

Chapter 2

Features of the 2011 Tohoku Earthquake and Tsunami

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Abstract

A giant earthquake of moment magnitude (Mw) 9.0 occurred off the Pacific coast of Tohoku on March 11, 2011, and is the largest earthquake on record to strike in or near Japan. The huge tsunami generated by this earthquake struck the east coast along Tohoku, and left more than 19,000 people either dead or missing. The tsunami waves were also responsible for severe accidents at the Fukushima Daiichi Nuclear Power Plant, which further intensified the scope of the disaster. More than 120,000 houses and buildings were destroyed and more than 240,000 were partially collapsed. While plenty of buildings were damaged by the earthquake, a majority of the damage to buildings was caused by the tsunami.

Keywords : Moment Magnitude, Tsunami, Strong Ground Motion, Catastrophic Damage, Seismic Hazard Map, Earthquake Headquarter, Central Disaster Management Council, Disaster Prevention Plan

1. Introduction

The earthquake of moment magnitude (Mw) 9.0, which struck off the Pacific Coast of Tohoku on March 11 2011 at 14:46 (Japan time), was the largest recorded in Japan's history. It was named the 2011 off the Pacific coast of Tohoku earthquake, hereafter called "the 2011 Tohoku Earthquake". The strong motions and tsunamis generated from this earthquake caused significant damage throughout wide regions from Tohoku to Kanto. Cabinet approval was given to name the disaster caused by the earthquake the "Great East Japan Earthquake." With the strong motions it generated, a maximum seismic intensity of 7 was observed at a station in Kurihara city of Miyagi Prefecture close to the hypocenter, while an intensity of upper 6 was observed over a wider area spanning the four prefectures: Miyagi, Fukushima, Ibaraki and Tochigi. Tsunami run-up heights up to a maximum of 40 m were also recorded around Miyako City on the Sanriku Coast, with waves reaching 10 m and higher along the approximately 500 km stretch of coast from Chiba to Aomori Prefectures. The coast along northern Miyagi through northern Iwate Prefectures in particular was hit by tsunami waves reaching 20 m and higher. Despite Iwate and Miyagi Prefectures boasting the world's most advanced tsunami countermeasures, those regions suffered catastrophic damage. More than 19,000 people were killed or lost, around 400,000 houses were fully or partially destroyed, up to 500,000 residents were evacuated, and the economic cost of the damage reached a staggering 16.9 trillion yen. One of the most substantial features of this great earthquake was the fact that around 90% of its victims perished due to drowning by the tsunami. It is this point in which it deviates significantly from the Great Kanto Earthquake (in which 90% of the victims died in fires) and the Great Hanshin Earthquake (in which 80% were crushed by collapsing buildings). Moreover, the accident at the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Plant (hereinafter referred to as "Fukushima Daiichi Plant") was a direct result of the tsunami.

2. Outlines of the 2011 Tohoku earthquake

The Japan Meteorological Agency determined the hypocenter of the earthquake to be at latitude 38°6'12"N, longitude 142°51'36"E, approximately 130 km east-southeast of the Oshika Peninsula, at a depth of 24 km. Detailed analysis of aspects such as the seismic waves, crustal deformation and tsunami waveforms generated by the earthquake

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revealed that the rupture propagated for around 180 seconds over a wide area spanning approximately 500 km in length and 200 km in width, at the boundary of the North American Plate and Pacific Plate, which runs along the Japan Trench off the coast of Tohoku, and that substantial slipping occurred between the two plates, exceeding 50 m at its greatest. As the Pacific Plate sinks below the North American Plate, on which Tohoku, Japan is situated, at an annual rate of approximately 8 cm, strain accumulates. The cumulative strain over 300 to 600 years as tens of meters of slipping occurred was ultimately released, all at once, in this earthquake.

After the Great Hanshin Earthquake of 1995, the Government pursued the promotion of earthquake research, observation and disaster mitigation in Japan with serious determination, through the Headquarters for Earthquake Research Promotion (hereinafter referred to as the “Earthquake Headquarters”). Each year since 2005, the Earthquake Headquarters has published long-term forecasts of earthquake activity and the National Seismic Hazard Maps for Japan (Figure 1: HERP, 2010) ⁽¹⁾, based on efforts including investigation of active inland and off-shore faults and examination of historical and geological records of subduction earthquakes. The long-term forecast for subduction earthquakes off the Pacific Coast of Tohoku that was released prior to the great earthquake divided the region into about six zones and predicted a 99% probability for an earthquake of around M7.5 off the coast of Miyagi Prefecture (off-Miyagi zone), 80–90% for an earthquake of around M7.7 south of the Sanriku Coast and east of the off-Miyagi zone (Southern Sanriku zone), a larger earthquake of around M8.0 presumed when generated by the combination of these two expected focal zones, off-Miyagi and Southern Sanriku, 7% or lower for an earthquake of around M7.4 off the coast of Fukushima Prefecture (off-Fukushima zone), 90% or more for an M6.7–M7.2 earthquake off the coast of Ibaraki Prefecture (off-Ibaraki zone), and around 20% for a tsunami earthquake of M8.2 near the Japan Trench from the coast of Sanriku to Boso. Since the hypocenter of the Tohoku Earthquake was located in the region between the off-Miyagi and southern Sanriku zones, where a high probability of earthquake occurrence had been predicted, we may regard the predictions of the location of earthquakes occurring as a partial success, and yet the rupture was not limited to that region. In fact, the rupture extended to all six of the divided forecast zones, from off-Iwate and Miyagi Prefectures and the Southern Sanriku zone, to off-Fukushima and Ibaraki Prefectures and near the Japan Trench from off-Sanriku coast to off-Boso Peninsula. Consequently, although the scale of the earthquake was predicted to be around M8.2 at its largest, it was in actuality M9.0. Considered in terms of energy, we find a discrepancy by as much as 15 times between the forecast and reality, which is quite a failure in the prediction of scale.

The Earthquake Headquarters has made its long-term forecasts for the source area of the Tohoku Earthquake, using only the historical earthquake activity data for the past 400 years, over which the level of accuracy is at its highest. In principle, it was not possible to forecast subduction earthquakes that exhibit long activity cycles exceeding 400 years. The problem has been known since before the Tohoku Earthquake struck, so investigative research on paleoseismicity and paleotsunamis commenced by examining tsunami deposits in order to extend the period for historical earthquake activity data, but the Tohoku Earthquake occurred before the results were released.

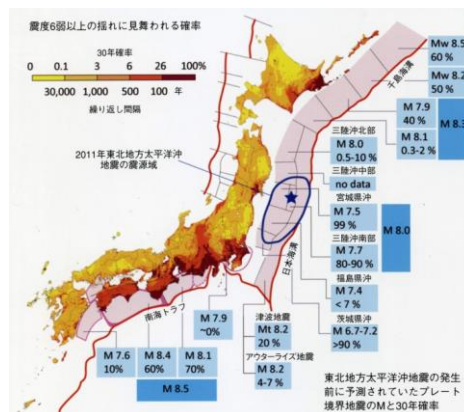


Figure 1. Long-term assessment of subduction earthquakes and National Seismic Hazard Maps (2010 version)

3. Tsunami that caused catastrophic disasters

Data on the heights of tsunamis for 5,900 points along the Japanese coast were compiled and published by the Tohoku Earthquake Tsunami Joint Survey Group (Figure 2: TTJS, 2011)⁽²⁾. Tsunami run-up heights up to a maximum of 40 m were also recorded around Miyako City on the Sanriku Coast, in addition to which, tsunami waves were recorded at more than 20 m in height along the stretch of coast of approximately 200 km from northern Miyagi through northern Iwate Prefectures, and more than 10 m along the approximately 500 km of coast from Chiba through Aomori Prefectures. The tsunami also caused flooding in the Sendai Plain in Miyagi Prefecture, which penetrated 5 km inland from the coast.

The Tohoku Earthquake was an “unexpected,” great M9-class earthquake, the likes of which had never previously been recorded in Japan, and yet, in terms of the tsunami, the Meiji Sanriku Earthquake that occurred on June 15, 1896 was accompanied by a huge tsunami that struck the Sanriku Coast, having a height that was roughly the same as that of the 2011 tsunami. The Meiji Sanriku Earthquake was by no means large in scale, at M7.2 based on the magnitude of strong ground motions, but it is known to have caused a huge tsunami that killed 22,000 people, primarily in Iwate Prefecture. This number surpasses the death toll of the Great East Japan Earthquake.

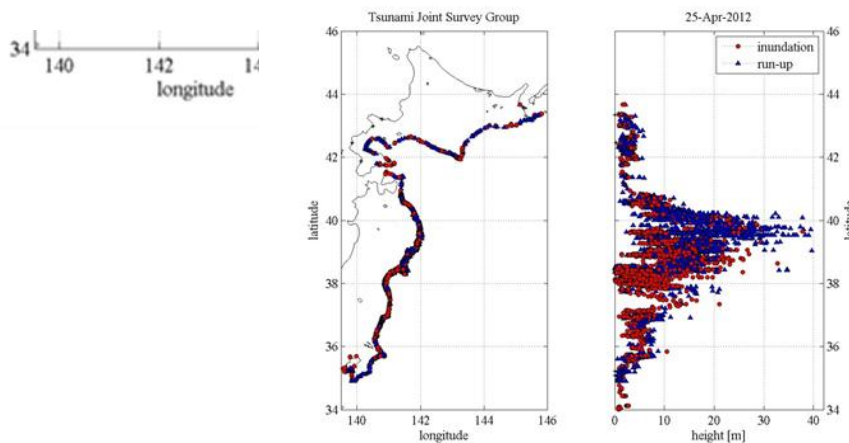


Figure 2. Results of tsunami survey by the Tohoku Earthquake Tsunami Joint Survey Group. Blue triangles indicate run-up height; red circles indicate inundation depth.

A tsunami warning for the Tohoku earthquake was broadcast at 14:49 by the Japan Meteorological Agency, 3 minutes after the earthquake occurred, predicting tsunami waves up to 6 m in Miyagi Prefecture, 3 m in Iwate and Fukushima Prefectures and 1 m along the Pacific Coast of Aomori Prefecture. The warning was transmitted on television and radio, as well as to the local authorities along the coast via a dedicated line, raising awareness among residents by disaster prevention wireless systems and other methods. Many people who felt the strong shaking caused by the earthquake fled to higher ground after receiving the warning. However, the predicted height of the waves was 3–6 m, so some people failed to evacuate as they had faith in the breakwaters, while others escaped to evacuation sites at low elevation, not far from the coast. Consequently, a great number of people lost their lives when the tsunami inundated the coast. The observational data of the Japan Meteorological Agency, which stated that the first waves of the tsunami were 0.2 m, has also been criticized for leading to delayed and cancelled evacuation by some. At 15:14, 28 minutes after the earthquake, the Agency revised its predicted tsunami heights to at least 10 m, 6 m and 3 m for Miyagi, Iwate and Fukushima, and Aomori Prefectures, respectively, based on data from GPS wave recorders situated on the seabed. Then, another 14 minutes later, at 15:30, it was determined that the tsunami waves along the Pacific Coast from Iwate Prefecture to the Boso Peninsula would be at least 10 m. The first warning update had been directly prior to the

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first tsunami waves reaching land on the Sanriku Coast. However, the strong ground motions from the earthquake had caused power outages over a wide area, and people had already started to evacuate, so the updated information did not adequately reach the inhabitants who lived along the coast (Imamura and Anawat, 2012)⁽³⁾.

The Fukushima Daiichi Plant lost all of its power due to the strong ground motions and tsunami waves at around 15 m in height, and was unable to cool its reactors. This led to a catastrophic accident involving a core meltdown, hydrogen explosions and the release of radioactive material. The main facilities of the Fukushima Daiichi Plant were sited 10 m above sea level. In order to ensure safety against tsunamis, it was assumed that the height of tsunami waves would be 6.1 m, based on the “Tsunami Assessment Method for Nuclear Power Plants in Japan” by the Japan Society of Civil Engineers and assuming future incidents to be similar in degree as the earthquake that occurred off the coast of Fukushima Prefecture in 1938 (M7.5). In the long-term forecast by the Earthquake Research Committee, the possibility was raised that a tsunami earthquake like the Meiji Sanriku Earthquake could occur at any points along the Japan Trench, so TEPCO estimated that if such an earthquake were to occur off the coast of Fukushima Prefecture, the maximum height of the tsunami waves at the Fukushima Daiichi Plant would be 15.7 m. However, the fact that it was not known whether tsunami earthquakes had occurred in the area in the past meant that the possibility itself was thought to be low, and so no specific countermeasures were taken (Satake et al.2013)⁽⁴⁾.

4. Characteristics of strong ground motions

The strong ground motions associated with the Tohoku earthquake were extended to the Kanto Region as well as the Tohoku Region; in fact, they were recorded at more than 1000 strong motion stations over almost the entire country (NIED, 2011)⁽⁵⁾. The fact that the peak ground velocity (PGV) and peak ground acceleration (PGA) of the earthquake attenuated with distance is roughly equivalent to the attenuation-distance decay observed in the 2003 Tokachi-oki Earthquake (Mw 8.3). Accordingly, although the moment magnitude of the present earthquake was 9.0, when considered based on the empirical attenuation-distance curves, i.e. Ground Motion Prediction Equations for the PGV and PGA of strong ground motions, it is actually around 8.3 (NIED,2011)⁽⁶⁾.

Several wavepackets consisting of distinctive isolated-pulse-waves observed in the strong motion waveforms for this earthquake have been understood based on the forward modeling to be generated from five strong motion generation areas distributed over the source fault plane. These strong motion generation areas are found to the west of the hypocenter, located deep in the seismic fault and arranged along the down-dip edge. Meanwhile, inversion analyses by many authors using very long-period data such as crustal deformation and tsunami data have led to results that show a large slip area is present further east of the hypocenter, near the Japan Trench, where the source fault is shallow. These observations suggest that mega-thrust subduction earthquakes such as this have a period-dependent source model (Kurahashi and Irikura, 2013)⁽⁷⁾. This result provides important information for the prediction of strong ground motion for future mega-thrust subduction earthquakes.

5. Preparation for future large-scale earthquakes

In its capacity as headquarters for disaster-prevention matters, the Central Disaster Management Council, established in the Cabinet Office, formulated the Basic Disaster Prevention Plan, set out and implemented guidelines for disaster-prevention and emergency-response measures, guidelines for reconstruction and restoration measures, as well as a measure for the prevention of, and reduction in damage caused by, earthquakes and tsunamis in Japan.

In an effort to prepare against large-scale earthquakes and tsunamis following the Tohoku Earthquake, the Central Disaster Management Council has taken the lessons learned from the enormous loss of life and extensive material damage inflicted by a great M9 earthquake that could not be predicted, as an opportunity to deliberate on the largest

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category of earthquakes and tsunamis, taking into account all eventualities, based on paleoseismic investigation and other scientific findings. Meanwhile, the Council took the premise that tsunamis fall into two levels, specifically, tsunamis that occur with high frequency, and low height, but that nevertheless cause significant damage (L1 tsunamis), and the largest category of tsunamis, which occur at very low frequency, but cause enormous amounts of damage (L2 tsunamis). Its conclusion is that to protect residential properties and economic activity, as well as human life against L1 tsunamis, tangible, “hard” improvements are to be made, such as the installation of breakwaters, whereas for L2 tsunamis, the protection of human life is the foremost priority, and intangible, “soft” efforts such as the development of hazard maps, implementation of disaster-prevention training and designation of evacuation centers are required (CDMC, 2011)⁽⁸⁾.

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