; Campedel 2008; Steinberg and Cruz 2004; Salzano et al. 2003), earthquake damage in the facilities analysed in this study occurred due to tank failure with losses from the roof top due to liquid sloshing, breaking of flanges and tank-pipe connections and rupture of pipes or containment structures due to liquefaction. In some warehouses, packed products fell from racks and were ripped open. These failure modes invariably led to minor or major releases of hazardous materials. Earthquake damage without releases was caused by shell buckling (Fig. 2), stretching of anchor bolts, sloshing damage and failure of support structures (Fig. 3). At the Chiba refinery, the ground motion caused the support braces of an LPG tank to buckle which led to complete tank collapse, thereby rupturing connected LPG pipes and eventually degenerating into a major refinery fire (Cosmo Oil 2011a).

Data on tsunami damage to chemical facilities are extremely scarce in the literature, and the 11 March 2011, tsunami offers an opportunity to learn important lessons on damage and failure mechanisms and the risk of Natech accidents. Due to the severity of the tsunami



**Fig. 2** Silos damaged by ground shaking at Sendai harbour (Photo Credit: E. Krausmann)



**Fig. 3** Coke oven damaged by the earthquake at a metal refining facility in the Kashima industrial complex (*Source*: Sumitomo Metal Industry)

and the large inundation area, damage due to hydrodynamic and hydrostatic water forces, as well as debris impact occurred (Fig. 4). These phenomena led to tank and pipe floating and displacement, overturning and destruction, and the breaking of pipe connections and ripping off of valves. Hazardous-materials releases were inevitable under these conditions. With the tsunami waters widely dispersing flammable spills and with ignition being highly probable under these circumstances, several large-scale fires developed (Fig. 5). In other cases, tank foundations were washed away, and buildings whose structural integrity was compromised by the tsunami collapsed onto equipment housed in them. The tsunami also damaged electrical systems due to water intrusion.



**Fig. 4** Oil tank destroyed by the tsunami at Haramachi thermal power plant and damage to the tank in the background due to shell buckling (Photo Credit: A. Kouchiyama)



**Fig. 5** Burned tanks at the Sendai refinery hit by the tsunami (Photo Credit: C. Scawthorn)

Two major Natech accidents were neither caused by the earthquake nor the tsunami but by a domino effect from the burning Chiba oil refinery. Air dispersion of a flammable vapour cloud from ruptured LPG pipes and subsequent ignition, heat impingement from the burning LPG storage tank farm as well as burning missile projection triggered fires at two neighbouring chemical facilities (Cruz et al. 2013).

Two surveys on damage to chemical plants by the earthquake and tsunami were carried out by Japanese authorities after the natural disasters. The Nuclear and Industrial Safety Agency (NISA) used a questionnaire survey to understand the damage sustained by 158 petrochemical installations. The Fire and Disaster Management Agency (FDMA)

performed a field survey to characterise the damage to storage tanks and the fires at oil refineries and petrochemical facilities (Wada and Wakakura 2011). The FDMA study found little earthquake impact on storage tanks. The damage that was observed was mostly due to minor spills on floating roofs due to liquid sloshing incited by the ground motion (FDMA 2011). The tsunami overturned several storage tanks due to the impinging water forces and by causing floating due to buoyancy, often accompanied by the release of significant amounts of hydrocarbons. Overall, the FDMA study found that 1,404 of hazardous facilities were damaged by the earthquake and 1,807 by the tsunami (Nishi 2012). The NISA questionnaire survey found damage and hazardous materials releases in 50 cases at high pressure gas facilities (4 fires/explosions, 6 leakages, 20 damage to pipes, 20 damage to structures), while 116 plants reported no damage. At other chemical facilities participating in the survey, 139 cases of damage were found (5 fires/explosions, 23 leakages, 59 damage to equipment, 52 damage to structures). No details on damage and failure mechanisms were provided.

### *3.2.3 Aggravating factors*

Once an accident is triggered, factors internal or external to the facility can contribute to the escalation of the event, often resulting in more severe consequences and complicating emergency response. In the case of natural disasters with a large impact zone, such as earthquakes and tsunamis, multiple and simultaneous releases of hazardous materials over wide areas are to be expected. Moreover, in addition to driving possibly debris-laden waters into a facility, tsunamis also disperse flammable spills caused by an earthquake, thereby exacerbating the emergency in case of ignition. The risk is particularly high where failed land-use planning puts industrial complexes in close proximity to residential areas or where separation distances between individual facilities are insufficient. Human and organisational failures can also exacerbate the consequences of an accident.

The refinery fire in Chiba is a good example of how a chain of fortuitous events eventually led to disaster. During the earthquake-induced breaking of the braces and collapse of an LPG tank under maintenance and thus filled with water, the connected pipes were ruptured and released LPG. Unfortunately, a safety valve on the ruptured pipes had been manually switched to open in violation of safety regulations and could not be reached once the fire ignited. This continuously provided LPG to feed the fire which eventually burned out of control (Chiba Prefecture Fire Department, personal communication; Cosmo Oil 2011a). Another example is the Sendai refinery where an oil tank was in the process of being filled when the tsunami hit (Sendai City Fire Department, personal communication). Since the valve on the tank-pipe connection was open as per normal operating procedures during tank filling, a significant amount of oil was released upon wave impact.

**Table 3** Damage severity (where known) as function of the accident trigger

Numbers in brackets indicate the number of incidents with a specific severity

| Natech trigger | Damage severity | |
|---|---|---|
| | Minor | Severe |
| Earthquake | 80 % (25) | 18 % (2) |
| Earthquake/tsunami or tsunami | 20 % (6) | 82 % (9) |

## 3.3 Consequences

### *3.3.1 Hazardous materials releases and damage*

As discussed in Sect. 3.2.1, the earthquake triggered the majority of the damage and accidents in the industrial installations analysed in this study. However, a simple correlation revealed that the earthquake forces generated—with two exceptions—only incidents of minor severity. The only two *major* accidents initiated by the earthquake in our analysis were due to aggravation by human error (Chiba oil refinery) or were caused by liquefaction affecting a tailings impoundment filled with toxic mining waste in Kesennuma City. On the other hand, the severity of incidents triggered by the tsunami or a combination of earthquake and tsunami was mostly major with sometimes devastating consequences (Table 3).

Only little information on hazardous materials releases from the affected chemical facilities is available. Data in the Japanese Pollutant Release and Transfer Register indicate that at many facilities in the severely impacted areas chemicals hazardous to human health and the environment may have been present (Bird and Grossman 2011). Hence, it is likely that toxic or flammable substances were released by the earthquake and/or tsunami, and the occurrence of several major fires and explosions confirms that releases and spills took place. For the 46 installations analysed in this study, in only 10 cases, information on releases of dangerous substances was available.

At the Sendai refinery, the tsunami triggered a major fire involving three tanks (sulphur, asphalt and gasoline) in the western area of the plant, a significant part of which was consumed by the flames. In addition, the tsunami also caused multiple breaks of pipelines and many small hydrocarbon leakages from pipe connections which ignited. In two places, releases of heavy oil (4,400 and 3,900 $m^3$, respectively) were triggered due to connected pipe breaking by the tsunami. The earthquake caused only minor spills on tank roofs and in the processing area of the facility (Shiogama City Fire Department, personal communication). In a nearby facility, the tsunami ripped off valves on two tanks, thereby spilling 1,200 $m^3$of gasoline and 1,400 $m^3$ of heavy fuel oil. While the releases were contained inside the containment wall around the tanks, they constituted a severe fire hazard. Liquefied natural gas (LNG) was intentionally flared from an LNG terminal at Sendai port to reduce pressure that had started to build up after the power blackout (Sendai City Fire Department, personal communication).

In Ibaraki Prefecture, 40,000 $m^3$ of mining waste containing arsenic were released from a slag heap that collapsed due to liquefaction during the earthquake. The tailings flowed into nearby fields, a river and the seashore (JX Nippon Mining and Metals 2012). In Fukushima Prefecture, the tsunami slammed into a coal-fired power station, causing the release of 16,500 $m^3$ of heavy and light oil from destroyed fuel tanks for power generators. The clean-up lasted until August 2011 with workers pumping out oil and removing oil-soaked soil (Asahi Shimbun 2011a). In the same Prefecture, the earthquake damaged a facility producing metallic salts and other fine chemicals. Besides damage to buildings and manufacturing equipment, finished products stored in a warehouse fell and were ripped open (Sakai Chemical Industry 2011a). At a steel mill in the Kashima industrial complex, the earthquake and tsunami ignited a fire in a blast furnace (Sumitomo Metal Industry 2011a).

In Chiba Prefecture, the earthquake-triggered fire destroyed all 17 LPG tanks in the storage tank farm of Chiba refinery (Fig. 6). The associated explosions damaged nearby asphalt tanks due to debris impact, causing asphalt to leak into the ocean (Cosmo Oil 2011a). Flammable vapour release from the LPG tank farm and debris from the explosion




**Fig. 6** The LPG tank farm at the Chiba refinery after the earthquake-triggered fires and explosions (©2012 Google, ZENRIN)

also started fires in two neighbouring chemical facilities, releasing methyl ethyl ketone and polypropylene (Cruz et al. 2013). It is reported that in one of these facilities heat impingement from the blaze at the refinery sparked a fire in a warehouse containing 765 kg of depleted uranium (EXSKF 2011). No further information supporting this statement could be found.

Many more hazardous substance releases are likely to have occurred. This information is, however, not easy to come by because companies might not publicly disclose information on spills and other releases. Bird and Grossman (2011) report a handful of further instances of releases and spills including hydrochloric acid and chromium, but they submit that attention to chemicals was probably a low priority in the immediate aftermath of the earthquake and tsunami.

### *3.3.2 Human and environmental impact*

The hazardous materials released from the many damaged industrial installations posed in some cases an immediate threat to the population due to toxicity or flammability, or created medium- to long-term concerns due to possible chemical contamination of the soil or groundwater.

At the Chiba industrial complex, 1,142 residents had to be evacuated due to the fires and explosions at the oil refinery's LPG tank farm. Pieces of tank insulation and sheet metal were found at a distance of over 6 km (Cruz et al. 2013). At the refinery, six injuries (one severe, five minor) were recorded (Cosmo Oil 2011a). Three persons were injured, one severely, at a facility adjacent to the tank farm where a fire was triggered via domino effect. Air quality monitoring at Ichihara Municipality did not show any excessive amounts of $SO_x$ or $NO_x$ due to the fires at the Chiba industrial complex (Chiba Prefecture Fire Department, personal communication).

At the Sendai refinery, four people were killed by the tsunami. Due to ignition of sulphur and the formation of a toxic cloud, the mayor issued an evacuation order in a 2 km radius around the refinery, thereby also delaying the intervention of the fire-fighting teams (Sendai City Fire Department, personal communication). At a nearby park, trees and grass were covered with thick crude oil from the accident (Daily Caller 2011). The release of toxic mining waste in Ibaraki Prefecture damaged houses, field and roads but fortunately did not cause any fatalities or injuries. The contamination caused is reported to have exceeded 25 times the safety standard in arsenic concentration (Asahi Shimbun 2011b).

Questions remain about the fate of chemical hazardous substances that were released during the earthquake and tsunami. In the direct aftermath of the disasters, chemical contamination was not a priority issue unless it posed an immediate severe health risk to the population or emergency responders. Resources were focused on urgent relief and recovery work, and chemical threats paled in comparison with the Fukushima Daiichi nuclear power plant accident. Nonetheless, many of the released substances are toxic and some are environmentally persistent, raising questions about the risk of long-term contamination. Environmental monitoring campaigns by the national and local governments tried to assess chemical contamination of the air, water and soil in some locations several months after the earthquake and tsunami. Bird and Grossman (2011) point out that "Judging from the extreme difficulty of obtaining concrete, detailed information about potential chemical hazards following the Japan disaster, this appears to be an aspect of emergency preparedness that, despite well-established formal disaster-response plans, remains inadequately addressed."

### *3.3.3 Business interruption and economic impact*

Overall, six oil refineries were affected by the earthquake and tsunami, effectively shutting in 30 % of Japanese refining capacity for a week after which 3 refineries came back online. Almost 25 % of Japanese ethylene production capacity was halted by the natural disasters with repair times of several months (IEEJ 2011). In addition to damage to many facilities and hazardous-materials releases, the resuming of industrial operations was hampered by aftershocks, tsunami alerts, evacuation of personnel, lack of utilities (water, electricity), damage to infrastructures (berths, roads, etc.) and in some cases by a shortage of raw materials. Tatano and Kajitani (2012) estimate that the earthquake impact caused a 34 % loss in production capacity in the affected regions, whereas the tsunami contributed 6 % losses. They also highlighted that in order to get a realistic picture of production capacity loss not only facility damage but also lifeline disruption has to be considered.

The shutdown time due to damage by the earthquake and/or tsunami for 40 of the analysed facilities is shown in Table 4. Where available, the time by which full production was resumed was used in the analysis; otherwise times to partial operations were considered. Consequently, Table 4 draws an optimistic picture, and the effective outage times for some parts of production could have been longer. Business interruption due to rolling blackouts or a shortage of raw materials is not considered in this table.

**Table 4** Shutdown time for 40 of the analysed facilities that were affected by the earthquake and/or tsunami (number of facilities in brackets)

| ≤1 week | >1 week ≤1 month | >1 month ≤6 months | >6 months ≤1 year | >1 year |
|---|---|---|---|---|
| – | 12 % (5) | 70 % (28) | 8 % (3) | 10 % (4) |

Only limited information is available on economic losses in companies damaged by the earthquake and/or tsunami. JX Holdings, Inc. published loss data for three of its companies which amounts to 92 billion ¥ (1.2 billion US$)[1] for the Sendai refinery, 20 billion ¥ (251 million US$) for Kashima Oil and 8 billion ¥ (100 million US$) for JX Nippon Mining and Metal's Isohara plant (JX Holdings 2011). These losses were incurred in the Japanese fiscal year (FY) 2010 which ends on 31 March 2011. Losses were due to restoration costs, extinguishment of assets and running costs. Another 30 billion ¥ (377 million US$) special loss was estimated for FY2011 due to fixed costs during suspended operations. For FY2010, the Cosmo Oil refinery reports a loss on disaster of over 5.7 billion ¥ (72 million US$) (Cosmo Oil 2011b). For FY2011, the company posted a net deficit of 9.1 billion ¥ (114 million US$) largely due to the suspension of operations at Chiba refinery and associated alternative supply costs (Cosmo Oil 2012). Sakai Chemical reports losses of 1.3 billion ¥ (16 million US$) due to the earthquake for FY2010 (Sakai Chemical Industry 2011b). Sumitomo Metals reports extraordinary losses due to the earthquake of approximately 60 billion ¥ (753 million US$) for FY 2010 (Sumitomo Metal Industry 2011b).

### 3.4 Emergency response activities

The impact of the Great East Japan earthquake and tsunami was so severe that resources for managing the disasters were insufficient in the responsible fire departments, and they had to be supported by the police and the army. The various actors were coordinated via the Japanese government's national emergency support system which dispatched response teams to the areas in need (Shiogama City Fire Department, personal communication).

The Natech accidents caused by the Great East Japan earthquake and tsunami clearly demonstrate the risk of cascading effects during natural disasters. Generally, Natech accidents pose a challenge for emergency response due to the necessity to contain possibly multiple and simultaneous hazardous-materials releases when first responders are busy combating the consequences of the natural disaster on the population. This situation can be further complicated by the downing of lifelines (water, power, communications) conceivably needed for mitigating the consequences of an accident. All these are ingredients for an escalation of the accident and the triggering of a domino effect. The released hazardous materials can also hamper emergency response by endangering both rescue personnel and disaster victims, possibly requiring evacuation. Steinberg and Cruz (2004) give a detailed description of these problems during the 1999 Kocaeli earthquake in Turkey.

A similar situation, albeit at a larger scale, presented itself to emergency responders in the Japanese Tohoku and Kanto regions on 11 March 2011. Especially in the areas affected by the tsunami, emergency response to Natech accidents was in many cases critically hampered by destroyed or blocked access roads to facilities, tsunami alerts, lack of utilities or compulsory evacuation of response teams due to toxic releases. In the Sendai area, fire-fighting teams in action had to closely monitor radiation levels from the Fukushima nuclear power plant accident and be ready to evacuate if a given threshold was exceeded.

Moreover, responders were faced with a number of major Natech accidents that had cascaded or were at risk of cascading onto neighbouring facilities, thereby increasing the likelihood of severe secondary consequences. At Sendai port, an LNG tank was sandwiched between tsunami triggered fires raging in a refinery to its north and flammable hydrocarbon releases in another facility to the south (Sendai City Fire Department,

[1] Numbers in US$ were calculated based on the average 2011 Yen → US$ yearly exchange rate.

personal communication). The fire fighters' prime objective was to prevent the released hydrocarbons from igniting as the LNG tank might not have withstood heat impingement from both sides. In addition to causing a potential disaster, damage to the LNG tank would also have resulted in a severe natural gas shortage in Sendai City. The fires in the refinery were extinguished after 5 days (Argus 2011).

Due to the many different LPG release sources, fires and explosions at the Chiba oil refinery, the intervention teams had little choice but to let the fires burn until the LPG was depleted. In order to speed up the process, water was sprayed on the burning tanks to accelerate the LPG evaporation rate (Chiba Prefecture Fire Department, personal communication). The fires triggered via domino effect in two neighbouring chemical facilities also required the emergency responders' attention. The refinery fire was declared extinguished after 10 days (Cosmo Oil 2011a).

These examples show the near impossibility of successfully coping with the consequences of a severe Natech accident if no proper preparedness exists. In the case of the Chiba refinery, neither the company itself nor the Chiba competent authorities were by their own admission prepared for an accident of such magnitude (Chiba Prefecture Fire Department, personal communication).

## 3.5 Lessons learned

The occurrence of the 11 March earthquake and tsunami as well their catastrophic consequences raised questions as to the accuracy of seismic model predictions, as well as on prevention, preparedness and response levels in industry and in communities as a whole. Taking stock of what happened, important lessons can be learned. Below, selected examples of lessons learned from the Tohoku disaster are provided.

### *3.5.1 General lessons learned*

The reasons for the numerous Natech accidents that occurred may be manifold. Factors worth mentioning are model uncertainties reflected in insufficient design and low levels of preparedness, overconfidence in existing safety measures, cost/benefit considerations, complacency or the violation of safety regulations. The most obvious lesson to learn is that industrial development, in particular of activities with a major accident potential, should be limited in natural hazard prone areas. Where hazardous installations exist, compliance with building codes and safety regulations must be monitored.

The Natech events showed that in many cases Natech preparedness levels both by the industry and authorities were low. Therefore, existing preparedness and response plans need to be improved to explicitly include the aspect of possible hazardous-materials releases, fires and/or explosions due to natural hazards to reduce the Natech risk. This includes the provision of sufficient fuel storage capacity for operating emergency response equipment and accommodation for emergency responders and support personnel (police, military) possibly mobilised at national level and dispatched to areas with major Natech accidents. With Japan being a country generally considered well prepared for natural disasters, it is likely that preparedness levels in less developed countries will be even lower.

The singularly devastating impact on the industry highlights the necessity for a better analysis of interdependencies and the potential for cascading effects. The crucial role played by utilities in ensuring business continuity or guaranteeing effective emergency response is often underestimated and needs to be reassessed. Similarly, businesses should

re-evaluate the adequacy of their stocks in case of disaster impact to avoid the shortage of raw materials for production and consequently an impact on the supply chain.

### *3.5.2 Lessons learned from the earthquake and tsunami*

The earthquake demonstrated that current models cannot satisfactorily predict seismic scenarios. Based on model predictions, Japanese seismologists did not believe that the Japan trench could store enough elastic energy to trigger an earthquake of such magnitude and hence did not foresee the event (Iio 2011). Consequently, model assumptions need to be reassessed to improve the reliability of predictions.

Land-use planning restrictions are difficult to implement for existing installations, requiring supplementary prevention and preparedness measures to protect hazardous facilities from earthquake or tsunami impact. Lessons have been learned from the damage caused by the Tohoku disaster, and companies have adopted several new risk mitigation measures. Figure 7 shows an example of post-earthquake retrofitting in the Sendai area where LPG tank braces were reinforced to enhance tank resistance to possible future earthquakes. An example of a preparedness measure is the creation of an artificial hill of 5 m height at Sendai refinery to safeguard emergency response equipment and teams and from which to coordinate response interventions in case of a tsunami (Fig. 8). Where retrofitting or hardening is difficult to achieve, it might be more cost-effective to move equipment or facilities out of harm's way. Consequently, in Sendai, the (un)loading facility of the refinery was moved northeast to a location better protected from tsunami impact.

In the aftermath of the Tohoku disaster, communication services were disrupted either due to physical damage to infrastructures, network congestion or power outages, and companies could not be reached by phone. In addition, in many cases, tsunami-generated debris hampered access of response teams to hazardous installations to ascertain their status. Hence, first responders mentioned the need for improving the communications flow



**Fig. 7** Retrofitting of an LPG sphere in Sendai by reinforcing the tank braces (*right*). This work is already finished on the tank to the *left* (Photo Credit: E. Krausmann)




**Fig. 8** Creation of an artificial hill at the Sendai refinery for safeguarding emergency response equipment and teams in case of a future tsunami (Photo Credit: E. Krausmann)

during the crisis to provide for faster emergency response in situations where telephones are not working and access roads are blocked or destroyed.

The emergency response teams we interviewed indicated that responders needed to be prepared for the consequences of a tsunami impact during response operations. They should, for instance, be equipped with life jackets. Moreover, aluminium boats instead of rubber boats would be better suited for moving around in debris-laden waters.

## 4 Conclusions

The Great East Japan earthquake and tsunami dramatically highlighted the vulnerability of hazardous installations to the effects of natural hazards. The natural disaster also emphasised evident gaps and shortcomings in Natech risk management which in many cases resulted in low preparedness levels in industry. Generally, both the earthquake and tsunami caused significant damage; however, the tsunami impact resulted in more severe Natech events. In terms of business interruption and loss of production capacity, the earthquake was the dominant trigger, with shutdown times between 1 and 6 months on average for the analysed data set. Lifeline disruption by the earthquake and tsunami contributed significantly to the production capacity loss. Work is in progress to describe in detail the earthquake- and tsunami-induced damage and failures in the Chiba, Kashima and Sendai industrial parks.

Strategies for reducing Natech risk include land-use-planning restrictions for new industrial sites and retrofitting of existing facilities that cannot be moved, risk analysis to ensure that adequate prevention and preparedness measures are in place, and emergency planning that considers the potential loss of off-site utilities possibly required for mitigating the consequences of a Natech accident. Particular attention should be given to the possible impact of hazardous materials on the rescue operations. An assessment of the vulnerability of the emergency resources themselves is also called for.

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