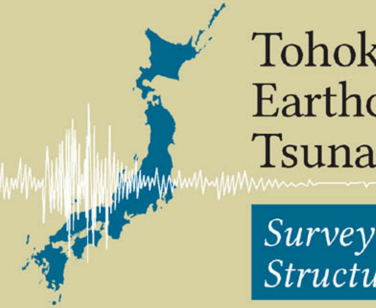
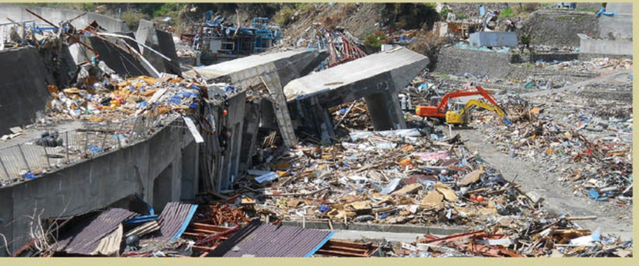


Tohoku, Japan, Earthquake and Tsunami of 2011

Survey of Coastal Structures



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Survey of Coastal Structures

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Preface

The March 11, 2011, magnitude 9.0 Great East Japan earthquake generated a tsunami that affected the entire Pacific Basin. Buoys off the coast of Japan measured offshore wave heights that exceeded six meters, with the first waves reaching the northeastern coast of Japan within 25 to 30 minutes of the seismic event. The extensive onshore inundation often exceeded the design heights of shoreline protective structures. Tsunami waves propagating throughout the Pacific damaged port and harbor areas in Hawaii, Oregon, and California, and buildings along the coasts of Guam and Chile; however, the greatest destruction, by far, occurred in Japan.

As of November 2, 2011 the reported deaths from the Great East Japan earthquake and tsunami had reached 15,829, with 3,679 missing and 5,943 injured in the event. The initial economic outlook after the earthquake and tsunami was grim: in addition to the enormous direct costs of reconstruction in Japan, the tsunami damaged areas around the Pacific and impacted Japanese industry, a key element in the global economy. Early damage estimates for Japan ranged from $(US) 250 to $(US) 309 billion (20 to 25 trillion yen) or about 4 to 6 percent of Japan's Gross Domestic Product (GDP) (Nanto, WSJ, 2011). More recently, damage estimates have dropped to expenditures between $126 billion to $152 billion (10 trillion to 12 trillion yen) over the next five years (Reuters, 2011).

The ASCE/COPRI Coastal Structures Team undertook its reconnaissance trip to investigate the earthquake and tsunami effects specific to engineered coastal structures, coastal landforms, and coastal processes in Japan. The team travelled in Japan from May 10 – 18, 2011. During their survey, team members observed examples of five major categories of coastal protection structures: coastal dikes, tsunami seawalls, floodwater gates, breakwaters, and vegetated greenbelts.

Throughout the several hundred kilometers of damage to various structures in the region, some structures performed remarkably well. The team sought to ascertain why some structures remained viable while others failed, many with disastrous consequences. The team's field investigation of coastal structures started in the north— at the Momoishi Fishing Port, located approximately 12 kilometers southeast of the Misawa Airport in Aomori Prefecture, and extended southward to Natori Beach, located immediately adjacent to the Sendai Airport in the Miyagi Prefecture.

Mechanisms for damage and failure included the following:

- Tsunami Overtopping without Structural Failure
- Tsunami Overtopping with Structural Damage or Failure

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- Tsunami Uplift Forces
- Movement of Structure from its Foundation due to Sliding, Rotation & Overtopping
- Impact Loads
- Hydrostatic Pressures
- Supercritical Flows
- Scour
- Erosion
- Subsidence: Regional and Local

An event of enormous consequences, the Great East Japan tsunami provided some significant success stories and some catastrophic failures. Observations and lessons came from both the successes and the failures. A few communities escaped relatively unscathed. In many other places, structures collapsed or slid off their foundations. Segments of walls detached from main structures. Armor units broke into pieces and revetments scattered. Provided below are some key observations, lessons learned and recommendations.

Key Observations

- Coastal structures remained standing – Many coastal protection structures survived the tsunami forces, despite having been overtopped. While these structures often failed to protect the inland areas from flooding, scour, high velocity flows and other effects from the tsunami, they remained stable and can be part of the future community planning and reconstruction efforts.

- Overtopping - The extreme tsunami waves overtopped most coastal barriers along the Tohoku coast. The height of the inundation over structures resulted in supercritical flow on the landward side, with increased velocity, turbulence, and scour as a consequence.

- High profile vs. low profile structures - The investigation team observed a pronounced difference in response between low profile and high profile structures. Many low profile structures with mechanical attachments to their supports or abutments remained in place. In many cases, the vertical uplift forces from the tsunami exceeded the connection resistance for higher structures spanning across multiple foundation supports or abutments. Typically bridge deck sections were observed to have fixed ends at one abutment and floating ends seated into platform holds at the adjacent abutment. This design was often used along the Tohoku coast. It appeared that these connections did not adequately resist the uplift and lateral forces at higher elevations in the flow which led to large losses for elevated structures and high bridges.

- Structural connections - Several of the seawall structures, designed for sectional construction, failed at the junctions between pre-cast segments. Small lengths of smooth reinforcing bars at infrequent intervals provided the only mechanical connections between units.

- Foundations and tie-ins - Many foundation failures occurred, often when the tsunami pushed structures off their foundations. In many instances, minimal connections attached structures to their foundations, and many gravity structures such as walls and dikes lacked mechanical connections to underlying soils.

- Scour and Erosion - The inland sides of projects—of walls or breakwaters, for example—often lacked scour protection. Beach scour and loss of sand was a second type of scour that was observed. Inland sand deposits were observed along the coastal roads. Broad ranging deflation of beach profiles was present in several locations, however beaches in front of remaining vertical walls showed little evidence of area-wide beach deflation.

- Greenbelts - Several coastal communities had developed “greenbelts” seaward of the main developed areas; these greenbelts consisted of wide beach and wooded areas. These barriers undoubtedly provided many benefits to the area but in most locations the team visited they were severely eroded or removed entirely.

- Land level change - The investigation team observed subsidence on several scales. On a localized scale, subsidence in some areas was due to soil liquefaction, as well as differential settlement and lateral spreading. This type of subsidence became most noticeable on large expanses of paved area, such as in ports and parking lots. On a regional scale, long sections of the Great East Japan coast dropped in elevation due to seismic activity. This large-scale subsidence converted the tidal flats at Gamo to an open water area. The City of Onagawa now regularly experiences overwash of the harbor quays during daily high tides.

Lessons Learned

- The damage due to overtopping is often the result of unforeseen conditions – flow conditions that were not considered as part of the design process. Contingency planning will become an important element of decisions on rebuilding and future choices for the damaged communities in Japan.

- Vertical uplift causes a great deal of structural damage. Large forces from flow under bridges can cause widespread damage in places that lack adequate connections between cross members and supports.

- Strong inter-segment connections are important if a structure or wall is to function as a continuous unit. The failure of a single section of a coastal protection structure can accelerate the failure of adjacent sections and increase damage to areas shoreward of the failed section.

- Tie-ins, end attachments, and abutment protection are important design details for both structures and foundations. Extreme events highlight the weaknesses of poor connections and tie-in design or installation.

- Scour was a significant source for structural instability or failure. All manner of scour was evident in the inundation areas. Scour on the land-side of structures and at ends was very common. Much of the scour could be considered a nuisance, but in some locations, it was sufficient to damage structures or put them in danger.

- Greenbelts do not necessarily provide effective protection from a tsunami, especially the extreme tsunami inundation and fast moving currents generated in the Great East Japan event.

- Subsidence provides a preview of the possible future coastal problems from both seismic activity and rising sea level. Large-scale subsidence poses a significant regional concern. Unlike differential settlement and lateral spreading, large-scale subsistence defies an effective property-by-property treatment.

Recommendations

- In design frameworks that are based upon a once in 100-year or once in 500-year event, it is understood that more extreme conditions are possible. Catastrophic failures or failures that trigger a chain reaction can change a destructive event to a disaster. Throughout project development, planners and designers should consider the consequences of structural failures and, if possible, include design safeguards that reduce conditions where structural failures can become catastrophic or initiate a chain of events that adds to the disaster. When possible, contingency planning, or examining the “what if” conditions, would help minimize situations where engineered structures contribute to the severity of a disaster.

- In connection with examination of "what if" conditions, communities should continue to include evacuation planning in response to tsunami generation.

- The Great East Japan tsunami provides valuable new information on extreme hydraulic loads that can be evaluated and incorporated into extreme event design guidance. The performance of a structure designed for tsunami exposure should take into account hydrodynamic loads like vertical uplift, fluid and debris impacts, hydrostatic loads, and drag. Internal and foundation connections, tie-ins, end attachments, and abutments must all be designed to withstand these loads as well.

- Current design practice does not address the scour patterns that were observed inland of coastal dikes or around building pads. Since scour can contribute significantly to structural instability, it is important to better understand scour formation, patterns of scour development and sediment transport around barriers and large scale structures. Based on our observations of various beaches throughout the inundation area, we also recommend that there be additional attention paid to beach response to tsunami wave conditions.

- Shore and scour protection in Japan relies heavily on concrete armor units often shaped differently than armor units currently employed in the U.S. The scant availability of quarry stone in Japan helps to explain the reliance on concrete. Before considering the use of these units in additional applications, engineers should investigate each unit's stability coefficient as well as each unit's performance under controlled conditions in a wave tank or through monitored field investigations.

- No evidence indicates that the use of greenbelts would have been effective immediately adjacent to the shoreline; however, these features may have provided some protection for more inland development. The level of protection that can be provided by various greenbelt configurations needs to be studied more to enable their future use as part of an overall coastal community protection program.