# Triple Disaster of Tohoku Earthquake, Tsunami, and Fukushima Reactor Failure March 2011

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## Introduction

On the afternoon of March 11th, 2011, a 9.1 magnitude megathrust earthquake ruptured where the Pacific plate subducts beneath the North American (or Okhotsk) plate approximately 80 miles east of the Oshika Peninsula in the Tohoku region of Japan (Takla et al., 2013). This earthquake, its subsequent catastrophic tsunami, and nuclear reactor failure claimed an estimated 22,252 lives, $157.5 billion (USD) in damages, and affected 474 northern Japanese Cities (Takla et al., 2013). This report aims to review the Tohoku earthquake, tsunami, and Fukushima nuclear disaster of 2011 for a comprehensive evaluation of the contributing geological and geophysical factors, cascading events, infrastructure vulnerabilities, social vulnerabilities, emergency response, and resilience in the management of this complex disaster.

## Contributing Geological and Geophysical Hazards

Geological and geophysical factors contribute to the earthquake and tsunami hazards typical of this archipelago. Japan lies along the western edge of the Pacific Ring of Fire, where four tectonic plates converge: the Pacific, Philippine, Eurasian (Amurian), and North American (Okhotsk) plates (JRailPass, 2022). Ongoing subduction of the older, more dense, oceanic Pacific and Philippine plates, as they descend beneath Japan's continental plates, contribute to their frequent and intense seismic and volcanic activity. Reportedly, Japan is the most seismically active country globally and suffers up to one-fifth of the most powerful earthquakes recorded on Earth (Lamb & Jones, 2020) (McCurry & Sample, 2011). Records dating back to 1900 reveal that earthquakes generate more than 80% of tsunamis (NOAA, 2018). According to NOAA (2018), tsunamis are extraordinarily long waves resulting from a sudden massive displacement of ocean water, typical of earthquakes below or near the ocean floor. As a set of islands with high subductive seismicity whose landmass has 18,480 miles of coastline, nearly all of Japan is at high risk of tsunami hazard (Association for Asian Studies, 2020) (ThinkHazard, 2017).

Tsunamis can move at over 500 miles per hour in the ocean with hundreds of miles-long wavelengths and become hazardous as they approach shallow waters and land (NOAA, 2018). As tsunamis approach land, their speed typically slows to 20 to 30 miles per hour as the wavelength between wave crests decreases, tsunami height increases, and the transferred energy intensifies currents (NOAA, 2018). Tsunamis can cause massive destruction as just six inches of fast-moving water can topple a person, and twelve inches of rushing water can move a vehicle (NOAA, 2018). As a tsunami approaches a landmass, the wave height can amplify with recorded heights up to 40 meters (NOAA, 2018).

## Risk Mitigation Methods

To mitigate the risks associated with earthquakes and tsunamis, the Japan Meteorological Agency (JMA) updated its Earthquake Early Warning system (EEW), which notifies citizens of recent earthquake magnitudes and warns of potential tsunami impact through television, radio, internet, and cell phone alerts (Koshimura & Shuto, 2015). Many buildings were built to be ‘quake-resistant’ and to sway while the earth shakes. Deep foundations and shock absorbers allow the structure to move in tandem with the Earth's surface (McCurry & Sample, 2011). Before the 2011 earthquake, the Japanese central government council issued updated guidelines for tsunami countermeasures. To protect life and property directly, they built floodgates, breakwaters up to a depth of 63m, and four-and-a-half to 10-meter-high seawalls and dikes to hold back incoming water (Koshimura & Shuto, 2015). As a mitigation method, they have instituted effective land-use management and vertical evacuation buildings to increase safe evacuation areas (Koshimura & Shuto, 2015). They also regularly promote disaster preparedness information distribution through public education and evacuation planning with frequent drills to prepare their citizens (Koshimura & Shuto, 2015). Many local governments prepared and distributed flood and tsunami hazard maps with listed evacuation shelters and survival instructions (Koshimura & Shuto, 2015). Many of Japan's modern mitigation methods have been the result of lessons learned in Tohoku in 2011.

**Cascading Events**

Thirty minutes after the earthquake off the coast of Tohoku, a massive tsunami inundated the coast, which caused the Fukushima Daiichi nuclear accident. Since disaster risk is context-dependent and influenced by latent local vulnerabilities, managing cascading disasters involves examining the root causes and the initial impacts. Significant tsunamis are typically linked with earthquakes, liquefaction, landslides, and many more disaster factors that amplify the overall scope of their impact (Suppasri et al., 2021).

The vulnerabilities in the design and safety measures of the Fukushima Daiichi nuclear power plant significantly contributed to the severity of the impact during the Tohoku earthquake and tsunami. The protective measures taken to protect the plant from tsunamis underestimated potential wave heights. The coastal power plant was built 10 meters above sea level to withstand tsunamis; it was not prepared, nor was it considered that a tsunami would exceed the 10-meter mark. In 2011, they faced a 13-meter tsunami that caused extensive flooding damage, leading to disastrous events, including the failure of backup power and cooling systems and the loss of electricity. Without power to run the cooling systems, the nuclear reactor core experienced a meltdown. Fukushima Daiichi also lacked a secondary containment structure. This vulnerability had severe repercussions as the reactors experienced partial meltdowns and released radioactive materials into the environment. This release

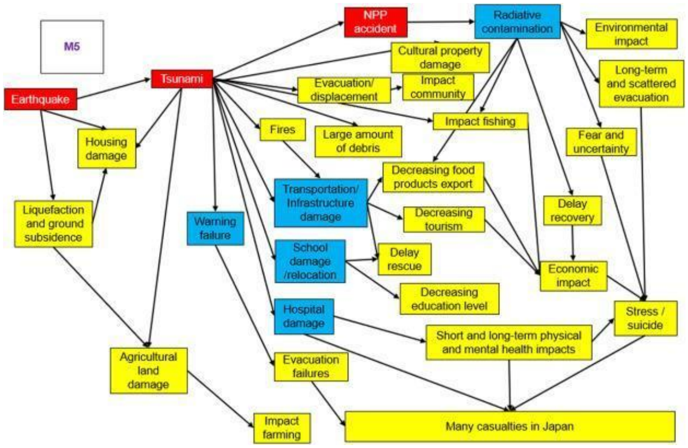

Figure 1: A schematic process and cascading impacts of the 2011 Great East Japan Earthquake and Tsunami (Suppasri et al., 2021).

caused the surrounding water to become infiltrated with radioactivity, leading to a loss of marine life and hardships in fishing. As a result, Japan's economy suffered.

Compared to other earthquakes and tsunamis, the Tohoku earthquake and tsunami stands out as one of the natural disasters with the most cascading events. It is considered an M5 on the cascading magnitude scale, with M5 being the highest and M0 the lowest. An M5 cascading disaster has "multiple causes, multiple chains of effects, and multiple escalation points" (Suppasri et al., 2021). Figure 1 demonstrates the cascading events after the main disaster took place. The tsunami was the leading cause of the issues that followed, which were worsened by the power plant accident. Many of the issues that the country endured economically can be rooted back to the tsunami and the spread of its aftermath. Table 1 illustrates the contrast between tsunami occurrences and interconnected components in a cascading system. This reinforces the idea that many cascading events can be linked to the cause, main effect, or even the escalation points, as interpreted from Figure 1.

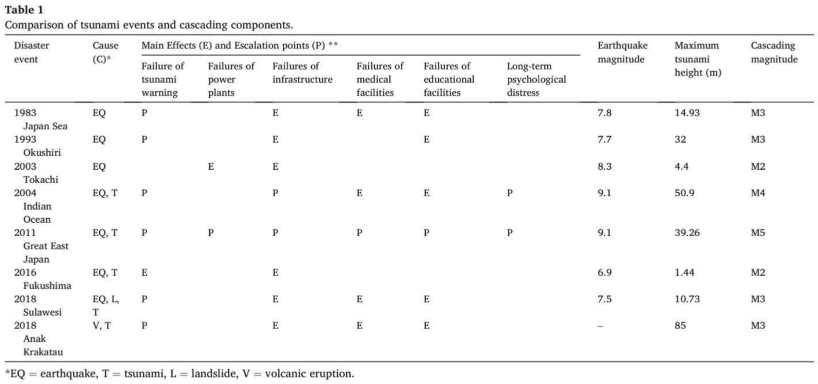

**Table 1**
Comparison of tsunami events and cascading components.

| Disaster event | Cause (C)* | Main Effects (E) and Escalation points (P) ** | | | | | | Earthquake magnitude | Maximum tsunami height (m) | Cascading magnitude |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Failure of tsunami warning | Failures of power plants | Failures of infrastructure | Failures of medical facilities | Failures of educational facilities | Long-term psychological distress | | | |
| 1983 Japan Sea | EQ | P | | E | E | E | | 7.8 | 14.93 | M3 |
| 1993 Okushiri | EQ | P | | E | | E | | 7.7 | 32 | M3 |
| 2003 Tokachi | EQ | | E | E | | | | 8.3 | 4.4 | M2 |
| 2004 Indian Ocean | EQ, T | P | | P | E | E | P | 9.1 | 50.9 | M4 |
| 2011 Great East Japan | EQ, T | P | P | P | P | P | P | 9.1 | 39.26 | M5 |
| 2016 Fukushima | EQ, T | E | | E | | | | 6.9 | 1.44 | M2 |
| 2018 Sulawesi | EQ, L, T | P | | E | E | E | | 7.5 | 10.73 | M3 |
| 2018 Anak Krakatau | V, T | P | | E | E | E | | – | 85 | M3 |

*EQ = earthquake, T = tsunami, L = landslide, V = volcanic eruption.

Table 1: Comparison of tsunami events and cascading components (Suppasri et al., 2021)

## Infrastructural Failures

Several buildings suffered significant damage or collapsed due to the tsunami's forces, which were brought on by the magnitude 9.0 earthquake. Different damage mechanisms resulted from varying tsunami loads acting on different structural systems. This was seen through the erratic destruction that occurred on the day that tragedy struck Tohoku and other neighboring regions. In most of these regions, the most significant damage was done to wood dwellings, as the tsunami carried most of them away. The distorted steel frames were left intact in many steel buildings even though the curtain walls had been damaged. Though several reversed cases were noted, many reinforced concrete buildings survived (Hayashi et al., 2012). Due to the fact that Japan experiences numerous earthquakes annually, its engineering has incorporated technology designed to withstand earthquakes. However, certain structural failures still occurred on March 11th, 2011 that significantly contributed to the disaster.

During this tragic event, buildings supported by a pile foundation proved fragile and brittle. Many of those with this substructure tilted or fully toppled over when the tsunami collided with them directly. The toppled structures were older and did not appear to have been constructed with seismic engineering in mind, so the pile-cap joints, as well as the piles themselves, sustained some harm from the earthquake and failed to endure both the buoyancy force and surge generated by the tsunami (Tokimatsu et al., 2013). What was noticed was that at the base of these buildings were pile caps, which were initially connected to a few piles each, but had been torn apart during the cascading disasters. The pile head joints used as the connecting device for the pile and pile caps were composed of concrete filling but were, unfortunately, swiftly dismantled. Additionally, through any seismic activity, the degree of liquefaction in any location is a major factor in the susceptibility of the structures in that area. During the Tohoku earthquake, the degree of liquefaction varied from place to place, but what was observed was that in those areas that were closer to the liquefaction zone, there was more structural damage.

Some structures in Japan were built to withstand such horrendous disasters. The Tokyo-based Kajima Corporation building and those surrounding it experienced little to no direct damage during the 2011 quake. Though these buildings were far from the epicenter, the seismic motion was just as intense in this vicinity, lasting several minutes. Kajima's resilience to the disaster was aided by their swing-reduction technology, an advancement implemented into their building construction to make them flexible so that when a quake hits, the buildings incorporate the seismic force and merely sway. Thanks to technical advancements like these, few tall buildings in Japan have directly incurred earthquake damage or collapse since the building standards were raised after the Great Hanshin-Awaji Earthquake ravaged Kobe in 1995 (Imahashi, 2021).

## Assessing Social Vulnerability

Overall, the Tōhoku, Japan, tsunami led to catastrophic damage along the coast, causing significant casualties and destruction. Following the tsunami, the Fukushima Daiichi Nuclear Power Plant faced a significant breakdown, resulting in a nuclear catastrophe. Widespread tsunami debris (Figure 2) and human casualties were limited to coastal areas in Fukushima, Iwate, and Miyagi prefectures, with the highest number of fatalities concentrated along the Sanriku Coast and the Sendai Plain. The flat topography of the Sendai Plain led to extensive flooding and increased mortality rates, particularly in its larger towns. Vulnerability comprises both external exposure and internal dimensions and stresses the active role of people in developing coping strategies and improving their resilience regarding natural and societal risks (Pongponrat & Ishii, 2017). Factors contributing to social vulnerability are myriad and include a low level of education leading to unemployment, poor health conditions, breakdown of social fabric, loss of indigenous knowledge, and various other factors. Critical factors such as historical context, ethno-cultural traits, minority status, immigration standing, age, gender, and educational background intensify the vulnerability of individuals as well as marginalized

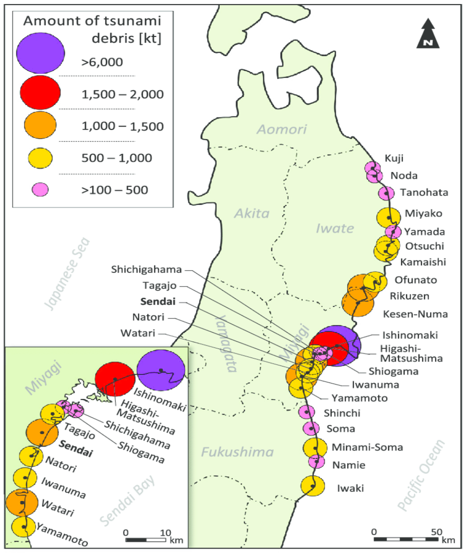

Figure 2: Map of the Tohoku region of Japan showing the amounts of tsunami debris in the most affected cities along the Pacific coast (Koyama et al., 2016).

communities. Scholars increasingly agree that age was crucial in determining disaster-related deaths, predominantly in the Sanriku region. According to Smith (2019), 57% of total fatalities across the disaster-affected zone were individuals aged 65 and older. Considering the physical conditions of the elderly community, these disaster events left them in an increased socially vulnerable position (Pongponrat & Ishii, 2017). Compared to the last three Japanese tsunami events, it was reported that child mortality in the 2011 disaster accounted for only 4% of the total death toll (Nakahara et al., 2013).

Beyond tsunami victims' age structures, marginalized people of other nationalities suffered intensified vulnerability to this disaster, including Filipinos, Chinese, Vietnamese, Koreans, and Thais (Pongponrat & Ishii, 2017). More specifically, Thai women living in Ishinomaki, Miyagi Prefecture, which experienced some of the worst destruction from the 2011 tsunami, faced increased vulnerabilities. Social vulnerability is not only about exposure to hazards but also encompasses sensitivity and the resilience of the target society. For example, the link between migration and vulnerability is stressed by social factors such as immigration status and ethnicity. Migrants arriving unofficially seeking low-wage employment face discrimination, stereotyping, exploitation, and even violence due to their lack of political and legal resources. This vulnerability intensifies during disasters, requiring migrants to face unique struggles to recover post-disaster (Pongponrat & Ishii, 2017). In migration studies, vulnerability is evident through language barriers, restricted information access in disasters, and a lack of awareness about preventive measures and evacuation. Thai migrant women in Japan face marginalization on three intricate dimensions. First, as migrants, they are disadvantaged legally, socially, and economically. Second, within the paternalistic socioeconomic structure of East Asia, they occupy a weak position as wives and daughters-in-law. Third, they become victims of the ethnic image of Thai women perpetuated by the international tourism industry. Despite maintaining a secure legal status, their socioeconomic standing remains disadvantaged, shaped by enduring societal distinctions between Japanese nationals and foreign residents (Pongponrat & Ishii, 2017).

As a result, vulnerability is a multidimensional concept influenced by historical, social, economic, and cultural factors. The discussion emphasizes the need for a holistic understanding to develop effective disaster resilience and migrant support strategies. The experiences of Thai migrant women in Japan serve as a poignant illustration of the complex relationship between legal, social, and economic vulnerabilities, further exacerbated by gender-specific challenges.

## Assessing Social Resources

Japan quickly responded to the disasters that struck the Tohoku region. In the immediate aftermath of the earthquake, the prime minister's office established its crisis management network and gathered an emergency council of ministers. Coordinating committees of national agency representatives were established in each prefecture. Within minutes of the earthquake, disaster headquarters were set up in Fukushima, Miyagi, and Iwate. Regional disaster headquarters were composed of representatives from multiple agencies and were overlooked by a head governor (Howitt, 2012). With limited information to guide their response, they aimed to gather intelligence to understand what happened and the best course of action moving forward.

Starting at a local level, governments dispatched responders to coastal regions. These first responders were primarily made up of locally stationed state defense force units and firefighters from communities that sustained limited damage. Requests for more aid were sent to the national government, specifically to self-defense forces and the Fire and Disaster Management Agency, hoping they would emergency dispatch additional firefighters (Howitt, 2012). As reinforcements arrived, responders were sent to determine what needed to be done in each community and take action. Individual groups such as the National Police Agency, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the Fire and Disaster Management Agency

(FDMA), Self-Defense Forces (SDF), and the Coast Guard launched their response and recovery efforts mostly independent of one another (Howitt, 2012).

MLIT launched “Operation Comb,” an early effort to clear east-west roads leading to the coast from the north-south highway some distance inland. When their assistance teams reached coastal communities, they were authorized to provide help, as needed, at the scene (Howitt, 2012). SDF provided the bulk of emergency response personnel who aided the communities impacted by the disaster. “107,000 troops, about half of the nation’s total, were mobilized for response” (Howitt, 2012). They aided in evacuation, decontamination, search and rescue, road re-opening and rubble removal, and victim support services. The FDMA dispatched emergency fire response teams from 44 other prefectures to Fukushima, Miyagi, and Iwate for fire suppression, search and rescue, and medical assistance. “More than 30,000 fire service personnel operated in the disaster-affected prefectures” (Howitt, 2012). The United States also supported Japan during this time through Operation Tomodachi, an operation improvised and adapted solely from defense plans in which U.S. forces, dispatched from nearby military stations, provided logistical support and advice to SDF and other first responders. “At peak, 16,000 U.S. personnel, 15 vessels, and 140 aircraft were active” (Howitt, 2012). This support allowed for the rapid mobilization of responders in Tohoku, which would have otherwise been impossible without the transportation assistance of U.S. forces and equipment. This eventually led to a larger direct support operation led by the Japanese prime minister. The “Team in Charge of Assisting the Lives of Disaster Victims” aimed to collect information, coordinate relief efforts, and oversee the delivery of goods. The Tokyo-based team held daily meetings to determine the needs and effectively coordinate individual agencies' field operations (Howitt, 2012).

Despite Japan’s efforts, the earthquake and tsunami response coordination was weak and unorganized, especially in the first few days following the disaster. Although prefectural governments acted quickly to set up disaster coordinating structures, they lacked information, sufficient personnel, and the resources necessary to handle an emergency of this capacity. At the national level, coordination efforts in the prime minister's office were hindered by poor situational awareness, distraction by the nuclear accident, and overshadowed by individual ministries' independent actions (Howitt, 2012). The disruption of communications and transport primarily hindered the unity of effort. As a result, aid at the local level was mainly the result of community self-help and the outside emergency responders independently reacting to conditions at the scene. It was not until the second week post-disaster that the national coordination improved with the improvisation of daily meetings of division directors (Howitt, 2012).

## Future Recommendations

Many believe the key to efficient emergency response is strengthening centralized command and control; however, landscape-scale disasters are inherently decentralized. Therefore, an alternative decentralized adaptation would be more effective. Decentralized operations consist of building a local capacity in advance and establishing a structure for operations (Howitt, 2012). Coordination and preparation in advance are critical. Resource procurement and allocation should be set beforehand. Goals and priorities should be established, and progress should be consistently monitored. A decentralized disaster response would help build community resilience and reduce overall risk. Overall, a change in emergency response design can make all the difference the next time a disaster like Tohoku strikes again.

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