Tohoku Earthquake & Tsunami Event Recap Report

August 30, 2011
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Executive Summary

A mega-earthquake and tsunami struck the northeastern coast of Japan on March 11, 2011, killing and injuring thousands of people and causing extensive damage. As of this writing, the death toll was 15,776 and expected to possibly reach 20,000. At least 5,929 others were injured and more than 4,225 people were officially listed as missing. The main magnitude-9.0 earthquake struck at 2:46 PM local time (5:46 UTC) with an epicenter 129 kilometers (80 miles) east of Sendai, Japan.

The Tohoku earthquake is the largest known tremor to have struck Japan. This mega-thrust event occurred in an area where the Pacific Plate is thrust beneath the Eurasian and North American Plates, and ruptured an area 400 kilometers (249 miles) long and 50 kilometers (30 miles) wide. The ensuing tsunami was triggered as typically seen in cases of subduction zone events. Early scientific analyses show how the tremor altered the pent up motions on neighboring faults. However, the Nankai-Tonankai-Tokai faults, located further south of the Tohoku event and sources of megathrust events with recurrences of 100 – 150 years, do not appear to have been altered in terms of their seismic behavior.

The vast majority of the fatalities and damage came not from the earthquake itself, but from the resulting tsunami. Official reports noted that tsunami waves reaching heights in excess of 10 meters (33 feet) swept away hundreds of thousands of homes, boats, cars, buildings and excessive amounts of debris. The waves rushed nearly ten kilometers (six miles) inland in some spots and flattened almost every home, structure, vehicle or vegetation in its path.

The most devastating property effects came in Miyagi, Iwate, Fukushima and Ibaraki prefectures, where many of the flattened areas may never be rebuilt. According to Japan's Fire and Disaster Management Agency, there were at least 385 fires reported after the earthquake and tsunami events occurred.

Widespread damage to commercial facilities was reported as product manufacturing sites were impacted and shipments were forced to stop. The most widely anticipated global commercial impact from the event was to the automotive industry.

The Tokyo Electric Power Company (TEPCO) and Tohoku Electric Power (TEP) reported that a combined seven million homes were without electricity at the height of the event, including at least four million customers in and around the greater Tokyo metropolitan area.

The energy industry (particularly oil, coal and natural gas) all saw disruptions arise during the event. Port damage led to import and export delays in coal and natural gas, while several oil refineries closest to the epicenter reported damage after multiple sites saw large fires erupt.

Infrastructure damage was widespread throughout the affected regions as roads, airports, railways, bridges, ports and dams were significantly impacted.

The event also led to a Level 7 nuclear power plant disaster at the Fukushima Daiiichi complex.

The Japanese government estimated total economic losses to range at least between JPY16.2 to 25.3 trillion (USD198 to 309 billion). Impact Forecasting estimates insured losses (including Japanese Earthquake Reinsurance losses) between JPY2.3 to 3.1 trillion (USD30 to 40 billion).
Introduction

A mega-earthquake and tsunami struck the northeastern coast of Japan on March 11, 2011, killing and injuring thousands of people and causing extensive damage. As of this writing, the death toll was 15,776 and expected to possibly reach 20,000. At least 5,929 others were injured and more than 4,225 people were officially listed as missing. The main magnitude-9.0 earthquake struck at 2:46 PM local time (5:46 UTC) with an epicenter 129 kilometers (80 miles) east of Sendai, Japan and 373 kilometers (231 miles) northeast of Tokyo at a depth of 32 kilometers (19.9 miles). Ground shaking from the temblor reportedly lasted for two full minutes. Following the main tremor, more than 1,235 aftershocks rattled the region with at least 70 shocks registering above magnitude-6.0. The earthquake was felt as far away as Beijing, China – some 2,500 kilometers (1,550 miles) from the epicenter. Scientists noted that the tremor was so strong that it shifted the earth’s rotational axis by 10 centimeters (3.93 inches) and shortened a normal day’s time by at least one-millionth of a second. Japan’s main Honshu Island was also shifted 2.4 meters (7.87 feet) to the east. According to officials, this is the strongest earthquake ever recorded in Japan and tied for the fourth strongest global earthquake recorded since 1900. In the days that followed the earthquake and tsunami, the attention shifted to several nuclear reactor failures in Fukushima and Miyagi prefectures. Japanese Prime Minister Naoto Kan described the aftermath of the earthquake as the “most difficult crisis for Japan” since the end of World War II.

The figure below is a simulated average of ground shaking from Impact Forecasting’s catastrophe model.
Seismological Recap

Tectonic Setting of Japan

Japan and its surrounding regions have endured many destructive earthquakes throughout history; in fact, this area of the globe is responsible for nearly one-tenth of the total annual occurrence of worldwide earthquakes.

The reason for this high seismic activity is that Japan is situated in an area of convergence between various crustal plates as shown in Figure 1. The most notable of these tectonic plates are the Philippine Sea and Pacific plates. The relative motion of these plates with respect to the Eurasian and North American plates (located towards the Northwest) is arrested at the plate boundaries, expressed at the seafloor as the Nankai Trough and Japan Trench. At these boundaries, the sudden release of pent up motion over geological time gives rise to earthquakes.

In the particular case of Japan, both the Pacific and Philippine Sea plates plunge underneath the North American and Eurasian plates, respectively, in a process known as subduction. The boundary between the plates is not a simple segment, but rather is defined as the surface of contact between the overriding and subducted plates. This area of contact is gently dipping and can be dozens of kilometers (miles) in width and hundreds of kilometers (miles) in length. Subduction zone earthquakes, also known as megathrust events, have the potential of rupturing large areas of the plate boundary, and consequently, are amongst the largest magnitude events experienced. Global studies of 19 of the world’s subduction zones indicate that more than 90 percent of the earthquake energy budget is released from large subduction zone earthquakes (with magnitudes more than 8.0) and that occur at depths shallower than 55 kilometers (35 miles). Because of the large magnitude and shallow depth of these tremors, their potential to affect large swaths of populated countries through the resulting ground shaking is great. In addition, by virtue of the fact that thrust events cause an upward motion of the overriding plate, those with large magnitudes invariably trigger tsunamis with potentially destructive wave run-ups not only on nearby, but global, coastal areas. This destructive scenario of ground shaking and tsunami played itself out during the Tohoku event; examples from the recent past include: the 2010 magnitude-8.8 Chile event, and the 2004 magnitude-9.1 Sumatra event.

Figure 1: Tectonics of Japan (Source: http://www.numo.or.jp)
The March 11, 2011 Magnitude-9.0 Tohoku Earthquake

The March 11, 2011 magnitude-9.0 tremor was the largest earthquake event in Japan’s history. It occurred north of the Tokai region, which typically experiences temblors with magnitudes greater than 8.0 every 100 to 150 years. The last major Tokai earthquake struck in 1854. The current event was a shallow thrust event that occurred at a depth of 32 kilometers (19 miles) and 129 kilometers (80 miles) east of Sendai. At the location of this earthquake, the Pacific plate moves towards Japan at about 8 cm/year. The main shock was preceded by foreshocks and there were several large (but smaller) aftershocks that have continued to cause alarm, as well as loss, in Japan in the weeks following the main event. See Figure 3 for a graphical depiction of foreshocks (with magnitudes greater than 4.0) and aftershocks (with magnitudes greater than 5.0) that were officially recorded in the days and weeks before and after the main tremor.

The USGS earthquake rupture model for the Tohoku event (Figure 2) shows displacements as large as 30 to 40 meters (98 to 131 feet) across the fault plane. The total area that experienced slip during the earthquake is approximately 400 kilometers (249 miles) long, parallel to the Japan trench (Northeast-Southwest direction) and 50 kilometers (30 miles) wide, down dip. The star in Figure 2 indicates the point of origin of the earthquake (i.e. hypocenter) from which the rupture propagated both in the northeast and southwest directions in less than 2 minutes to cover the whole rupture area.

Recorded ground motions in Japan reached 3g (where g is the acceleration due to gravity and equal to 980cm/s²) near the eastern coast of Japan closest to the epicenter (Figure 4). These peak ground acceleration values are equivalent to the Japan Meteorological Agency’s (JMA’s) seismicity intensity of 7 – based on a scale of 0 to 7 (Figure 5). An intensity of 7 is defined as: “very severe, can cause collapse of more than 30% of all houses, intense landslides, large fissures in the ground and surface faulting.”
Future Seismic Potential in Japan

On global and geological time scales, plate motions are accommodated on plate boundaries (faults) mainly through violent, episodic movements that we call earthquakes. However, recent scientific studies have pursued the question of whether, on a local scale, the occurrence of a large magnitude event such as the Tohoku earthquake, can influence the spatial distribution of pent up forces caused by plate motions on neighboring faults. This influence could potentially change the expectation of future earthquake occurrence on a fault.

Figure 6 shows preliminary results of this type of analysis for the Tohoku earthquake, and how the movement on the causative fault might have advanced or retarded the occurrence of future earthquakes on known faults in Japan. The notion of advancing or retarding a future event is in reference to the average rate of occurrence as dictated by plate motions. Faults shown in blue in Figure 6 indicate that the Tohoku event most likely accommodated enough of the pent up plate motion so as to have taken up the need for future earthquakes on these. In other words, earthquake occurrence has been retarded. Faults shown in red indicate that, in addition to the stresses accumulating from plate motions, an additional stress has been added by the Tohoku event. The likelihood of future earthquakes on these faults has then been increased.
It is important to note that the ‘stress transfer’ from the Tohoku event is negligible on megathrust earthquakes towards the south where the Philippine plate is being subducted underneath the Eurasian Plate. Historically, the Nankai-Tonankai-Tokai segments of this plate boundary experience earthquakes every 100 – 150 years. All three segments ruptured during earthquakes in 1707 and 1854. Whereas there has been no significant event on the Tokai segment (which is closest to Tokyo), in the last century, the Nankai segment ruptured in a 1946 earthquake and the Tonankai ruptured in a 1944 earthquake.

Figure 6. The figure shows the effects from the Tohoku event on known faults in Japan for two plausible values of fault friction. Faults shown in blue indicate that future earthquake occurrence has potentially been retarded in time, for those shown in red, future earthquake occurrence has potentially been advanced in time. The three offshore faults southwest of the Tohoku fault are known as the Nankai – Tonankai – Tokai segments. Effects from the Tohoku event on these are negligible in terms of changing their expected rate of earthquake rupture. (Source: Shinji Toda (DPRI, Kyoto Univ.), Ross Stein & Volkan Sevilgen (USGS))
Human Casualty Effects

The combination of the earthquake and the resulting tsunami caused a tremendous loss of life. It is expected that the vast majority of the fatalities occurred due to the tsunami quickly coming ashore in Japan after the main temblor. In some locations, the tsunami struck within nine minutes. As noted in the table to the right, the National Police Agency of Japan (NPA) has recovered over 15,700 bodies after many washed back ashore along the coastline or were discovered buried in rubble. In excess of 4,200 people remain listed as missing. The final death toll may never be fully known. See Appendix A for a map of Japan’s prefecture locations.

See the graphic below for an official breakdown of casualties, injuries and missing people by prefecture as supplied by the National Police Agency. The data is accurate as of early-September 2011:

Outside of Japan, single fatalities were recorded in Papua, Indonesia and near Crescent City, California in the United States. Both casualties occurred after each individual was swept out to sea by the strong current.

The event also led to a major loss of wildlife. Tsunami waves reportedly killed 110,000 nesting seabirds at the Midway Atoll National Wildlife Refuge, along with at least 1,000 adult Laysan albatrosses and tens of thousands of albatross chicks after the waves submerged Midway’s reef inlets and Spit Island.
Tsunami Impacts

The most significant effects from this event came not from the earthquake itself, but from the large tsunami that was triggered afterwards. Almost immediately after the main jolt was recorded, the Japan Meteorological Agency (JMA) and the Pacific Tsunami Warning Center (PTWC) both issued tsunami watches and warnings for the nearly all areas bordering along the rim of the Pacific Ocean. Notable warning areas included Japan, Russia, Guam, Taiwan, Philippines, Indonesia, Papua New Guinea, Hawaii, Samoa, Australia, Fiji, Tonga, Mexico, New Zealand, Guatemala, El Salvador, Costa Rica, Nicaragua, Antarctica, Panama, Honduras, Chile, Ecuador, Colombia, Peru and the entire western coasts of the United States and Canada.

Reports from Japan noted that tsunami waves reaching heights in excess of 10 meters (33 feet) swept away hundreds of thousands of homes, boats, cars, buildings and excessive amounts of debris. The waves rushed nearly ten kilometers (six miles) inland in some spots and flattened almost every home, structure, vehicle or vegetation in its path. The JMA recorded large tsunami waves washing ashore along a 2,100-kilometer (1,300-mile) stretch of land from the northern island of Hokkaido to central Wakayama Prefecture. The most significant impacts from the tsunami were felt along a 670-kilometer (420-mile) long stretch of coastline from the towns of Erimo to Oarai.

One of the most affected locations came in Sendai, where a nearly 10-meter (33-foot) wave of water submerged a large part of the city. Media reports indicated that waves of muddy water carried homes, buildings and structures (some of which were on fire) that swept over vast areas of farmland. The tsunami waves later reversed their direction after coming inland and washed debris back out into the ocean. Several large ships were swept away and later crashed into breakwaters.

Overall, the prefectures of Miyagi, Iwate, Fukushima and Ibaraki sustained the brunt of the tsunami damage after multiple towns were almost completely washed away. Some of the towns included: Minamisanriku, Kuji, Ofunato, Onagawa, Natori, Ishinomaki, and Kesennuma (Miyagi Prefecture); Rikuzentakata, Miyako, Ōtsuchi, and Yamada (Iwate Prefecture); and Namie, Sōma and Minamisōma (Fukushima Prefecture). The tsunami was also blamed for triggering dozens of fires after rupturing gas lines and causing explosions. Appendix A provides a detailed map of Japan’s prefecture locations.

See the next page for an Impact Forecasting-generated map showing tsunami inland inundation along the hardest hit coastal locations of Miyagi and Fukushima prefectures. Water from the tsunami rushed several kilometers (miles) inland. See Appendix C for additional tsunami coastal inundation maps.
Map of the areas of Miyagi and Fukushima prefectures, which sustained the brunt of the massive tsunami waves (Source: Impact Forecasting)
See the table below with JMA-measured tsunami wave heights along the northeastern Japan coastline. The JMA later noted that “at some parts, tsunamis may be higher than those observed at the observation sites.” See Appendix D for a list of updated and additional port and coastal tsunami heights.

Note that the earthquake struck at 14:46 JST local time:

<table>
<thead>
<tr>
<th>Recording Station &amp; Time</th>
<th>Wave Heights (meters)</th>
<th>Wave Heights (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:12 JST – Iwate Kamaishi-oki</td>
<td>6.8+</td>
<td>22.3+</td>
</tr>
<tr>
<td>15:15 JST – Ōfunato</td>
<td>3.2+</td>
<td>10.5+</td>
</tr>
<tr>
<td>15:20 JST – Ishinomaki-shi Ayukawa</td>
<td>3.3+</td>
<td>10.8+</td>
</tr>
<tr>
<td>15:21 JST – Miyako</td>
<td>4.0+</td>
<td>13.1+</td>
</tr>
<tr>
<td>15:21 JST – Kamaishi</td>
<td>4.1+</td>
<td>13.5+</td>
</tr>
<tr>
<td>15:44 JST – Erimo-cho Shoya</td>
<td>3.5+</td>
<td>11.5+</td>
</tr>
<tr>
<td>15:50 JST – Soma</td>
<td>7.3+</td>
<td>24.0+</td>
</tr>
<tr>
<td>16:52 JST – Oarai</td>
<td>4.2+</td>
<td>13.8+</td>
</tr>
</tbody>
</table>

In the hours that followed, and the tsunami waves continued to quickly traverse across the open waters of the Pacific Ocean, reports of inundation were recorded in islands within the main ocean basin and later along the outer rim. Tidal rises ranging from 0.5 to 3.5 meters (1.6 to 11.5 feet) were recorded along coastal sections of Russia, Canada, the United States, Mexico and Latin America. However, widespread damage was not prevalent and the impact was modest compared to areas closest to the epicenter.

Areas within the Pacific basin, including the Galapagos Islands and Jayapura, Indonesia, reported coastal home damages to hundreds of dwellings after recorded waves of 3 meters (9.8 feet) came ashore. Along the Pacific Rim, the towns of Crescent City and Santa Cruz in northern California both reported significant damage to local harbors, docks and boats. Total damages in California from the tsunami were listed at more than USD50 million. In Hawaii, the state estimated that more than USD8.5 million in damages to the transportation infrastructure while direct damage to personal property and local businesses was in excess of USD29.9 million. Reports out of Latin America indicated that 300 homes were damaged in the towns of Pueblo Nuevo de Colan and Pisco in Peru, and 200 additional coastal homes were destroyed in Chile.

See below for a table of selected officially measured tsunami wave heights by the PTWC across the Pacific basin: (http://www.ngdc.noaa.gov/nndc/struts/results?EQ_0=5413&t=101650&s=9&d=92,183&nd=display).

<table>
<thead>
<tr>
<th>Recording Station</th>
<th>Wave Heights (meters)</th>
<th>Wave Heights (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crescent City, California, USA</td>
<td>2.47</td>
<td>8.1</td>
</tr>
<tr>
<td>Arica, Chile</td>
<td>2.45</td>
<td>8.0</td>
</tr>
<tr>
<td>Santa Cruz, Galapagos Islands</td>
<td>2.26</td>
<td>7.4</td>
</tr>
<tr>
<td>Port San Luis, California, USA</td>
<td>2.00</td>
<td>6.6</td>
</tr>
<tr>
<td>Kahului, Hawaii, USA</td>
<td>2.00</td>
<td>6.6</td>
</tr>
<tr>
<td>Manzanillo, Mexico</td>
<td>1.70</td>
<td>5.6</td>
</tr>
<tr>
<td>Nuku Hiva, French Polynesia</td>
<td>1.51</td>
<td>4.9</td>
</tr>
<tr>
<td>Winter Harbor, British Columbia, Canada</td>
<td>0.99</td>
<td>3.2</td>
</tr>
<tr>
<td>Owenga Chatham, New Zealand</td>
<td>0.91</td>
<td>2.9</td>
</tr>
</tbody>
</table>
The graphics below illustrate a comparison between the amount of energy released and distributed across the Pacific Ocean by both the magnitude-8.8 earthquake in Chile in 2010 (top), and the magnitude-9.0 earthquake in Japan in 2011 (bottom). The Japan tremor released at least twice as much underwater energy as the Chile tremor.
Property Effects

Both the earthquake and the tsunami caused tremendous damage to personal property across Japan, primarily in areas on Honshu Island. Beyond the ground shaking, fires, liquefaction, flooding and 197 separate landslides also led to the extensive damage. The tsunami caused the majority of the damage, though the earthquake itself also led to tens of thousands of buildings being affected. Well in excess of 500,000 people were left homeless in the wake of the event, not including the 170,000 residents evacuated from their homes due to the nuclear crisis. See the table at right for official property effects (by cause) as provided by the NPA. The data is updated as of late-May 2011.

Although Japan had invested billions of dollars (USD) on anti-tsunami seawalls, some which stand as high as 12 meters (39 feet) in height, the tsunami simply washed over (or even collapsed) the walls at several locations. An estimated 40 percent of the Japanese coastline is currently protected by seawalls. As noted earlier in this report, the most devastating property effects came in Miyagi, Iwate, Fukushima and Ibaraki prefectures, where many of the flattened areas may never be rebuilt. However, areas further south on Honshu Island (including the prefectures of Tochigi, Gunma and Chiba) also sustained various levels of tsunami damage to tens of thousands of dwellings.

Nearly the entire Tohoku region, located to the north of Tokyo, was impacted by both the main tremor and the tsunami. The most significant earthquake shaking damage came in Iwate, Miyagi and Fukushima prefectures, though damage was recorded in most areas on Honshu Island. Besides homes, there were reports that businesses, libraries, schools, hotels and churches were also affected. The Tsukuba Space Center in Ibaraki Prefecture was also damaged and forced to close. In the city of Tokyo itself, damage was largely absent though highrises and skyscrapers shook violently and several windows shattered.

Fire Following Earthquake

In the wake of the main earthquake, tsunami and subsequent aftershocks, there were widespread reports of fires following. According to Japan’s Fire and Disaster Management Agency, there were at least 385 fires reported and responded to after the earthquake and tsunami events occurred. At least 357 fires occurred directly after the March 11th tremor, with 28 additional fires reported in subsequent aftershocks.
However, Japanese officials noted that it was extremely difficult to determine precisely just how many of March 11th fires (primarily caused by ruptured gas lines) were triggered by the earthquake shaking itself or by the tsunami as it washed ashore.

One of the more high profile fire events came in the town of Kesennuma in Miyagi Prefecture, which led to large conflagrations. According to Japanese public broadcaster NHK, the fire(s) began after the tsunami came ashore and caused several large tuna fishing ships to crash into each other. This caused an initial fire. As the successive tsunami waves pushed the on-fire ships further inland, the ships settled within damaged neighborhoods that caused homes to ignite. As these homes burned, it caused additional hot embers to release into the air and spread to other structures. Once firefighters were able to extinguish the blazes, it was determined that a large section of Kesennuma had sustained significant fire damage.

Elsewhere, several large fires were reported at oil refineries (Fukushima, Miyagi and Chiba prefectures), petroleum complexes (Miyagi, Chiba and Kaganawa prefectures), a Japan Coast Guard building (Tokyo Prefecture), city centers (Iwate Prefecture) and residential areas (Chiba, Saitama, Ibaraki, Tokyo, Fukushima, Miyagi and Iwate prefectures).

Following the large aftershocks (magnitudes 7.1 and 6.6) on April 7th and the 11th, there were many fires that were spawned solely by ground shaking. According to NHK, there were 21 separate reports of fires and gas leaks in Miyagi Prefecture (including 18 in the city of Sendai alone). Three additional fires each broke out in Iwate and Ibaraki prefectures, which led to the evacuation of 500 homes.

The table below provides the most recent available data as released by the National Police Agency of Japan and the Fire and Disaster Management Agency as of early-September 2011.

<table>
<thead>
<tr>
<th>Prefecture</th>
<th>Number of Fires</th>
<th>Number of Affected Structures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miyagi</td>
<td>188</td>
<td>135</td>
</tr>
<tr>
<td>Ibaraki</td>
<td>49</td>
<td>37</td>
</tr>
<tr>
<td>Tokyo</td>
<td>35</td>
<td>3</td>
</tr>
<tr>
<td>Iwate</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>Chiba</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Fukushima</td>
<td>15</td>
<td>80</td>
</tr>
<tr>
<td>Saitama</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Kaganawa</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>Aomori</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>Gunma</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Shizouka</td>
<td>1</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Breakdown of Property Damage

As alluded to earlier in this section, the earthquake and tsunami event had a significant impact on homes, buildings and other structures. See below for a graphical representation and breakdown of affected homes and structures by the source of damage. The data is provided by the National Police Agency of Japan and is accurate as of early-September 2011:

Japanese Building Codes

Earthquakes in Japan are more common than they are in the United States and the research on earthquake engineering is one of the most advanced in the world. The combination of good seismic building codes in addition to the high degree of compliance in different areas (especially cities) is responsible for minimal loss of life and property in the areas subject to ground shaking.

Following the Kobe earthquake in 1995, Japan invested significantly in earthquake engineering research. Structures of different size have been designed to resist the shake given the seismic load demand in the area. Buildings have been designed to absorb energy and deform under significant lateral loads. Many of the buildings have designed mechanisms, which reduce the damage by adding damping to the system or base isolation systems to reduce the resonance loads. The base isolation systems are basically large rubber-and-steel pads that are installed at the bottom of a building’s structural base and are essentially hydraulic cylinders that elongate and contract as a building sways. This helps eliminate much of the shake energy. In addition, various low-rise buildings have been mitigated in order to improve their response in relatively large quakes.
Commentary on Property Damage

During the dates of April 10-18, 2011, the Impact Forecasting team performed a reconnaissance to survey various parts of the Tohoku region, focusing on the cities of Mito, Hitachi and the prefectures of Miyagi and Iwate for tsunami damage.

The assessments confirmed what the data from the National Police Agency of Japan and what media reports suggested which was that the large majority of the damage was caused primarily by the tsunami itself. The survey noted that even areas that saw a small and slow-flowing tsunami height (1 to 2 meters (3.3 to 6.6 feet)) sustained severe content losses even without buildings suffering any structural damage. In most of the hardest-hit coastal locations, it was evident that the protection system put into place (i.e. anti-tsunami seawalls) severely underestimated the maximum tsunami potential as waves easily washed over the walls or even washed away the entire wall itself.

The survey also found that structural damage from the main earthquake itself was surprisingly low, given the ground shaking recorded by the JMA (Level 6 or 7). Despite widespread and expensive non-structural and contents damages, this demonstrated the efficiency of properly designed and enforced building codes. The few structurally affected buildings and homes observed during the reconnaissance were all either built prior to 1981 or were non-engineered. However, heavy roofs on traditional houses performed as poorly as to be expected and there were widespread indications of other non-structural damage in buildings (i.e. indoor cracks, infill walls, etc.). It was also determined that soil conditions clearly aggravated the pattern of non-structural damage. In the reconnaissance focus cities, it is estimated that between 30% – 50% of buildings sustained non-structural damage in Mito (often due to liquefaction and soil settlement), 10% in Sendai, and less than 10% in Hitachi.

One of the challenges during the assessment was trying to understand the origin of some of the damages. This was an issue due to the speed at which Japanese officials had begun repairing or covering affected structures.

To view additional photos from the Impact Forecasting on-site trip, please see Appendix E.
Commercial Effects

Widespread damage to commercial facilities was reported as product manufacturing sites were impacted and shipments were forced to stop.

The most widely anticipated global commercial impact from the event was to the automotive industry. It was expected that stoppage in auto production could temporarily reduce output by nearly 500,000 vehicles.

In late-April 2011, the Toyota Motor Corporation reported that domestic car production levels in March plummeted at least 62.7 percent, due to power shortages, general damage to factories and lack of parts supply. In excess of 260,000 vehicles saw production halted, with 60 percent of those vehicles scheduled for shipments to international markets – including the United States. The company was forced to close at least 12 separate plants throughout the country, and production was at its lowest level since 1976.

Honda was also affected by the event, due to several of its plants having been damaged. Automobile and motorcycle production was halted at the following factories: Tochigi R&D Center (Tochigi Prefecture), Sayama Plant at the Saitama Factory (Saitama Prefecture), the Suzuka Factory (Mie Prefecture) and Kumamoto Factory (Kumamoto Prefecture). Both Honda and Nissan (which had six of its plants damaged) saw domestic March production levels decrease by 62.9 and 52.4 percent, respectively. Mazda, Mitsubishi, Subaru and Suzuki also reported temporary suspension of production at all of its Japanese plants as well. General Motors halted production at plants in Spain and Germany due to a lack of Japanese-made parts.

Severe damage to non-vehicle manufacturing facilities also occurred. The Sony Corporation was forced to close several plants. Some of the affected production sites included the Sony Chemical & Information Device Corporation in the town of Tagajyo, where magnetic tapes and Blu-ray discs are manufactured; Tome plant, Nakada/Toyosato sites, where optical devices and IC cards are made; Sony Shiroishi Semiconductor in Miyagi prefecture; Sony Energy Devices Corporation in Koriyama, where lithium-ion secondary batteries are produced; Sony Energy Devices Corporation in Motomiya, which is also a lithium-ion secondary batteries facility; Sony Manufacturing Systems Corporation in Kuki, which makes surface mounting equipment; and Sony DADC Japan in Ibaraki, which makes CDs and DVDs.

Some other commercial impacts were felt by the Nippon Steel Corporation, which was forced to suspend production. Toyo Tire & Rubber Company and Sumitomo Rubber Industries both shuttered their tire and rubber production lines, while GS Yuasa closed its automotive battery production plant. All three of these suspensions were poised to limit supply availability for automakers. Fuji Heavy Industries discontinued production at most of its factories in the Gunma and the Tochigi Prefectures. Other factories suspending operations included Kirin Holdings, GlaxoSmithKline and Nestlé. East Japan Railway Company and Shin-Etsu Chemical were also left vulnerable to limited productivity as a result of the earthquake.
Additional commercial impacts at some notable companies included:

- **Canon**: The company’s plant in Utsunomiya suffered extensive damage, which makes a variety of specialized lenses used in camcorders, office machines and other devices.
- **Fujitsu, Ltd.**: The company, which makes personal computers and home appliances, was forced to indefinitely halt production at 10 separate plants.
- **Hitachi**: Seven factories making products such as elevators, car parts and home appliances were closed. An air-conditioning unit factory in Tochigi Prefecture was operating at reduced hours due to power shortages.
- **Hewlett-Packard Co. (HP)**: The company reported that its Sendai office sustained significant interior damage and was closed indefinitely. The Tokyo office was generally unaffected.
- **Nikon**: The most significant damage occurred at its factory in Sendai, where production stopped on cameras including the D3x, D3s and D700. Also sustaining damage to facilities and/or equipment were group companies, including Sendai Nikon Corporation, Miyagi Nikon Precision, Zao-machi, Katta-gun, Tochigi Nikon Corporation and Tochigi Nikon Precision Co.
- **Panasonic**: Damage and injuries were reported at locations including at its AVC Networks Company in Fukushima (manufacturing digital cameras); AVC Networks Company in Sendai (manufacturing optical pickups); Panasonic Electric Works Co., Ltd. in Koriyama (manufacturing electronic materials); and Sanyo Electric Co., Ltd. in Gunma (manufacturing washer/dryers, etc.).
- **Sharp**: While the company did not report any damage to its factories, its main audiovisual products plant in Tochigi Prefecture was working at reduced hours in an effort to conserve power.
- **Texas Instruments**: Two plants were severely damaged (in Miho and Aizu-wakamatsu) which produced analog chips and digital light processing technology used in televisions and projectors.
- **Toshiba**: There was no immediate damage reported to any of its production facilities, though the company agreed to limit electrical consumption as requested by Tokyo Electric Power Company. This caused temporary delays in some manufacturing plants that produce computer chips used to store data in cameras, smart phones and tablet computers.

Japan is responsible for 14 percent of all global electronic equipment. Japanese makers for certain parts, such as flat screen panels, hold an even larger stake in the supply markets. Sixty percent of the world’s silicon wafers (used in semiconductor chips) are also made in Japan. NAND flash memory, a major storage component for mobile phones and tablets, faced temporary shortages as 40 percent of these chips are Japanese-made. Shortages for electronics such as tablets, smart phones and LCD TV’s may also occur. Some experts noted that it took upwards of six months before the tech supply to begin returning to normal.

In addition to the actual damage caused at commercial facilities, an even more significant hindrance was the extensive damage caused to Japan’s infrastructure. The inability to distribute or ship goods posed a major problem for most large global companies.
Utility Effects

The Tokyo Electric Power Company (TEPCO) and Tohoku Electric Power (TEP) reported that a combined seven million homes were without electricity at the height of the event, including at least four million customers in and around the greater Tokyo metropolitan area.

In the days following the main earthquake, TEPCO, which normally provides approximately 40 GW of electricity, announced that it was only capable of providing 30 GW. The loss of electricity was blamed on the automatic shutdown of the Fukushima Daiichi and Fukushima Daini power plants in the aftermath of the main tremor. Both of those plants normally supplied upwards of 40 percent of Tokyo’s electricity. At the request of the government, TEPCO enacted three-hour blocks of rolling blackouts throughout the prefectures of Tokyo, Kanagawa, Shizuoka, Yamanashi, Chiba, Ibaraki, Saitama, Tochigi, and Gunma. Scheduled blackouts were enacted sporadically throughout the summer of 2011.

Elsewhere in Japan, TEP officials noted that it was unable to provide the Kanto region with additional power, due to power plants also sustaining damage in the earthquake. Kansai Electric Power Company (KEPCO) was incapable of sharing electricity as its systems were operating at a higher level of energy (hertz).

With the damage to so many power plants, it was estimated that it could take years before electricity production returns to pre-quake levels in eastern Japan.

In terms of telecommunications (including landline and mobile phone service), access was significantly minimized as mobile networks were downed and carriers limited the number of allowed calls to avoid further system overloading. NTT Communications in Tokyo reported at the peak of the event that 90 percent of all calls were restricted. It was later determined that several undersea telecommunication cables sustained major damage during the main tremor and the tsunami. Japanese officials noted that remote-controlled robots were being sent 2,500 meters (8,200 feet) to the ocean seabed to repair these damaged cables. With strong aftershocks continuing to occur, the ability to completely repair the cables was expected to take additional months before being fully back online. Internet services were largely unaffected in areas where basic infrastructure remained.

According to TeleGeography (an agency which tracks and plots undersea communications data), there are 20 undersea trans-Pacific and intra-Asia cable systems that reach Japan. Additional telecom companies such as KDDI, Telstra International, Chunghwa Telecom and Pacnet all reported service interruption due to more than 750,000 internet and telephone circuits being downed.
Energy Effects

The energy industry (particularly oil, coal and natural gas) all saw disruptions arise during the event. Port damage led to import and export delays in coal and natural gas, while several oil refineries closest to the epicenter reported damage after multiple sites saw large fires erupt.

The most notable fire came at the Cosmo Oil Company's refinery in Ichihara, Chiba Prefecture (just to the east of Tokyo) which produced 220,000 barrels per day. Japan's largest refiner, JX Nippon Oil & Energy Corporation, saw its refinery in Sendai set ablaze. That site typically produced 145,000 barrels per day. The company also reported that a subsidiary (Kashima Oil Company) had sustained damage to refining and shipping facilities in Ibaraki Prefecture, located to the northeast of Tokyo. JX Nippon Oil's 460,000 ton per year naphtha cracker in Kawasaki, as well as an olefins conversion unit (OCU) at the same site, which produced 140,000 tonnes/year of propylene, was also shut. Additional refineries in Kashima and Negishi were also shut down. ExxonMobil reported that its Japanese subsidiary (Kyokuto Petroleum Industries (KPI)) in Chiba Prefecture was able to restart five days after the earthquake struck. That facility produces 175,000 barrels per day.

At the event's peak, more than 30 percent of Japan's refinery capacity (approximately 1.4 million barrels per day) had been shut down. This caused Japan to sell crude oil that it was not able to process into refined products, and also import products where it was in deficit, such as diesel and gasoline. To make up for the lost productivity, companies eventually ordered production to increase as much as 24 percent at the 22 refineries unaffected by the event.

The vast majority of Japan's oil terminals were closed immediately following the earthquake and tsunami, though all but two oil handling ports (Onahama and Kashima) were reopened. However, Cosmo Oil's terminal at the Port of Chiba remained closed. Several energy companies also reported damage to large cargo ships that were run aground and damaged by the tsunami. The Nippon Yusen Kaisha (NYK) Line reported damage to three of its cargo ships, including one which was in the midst of unloading 70,000 tons of coal at the Port of Soma. Kawasaki Kisen Kaisha (K Line), Mitsui OSK Lines (MOL), Mitsubishi Logistics Corp., Pac Athena and Nisho Kisen all reported ship damage at dozens of ports along Japan's eastern coastline.

Gas prices in Japan quickly rose in the aftermath, with prices reaching and exceeding a level not seen since 2008. Here is a listing of average gas prices (per liter) in the weeks after the event: March 14: JPY148.5 (USD1.80), March 24: JPY151.2 (USD1.83), April 4: JPY162.6 (USD1.97) and April 14: JPY162.6 (USD1.97).

In terms of the liquefied natural gas (LNG) industry, the majority of the available terminals in the region went largely unaffected. However, Japan's Sendai Gas reported that its LNG terminal near the Port of Sendai had been severely damaged and that supplies would be halted for at least one month's time. As the nuclear crisis unfolded, the production and delivery of LNG was enhanced as Japan tried to fill the void of lost energy production.
Nuclear Power Plants

As preliminary assessments were being made following the earthquake and tsunami, much of the focus was shifted to the Fukushima Daiichi nuclear power plant facility.

After the earthquake on March 11\textsuperscript{th}, the facility lost electricity and the back-up generators failed after a recorded 10-meter (32.8-foot) tsunami wave struck Daiichi. This caused the essential cooling systems to shut down and become incapable of cooling the nuclear reactors. On several occasions, plant operators were forced to release radioactive steam from reactor buildings and use large amounts of sea water to help cool the reactors, alleviate pressure and prevent the possibility of a full meltdown.

The first five days after the main jolt proved to be some of the most difficult for Japanese nuclear officials. On March 12\textsuperscript{th}, an initial explosion caused by hydrogen buildup led to the collapse of a concrete outer containment building that housed the plant’s Reactor 1 reactor. However, the integrity of the inner core-containment vessel was not compromised. A second blast occurred at Reactor 3 on March 14\textsuperscript{th} also due to hydrogen buildup. It was later discovered that the fuel rods at Reactor 2 were at one point fully exposed. On March 15\textsuperscript{th}, multiple explosions occurred. The first blast happened again at Reactor 2, while a more dangerous explosion was reported at Reactor 4. For a brief time, all workers from Tokyo Electric Power Company were evacuated after radiation levels became too dangerous for human exposure. It was later determined that four of the plant’s six reactors had seen fires and explosions, all of which led to the leaking of various levels of radioactive steam into the atmosphere.

In the weeks after the event, TEPCO workers laid power grid cabling to all six reactors in hopes of being able to restore electricity to the entire facility and also restart the critical Emergency Core Cooling System and Residual Heat Removal pumps at the reactors. Officials later reported that more damage was done to the facility than previously feared and additional checks and repairs were needed to ensure safety before electricity was powered back on.
The International Atomic Energy Agency (IAEA), after initially rating the event as a Level 4 accident on the International Nuclear and Radiological Event Scale (INES), later upgraded the event to a Level 5 following a submitted report from Japan’s Nuclear and Industrial Safety Agency. On April 12th, the Japanese government reported that further investigation necessitated yet another upgrade to a Level 7 event – which is listed by the IAEA as a “major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures.”

In an effort to provide human safety during the event, the Japanese government issued an evacuation order for all residents living within a 20-kilometer (12-mile) radius of the Fukushima Daiichi nuclear facility. Residents living inside a 30-kilometer (19-mile) radius were asked to remain indoors. The United States government later suggested that its citizens living within an 80-kilometer (50-mile) radius to evacuate for precautionary measures.

According to Japan’s Health Ministry, leakage from the Fukushima complex led to low amounts of radiation being found in vegetables (including spinach, broccoli, canola and chrysanthemum greens), raw milk, the water supply and seawater. Government officials and health experts noted that the measured doses were not anticipated to pose any threat to human health unless consumed in excessive quantities. Officials also ordered increased monitoring of seawater and seafood after elevated levels of radioactive iodine and cesium were found in ocean water near the complex.

It should be noted that officials from the U.S. government reported at the time that there was never a serious threat of nuclear radiation crossing the Pacific Ocean and posing any risk of human health problems in the western United States or any of its island territories. In the weeks after the event, the Environmental Protection Agency reported that many states and territories had recorded very minor traces of radioactivity. Locations included the states of Alaska, Alabama, California, Colorado, Florida, Hawaii, Idaho, Massachusetts, Nevada, North Carolina, Pennsylvania, South Carolina and Washington; and also the territories of Guam, the Northern Mariana Islands and Saipan.

To put the Fukushima Daiichi Level 7 accident into historical context, the only other event in history on par is the 1986 Chernobyl nuclear power plant accident in Ukraine. 1979’s Three Mile Island accident in the United States was listed as a Level 5 event as well.

The IAEA also reported that all other nuclear power plant facilities which were impacted by the earthquake and tsunami (Fukushima Daini, Onagawa, and Tokai nuclear power plants) were listed “in a safe and stable condition” after initially being shut down for thorough inspection. In total, at least 11 of Japan’s 55 nuclear reactors were temporarily shut down following the main earthquake.
Infrastructure Effects

Roads and Highways

Widespread damage was reported throughout the country by the earthquake and tsunami. According to official statistics from the NPA, damage occurred to 3,559 roads and 77 bridges. Approximately four percent of roads in Japan’s north and east were affected. Many sections of the Tohoku Expressway serving northern Japan were severely damaged and all roads out of Tokyo towards quake-damaged areas were closed only for emergency vehicles. The Japanese government reported that initial relief and recovery efforts across northern, central and eastern sections of the country were hampered due to extensive damage to the road and highway network. The damaged roads also led to ground shipment hindrances and delays.

Airports

Several airports throughout Japan were directly impacted or damaged during the event. Sendai Airport was significantly damaged by the tsunami, which saw water and debris submerge its runway, tarmac and taxiways with cars, trucks, buses and thick mud. Floodwaters also reached the second level of the passenger terminal which left electrical equipment, transformers and safety equipment inoperable. At the one-year-old Ibaraki Airport in Omitama City in Ibaraki Prefecture, a large section of the main terminal ceiling collapsed to the ground.

Tokyo’s Narita International Airport and Haneda International Airport were both closed immediately after the earthquake struck, which left a combined 25,000 passengers temporarily stranded. However, there was no reported damage and both airports gradually resumed normal operations.
Railways

Train service throughout Japan was substantially affected both directly and indirectly throughout the entire event. The NPA officially reported that at least 29 railways were damaged or destroyed.

Immediately following the earthquake, the East Japan Railway Company suspended all services after it was determined that four trains on coastal lines lost contact with operators. It was later determined that one train on the Senseki Line had derailed (see the picture on the left). There were no derailments on any of the Shinkansen bullet train services in and out of Tokyo, though service was suspended. In the hours after the main jolt, the Tōkaidō Shinkansen resumed limited service and returned to its normal schedule by the next day. The Jōetsu and Nagano Shinkansen resumed services the day after as well. However, the Tohoku Shinkansen was suspended for several days after visible damage was noted to electrical poles and elevated power lines. Minami-Kesennuma Station on the Kesennuma Line was destroyed (outside of its platform). Severe damage was also reported along other coastal lines including the Ishinomaki Line and Senseki Line.

As the Fukushima Daiichi nuclear power plant situation grew more severe, Japan’s Land, Infrastructure, Transport and Tourism Ministry asked railway operators serving Tokyo to reduce the number of trains in and out of the city. TEPCO later began rolling blackouts in the Kanto region which led to profound effects to Tokyo rail networks. Major railway operators (including East Japan Railway Company and Tokyo Metro Company) significantly cut back transit operation, while others were completely shut down during the first week after the earthquake struck. The Tokaido Main Line, Yokosuka Line, Sobu Main Line and Chūō-Sōbu Line were all lines that were forced to stop.

The loss of railway transportation led to near travel paralysis within the capital, with many people unable to come to work or get home. Railway operation gradually increased capacity to 80 percent in the weeks that followed.

Ports

The tsunami caused substantial damage to Japanese ports along parts of the northeast coastline. The ports of Hachinohe, Sendai, Ishinomaki and Onahama were damaged so severely that they were not expected to return to operation for months, or possibly years. The Port of Hachinohe supplied fuel products to the local fishing fleet and United States military installations in Japan and South Korea. The Port of Sendai handled a range of goods including rubber products, paper and machinery.

Other damaged ports included Kashima, Hitachinaka, Hitachi, Soma, Shiogama, Kesennuma, Ofunato, Kamashi and Miyako. These ports primarily handled products including sugar, non-ferrous metals, cars and wood products.
The affected ports handled as much as seven percent of the country's entire industrial output, and it was expected for global supply chains to be disrupted. The box shipping industry was most notably affected, as the destroyed ports handled containerized cargo for dozens of companies including Hitachi, Ltd. and Daikin Industries. These disruptions likely caused billions of dollars in losses (USD). Published reports indicated that the brief closure of all of Japan's ports was expected to cost the country more than JPY275 billion (USD3.4 billion) in lost seaborne trade per day. Maritime trade in Japan totaled JPY121 trillion (USD1.5 trillion) in 2010.

It should be noted that the Port of Tokyo suffered only minor damage. The port reported a small fire at an on-site building and some areas being flooded. Ports to the south of Tokyo were only minimally affected, and were operating normally after a brief shut down of operations.

Dams

There were 45 reports of dam failures, all in Miyagi Prefecture. The most notable failure occurred at the Fujinuma irrigation dam in Sukagawa, which led to floods that washed away homes. At least four fatalities were blamed on the dam failure. Japanese officials inspected 252 other dams across the country and discovered that six embankment dams had shallow cracks on their crests. A reservoir at one concrete gravity dam suffered a small non-serious slope failure. All damaged dams were listed as functioning with no major problems.
Economic Impacts

In the days, weeks and months that followed, the true economic impact from the Tohoku earthquake and tsunami event began to slowly come into focus. As of this writing, the Japanese government noted that total economic losses were anticipated to range between JPY16.2 to 25.3 trillion (USD198 to 309 billion). It was later reported that during the first quarter of 2011, Japan’s GDP contracted 3.5 percent.

Impact Forecasting estimates that total insured losses from the earthquake and tsunami event (including Japanese Earthquake Reinsurance losses) will range between JPY2.3 to 3.1 trillion (USD30 to 40 billion).

Below are some selected insured losses by breakout, including:

- Personal: USD20 billion
- Commercial and Industrial: USD8 billion
- Specialty (Marine, Aviation, Energy): USD1 billion
Appendix

Appendix A: Regions and Prefectures of Japan

(Source: Impact Forecasting)
Appendix B: Lists of historical earthquakes since 1900

The table below lists the strongest earthquakes, by magnitude, since 1900:

<table>
<thead>
<tr>
<th>Date</th>
<th>Closest Epicenter Location</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 22, 1960</td>
<td>Valdiva, Chile</td>
<td>9.5</td>
</tr>
<tr>
<td>March 27, 1964</td>
<td>Prince William Sound, Alaska, USA</td>
<td>9.2</td>
</tr>
<tr>
<td>December 26, 2004</td>
<td>Sumatra, Indonesia</td>
<td>9.1</td>
</tr>
<tr>
<td>March 11, 2011</td>
<td>Tohoku region, Japan</td>
<td>9.0</td>
</tr>
<tr>
<td>November 4, 1952</td>
<td>Kamchatka, Russia (then USSR)</td>
<td>9.0</td>
</tr>
<tr>
<td>February 27, 2010</td>
<td>Maule, Chile</td>
<td>8.8</td>
</tr>
<tr>
<td>January 31, 1906</td>
<td>Esmeraldas, Ecuador</td>
<td>8.8</td>
</tr>
</tbody>
</table>

The table below lists notable earthquake events with 10,000 or more deaths since 1900:

<table>
<thead>
<tr>
<th>Date</th>
<th>Closest Epicenter Location</th>
<th>Deaths</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 27, 1976</td>
<td>Tangshan, China</td>
<td>255,000</td>
<td>7.5</td>
</tr>
<tr>
<td>December 26, 2004</td>
<td>Sumatra, Indonesia</td>
<td>227,898</td>
<td>9.1</td>
</tr>
<tr>
<td>January 12, 2010</td>
<td>Haiti</td>
<td>222,000</td>
<td>7.0</td>
</tr>
<tr>
<td>December 16, 1920</td>
<td>Haiyuan, Ningxia (Ning-hsia), China</td>
<td>200,000</td>
<td>7.8</td>
</tr>
<tr>
<td>September 1, 1923</td>
<td>Kanto (Kwanto), Japan</td>
<td>142,800</td>
<td>7.9</td>
</tr>
<tr>
<td>October 5, 1948</td>
<td>Ashgabat, Turkmenistan (Turkmeniya, USSR)</td>
<td>110,000</td>
<td>7.3</td>
</tr>
<tr>
<td>May 12, 2008</td>
<td>Eastern Sichuan, China</td>
<td>87,587</td>
<td>7.9</td>
</tr>
<tr>
<td>October 8, 2005</td>
<td>Pakistan</td>
<td>86,000</td>
<td>7.6</td>
</tr>
<tr>
<td>December 28, 1908</td>
<td>Messina, Italy</td>
<td>72,000</td>
<td>7.2</td>
</tr>
<tr>
<td>May 31, 1970</td>
<td>Chimbote, Peru</td>
<td>70,000</td>
<td>7.9</td>
</tr>
<tr>
<td>December 26, 1939</td>
<td>Erzincan, Turkey</td>
<td>32,700</td>
<td>7.8</td>
</tr>
<tr>
<td>January 13, 1915</td>
<td>Avezzano, Italy</td>
<td>32,610</td>
<td>7.0</td>
</tr>
<tr>
<td>December 26, 2003</td>
<td>Southeastern Iran</td>
<td>31,000</td>
<td>6.6</td>
</tr>
<tr>
<td>January 25, 1939</td>
<td>Chillan, Chile</td>
<td>28,000</td>
<td>7.8</td>
</tr>
<tr>
<td>December 7, 1988</td>
<td>Spitak, Armenia</td>
<td>25,000</td>
<td>6.8</td>
</tr>
<tr>
<td>March 11, 2011</td>
<td>Tohoku region, Japan</td>
<td>~20,000</td>
<td>9.0</td>
</tr>
<tr>
<td>April 4, 1905</td>
<td>Kangra, India</td>
<td>19,000</td>
<td>7.5</td>
</tr>
<tr>
<td>August 17, 1999</td>
<td>Turkey</td>
<td>17,118</td>
<td>7.6</td>
</tr>
</tbody>
</table>
Appendix C: Additional Japan tsunami inland inundation maps

Tsunami flood inundation along parts of coastal Miyagi Prefecture (Source: Impact Forecasting)

Tsunami flood inundation along parts of coastal Iwate Prefecture (Source: Impact Forecasting)
Appendix D: Additional recorded Japan tsunami wave heights

Note that the information below is from separate official reports released by the Pacific Tsunami Warning Center, the Port and Airport Research Institute of Japan and the University of Tokyo. The data includes both recorded and approximate tsunami heights.

<table>
<thead>
<tr>
<th>Recording Station/Location</th>
<th>Wave Heights (meters)</th>
<th>Wave Heights (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miyako</td>
<td>37.9</td>
<td>124.3</td>
</tr>
<tr>
<td>Ōfunato</td>
<td>24.0</td>
<td>78.7</td>
</tr>
<tr>
<td>Port of Onagawa</td>
<td>15.0</td>
<td>49.2</td>
</tr>
<tr>
<td>Minami Sanriku</td>
<td>13.0</td>
<td>42.7</td>
</tr>
<tr>
<td>Sendai Airport area</td>
<td>12.0</td>
<td>39.3</td>
</tr>
<tr>
<td>Port of Ōfunato</td>
<td>9.5</td>
<td>31.1</td>
</tr>
<tr>
<td>Port of Hachinohe</td>
<td>8 to 9</td>
<td>26.2 to 29.5</td>
</tr>
<tr>
<td>Port of Kuji</td>
<td>8 to 9</td>
<td>26.2 to 29.5</td>
</tr>
<tr>
<td>Port of Kamaishi</td>
<td>7 to 9</td>
<td>22.9 to 29.5</td>
</tr>
<tr>
<td>Sendai section of the Shiogama-Sendai port</td>
<td>8.0</td>
<td>26.2</td>
</tr>
<tr>
<td>Port of Ishinomaki</td>
<td>5.0</td>
<td>16.4</td>
</tr>
<tr>
<td>Shiogama section of the Shiogama-Sendai port</td>
<td>4.0</td>
<td>13.1</td>
</tr>
</tbody>
</table>

It should be noted that the Port and Airport Research Institute conducted a study and concluded that offshore run-up heights included:

- 6.2 meters (20.3 feet) offshore of central Iwate Prefecture near the town of Miyako
- 6.6 meters (21.6 feet) offshore of southern Iwate Prefecture near the town of Kamaishi
- 5.6 meters (18.3 feet) offshore of northern Miyagi Prefecture

The study was conducted using global positioning system (GPS) and measuring instruments.
Ground floor office in Tagajo after the tsunami receded. Maximum water level in the room was about one meter (3.3 feet), causing total devastation. (Source: Impact Forecasting)

The city of Natori, close to the fishing harbor, looking inland. The graveyard in the back had just been overtopped by the tsunami. Intact houses have been uprooted from their loose foundations by the fast-moving tsunami and moved up to two kilometers (one-mile) inland. (Source: Impact Forecasting)
Typical ‘short-column failure’ in the upper floor of an old school building in Mito. This indicates strong shaking. (Source: Impact Forecasting)

An example of liquefaction. (Source: Impact Forecasting)
Complete devastation in Onagawa. Note the different degree of damage in the different stories. (Source: Impact Forecasting)

A small wooden house uprooted and disposed on top of the concrete building by the receding tsunami in Onagawa. The watermark at the building indicates the maximum water level. (Source: Impact Forecasting)
## Appendix F: Glossary of earthquake and tsunami terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aftershock</td>
<td>Aftershocks are earthquakes that follow the largest shock of an earthquake sequence. They are smaller than the mainshock and within 1-2 rupture lengths distance from the mainshock. Aftershocks can continue over a period of weeks, months, or years. In general, the larger the mainshock, the larger and more numerous the aftershocks, and the longer they will continue.</td>
</tr>
<tr>
<td>Epicenter</td>
<td>The epicenter is the point on the earth's surface vertically above the hypocenter (or focus), point in the crust where a seismic rupture begins.</td>
</tr>
<tr>
<td>Focal Depth</td>
<td>The focal depth refers to the depth of an earthquake hypocenter.</td>
</tr>
<tr>
<td>Hypocenter</td>
<td>The hypocenter is the point within the earth where an earthquake rupture starts. The epicenter is the point directly above it at the surface of the Earth. Also commonly termed the focus.</td>
</tr>
<tr>
<td>JMA Seismic Intensity Scale</td>
<td>A seismic scale used in Japan and Taiwan to measure the strength of earthquakes. Unlike the moment magnitude scale (which measures the total magnitude of the earthquake, and represents the size of the earthquake with a single number) the JMA scale describes the degree of shaking at a point on the Earth's surface.</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>A process by which water-saturated sediment temporarily loses strength and acts as a fluid, like when you wiggle your toes in the wet sand near the water at the beach. This effect can be caused by earthquake shaking.</td>
</tr>
<tr>
<td>Modified Mercalli Intensity</td>
<td>The Mercalli intensity scale is a scale used for measuring the intensity of an earthquake. The scale quantifies the effects of an earthquake on the Earth's surface, humans, objects of nature, and man-made structures on a scale of I through XII, with I denoting not felt, and XII total destruction. The values will differ based on the distance to the earthquake, with the highest intensities being around the epicenter. Data is gathered from individuals who have experienced the quake, and an intensity value will be given to their location.</td>
</tr>
<tr>
<td>Moment Magnitude</td>
<td>The magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (ML), commonly referred to as “Richter magnitude,” (2) surface-wave magnitude (Ms), (3) body-wave magnitude (Mb), and (4) moment magnitude (Mw). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (Mw) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales should yield approximately the same value for any given earthquake.</td>
</tr>
<tr>
<td>Normal (Dip-slip) Fault</td>
<td>Dip-slip faults are inclined fractures where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed normal, whereas if the rock above the fault moves up, the fault is termed reverse.</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Peak Ground Acceleration (PGA)</td>
<td>During an earthquake when the ground is shaking, it experiences acceleration (changing from one speed to another). The peak ground acceleration is the largest acceleration recorded by a particular measuring station during an earthquake.</td>
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<tr>
<td>Seismic Moment</td>
<td>The seismic moment is a measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the force that was required to overcome the friction sticking the rocks together that were offset by faulting. Seismic moment can also be calculated from the amplitude spectra of seismic waves.</td>
</tr>
<tr>
<td>Seismograph</td>
<td>A seismograph, or seismometer, is an instrument used to detect and record earthquakes. Generally, it consists of a mass attached to a fixed base. During an earthquake, the base moves and the mass does not. The motion of the base with respect to the mass is commonly transformed into an electrical voltage. The electrical voltage is recorded on paper, magnetic tape, or another recording medium. This record is proportional to the motion of the seismometer mass relative to the earth, but it can be mathematically converted to a record of the absolute motion of the ground. Seismograph generally refers to the seismometer and its recording device as a single unit.</td>
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<tr>
<td>Slip</td>
<td>Slip is the relative displacement of formerly adjacent points on opposite sides of a fault, measured on the fault surface.</td>
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<tr>
<td>Strike-Slip Fault</td>
<td>Strike-slip faults are vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral.</td>
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<tr>
<td>Thrust Fault</td>
<td>A thrust fault is a reverse fault with a dip of 45 degrees or less. Oblique-slip faults have significant components of different slip styles.</td>
</tr>
<tr>
<td>Tsunami</td>
<td>Tsunamis are ocean waves produced by earthquakes or underwater landslides. The word is Japanese and means &quot;harbor wave,&quot; because of the devastating effects these waves have had on low-lying Japanese coastal communities. Tsunamis are often incorrectly referred to as tidal waves, but a tsunami is actually a series of waves that can travel at speeds averaging 450 to 600 mph (725 to 965 kph) in the open ocean.</td>
</tr>
<tr>
<td>Tsunami Watch</td>
<td>An alert issued to areas outside the warned area. The area included in the watch is based on the magnitude of the earthquake. For earthquakes over magnitude 7.0, the watch area is 1 hour tsunami travel time outside the warning zone. For all earthquakes over magnitude 7.5, the watch area is 3 hours tsunami travel time outside the warning zone. The watch will either be upgraded to a warning in subsequent bulletins or will be cancelled depending on the severity of the tsunami.</td>
</tr>
<tr>
<td>Tsunami Warning</td>
<td>Indicates that a tsunami is imminent and that coastal locations in the warned area should prepare for flooding. The initial warning is typically based on seismic information alone. Earthquakes over magnitude 7.0 trigger a warning covering the coastal regions within 2 hours tsunami travel time from the epicenter. When the magnitude is over 7.5, the warned area is increased to 3 hours tsunami travel time. As water level data showing the tsunami is recorded, the warning will either be cancelled, restricted, expanded incrementally, or expanded in the event of a major tsunami.</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>Unreinforced Masonry</td>
<td>A description of the construction type of a building where walls or other structures are made of masonry (brick, cinderblock, tiles, adobe or other masonry material) which is not braced by (steel) reinforcing beams.</td>
</tr>
</tbody>
</table>
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