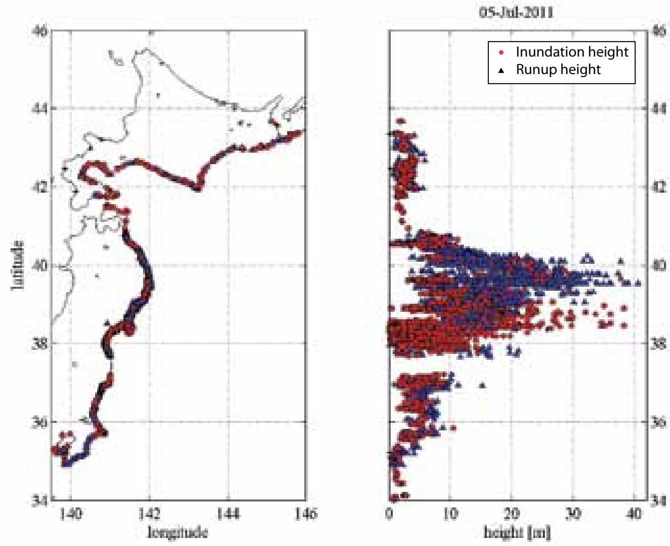
The Japan Tohoku Tsunami of March, 2011

Part 2: Preliminary Findings on Tsunami Effects on Structures

By Gary Chock, S.E.

The first article of this series, August 2011 issue of STRUCTURE®, offered preliminary observations of the effects of the March 11, 2011 Tohoku Tsunami, generated by the Great East Japan Earthquake of Moment Magnitude (M_w) 9.0. This subduction earthquake was the world's fourth largest since 1900. Japan is located near the meeting point of the Eurasian Plate, Philippines Sea Plate, North American Plate, and the Pacific Plate. Off the Tohoku coast of Honshu, the Japan Trench is where the Pacific Plate subducts beneath the North American Plate. The Great East Japan Earthquake successively ruptured over 4 segments, encompassing an area of approximately 300+ km by 150 km (more than 17,000 square miles). At the megathrust fault, vertical movement of the ocean floor was estimated by Japanese researchers to be about 3 meters (about 10 feet) upward and 24 meters (about 80 feet) laterally. Horizontal displacement on land was over 5 meters (16.4 feet), with a vertical subsidence of over 1 meter. The Great East Japan Earthquake has been compared to the July 13, 869 A.D. Ms 8.6 Jogan Sanriku Earthquake that occurred in a similar offshore area near the northeast coast of Honshu. In other words, the 2011 event has been suggested to represent a 1,200-year return period megathrust subduction earthquake. However, it also surpassed the size of the Jogan earthquake by a wide margin as the largest earthquake known to have ever hit Japan (*Figure 1*).



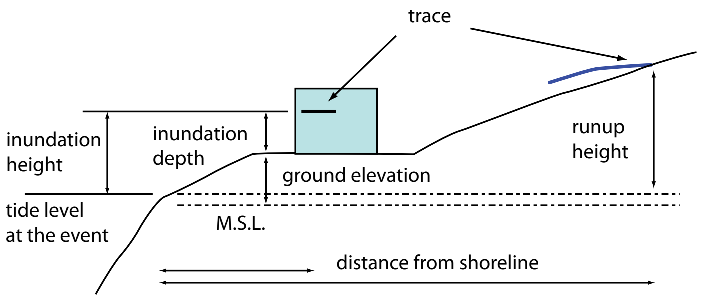


Figure 2: Tsunami Terminology Illustrated (Port and Airport Research Institute).

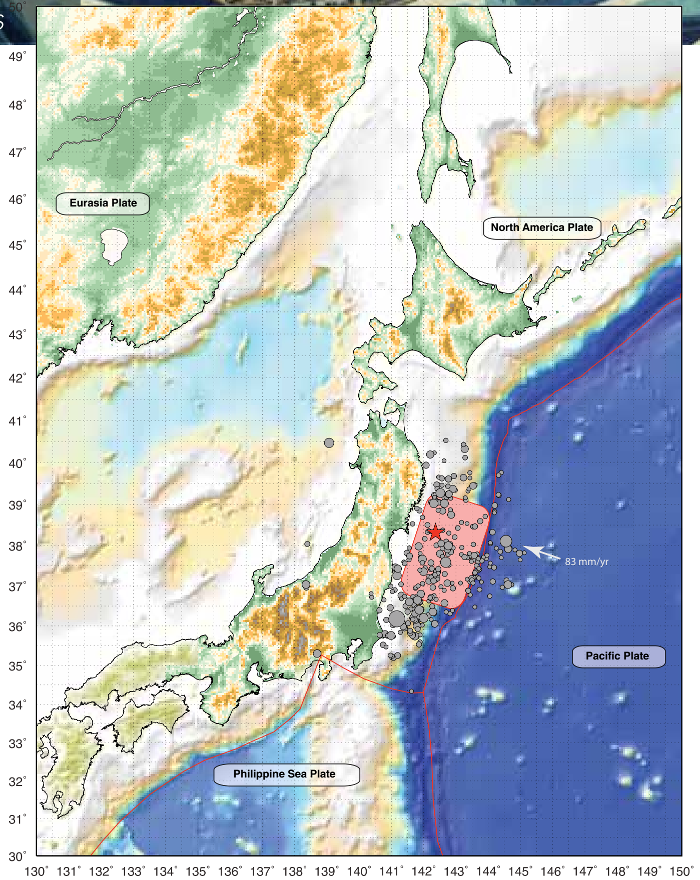


Figure 1: Tectonic Setting of Japan with Epicenters of the Great East Japan Earthquake and its Aftershocks off the Tohoku Region of Honshu Island (USGS).

It has been estimated from aerial and satellite photography that almost 535 square kilometers (207 square miles) of land were inundated. The Tohoku Earthquake Tsunami Joint Survey Group (clearinghouse at **www.coastal.jp/ttjt**) published numerous online data of the peak inundation and runup heights, compiled from the work of over 100 Japanese researchers who worked in the field for at least three weeks in late March and early April. As *Figure 2* shows, runups in the Tohoku region of Honshu ranged from about 10 meters to almost 40 meters (32 to over 131 feet).

The ASCE-SEI Tsunami Reconnaissance Team visited the Tohoku coast in mid-April to examine tsunami effects to buildings, bridges, and coastal protective structures within the inundation zone along over 241 km (150 miles) of coastline. This second article, discusses of some of the team's broader findings. Although a large number of coastal protective structures were studied, these are typically not used in North America, so they are not discussed here. ASCE will be publishing a complete report, with documentation of case studies of a much broader scope than is included here.

In general, complete collapses of nearly all residential light-frame construction in the affected areas, extending to the edge of the inundation limit, was observed. In commercial and industrial areas, low-rise building collapses occurred in the approximate range of 75% towards 95%. In these coastal inundated areas, the Team did not find any high-rise buildings; most of the taller buildings were four to eight stories tall. Despite this devastation, there were a number of larger multi-story buildings that survived the tsunami without loss of structural integrity of their vertical load carrying system or foundation. In fact,

Figure 3: Minamisanriku Post-Tsunami Aerial Photograph. Courtesy of Ioan Nistor, ASCE.

Figure 4: Minamisanriku designated vertical evacuation apartment building. Courtesy of David Kriebel, ASCE.

a significant proportion of the surviving buildings did not appear to have significant structural damage. This provides some encouragement regarding the potential resilience of larger modern buildings having robust seismic designs with scour and uplift-resistant foundations.

Figures 3 and *4* show the town of Minamisanriku, with inundated depths of 15 meters (49.2 feet), highlighting the survival of several low to mid-rise reinforced concrete buildings.

One of the Minamisanriku vertical evacuation buildings was a four-story shoreline apartment building with a roof height 15.25 meters (50 feet) above sea level. However, the tsunami reached 15.8 meters (51.8 feet) above sea level and it actually overtopped its roof level. Those who evacuated to the roof, which had been designed for access/occupancy, remained safe. This building was oriented perpendicular to the flow, which scoured almost a complete moat around the structure. However, it has a pile foundation system and was not structurally damaged despite being completely inundated and having no "breakaway" walls.

Several other tall mid-rise reinforced concrete buildings that served as tsunami evacuation buildings were visited. They performed well, the evacuees furnishing a number of spectacular videos of tsunami flow destroying neighboring buildings around them. The Kesennuma Port Authority Building (*Figure 5*) served as a vertical evacuation building from the 3rd floor upward, which was inundated to 8.25 meters (27 feet) above local grade. Most other neighboring low-rise industrial buildings in the port area were swept away.

Bridge outages were numerous, including both highway and rail bridges and overpasses. Whereas roadway bridges can be replaced by temporary or by-pass structures, the failure of a railway bridge generally results in a much longer outage of the rail line. In the case of railways, these failures were a result of large sustained lateral forces on the bridge spans, sufficient to fail seismic anchorages or pull down the overpass piers themselves. In many other cases, seismic lateral blocking and ductile anchorage of highway bridge girders were ineffective in resisting uplift. The example of a railway overpass in Otsuchi demonstrates the severity of hydrodynamic loads (*Figure 6*).

Figure 5: Kesennuma Port Authority Building. Courtesy of Ioan Nistor, ASCE.

During the Tohoku Tsunami, sustained hydrodynamic forces exceeded the minimum seismic design code forces for most structures. There is an analogous threat to the Pacific Northwest of North America posed by the Cascadia subduction zone, which in 1700 generated a tsunami-genic earthquake also estimated to be magnitude 9. The Japanese seismic design code generally results in greater lateral forces and stiffer systems for reinforced concrete and steel buildings than in the USA, so additional analytical comparisons are necessary, rather than directly extrapolating the performance of Japanese buildings (a paper on this subject is in preparation). Having traveled throughout the area both within and outside the inundated areas, it should be noted that the structures observed by the team did not appear to have earthquake damage preceding the tsunami. Structures of all material types can be subjected to general and progressive collapse during tsunami. However, larger scaled and taller buildings will be inherently less susceptible.

As discussed in the Part I and II articles, fluid and impact loads and scouring from tsunami inundation poses a significant risk to coastal buildings and infrastructure. Loading and effects include:

Hydrostatic Forces: Buoyant Forces, Additional Loads on Elevated Floors, Unbalanced Lateral Forces

Hydrodynamic Forces: Lateral and Uplift Pressures of Tsunami Bore and Surge Flows

Debris Damming and Debris Impact Forces: External and Internal Debris Accumulation and Striking

Scour Effects: Shear of cyclic inflow and outflow, and transient liquefaction due to de-pressurization

The following factors should be considered in design for tsunami risk mitigation:

- Probabilistic Tsunami Hazard Analysis for design should include longer return period tsunami-genic subduction earthquakes commensurate with the maximum considered risk level utilized in seismic codes. The severity of tsunamis correlate to the amount of vertical displacement of the sea floor rather than ground acceleration; therefore, unlike earthquake shaking transmitted through the ground, tsunami heights do not asymptotically reach a saturation limit with magnitude.
- Light-frame construction will not survive tsunami inundation depths of more than a few meters (roughly 6 feet), nor the flow velocities of tsunamis. However, to guard against more frequent, lower amplitude events, elevation of the superstructure above the base flood elevation should consider 100-year flood hazards of all sources including tsunami.
- Debris accumulation in tsunami inflow occurs rapidly once structures and forests are encountered. Loads on structures should consider debris damming/blockage and debris strikes. Enhanced local element resistance to debris strikes should be included in design.

- Buoyancy should be considered in design; there should be sufficient openness in buildings to alleviate buoyancy. The value of breakaway cladding would be more to prevent buoyancy than to reduce hydrodynamic forces, due to the inevitable debris loading from internal and external sources in repeated tsunami flow cycles.
- Avoid potential structurally boxed-in areas subject to hydrodynamic pressurization of load-bearing walls.
- Foundation systems should consider scour effects (particularly at corners) to resist undermining.
- Flow acceleration around large buildings significantly increases the flow velocity on downstream buildings.
- Depending on the tsunami hazard level, seismic design may not ensure sufficient tsunami resistance, particularly for low-rise buildings.
- In order to resist the effects of a near-field tsunami, structures must first perform adequately with limited structure damage during the causative earthquake that precedes the tsunami arrival.
- Mid- to high-rise reinforced concrete buildings with robust shear walls can survive structurally, even with many walls at the exterior. These could become evacuation structures if tall enough. Steel buildings robustly proportioned at their lower stories could also have similar capabilities.
- It is quite possible to design buildings and other structures to withstand tsunami events. This is desirable for taller buildings that may serve as refuges, taller buildings that may not be easily evacuated, buildings whose failure may pose a substantial risk to human life, essential facilities, and critical infrastructure.▪

Figure 6: Multiple span and pier failures of a railway overpass and river bridge in Otsuchi, having braced steel plate girders. Courtesy of Ian Robertson, ASCE.

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