Chapter 4
2011 Tohoku-Oki Earthquake and Tsunami

Abstract The March 11, 2011 Tohoku earthquake of Mw 9.0 was a surprise to seismologists in Japan and globally. This earthquake and the resultant tsunami claimed about 20,000 human lives and caused wide spread damage to structures. The tsunami also caused a number of nuclear accidents. This earthquake gave rise to a global debate on the anticipated maximum size of earthquakes and the safety of nuclear power plants globally. This chapter includes a discussion on the Mw 9.0 earthquake, an in-depth analysis of the generation and propagation of the tsunami and a brief description of the damage to nuclear power plants and the future plans for protection.

4.1 Introduction

Japan is known for earthquakes and tsunamis and that is why the Japanese language word "tsunami" is so popular and used all over the world. Japan is located near the subduction zone formed by the Pacific, North America, Philippines and Eurasian plates. The Pacific plate moves approximately westwards with respect to the North America plate at a rate of ~8 cm/yr and subducts beneath Japan at the Japan Trench (Fig. 4.1). In the north of Tokyo, earthquakes are caused by the subduction of the Pacific plate under the North America plate while in the south, it is the subduction of the Philippines plate under the Eurasian plate that causes earthquakes. Japan has experienced several major and great earthquakes. Probably the most damaging earthquake in history was the 1923 Kanto earthquake of 8.3 magnitude claiming 142,800 human lives. This earthquake also caused a tsunami with a height of about 10 m. However, the damage and loss of lives was more because of shaking and the fire that broke after the earthquake. In the northern region, large earthquakes have occurred in 1611, 1896 and 1933 and every one of them produced devastating tsunamis on the Sanriku coast of Pacific NE Japan. The M 7.6 subduction earthquake of 1896 created high tsunami of 38 m and caused a reported death toll of 27,000. The M 8.6 earthquake of March 2, 1933, though not a subduction zone earthquake, produced 29 m high tsunami waves on the Sanriku coast and inundated 10 km inland along the coastal plains and claimed more than 3000 human lives.

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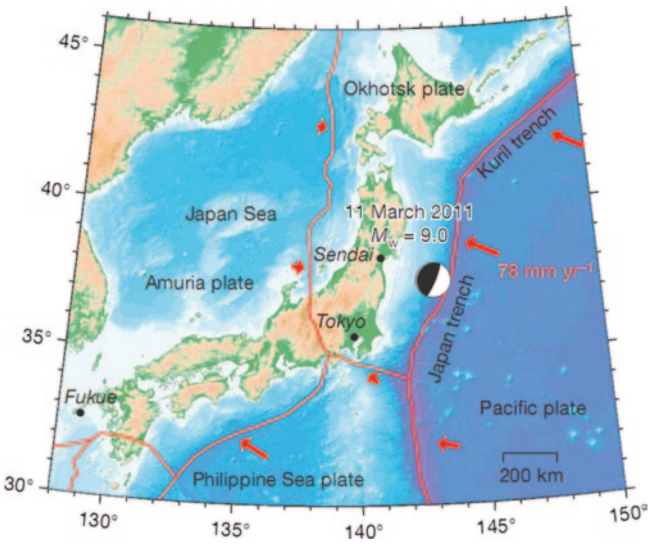

Fig. 4.1 General tectonic set-up of Japan. Location of the March 11, 2011 Tohoku earthquake is shown by the beach ball, depicting the focal mechanism of the earthquake (after Ozawa et al. 2011)

4.2 2011 Tohoku-Oki Earthquake and Tsunami

The 11 March 2011 Tohoku-Oki earthquake, which occurred at 14:46 local time (05:46 UTC), was the largest earthquake (Mw 9) in the known history of Japan (Figs. 4.2 and 4.3). The rupture of the earthquake, as estimated from the distribution of aftershocks and derived from models based on GPS, seismic waveform and tide gauge data, stretches about 300–400 km in length and 200 km in width. It generated a huge tsunami and caused 15,073 fatalities and 8,657 missing in the Tohoku and Kanto regions (Fig. 4.4). A large foreshock of 7.3 magnitude of this earthquake took place at 11:45 local time on 9 March 2011. Following the Tohoku-Oki mainshock, many aftershocks, including three with $M \geq 7.4$, occurred on the same day. Detailed analysis of the seismic waves suggests that the rupture started near the down-dip edge of the main thrust zone and propagated up-dip in both north and south directions. GPS measurements show that the coastal parts of northeastern Honshu moved up to 4 m westwards and sank by almost 1 m. Just above the earthquake hypocenter, the surface coseismic displacement was 24 m predominantly towards the east and 3 m in the up direction (Fig. 4.5). This was calculated by sea-floor geodetic observations using GPS and acoustic measurements. This was the first time that such a large coseismic displacements were measured using GPS. Such large displacements imply that the slip on the subsurface rupture must have exceeded

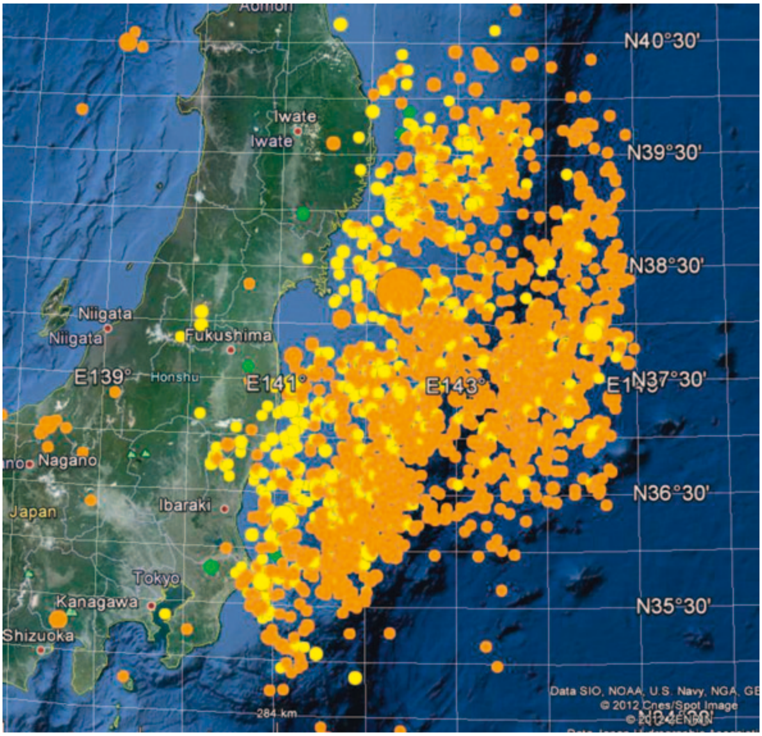

Fig. 4.2 March 11, 2011 Tohoku-Oki mainshock (the largest circle) and its aftershocks (M > 4) from USGS plotted on Google Earth. The *dark* and *light yellow* and *green colors* denote the focal depths of the aftershocks as 0–35, 35–70 and 70–150 km, respectively. The *dark blue/black color* marks the trench location

the surface displacement and when all the data are collated, the maximum slip on the rupture appears to be more than 50 m (Sato et al. 2011). This is almost double of that during the 2004 Sumatra –Andaman earthquake (Mw 9.1) and is the largest ever measured for any earthquake globally. Combined with extensive recordings from global seismic networks, the data from these seismic stations, tide gauges and GPS make the 2011 Tohoku-Oki event the best-recorded earthquake and tsunami in history. Seismic waves shook the ground in Japan with a high frequency of about 10 Hz. Ground accelerations as large as almost three times of acceleration due to gravity and peak ground velocities of 80 cm/s across Honshu were recorded. The tsunami caused by this earthquake was enormous and severely devastated the coastal regions of eastern Japan. Japan's Prime Minister Naoto Kan told reporters at a televised news conference on March 13, 2011 "*In the 65 years after the end of World War II, this is the toughest and the most difficult crisis for Japan*".

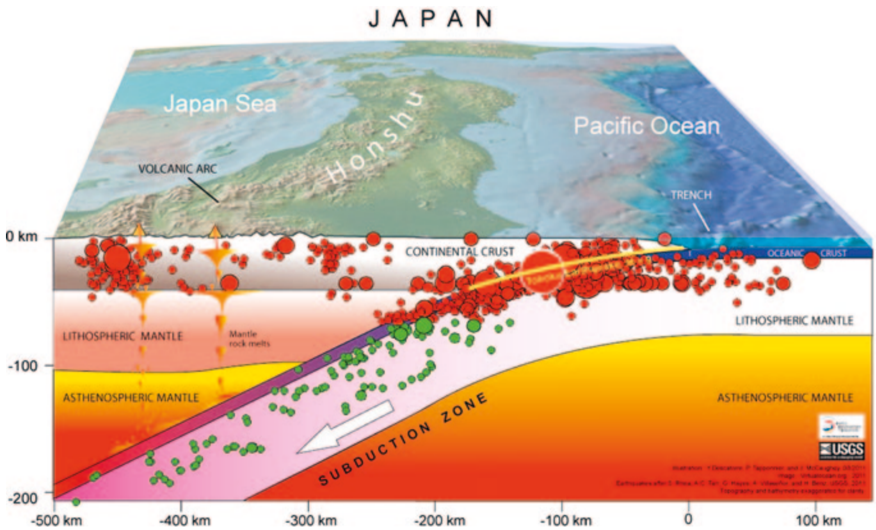

Fig. 4.3 An east–west vertical cross-sectional view of the subduction zone (USGS). *The yellow line* through the *largest circle*, showing the 2011 mainshock, depicts the earthquake rupture

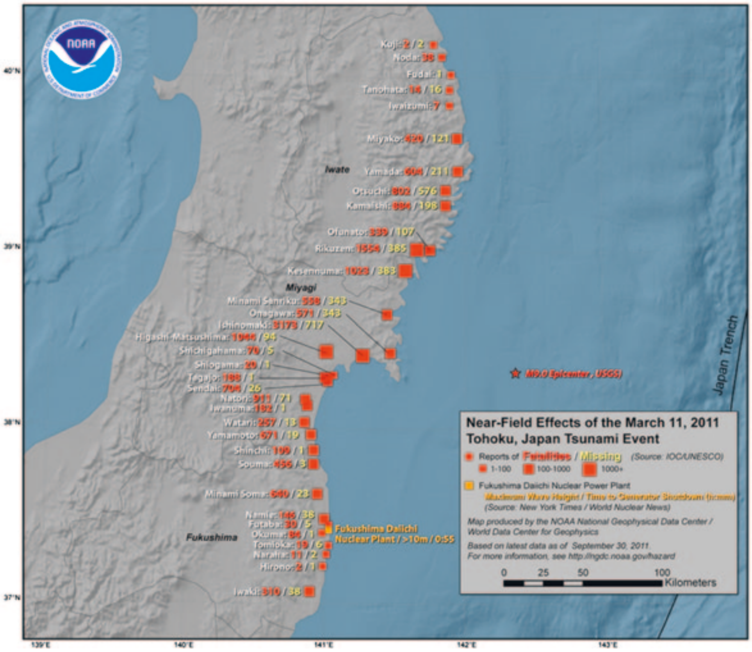

Fig. 4.4 Fatalities and missing people along the eastern coast of Japan (NOAA)

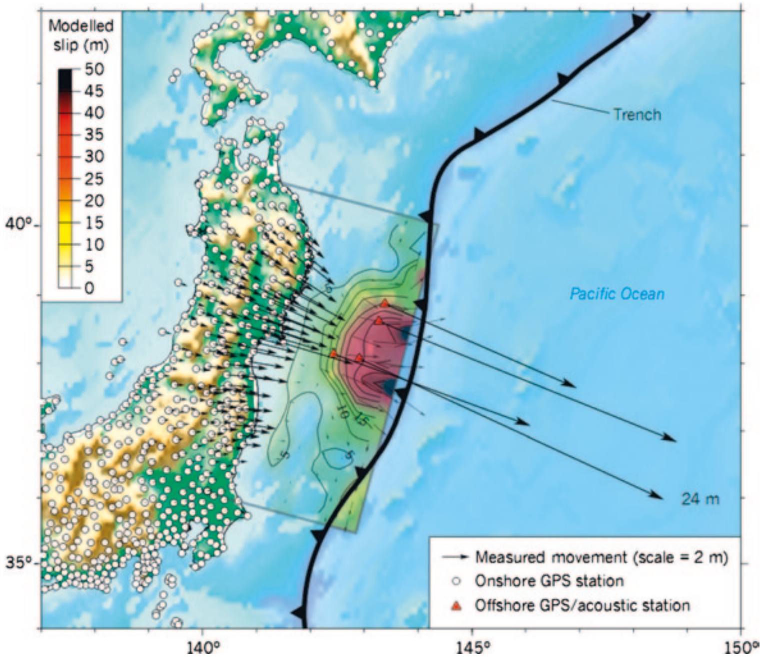

Fig. 4.5 Horizontal displacement caused by the 2011 Tohoku-Oki earthquake. The GPS sites on land are marked by *white circles* whereas the *red triangles* mark the geodetic measurements in the offshore region. The rupture model derived from these observations shows a high slip reaching 50 m (Sato et al. 2011; Newman 2011)

4.3 An Unexpected Event

The occurrence of such a large magnitude earthquake was a surprise. The observed magnitude is significantly larger than any of the earthquakes that occurred along this part of the subduction system in the past few hundred years. It appears that no earthquake larger than 8.3 had occurred earlier in this region. It had been thought that subduction of a relatively old, less buoyant oceanic lithosphere would cause an earthquake with a maximum magnitude of 8. It is now suggested that the complex plate geometry in the region had resulted in contortion of the subducting slab that actually increased plate coupling and stress build-up before the earthquake. Moreover, the shallow part of the plate interface, which was considered to be slipping aseismically, also contributed and released strain, making the width of the fault wider. This led to the extremely violent and powerful Tohuku-Oki earthquake.

Another surprise of this earthquake was the enormous tsunami it generated that swept along 70 km of the coastal plains. Several tide gauges recorded wave heights of over 4 m (Fig. 4.6) with that at Soma recording at least 7.3 m. In fact,

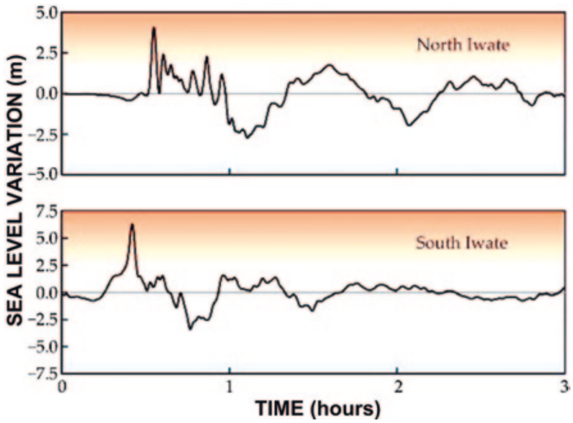

Fig. 4.6 Measurements of sea-level variation from GPS gauges offshore north and south Iwate in the Sanriku region. The tsunami reached each station 20–30 min after the earthquake struck (Lay and Kanamori 2011)

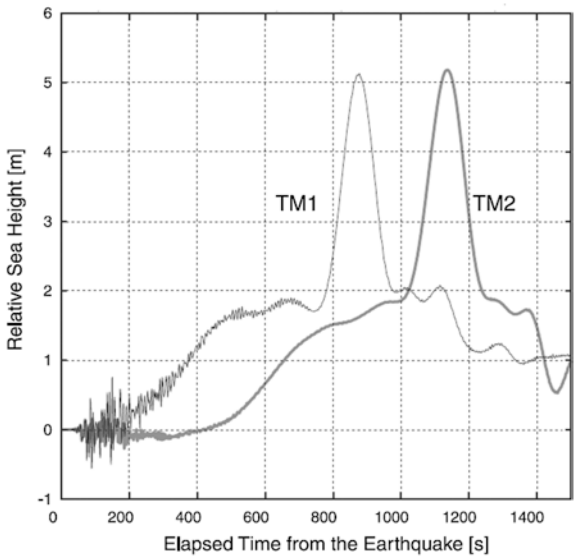

Fig. 4.7 Record of the tsunami at two ocean-bottom pressure gauges (TM1 and TM2), about 50–80 km off the coast of Kamaishi, Sanriku (Maeda et al. 2011)

many tide gauges became saturated and the amplitude got clipped. Two ocean-bottom pressure gauges, which are located about 50–80 km off the coast of Kamaishi, Sanriku, recorded a 5 m high tsunami (Maeda et al. 2011) (Fig. 4.7). Despite much of the coast being protected by tsunami walls, these were not designed to stop 10–15 m high waves that inundated the coast. In Sendai city, the area inundated by the tsunami was almost 5 km inland, whereas official maps indicated only about 1 km of tsunami evacuation area from the coast (Fig. 4.8). Several towns, with houses built using timber frames designed to be flexible to withstand earthquake shaking, were simply swept away. Even the tree line that was planted on the coast could not be of any use in arresting the fury of the tsunami. In fact the uprooted trees, which were swept along with the tsunami waves, added to the force of these waves and caused more damage than providing any protection.

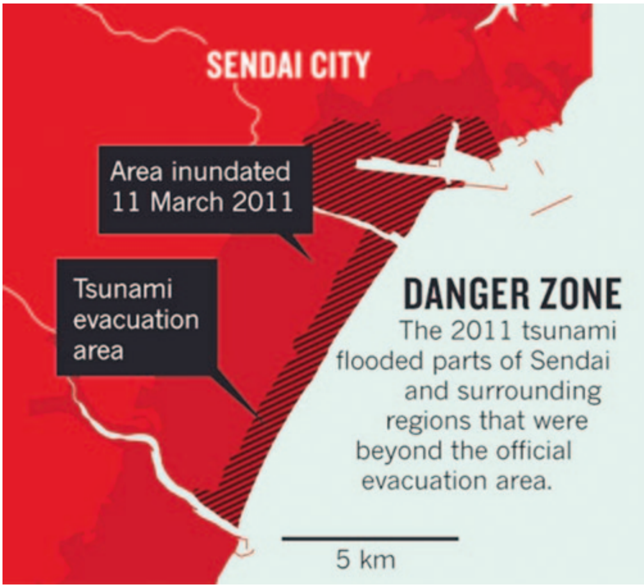

Fig. 4.8 Part of the map of Sendai city showing the official tsunami evacuation area and the actual area that was inundated during the 2011 Tohoku-Oki earthquake (Cyranoski 2012)

The tsunami waves inundated more than 500 km^2 of land across six prefectures, destroying nearly 130,000 buildings and damaging 245,000 others (Figs. 4.9 and 4.10). About 240,000 cars were washed away and destroyed. About fifteen thousand people are known to have been killed and about three thousand people are still missing. Estimates of the damage in this region range from US$14.5 to 34.6 billion. The World Bank estimated the total economic cost as US$235 billion, thus becoming the world's most expensive natural disaster.

In Japan, earthquake monitoring systems have been deployed quite extensively. Building codes have been strictly implemented. These two factors undoubtedly saved lives. Moreover, as tsunami waves travel slowly in shallow coastal water, many people were able to reach high ground in time to escape the flooding. However, some reports indicate that many people did not take immediate action out of a belief that the extensive network of tsunami walls would protect them. Given a more accurate early estimate of the true enormity of the event, $Mw = 9$, the JMA would have been able to issue a warning that might have prompted more extensive evacuations (Lay and Kanamori 2011). In Tokyo, the early warning system issued an alert one minute before the earthquake waves arrived as data from seismometers close to the epicenter could be transmitted and processed faster than the seismic waves could travel. But the initial 5–10 s of shaking produced by the Tohoku-Oki earthquake was weak, comparable to a magnitude 4.9 event and the JMA's earthquake early warning system underestimated the expected overall intensity (Lay and Kanamori 2011). Nevertheless, due to the availability of other early warning systems, more than 20 high-speed bullet trains could be stopped in the Tohoku district when the earthquake struck.

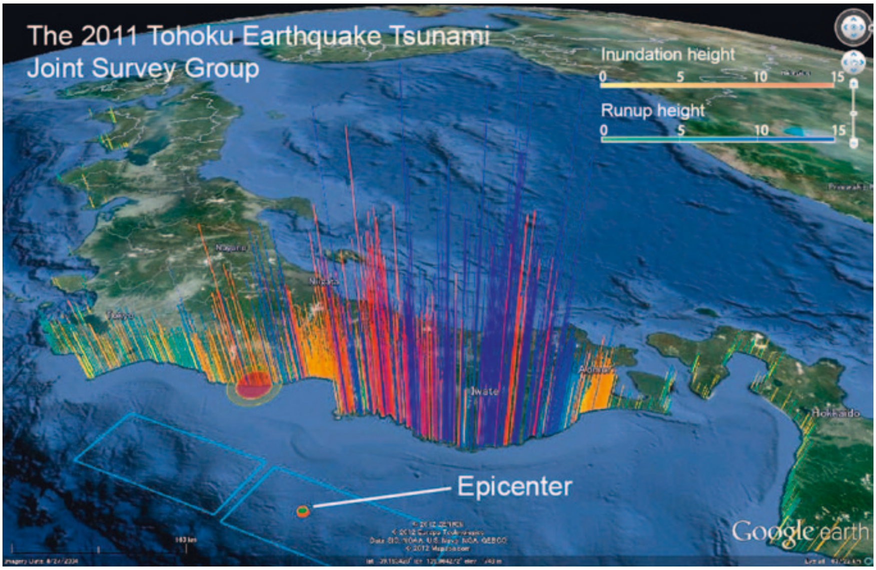

Fig. 4.9 Inundation and run-up heights along the eastern coast of Japan caused by the tsunami (Tsunami Joint Survey group http://www.coastal.jp/tsunami2011/). The source zone of the earthquake is shown by the two rectangles

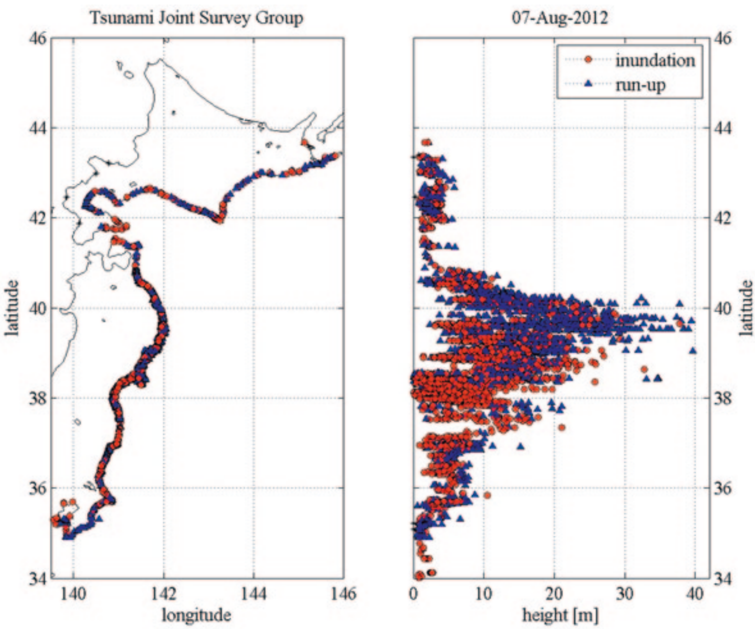

Fig. 4.10 Inundation and run-up heights along the eastern coast of Japan caused by the tsunami (Tsunami Joint Survey group http://www.coastal.jp/tsunami2011/)

4.4 Effect of the 2011 Tsunami in Japan

The USGS initially estimated the size of the earthquake as 7.9 and then upgraded it to 8.8 and then quickly to 8.9 and finally to 9.0. The Pacific Tsunami Warning Centre issued its first preliminary regional tsunami warning ten minutes after the earthquake struck, upgrading it to a widespread tsunami warning after another hour and a half. The tsunami warning issued by the Japan Meteorological Agency, after only 2 min and 40 s, was the most serious with its warning scale and rated it as a “major tsunami” and advised that 6 m, 3 m and 3 m tsunamis could be expected along the coast of the Miyagi, Iwate and Fukushima prefectures, respectively. Initial estimates indicated that the tsunami would reach in 10–30 min the areas first affected and then the areas farther north and south, based on the geography of the coastline, would be affected. However, the actual tsunami caused by the earthquake was much more severe and an underestimated forecast led to slow evacuation. Also, many people caught in the tsunami thought that they were located on high enough ground to be safe. The tsunami seawalls at several of the affected cities were based on much smaller estimated tsunami heights. Thus, among several factors causing the high death toll from the tsunami, one was the unexpectedly large size of the water surge. Just over an hour after the earthquake at 15:55 JST, a tsunami was observed flooding Sendai Airport, which is located near the coast of Miyagi Prefecture, with waves sweeping away cars and planes and flooding various buildings as they traveled inland. A 4 m high tsunami hit Iwate Prefecture. Wakabayashi Ward in Sendai was also particularly hard hit (Figs. 4.11, 4.12, 4.13, 4.14, 4.15, 4.16, 4.17, 4.18, 4.19, 4.20, 4.21).

The Japan Meteorological Agency (JMA) published details of tsunami observations recorded around the coastline of Japan following the earthquake. The timing of the earliest recorded tsunami maximum readings ranged from 15 h 12 min to 15 h 21 min, that is 26 and 35 min after the earthquake had struck. The bulletin also included initial tsunami observation details, as well as more detailed maps for the coastlines affected by the tsunami waves. These observations included maximum tsunami readings of over 3 m at the following locations:

Arrival time	Place	Height of the tsunami (m)
15:12 JST	Off Kamaishi	6.8
15:15 JST	Ōfunato	>3.2
15:20 JST	Ishinomaki-shi Ayukawa	>3.3
15:21 JST	Miyako	>4.0
15:21 JST	Kamaishi	>4.1
15:44 JST	Erimo-cho Shoya	3.5
15:50 JST	Sōma	7.3
16:52 JST	Ōarai	4.2

At a few places, the tsunami height was inferred to be more than 30 m. A joint research team from Yokohama National University and the University of Tokyo reported that the tsunami at Ryōri Bay, Ōfunato was about 30 m high. At Tarō, Iwate, a University of Tokyo researcher reported an estimated tsunami height of 37.9 m, which reached the slope of a mountain some 200 m away from the coastline.

Fig. 4.11 People watching the tsunami at Sendai (H Kawahara/AFP/Getty)

Fig. 4.12 Sendai airport on March 16, 2011 flooded with water inundation due to the tsunami

4.5 Tsunami Across the Pacific

Immediately after the warning by the Pacific Tsunami Warning Center (PTWC) in Hawaii, evacuation around the Pacific Ocean started where tsunami waves reached more than 6 h after the earthquake (Fig. 4.22). Russia evacuated 11,000 residents from coastal areas of the Kuril Islands. The United States West Coast and Alaska Tsunami Warning Center issued a tsunami warning for the coastal areas in most

Fig. 4.13 Smoke rises from a burning factory in Sendai, March 12. (Kyodo/Reuters)

Fig. 4.14 Tsunami debris scattered over a devastated area of Sendai, March 14, 2011. (STR/AFP/Getty Images)

of California, all of Oregon and the western part of Alaska and a tsunami advisory covering the Pacific coastlines of most of Alaska and all of Washington and British Columbia, Canada. In California and Oregon, up to 2.4 m high tsunamis hit some areas, damaging docks and harbors and causing over US$10 million in damage. A tsunami of up to 1 m hit Vancouver Island in Canada prompting some evacuations and a ban of boats in the water surrounding the island for 12 h. In

Fig. 4.15 Vehicles pass through the ruins of the leveled city of Minamisanriku, northeastern Japan, Tuesday March 15, 2011. (AP Photo/David Guttenfelder)

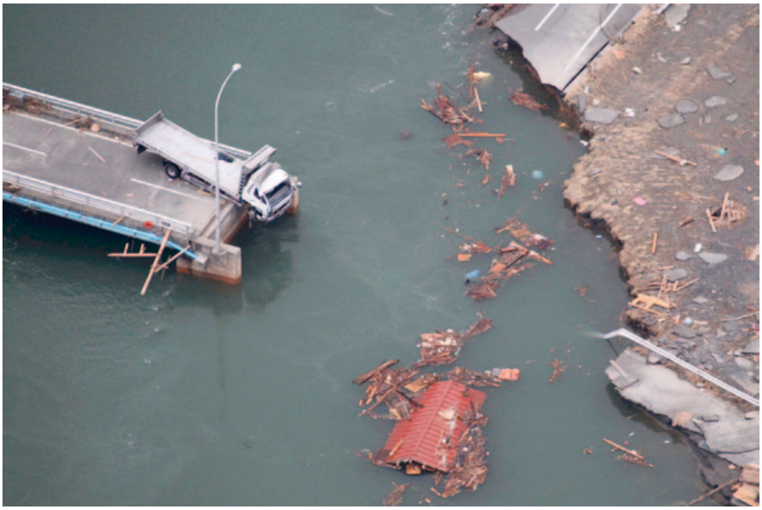

Fig. 4.16 A truck dangles from a collapsed bridge in Ishinomaki, northern Japan, four days after the earthquake (AP Photo/The Yomiuri Shimbun, Hiroshi Adachi)

Fig. 4.17 People walk a road between the rubble of destroyed buildings in Minamisanriku town, Miyagi Prefecture, northern Japan, three days after the earthquake (AP Photo/The Yomiuri Shimbun, Tsuyoshi Matsumoto)

Fig. 4.18 A fishing boat rests surrounded by debris in the city of Kamaishi, Iwate Prefecture on March 12. (Yomiuri Shimbun/AFP/Getty Images)

Fig. 4.19 Buildings are covered with mud in Minamisanriku, Miyagi Prefecture, March 12. (Naoki Ueda/The Yomiuri Shimbum/Associated Press)

the Philippines, waves of up to 0.5 m high hit the eastern seaboard of the country. Authorities in Wewak, East Sepik, Papua New Guinea evacuated 100 patients from the city's Boram Hospital before it was hit by waves, causing an estimated US$4 million of damage. In Hawaii, the estimated damage to public infrastructure was US$3 million. It was reported that a 1.5 m high wave completely submerged Midway Atoll's reef inlets and Spit Island, killing more than 110,000 nesting seabirds at the Midway Atoll National Wildlife Refuge. Some other South Pacific countries, including Tonga and New Zealand and U.S. territories including American Samoa and Guam, experienced larger-than-normal waves but did not report any major damage. However, in Guam, some roads were closed and people were evacuated from low-lying areas. Along the Pacific Coast of Mexico and South America, tsunami surges were reported but in most places caused little or no damage. Peru reported a wave of 1.5 m and more than 300 homes damaged. The tsunami in Chile was large enough to damage more than 200 houses, with waves up to 3 m in height.

The wave height was generally a few tens of cm as the tsunami crossed the Pacific but increased as it reached shallow coastal waters, with waves up to 3 m arriving on the coast of Chile about 20–21 h after the earthquake. One man was killed in Indonesia and another died in California attempting to photograph the waves. The impact on the coast of the United States was lessened as the arrival of the tsunami waves largely coincided with low tide but tens of millions of dollars' worth of damage was inflicted to ports and harbors. Damage to houses was also reported from Peru, Chile and Indonesia.

Fig. 4.20 People walk on debris scattered across the town of Minamisanriku, Miyagi Prefecture on March 12. (Yomiuri Shimbun/AFP/Getty Images)

4.6 Fukushima Meltdown

The unprecedented height of the tsunami waves not only damaged property and killed several thousand people, it also caused another scare, a nuclear accident. This accident is the second biggest after the Chernobyl nuclear disaster of 1986 but more complex as all eleven reactors were involved. Japan produces about 1000 TWh of electricity and about one fourth of this is met by 53 nuclear reactors. Japan had 282 GW of total installed electricity generating capacity in 2010. However, after the damage by the 2011 earthquake, the capacity was estimated to be around 243 GW in mid-2011.

Fig. 4.21 A home drifts in the Pacific Ocean on March 13, 2011 (REUTERS/U.S. Navy/Mass Communication Specialist 3rd Class Dylan McCord)

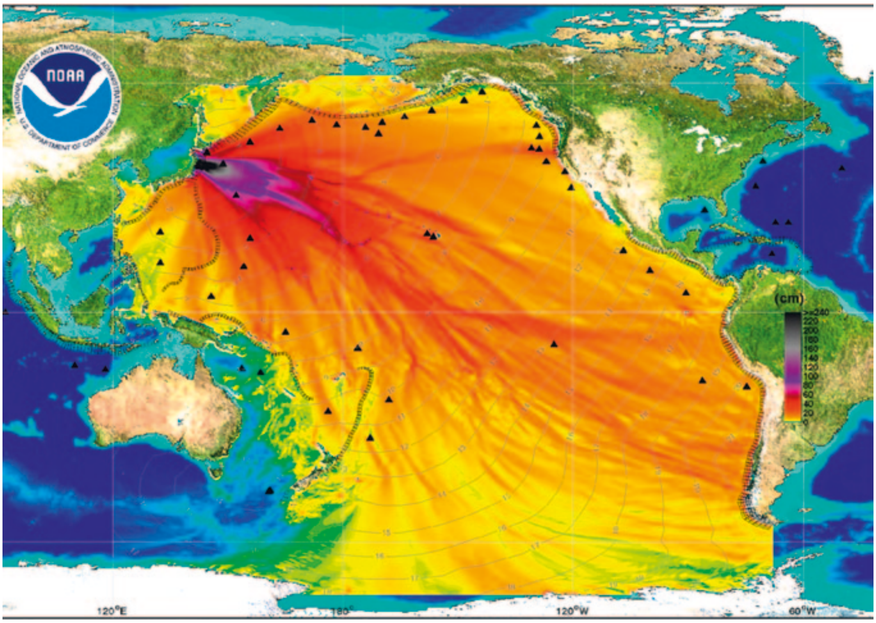

Fig. 4.22 Simulated tsunami amplitude in the open ocean for the 2011 Tohoku-Oki earthquake (National Oceanic and Atmospheric Administration, NOAA, USA). The *grey color* contours show the traveltimes of the tsunami waves

The Fukushima Daiichi, Fukushima Daini, Onagawa Nuclear Power Plant and Tōkai nuclear power stations, consisting of eleven reactors, were automatically shut down following the earthquake. Cooling is needed to remove decay heat after a reactor has been shut down and to maintain spent fuel pools. The back-up cooling process is powered by emergency diesel generators at the plants and at the Rokkasho nuclear reprocessing plant. At Fukushima Daiichi and Daini, tsunami waves overtopped seawalls and destroyed diesel back-up power systems. Three large explosions and radioactive leakage occurred (Fig. 4.23). Japan declared a state of emergency, following the failure of the cooling system at the Fukushima Daiichi nuclear power plant, resulting in the evacuation of nearby residents. Over 200,000 people were evacuated. Officials from the Japanese Nuclear and Industrial Safety Agency reported that radiation levels inside the plant were up to 1,000 times more than normal levels and that radiation levels outside the plant were up to 8 times more than normal levels. Later, a state of emergency was also declared at the Fukushima Daini nuclear power plant located about 11 km south. Radioactive iodine was detected in the tap water in Fukushima, Tochigi, Gunma, Tokyo, Chiba, Saitama and Niigata and radioactive cesium in the tap water in Fukushima, Tochigi and Gunma. Radioactive cesium, iodine and strontium were also detected in the soil in some places in Fukushima. Food products were also found contaminated by radioactive matter in several places in Japan. On 5 April 2011, the government of Ibaraki Prefecture banned the fishing of *sand lance* (or sand eels, a variety of fish) after discovering that this species was contaminated by radioactive cesium above legal limits. Only after a few years will we know the actual damage done by the radiation to living beings and the ecosystem.

4.7 Lessons Learnt from the 2011 Earthquake

The amount of data generated by this earthquake is unprecedented. These data will be used to understand the occurrence of giant earthquakes, their potential of generating tsunamis and causing damage. Insights gained from the Tohoku earthquake are helpful to scientists to re-evaluate the seismic hazard. This will contribute to improved scenario building, code development and public warnings about tsunami threats. It is expected that these studies will help in mitigating the hazards due to future large earthquakes. One thing that seismologists have now learnt is the possibility of occurrence of giant earthquakes along subduction zones. Japanese scientists had not estimated that an earthquake of such a large magnitude could occur in that area. The tsunami seawalls in the area were built for a tsunami resulting from a magnitude 8.0 earthquake and not a 9.0 magnitude earthquake. Thus, even though the Japanese had planned and were well-prepared for an M 8 earthquake, which might have a recurrence interval of 200–300 years, they were not prepared for a giant earthquake with a recurrence interval of, say 1000 years. Another issue worth mentioning here is that Japan was focusing more on the Tokai and Nankai regions (south of Tokyo) where they expected large earthquakes to occur. Thus the

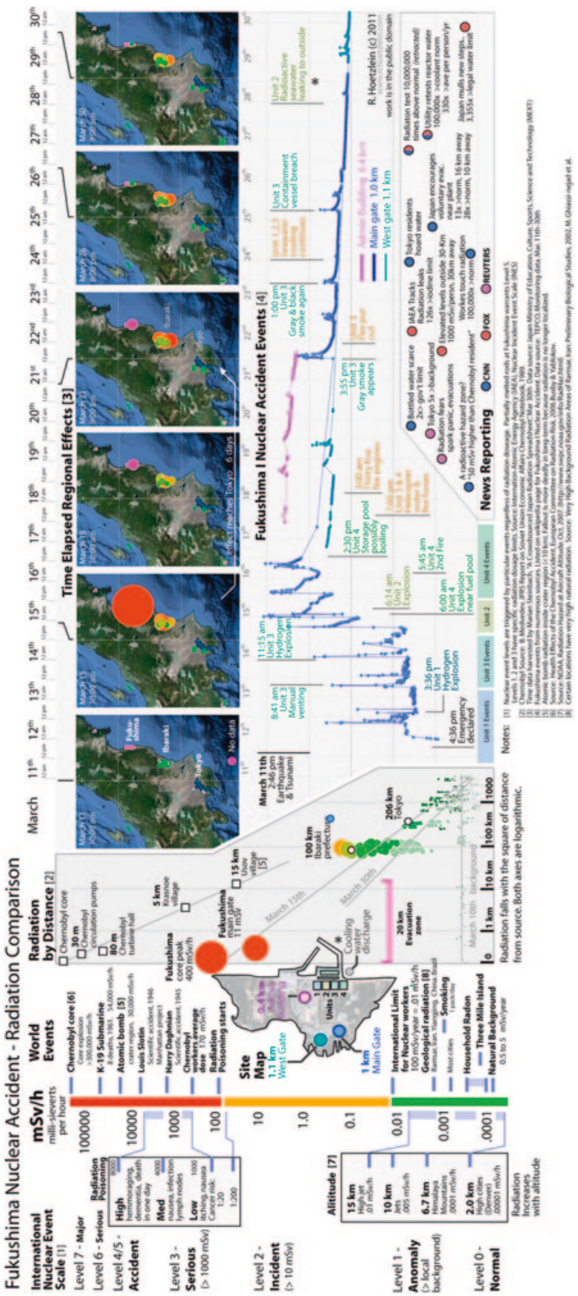

Fig. 4.23 Severity of the Fukushima nuclear accident (*source* Wikipedia)

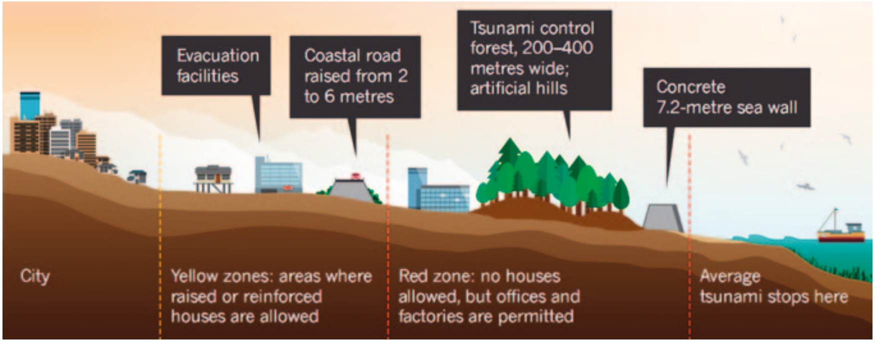

Fig. 4.24 A new proposed plan for Sendai city (Cyranoski 2012)

projected seismic hazard in those regions was higher than in the region hit by the 2011 earthquake (Geller 2011). Consequently, Japan is currently updating its tsunami disaster plans for all of its coastal areas (Fig. 4.24). It has been suggested that all plans take evidence from paleo-tsunami deposits into consideration. Even relatively long seismological records are too limited to adequately assess the hazard from infrequent but devastating events. From a recent re-evaluation of palaeo-tsunami deposits, more than three kilometers inland of the Sendai plain, it is now inferred that an earthquake of magnitude ~9 did occur in the same region of Japan in 869 (Minoura et al. 2001).

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