

Learning from Earthquakes

The Japan Tohoku Tsunami of March 11, 2011

This report summarizes the field reconnaissance observations of the EERI team led by Lori Dengler, Humboldt State University, and Megumi Sugimoto, Earthquake Research Institute, University of Tokyo, who visited the hardest-hit areas of Miyagi and Iwate Prefectures in April and May 2011. It also includes observations from two International Tsunami Survey Teams (ITSTs) deployed to study tsunami deposits. The first team visited the Sendai area in May and was made up of Kazuhisa Goto, Chiba Institute of Technology; Shigehiro Fujino, University of Tsukuba; Wittek Szczuciski, Adam Mickiewicz University, Poland; Yuichi Nishimura, Hokkaido University; Daisuke Sugawara, Tohoku University; Eko Yulianto, Indonesian Institute of Science; Rob Witter, Oregon Department of Geology and Mineral Industries; Catherine Chagué-Goff, University of New South Wales, Australia; Masaki Yamada, University of Tsukuba; Dave Tappin, British Geological Survey; Bruce Richmond, U.S. Geological Survey (USGS); and Bruce Jaffe, USGS. In August, Rick Wilson, California Geological Survey; Robert Weiss, Virginia Tech University; James Goff, University of New South Wales, Australia; and Yong Wei, NOAA Pacific Marine Environmental Laboratory, joined Nishimura, Sugawara, Goto, Fujino and Jaffe from the first ITST, and revisited Sendai as well as the Kuji and the Miyako areas in Iwate Prefecture. Also included here is information compiled by Masahiro Yamamoto for UNESCO's International Oceanographic Commission (IOC) and material from other field and government reports, as noted in the text. This report focuses on the tsunami impacts in Miyagi and Iwate Prefectures; it does not cover

Fukushima Prefecture because high radiation levels from the damaged Fukushima Dai-Ichi nuclear power plant have prevented field teams from working there. Much of the information in this preliminary report may change as more data and reports are released.

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Introduction

The M_w 9.0 earthquake produced a great tsunami that killed nearly 20,000 people and wreaked destruction along the Tohoku (eastern) coast of Japan. The tsunami traveled across the Pacific basin, triggering evacuations and causing some damage in many countries; one person was killed in California. The earthquake struck at 2:46 p.m. local time in Japan, and the shaking lasted for about three minutes (USGS, 2011). Located on the subduction zone interface off the coast of the Tohoku Region, it ruptured a 300 km-long fault extending from near the southern end of Ibaraki Prefecture to central Iwate Prefecture (Figure 1). It was the largest magnitude earthquake recorded in Japan in historic time, and the combined impacts of the earthquake and tsunami left 15,749 dead and 3,962 missing (IOC/UNESCO, 2011). Associated economic losses may approach

US\$300 billion, making it the most costly natural disaster of all time (VoA, 2011).

There is no question that the tsunami was responsible for the huge scale of the catastrophe. A preliminary report released in April 2011 summarizing autopsy results showed 92% of the victims died as a result of drowning (SEEDS Asia, 2011). If it is assumed that most of the missing were washed to sea or deposited in accessible areas by the tsunami, the tsunami casualty contribution increases to over 96%.

This report summarizes field reconnaissance efforts and reports, emphasizing factors that exacerbated impacts; it considers factors that promoted or hindered successful evacuation. Refer to the companion LFE report, *The Japan Tohoku Tsunami of March 11, 2011: Effects*

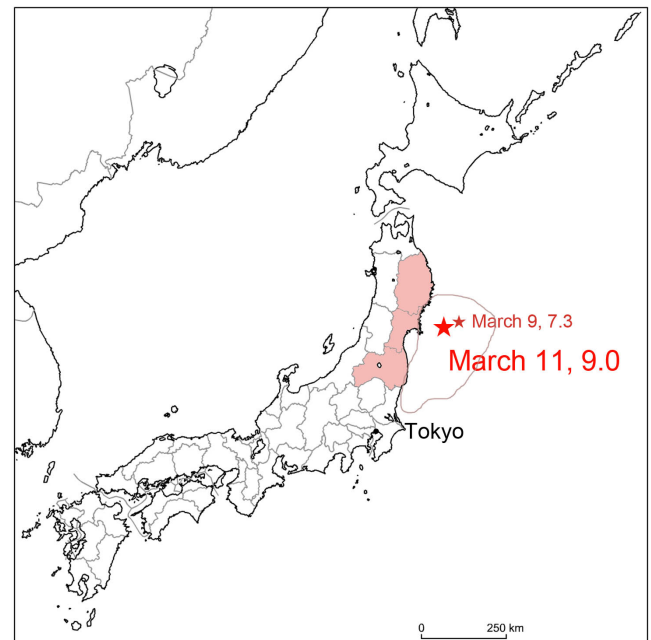
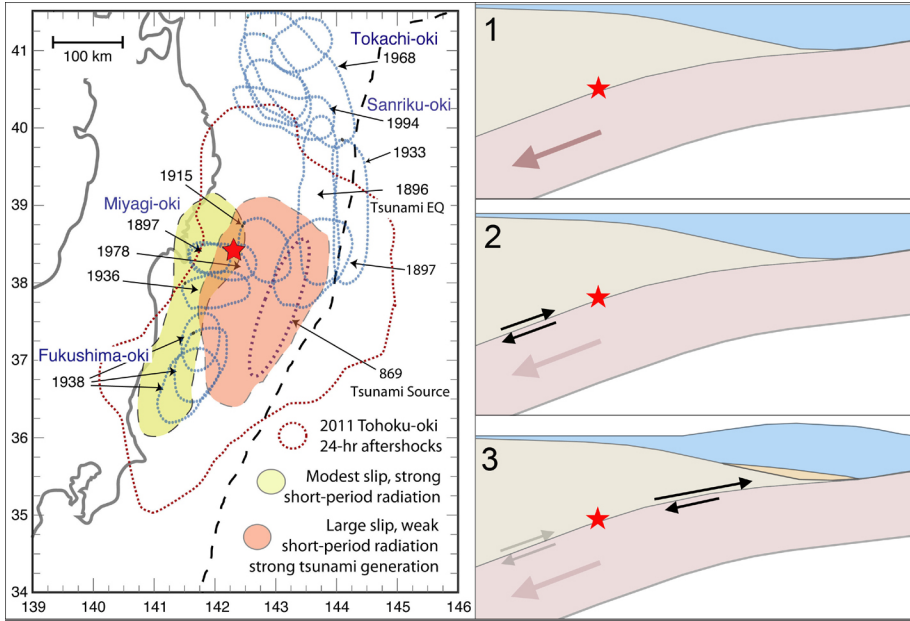


Figure 1. Location map of the March 11 main shock and March 9 foreshock. Outlined area shows the approximate source dimensions (after Kanamori, 2011). The three shaded prefectures, Iwate, Miyagi, and Fukushima, were the most affected by the tsunami (USGS, 2011).



yellow area) and was characterized by normal rupture velocities and moderate slip (Kanamori, 2011). It produced strong ground shaking in much of the Tohoku region. After about 75 seconds, the rupture moved updip of the hypocenter into the much weaker rocks of the megathrust accretionary prism. This rupture (Figure 2, pink area) was characteristic of a “tsunami earthquake”: relatively slow rupture velocity with weak ground shaking and very large slip. Some models (Ozawa et al., 2011; Pollitz et al., 2011) suggest the peak slip may have exceeded 50 m in some areas of this zone. This second phase of the earthquake likely accounted for the majority of the tsunami generation.

Elastic rebound associated with the rupture produced permanent changes in the land surface. Japan’s dense network of GPS instruments documented both hori-

on Structures, by the ASCE/EERI team, for an overview of impacts on the built environment in Japan.

The Tsunami Source

The March 11 earthquake ruptured an area roughly 300 km long and 200 km wide on the boundary between the subducting Pacific plate and the overriding North American plate (USGS, 2011). This region of Japan has a well-documented history of earthquakes, including at least 32 ranging from 7 to mid-magnitude 8 since 1900 (NGDC, 2011). The Tohoku sequence began on March 9 with a magnitude 7.3 earthquake that was widely felt. The Japan Meteorological Agency (JMA) issued a tsunami warning for the Miyagi and Iwate coasts, projecting water heights of 3 m. Tide gauges recorded a 0.5-m tsunami in Ofunato, but no damage was reported. The main shock initiated about 43 km WSW of the March 9 foreshock. The initial zone of rupture was down-dip of the hypocenter (Figure 2,

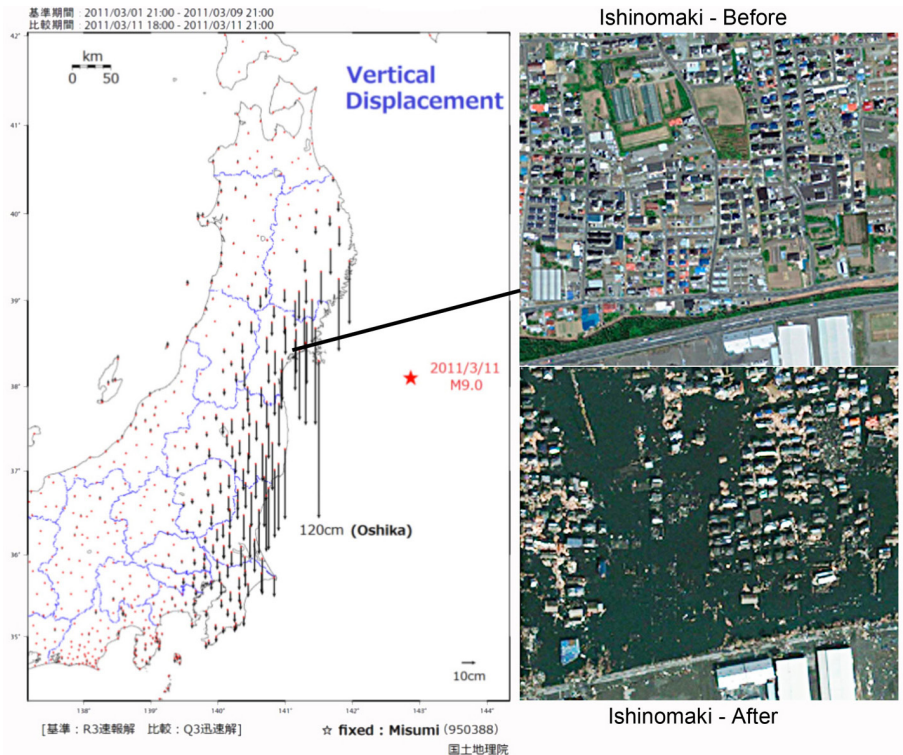


Figure 3. Left: vertical displacement field of the Tohoku earthquake from GPS measurements provided by the Geospatial Institute of Japan (2011). All coastal areas from Iwate to Chiba subsided during the earthquake. In this preliminary map, the peak vertical displacement (1.2 m) was in the Oshika district of Miyagi Prefecture near Onagawa City. Right: Google Earth images taken before and after the earthquake show the impacts of subsidence at Ishinomaki.

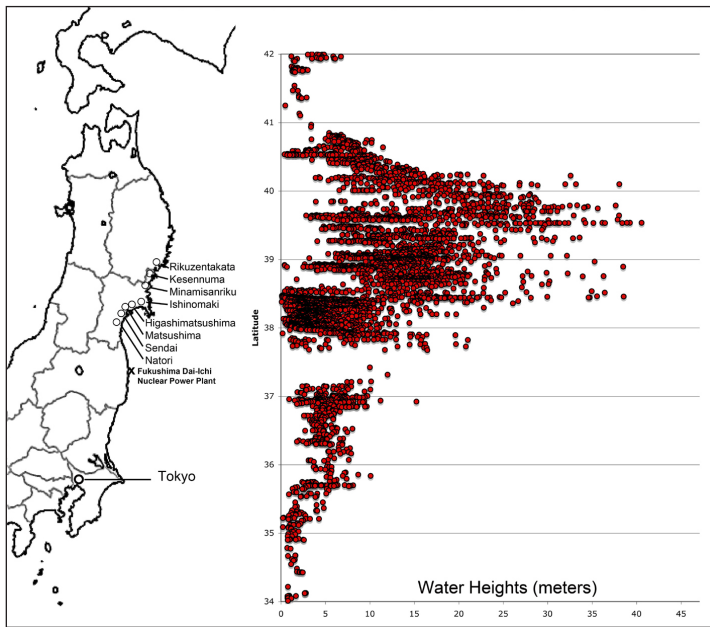


Figure 4. Measured tsunami water heights as a function of latitude from post-tsunami surveys, as compiled by the NGDC (2011). The gap in measurement in Fukushima Prefecture is due to access restrictions associated with the Fukushima Dai-ichi nuclear power plant (shown by the x).

Miyagi prefectures. On the broad plain that characterizes the coast of Miyagi Prefecture south of Sendai, peak water heights averaged 8-10 m. There were significant tsunami impacts as far south as Chiba Prefecture.

Table 1 summarizes the characteristics of the tsunami at selected locations along the Tohoku coast, with data from IOC/UNESCO bulletins (2011), the NGDC, and Mori et al., 2011. Although peak water heights are higher in Iwate and northern Miyagi Prefectures, the inundation areas are smaller, as the coast is rugged and inundation is limited to the low areas near river mouths. In most coastal communities, the

zontal and vertical changes (Gräpenthin and Freymueller, 2011). There was subsidence along the Tohoku coast after the earthquake, with some areas dropping down more than a meter (Figure 3a). As a result, some low-lying areas are now below sea level (Figure 3b) and parts of the region are more susceptible to tsunami inundation.

The Tsunami in Japan

Over 5,400 water level measurements have been collected along 2,000 km of the Japanese coastline as of the time of this report (Tohoku Earthquake Tsunami Joint Survey Group, 2011), making this the largest collection of tsunami height measurements for a single tsunami event. The data have been summarized in reports of the IOC/UNESCO intergovernmental commission on tsunamis (2011) and have also been posted at NOAA's National Geophysical Data Center (NGDC) Tsunami Data Base (2011). Figure 4 shows the NGDC water height compilation. The highest water levels (38.9 m) at Aneyoshi Bay south of Miyako City in Iwate Prefecture were the maximum ever measured in a Japan tsunami. Water heights were close to or exceeded 20 m in most populated coastal communities in Iwate and northern

Table 1. Tsunami Characteristics and Impacts at Selected Locations

| City/Town | Exposed Population | Deaths & Missing | % Casualty | Peak Water Height | Total Area | Inundation Area (km ²) | % inundated | Arrival time (minutes) |
|------------------------|--------------------|------------------|------------|-------------------|------------|------------------------------------|-------------|------------------------|
| Hachinohe | 2733 | 0 | 0.00 | 2.7 | | | | 36 |
| Hirono Town | 7171 | 0 | 0.00 | 5.5 | 303 | 1 | 0.33 | |
| Kuji City | 3177 | 4 | 0.13 | 18.6 | 623 | 4 | 0.64 | |
| Noda Village | 1115 | 38 | 3.41 | 17 | 81 | 2 | 2.47 | |
| Fudai Village | 1582 | 1 | 0.06 | 28 | 50 | 0.5 | 1.00 | |
| Iwaizumi Town | 1137 | 7 | 0.62 | 6.8 | 993 | 1 | 0.10 | |
| Miyako City | 18378 | 541 | 2.94 | 37.88 | 1260 | 9 | 0.71 | 31 |
| Yamada Town | 11418 | 815 | 7.14 | 10 | 263 | 4 | 1.52 | |
| Otsuchi Town | 11915 | 1378 | 11.57 | 19 | 201 | 4 | 1.99 | |
| Kamaishi City | 13164 | 1082 | 8.22 | 9 | 441 | 7 | 1.59 | 35 |
| Ofunato City | 19073 | 446 | 2.34 | 23.6 | 323 | 6 | 1.86 | 24 |
| Rikuzentakata City | 16640 | 1939 | 11.65 | 19 | 232 | 9 | 3.88 | 20 |
| Kesenuma City | 40331 | 1406 | 3.49 | 22.2 | 333 | 15 | 4.50 | 20 |
| Minamisanriku Town | 14389 | 901 | 6.26 | 15.5 | 164 | 7 | 4.27 | 25 |
| Ishinomaki City | 112276 | 3890 | 3.46 | 16 | 556 | 7 | 1.26 | |
| Onagawa Town | 8048 | 914 | 11.36 | 18.4 | | | | |
| Higashimatsushima City | 34014 | 1138 | 3.35 | 10.4 | 102 | 36 | 35.29 | |
| Matsushima Town | 4053 | 2 | 0.05 | 2.4 | 54 | 2 | 3.70 | |
| Shiogama City | 18718 | 21 | 0.11 | 4 | 18 | 5 | 27.78 | |
| Shichigahama Town | 9149 | 75 | 0.82 | 10 | 13 | 6 | 46.15 | |
| Tagaiyo City | 17144 | 189 | 1.10 | 7 | 20 | 6 | 30.00 | |
| Sendai City | 29962 | 730 | 2.44 | 9.9 | | | | 65 |
| Sendai-Miyagino | 17375 | * | | | 58 | 20 | 34.48 | |
| Sendai-Wakabayashi | 9386 | * | | 9.4 | 48 | 29 | 60.42 | |
| Sendai-Taihaku | 3201 | * | | | 228 | 3 | 1.32 | |
| Natori City | 12155 | 982 | 8.08 | 12 | 100 | 27 | 27.00 | 74 |
| Iwanuma City | 8051 | 183 | 2.27 | 7.6 | 61 | 29 | 47.54 | |
| Watarai Town | 14080 | 270 | 1.92 | 8 | 75 | 35 | 46.67 | |
| Yamamoto Town | 8990 | 690 | 7.68 | 5 | 64 | 24 | 37.50 | |
| Shinchi Town | 4666 | 110 | 2.36 | 7.9 | 46 | 11 | 23.91 | |
| Soma City | 10436 | 459 | 4.40 | 8 | 198 | 29 | 14.65 | |
| Minamisoma City | 13377 | 663 | 4.96 | 4.5 | 399 | 27 | 6.77 | |

* Totals included in the Sendai numbers (source: summarized from IOC/UNESCO bulletins).



Figure 5. *Tsunami evacuation building, Rikuzentakata. Measured water levels were 19 m, shown by the yellow arrow (photos: L. Dengler).*

dense city and town centers were very vulnerable, though much of the town or city land area was outside of the inundation zone on the hill slopes and farther inland. Communities on the low-lying areas of the Sendai plain, such as Wakabayashi and Yuriage in Natori City, had little higher ground, and a larger percentage of these communities was flooded.

The amount of time between the earthquake and the arrival of significant surges varied along the Tohoku coast. The tide gauges show the first tsunami wave arriving 36 minutes after the earthquake at Hachinohe and 29 minutes post-quake in Okai Town in Chiba Prefecture. A webcam at the Sendai Airport in Natori City showed water arriving at 3:37 p.m., and the generators ceased to function at 4 p.m. This agrees with a series of time-stamped photographs in the Yuriage area of Natori City (see Figure 17) that show peak flooding at 4:11 p.m. Generators at the Fukushima Dai-ichi Nuclear Plant stopped at 3:41 p.m., 55 minutes after the earthquake. Eyewitnesses in Northern Miyagi and Southern Iwate Prefectures generally reported 25-30 minutes between the earthquake and the tsunami. A time-stamped photo taken from the top of the Minami-

sanriku Disaster Management Building shows the structure fully engulfed at 3:35 p.m., 48 minutes after the earthquake. Analysis of the voluminous set of photographs and video imagery taken of the tsunami, and more detailed study of tide gauge recordings, should provide better constraints on the time of arrival.

The impact of the tsunami on populated areas of the Tohoku coast was strongly dependent upon the local setting. There are factors unique to each setting, and the following brief descriptions illustrate many of them.

Rikuzentakata City (population 23,000) is located at the mouth of

the Kesen River in southern Iwate Prefecture. The tsunami reached heights of 19 meters, reaching the fifth floor elevation in much of the central part of the city, destroying all structures in this area except for two large reinforced concrete buildings: the seven-story Capital Hotel and the adjacent tsunami evacuation building (Figure 5). The evacuation building featured a unique design, with exterior stairs leading up to a series of concrete seat platforms. The structure survived even though water heights exceeded the design tsunami, and only the two or three uppermost rows were above the water height and provided life safety.

Rikuzentakata was typical of many cities in the Tohoku region where forests of pine trees had been planted along the coast to provide protection from both storm waves and tsunami surges. The trees in Rikuzentakata were mature, with diameters of 25 to 40 cm. With one notable exception, all of the estimated 70,000 trees on the Rikuzentakata coast were destroyed by the tsunami (Figure 6). The one surviving tree, called “the tree of hope,” has become a national symbol of resilience, featured in songs and poems. Unfortunately, the tree is showing signs of stress caused by the high levels of salt in the soil and may not survive.



Figure 6. *Left: the sole surviving pine tree out of a forest of 70,000 trees planted to protect the Rikuzentakata coast from tsunamis and storm surge. The towers on the left are part of the tsunami gates built to prevent tsunami surges from flooding the Kesen River. Right: the remains of the pine forest. Mature pine tree trunks were 20-40 cm in diameter and typically snapped 1-2 m above the ground (photos: L. Dengler).*



Figure 7. The tsunami deposited boats in many areas of Kesennuma City and left others to burn or sink in Kesennuma Bay (photos: L. Dengler).



Figure 8. The approximate inundation zone in Minimisanriku Town. The tsunami surges destroyed the town center and went up the narrow Hachiman River (center) and the Sakura River (on left) and the Oretate River (on right). Black arrow is 2 km long. (A) marks the location of the disaster management building shown in Figure 10 and (B) shows the tsunami evacuation building in Figure 26. The gates shown in Figure 9 are just to the right of B. The inundation area shown here (and in Figures 12 and 15) is based on Google earth imagery and may change when data from field teams is included.

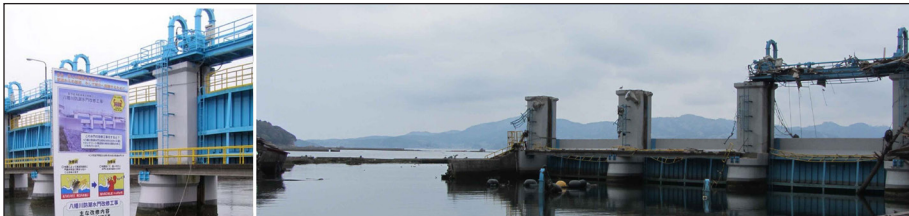


Figure 9. Left: gates on the Hachiman River, Minamisanriku, in April 2010 in the up position (photo courtesy of J. Bourgeois). Right: the same gates in May 2011 after the tsunami. They closed before the tsunami struck, but failure of the sea walls negated their effectiveness (photo: L. Dengler).

Kesennuma City (population 73,000) is located at the head of Kesennuma Bay and, before the tsunami, was a thriving commercial fishing port and the center of Japan's shark fin trade. Many of the large packing plants along the harbor suffered damage due to liquefaction. Dozens of boats were torn from moorings, some of which were deposited inland, and others sank in the bay (Figure 7). The long-term ecological impacts of the fuel and other hazardous materials released in the bay are difficult to predict.

Minamisanriku Town (population 17,000) had gained an international reputation for tsunami preparedness before the tsunami and was a featured field trip stop for tsunami experts. The three rivers flowing through the town featured tsunami gates that could be shut in 15 minutes to keep the tsunami from penetrating inland up the river channels. Figure 8 is an approximation of the inundation zone, showing that the tsunami extended nearly 3 km up the Hachiman River and nearly 2 km up the adjacent river valleys. Officials successfully lowered the gates on March 11 (Figure 9), but the adjacent sea walls were overtopped and undermined, and did not prevent the city from being flooded. An estimated 31 of 80 designated tsunami evacuation buildings were destroyed (*Japan Times*, 2011). At the Disaster Management Center (Figure 10), more than 30 officials, including the town mayor, gathered on the rooftop during the tsunami event, and twenty died (*Asahi Shimbun*, 2011). Miki Ando, a municipal official responsible for broadcasting emergency information to the public, remained at her post on the second floor of the building and continued broadcasting announcements; she was credited by many for saving their lives as they heeded her warnings to get to higher ground, but she did not survive.

Ishinomaki City (population 164,000) is one of the largest ports north of Sendai and is a center of



Figure 10. The disaster management headquarters for the town of Minamisanriku. About 30 officials gathered on the upper floor and roof on March 11. The tsunami completely flooded the structure and only 11 people survived. Note the location of high ground in the background (photo: L. Dengler).

the rice trade. The main port facilities are located to the southwest of the population center and experienced water heights in the 4.5 to 5 meter range (PARI, 2011). Warehouses and reinforced concrete buildings suffered some damage but did not collapse. The port was nearly fully operational in May. Much of the rest of the city was very badly damaged and, because of the large exposed population, had the highest casualty total of any community in the Tohoku region. The large amount of debris in the water, including boats, caused some areas to be damaged that were above the inundation level (Figure 11).

Higashimatsushima City (population 34,000) is located in the transitional zone between the much steeper terrain to the north and the broad, low-lying Sendai plain to the south. This city was particularly vulnerable, as tsunami surges attacked it from four different sources: the coast, the Naruse River, the Tona Canal, and Matsushima Bay (Fig-

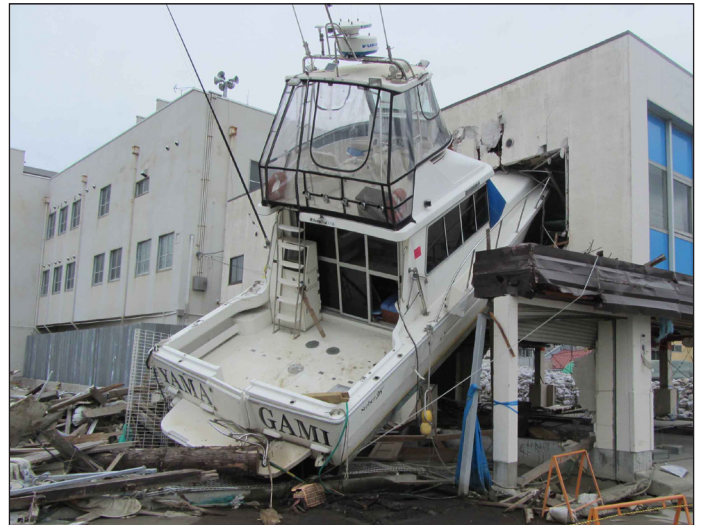


Figure 11. The inundation level in this area of Ishinomaki City was at the base of the second floor, but large objects in the water such as the boat shown caused extensive damage above the flow depth (photo: L. Dengler).

ure 12). Parts of the city south of the Tona Canal had no direct access to high ground. One

of the designated evacuation sites (Figure 13) was the multipurpose room adjacent to an elementary school. The elementary school was a

three-story building and the upper floors were above the inundation zone; however, it was not used for vertical evacuation, perhaps because the stairways were inside the building and would not have been accessible if the building were closed. An estimated 200 people gathered in the multipurpose room after the earthquake, but it did not

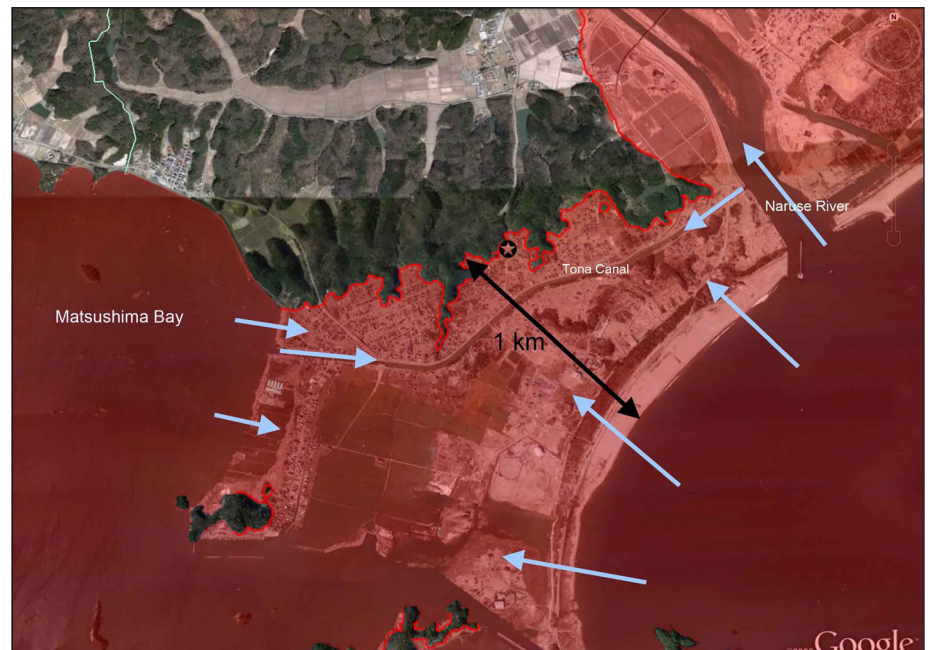


Figure 12. Approximate inundation area in the west area of Higashimatsushima City. This region was particularly vulnerable because the tsunami attacked from several directions. The star marks the location of the evacuation building shown in Figure 13. Note its proximity to higher ground on the hillside.



Figure 13. The multipurpose room of the Higashimatsushima elementary school, where 200 people gathered after the earthquake. The site was flooded to the base of the windows and most of the evacuees did not survive. The floor was used as morgue after the tsunami (photo: L. Dengler).

provide protection as the water level reached the base of the windows, and only a few people were able to get to safety on the ledge next to the windows. This site was located at the base of a hill where everyone could have reached high ground had they walked a few more minutes. One family of survivors lived close to the evacuation site, but they had only recently moved to the area and weren't aware of the designated building. Instead, they headed up the hillside behind their house after the earthquake and were able to see the waves approaching and to move up the hill when it became clear that the tsunami was very large.

Matsushima Town (population 4,000) overlooks Matsushima Bay and is considered to have one of Japan's most famous views. The bay protected the town from the brunt of the tsunami, and water heights reached only 2.5 m, with flooding extending into the ground floors of buildings near the waterfront. Because of the large tourist population, the town has numerous tsunami evacuation route signs, some painted on the sidewalk for



Figure 14. Tsunami evacuation route signs in Matsushima Town (photo: L. Dengler).

an easy visual guide (Figure 14).

Natori City (population 73,000), to the south of Sendai, is situated simi-

larly to other towns and cities on the Sendai plain. Landward of the coastal dunes and sea walls, the land elevation is close to sea level for more than 4 km. Once the walls were overtopped, the tsunami, unconfined to river valleys, spread out over the land surface (Figure 15). Although the peak water heights on the Sendai plain were less than those farther north,

a much larger areal extent was inundated (see Table 1). Much of the inundation zone was agricultural and the population density was low, but there were two notable exceptions in the city limits: the Sendai Airport area and Yuriage, close to the Natori River.

Located within 800 m of the coast, most of Yuriage was inundated. Like Higashimatsushima, Yuriage was attacked from several directions: the coast, the river, and a canal that cut off the most exposed area of the community from ready access to higher ground (Figure 16), and few structures exceeded three stories

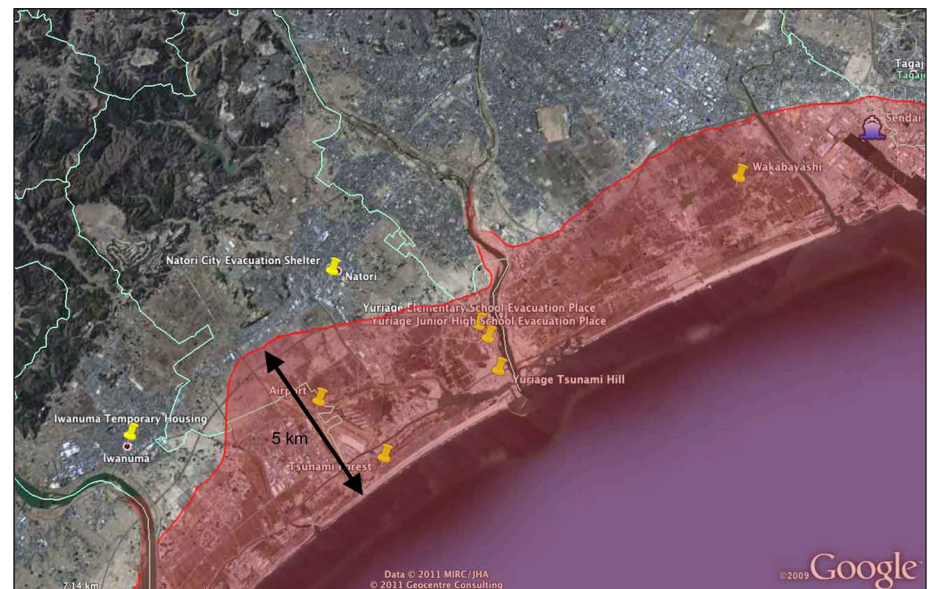


Figure 15. Approximate inundation area in Sendai, Natori, and Iwanuma Cities. Pins mark the locations of Wakabayashi, Yuriage, and the Sendai Airport, discussed in the text. The tsunami deposits transect is close to the black arrow where the tsunami penetrated about 5 km.



Figure 16. View from the top of the Yuriage memorial hill shown in Figure 15 (photo: L. Dengler).

in elevation. The junior high and elementary schools had been designated as vertical evacuation sites. Figure 17A shows the elementary school with several hundred people assembled on the roof at the peak of inundation about an hour and 25 minutes after the earthquake. Many schools like the Yuriage Elementary School were designed with external stairways (Figure 17B) for easy

access by students, staff, and community members.

After the tsunami, the gymnasium at the elementary school was cleaned and became a “Memory Hall.” Members of the Japanese Civil Defense Force, who were first to enter the regions after the disaster, collected photographs and other surviving items from the surrounding neighborhood, and volunteers organized them on

walls and stands by location for survivors to claim and friends and relatives to view (Figure 17D).

This school, like many other evacuation sites in the Tohoku area, was not equipped to serve the needs of people stranded for many days. Neither food nor water was stored on the premises, nor were blankets or bedding; there were no sanitary facilities and no access to first aid or emergency medical care. After the earthquake, winter temperatures were close to 0° C in much of the Tohoku region. Some elderly and injured tsunami survivors succumbed to the difficult conditions after extended time at such evacuation sites.

Sendai Airport served as a vertical evacuation site for passengers, staff, and nearby neighbors (Figure 18). Although a security guard told employees that a tsunami was expected within 30 minutes, many believed there was no tsunami hazard at the site, although it is located within the mapped tsunami inundation zone.

The earthquake caused nonstructural damage at the airport, and, initially, security personnel attempted to assign people to floors, with those on the first floor not allowed on the upper floors. It took two days before helicopters evacuated stranded passengers and neighborhood residents, and at least some of the staff walked out of the inundation zone through standing water more than half a meter deep in some places.



Figure 17. The Yuriage Elementary School evacuation site. Clockwise from upper left: A) photo taken at 4:11 p.m. during the peak of inundation (photo from the Memory Hall); B) detail of the exterior stairs; C) classroom that was used as a sleeping place for evacuees; D) the Memory Hall in the elementary gymnasium (photos: L. Dengler).



Figure 18. View out the third floor windows of the Sendai Airport during the tsunami (photo from Sendai Airport display).

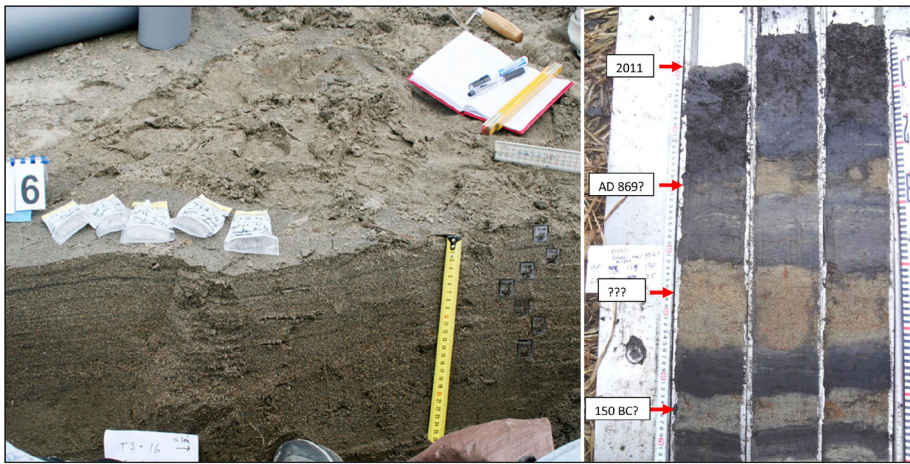


Figure 19. Wall of excavated trench from the line north of the Sendai Airport. Rectangular markers on right show locations where sediment samples were collected for further analysis (left photo: B. Jaffe; right photo: R. Wilson).

Tsunami Deposits

Two International Tsunami Survey Teams studied tsunami deposits on the Sendai plain. The first team (Jaffe et al., 2011; Chagué-Goff et al., 2011; Sugawara et al., 2011) visited the area in May 2011 and made careful observations along a line just north of the Sendai Airport in Natori City (near the arrow in Figure 15). They measured water levels, flow directions, topography, sediment thickness, grain size and sedimentary structures, and collected sediment samples for other analyses (Figure 19) to examine how the tsunami characteristics varied with tsunami speed and flow depth, topography, distance from the coast, urban and rural settings, subsidence, and other aspects of the landscape. New sand deposits >0.5 cm thick were observed up to 2.8 km inland.

The team also identified paleo-tsunami deposits as far inland as 3 km that were likely deposited by the 869 CE Jogan tsunami, an event (described by Abe et al., 1990) that has attracted considerable interest in the past decade from both paleoseismologists and modelers (Minoura, 2001; Satake et al., 2008; Sawai, 2008; Sawai et al., 2008; Namegaya et al., 2010). At this location, the Jogan event apparently extended at least 200 m farther

inland than the 2011 tsunami. The sedimentary evidence of the 2011 tsunami was complicated by liquefaction of some coastal-plain sediment during the earthquake and an extensive canal system that affected the movement of the tsunami waves and the sediment they carried.

The second team (Wilson, 2011) visited the area in August and examined the deposits in the vicinity of the first team's line to see how they had changed in the intervening four months. To identify other possible paleotsunamis, they also took a number of gouge core samples along the line that the May team studied. The cores showed several pre-2011 sand layers interpreted as possible tsunami candidates, including the Jogan and two

earlier deposits (Figure 19). Archeologists studying early human habitation on the Sendai plain have excavated a trench about 4 km inland of Arahama and 10 km north of the Airport. That trench shows a similar stratigraphy to the gouge cores. A large deposit dated to about 150 BCE may have been responsible for a temporary hiatus in rice cultivation in the region (Wilson, 2011). Considering the tsunamis in historic time, the paleotsunami deposits, and an older tsunami deposit found in some locales dating back about 3,000 years before the present, the average recurrence of great tsunamis on the Sendai plain appears to be on the order of 1,000 years (Minoura et al., 2001; Sawai et al., 2008).

The Tsunami in the Pacific Basin

The earthquake generated a tsunami that affected the entire Pacific basin (Figure 20). Tsunami warnings and advisories were issued by the Pacific Tsunami Warning Center (PTWC), the West Coast Alaska Tsunami Warning Center (WCATWC), and other national warning centers. The largest water heights outside of Japan were recorded in Crescent City, California (2.49 m recorded on a tide gauge, 3 m from eye witness accounts). Two other tide gauges on the U.S. West Coast recorded heights in excess of 2 m. Similar water heights were recorded at

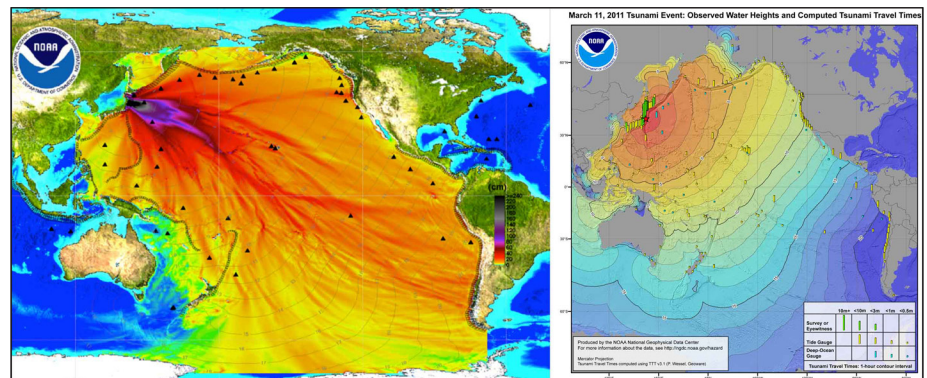


Figure 20. Left: computed maximum tsunami amplitudes throughout the Pacific (from NOAA PMEL). Note higher amplitude peak directed to northern California and southern Oregon. Right: tsunami travel times and measured water heights (NGDC, 2011).

Table 2. Tohoku tsunami heights exceeding 2 meters outside of Japan

| LOCATION | DISTANCE (km) | ARRIVAL TIME (hrs) | WATER HT (m) |
|-----------------------------------|---------------|--------------------|--------------|
| Arica, Chile | 16167 | 21.4 | 2.45 |
| Caldera, Chile | 16693 | 21.7 | 2.14 |
| Coquimbo, Chile | 16799 | 22.1 | 2.42 |
| Talcahuano, Chile | 16904 | 23.0 | 2.09 |
| Galapagos Islands, Ecuador | 13228 | 17.8 | 2.26 |
| Holtekamp II, Indonesia | 3971 | | 2.8 |
| Crescent City, California | 7543 | 9.8 | 2.47 |
| Crescent City, California | 7543 | | 3 |
| Klamath River, California | 7563 | | 2.5 |
| Moss Landing Harbor, CA | 8020 | | 2 |
| Port San Luis, California | 8195 | 10.4 | 2.02 |
| Smith River, California | 7531 | | 2 |
| Kahalui, Maui, Hawaii | 6108 | 7.7 | 2 |
| Port Orford, Oregon | 7463 | 9.6 | 2.02 |

Source: NGDC, 2011; data in bold from tide gauge recordings

four locations in Chile as well as in the Galapagos Islands and Maui, Hawaii (Table 2).

The tsunami caused damage on Midway Island and in California, Oregon, and Hawaii, portions of which were declared federal disaster areas. The California Geological Survey activated a post-tsunami clearing-house after the event and organized teams of scientists and engineers that examined or received reports about every port and harbor facility in the state. Two harbors (Santa Cruz and Crescent City) had major damage (Figure 21), and less serious impacts were observed at 22 other locations in California. All the damage was attributed to strong currents, which were measured at speeds of up to 10 knots (Wilson et al., 2011). Losses in California were estimated at over \$50 million.

In Hawaii, the most serious damage was at Kealahou Bay and in Kailua-Kona, where one house floated to sea and 26 were damaged. A number of hotels were damaged, including the landmark Kona Village Resort, which remains closed to date. Damage was also reported on

Maui and Oahu. At the Keehi Lagoon marina on Oahu, floating docks broke loose and sank an estimated 25 boats and damaged 200 others. Economic losses in Hawaii were exacerbated by the cancellations of large numbers of Japanese tourists.

Brookings Harbor in southern Oregon was badly damaged by the strong currents caused by the tsunami. Docks broke loose and several boats sank, causing an estimated \$6.7 million in damage. Damage to docks was also reported in Depoe Bay and Coos Bay.

The only life lost outside of Japan was in northern California, where three young men had gone to the

mouth of the Klamath River to photograph the tsunami; all were swept into the water, but two managed to get back to land. The body of the third was recovered three weeks later near the mouth of the Columbia River in Oregon, about 500 km to the north. Other people were swept into the water in the Port Orford and Gold Beach areas of Oregon and at Ocean Beach in southern California, but were rescued.

The impacts on the West Coast of the U.S. were reduced by the ambient tidal conditions. In California and Oregon, the strongest tsunami surges coincided with a low neap tide and ambient water levels close to zero. The highest absolute water levels in the Crescent City area coincided with the highest tide, nearly 24 hours after the onset of the tsunami when the tide was 2 m and the tsunami still had amplitudes over 1 m. Had the largest surges coincided with high tides, there would have been significant on-land flooding at a number of West Coast locations. The impacts were also reduced by the effectiveness of tsunami warning systems that allowed commercial fishermen in both Crescent City and Brookings to move most of the commercial fleet out of the harbors before the tsunami arrived.

In South America the largest amplitude tsunami waves coincided with high tide. Damage was reported in Chile and the Galapagos Islands. At Tongoy, in Chile's Co-

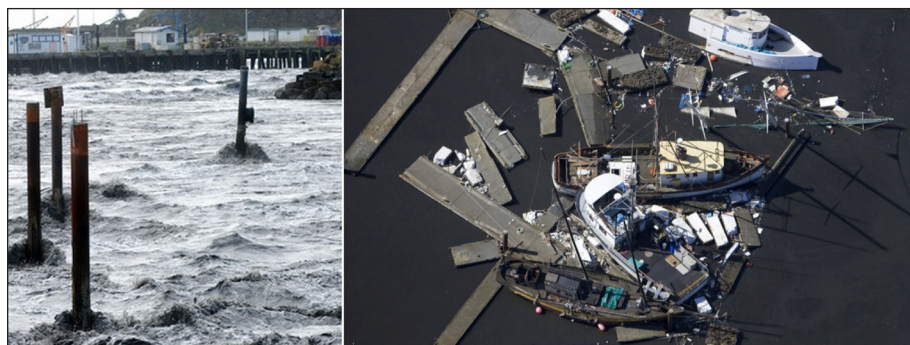


Figure 21. Crescent City, California. Left: the inner boat basin during the tsunami. Right: damaged docks and boats (photos: R. Hiser).

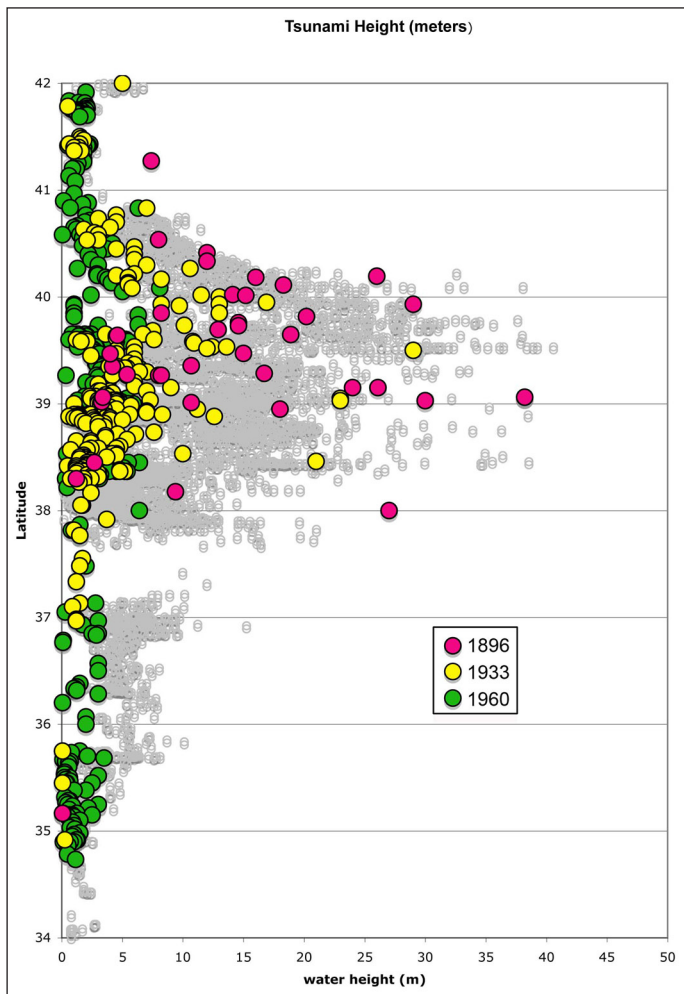


Figure 22. Historic tsunami water heights along the Tohoku coast. Water heights from the 1896 Meiji tsunami (red), 1933 Showa tsunami (yellow), and 1960 Chilean tsunami (green) are superimposed on the 2011 water levels (data from NGDC).

quimbo region, strong currents displaced concrete blocks and damaged the shellfish industry (Le-grande, 2011); in the Galapagos on Santa Cruz Island, a hotel and the Biomar Building at the Charles Darwin Research Station were seriously damaged (Lopez, 2011).

Recommendations for Further Research

Failure to evacuate was the primary cause of the high casualty rate in the Tohoku tsunami. A number of factors, each discussed below, contributed to the evacuation failures and should be studied in more detail.

agencies have made detailed assessments of the capability of identified fault systems to produce significant earthquakes. An earthquake hazard map published in 2008 (Headquarters for Earthquake Research Promotion) identified a number of possible sources of earthquakes in the Tohoku region likely to produce earthquakes in the magnitude 7-8.2 range. The Tohoku earthquake was not only larger than most of the scientific community expected, but it also may have produced the largest fault slip ever observed. The earthquake has prompted a reconsideration of why the magnitude was unexpected (Stein and Okal, 2011), of the relationship between magnitude and slip, and whether it



Figure 23. Evacuation and inundation map of Unosumai Town near Kamaishi. The orange line shows the evacuation area, the red line is the approximate inundation from the 1896 and 1933 tsunamis, and the blue line is the 2011 inundation (source: Mainichi Newspaper).

1) Hazard assessments that underestimated the size of the earthquake and tsunami. The basis for evacuation planning is an accurate assessment of hazard, and Japanese scientists and government agencies

is possible to identify conditions that constrain or permit such “overslip.”

The rich historic record of major tsunamis in Japan and sophisticated numerical modeling had produced consensus about the relation between earthquake source characteristics and the expected tsunami size. In particular, the tsunami events from 1896, 1933, and 1960 (Figure 22) had provided a basis for tsunami planning. Consensus about the hazard based on these relatively recent historic events informed such hazard reduction efforts as seawall construction, evacuation zone mapping, designation of evacuation sites, the warning system, and outreach and education efforts. Potentially larger events had been recognized in much earlier historical records by paleoseismologists (Abe et al., 1990; Minoura et al., 2001; Sawai et al., 2008) but they had not been incorporated into hazard assessment efforts. The Tohoku tsunami raises fundamental questions about hazard assessment, the inclusion of paleoseismic data in the assessment, and planning for rare but potentially catastrophic events.

Table 3. Japan Meteorological Agency Tsunami Bulletins

| Earthquake Magnitude | | JMA Bulletins | | | | |
|-------------------------------------|-----------|-----------------------------------|--------|---------|---------|---------|
| | | Bull 1 | Bull 6 | Bull 10 | Bull 16 | Bull 31 |
| | | 14:50 | 15:14 | 15:31 | 16:09 | 18:47 |
| Earthquake Magnitude | | 7.9 | 7.9 | 7.9 | 8.4 | 8.8 |
| Tsunami Forecast Region | Arr. Time | Forecast tsunami heights (meters) | | | | |
| IWATE PREF. | ** | 3 | 6 | >10 | >10 | >10 |
| MIYAGI PREF. | 15:00 | 6 | >10 | >10 | >10 | >10 |
| FUKUSHIMA PREF. | 15:10 | 3 | 6 | >10 | >10 | >10 |
| KUJUKURI & SOTOBO AREA, CHIBA PREF. | 15:20 | 2 | 3 | >10 | >10 | >10 |
| IZU ISLANDS | 15:20 | 1 | 2 | 4 | >10 | >10 |
| UCHIBO AREA, CHIBA PREF. | 15:20 | 0.5 | 1 | 2 | 4 | 4 |
| CENTRAL HOKKAIDO | 15:30 | 1 | 2 | 6 | 8 | 8 |
| PACIFIC COAST OF AOMORI PREF. | 15:30 | 1 | 3 | 8 | >10 | >10 |
| IBARAKI PREF. | 15:30 | 2 | 4 | >10 | >10 | >10 |
| E. PACIFIC COAST OF HOKKAIDO | 15:30 | 0.5 | 1 | 3 | 6 | 6 |
| SAGAMI BAY AND MIURA PENINSULA | 15:30 | 0.5 | 0.5 | 2 | 3 | 3 |
| W. PACIFIC COAST OF HOKKAIDO | 15:40 | 0.5 | 1 | 4 | 6 | 6 |
| OGASAWARA ISLANDS | 16:00 | 0.5 | 1 | 2 | 4 | 4 |
| SHIZUOKA PREF. | 15:30 | 0.5 | 0.5 | 2 | 3 | 3 |
| TOKYO BAY | 15:40 | - | 0.5 | 1 | 2 | 2 |
| SOUTHERN PART OF MIE PREF. | 16:00 | 0.5 | 0.5 | 2 | 2 | 2 |
| PACIFIC COAST OF AICHI PREF. | 16:10 | 0.5 | 0.5 | 1 | 2 | 2 |
| JAPAN SEA COAST OF AOMORI PREF. | 16:10 | 0.5 | 1 | 2 | 3 | 3 |
| WAKAYAMA PREF. | 16:10 | 0.5 | 0.5 | 2 | 3 | 3 |
| KOCHI PREF. | 16:30 | 0.5 | 0.5 | 2 | 2 | 2 |
| TOKUSHIMA PREF. | 16:40 | 0.5 | 0.5 | 2 | 3 | 3 |
| MIYAZAKI PREF. | 17:00 | 0.5 | 0.5 | 1 | 2 | 2 |

Source: http://www.jma.go.jp/en/tsunami/info_04_20110311145026.html (Ozaki, 2011).

2) Limitations of published hazard maps. All coastal communities used the tsunami hazard assessment to develop inundation and evacuation maps. Figure 23 shows the evacuation map for Unosumai Town located near Kamaishi City. The 1896 and 1933 tsunamis flooded the town to the red line. Seawalls and large river dikes had been constructed since 1933 and were believed to be able to prevent the level of flooding seen previously. The hazard map, including the mitigating effect of the seawall, is shown by the orange line. The actual inundation in 2011 (blue line) exceeded both the historic inundation and the mapped hazard areas. A study done by *Mainichi Newspaper* (Sugimoto, 2011) reported

485 deaths in Unosumai, 419 of which (86%) had residences within the 2011 inundation area, but outside of the mapped hazard area.

In Unosumai, over 500 students from the junior high and elementary schools successfully made it to high ground (*Asahi Shimbun*, 2011b). Both schools were located just outside of the mapped hazard zone, and the students in the elementary school had been taught to go to the building's third floor after an earthquake. At the adjacent junior high school, students and staff had been taught to evacuate. When the elementary students saw the older students evacuating, they joined them, the older students assisting the younger ones. The group first headed to a location well outside of the mapped zone (red circle Figure 23), but changed

their plans when they saw the surges heading into the community. They changed plans twice before finally running to the hills (green circle). Professor Katada at Gunma University had served as an advisor to the Unosumai school disaster planning effort and had emphasized that children should be taught to head to high ground, to evaluate the situation with their own eyes, and to assist others.

3) Changing official warning information. The Japanese Meteorological Agency (JMA) has the responsibility for issuing tsunami warnings in Japan. On March 11, the JMA issued a series of bulletins assessing the likely tsunami hazard posed by the earthquake (Table 3). The initial bulletin issued three minutes after the earthquake estimated a magnitude of 7.9 and forecast 3-m surges along the Iwate and Fukushima coasts, and waves as high as 6 m in Miyagi. This information was disseminated to emergency officials and to the public via television, radio, and cell phones. Succeeding bulletins expanded the warning areas and increased the expected water height; however, it took nearly four hours before the designated warning areas stopped changing. JMA recently changed its protocol for very large earthquakes because of the underestimation on March 11. For earthquakes of magnitude 8 or larger, anticipated water heights will no longer be announced; instead, the warning will focus on "the possibility of a huge tsunami" (Cyranoski, 2011). An important research question is how officials and the public responded to the changing hazard assessment and what level of detail is sufficient to motivate people to evacuate.

4) Importance and effectiveness of visual inundation markers. Many communities featured vis-



Figure 24. Water height markers. A) Marker commemorating the 2.6 m height of the 1960 Chilean tsunami at Minamisanriku Town (2010 photo courtesy of J. Bourgeois). B) The same marker in May 2011 (photo: L. Dengler). Water height at this location was over 15 m. C) Pole with expected 2 m tsunami height in Kesenuma City (photo: L. Dengler). Tsunami height reached the 3rd floor of the evacuation building in the background. D) Tsunami stone commemorating the height of the 1896 tsunami in Aneyoshi Bay (photo: B. Jaffe).

ual reminders of the height of past tsunamis or the expected highest water level (Figure 24). At Minamisanriku, a series of monuments and statues commemorates the 1960 Chilean tsunami (Figure 24A). The 2011 tsunami exceeded the 1960 water levels by more than 12 m (Figure 24B). At Kesenuma, the modeled tsunami height was printed on light poles as a visual reminder of the hazard (Figure 24C). The actual tsunami at this location was about 10 m higher.

10 m above the inundation zone, and no houses in Aneyoshi Village were flooded. More than two dozen tsunami stones have been identified in the Tohoku region, and preliminary reconnaissance suggests that about 20% were flooded in 2011 (Sugimoto, 2011). Unraveling the stories behind the stones will require careful investigation, as the original intent of the stone is not always clear, nor is whether it is still located in its original position, or how people understood its meaning.



Figure 25. Tsunami evacuation building in Manamisanriku (B on map, Figure 8). The building is adjacent to the sea wall (white arrow on the left). The tsunami left debris on the fourth floor windows (red arrow) (photo: L. Dengler).

A number of media stories have described tsunami stones that mark safe areas based on past tsunami heights (Fackler, 2011). Figure 24D shows the tsunami stone in Aneyoshi Bay, reputed to have been erected after the 1896 Meiji tsunami, directing people to build houses above its elevation. Although Aneyoshi Bay had the highest runup (38.9 m) in the 2011 tsunami, the stone was about

5) Reliance on evacuation buildings. Tsunami evacuation planning in most coastal areas of Japan involves designating buildings thought to be safe and teaching residents to go to those buildings after an earthquake. The buildings are generally three or more stories in elevation and usually feature exterior stairs to facilitate access. Towns and cities had designated tens to hundreds of structures as evacuation buildings; there were 80 in Minamisanriku alone. Unfortunately, many of the buildings were either overtopped or destroyed by the tsunami; preliminary reports are that over 100 evacuation buildings failed to provide life safety (*Japan Times*, 2011). Even when buildings survived, they created other problems for the people sheltering there. In many cases, the buildings were located close to the coast (Figure 25), where they could be quickly cut off from high ground. Once people had gone to a building, it was impossible to make another decision as the situation evolved. The water heights, trapping of water, level of damage and permanent subsidence isolated people in these structures for several days without adequate supplies or access to emergency care. While vertical evacuation may provide the only life safety in areas where

no high ground is nearby, research should assess its effectiveness in areas where there are other options.

- 6) Effectiveness of seawalls as a mitigation measure.** It is not the purpose of this report to assess the engineering issues associated with seawalls, but an important research issue is the relative effectiveness of seawalls compared to other mitigation measures, such as land use planning, and education. This discussion has already begun in the media (*Yomiuri Shimbun*, 2011), and can be seen in greater detail in the companion LFE report, “The Japan Tohoku Tsunami of March 11, 2011: Effects on Structures,” by the ASCE/EERI team.
- 7) Perception of risk.** A recurring chorus among the people interviewed during this and other field reconnaissance trips is that they did not perceive themselves to be at risk. An NHK survey of tsunami survivors found that over half did not think they were in an inundation area (Sugimoto, 2011). For a significant number of people, the earthquake was a trigger — not to head to higher ground, but rather to go into hazard zones where they lived, either to rescue a relative or to retrieve belongings. Although taught to evacuate on foot, most people relied on cars; this made it difficult for them to assess the situation around them and caused massive traffic jams that hindered evacuation (*Japan Times*, 2011b). A number of factors may have contributed to the reduced sense of risk: the perceived safety of seawalls, previous events that had failed to produce significant tsunamis (warnings had been issued for the 2010 Chilean quake and the March 9 foreshock), confusion over or misinterpretation of tsunami warning bulletins, and the failure of education efforts to reach people.

Outside of Japan, risk perception also posed a problem. While evacuation efforts on the U.S. West Coast were more successful than in the past (Dengler et al., 2011), a significant number of people headed to the coast to watch the event. There continue to be problems with warning message comprehension, especially for non-English speaking communities (Wilson et al., 2011). A high-priority research effort would be to examine the primary influences on individual perception of risk, and how those perceptions informed evacuation behavior.

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