Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

TOHOKU TSUNAMI-INDUCED BUILDING DAMAGE ANALYSIS INCLUDING THE CONTRIBUTION OF EARTHQUAKE RESISTANT DESIGN TO TSUNAMI RESILIENCE OF MULTI-STORY BUILDINGS

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ABSTRACT: The structural details of numerous buildings in the Tohoku region were documented by the American Society of Civil Engineers. Tsunami flow depths and velocities were determined based on analysis of video records and the effects on simple benchmark structures in the flow. Failure analysis of several buildings was then used to evaluate design equations for hydrodynamic loading conditions. These findings will influence the design objectives of the forthcoming chapter on Tsunami Loads and Effects in the ASCE 7 Standard, Minimum Design Loads for Buildings and Other Structures.

Key Words: Great East Japan earthquake, Tohoku Tsunami, seismic design, tsunami loads and effects, tsunami flow velocities, failure analysis, ASCE 7 Standard, multi-story buildings, LiDAR

INTRODUCTION

The Great East Japan earthquake and Tohoku Tsunami inflicted substantial damage to many coastal communities in Japan, including their critical port facilities, residential and commercial buildings, and infrastructure. In April, 2011, the American Society of Civil Engineers (ASCE) sponsored a team of engineers to survey tsunami effects on structures along the Tohoku coastline of Honshu. The team consisted of members of the ASCE 7 subcommittee on Tsunami Loads and Effects. The survey objectives were to investigate structural failures and successes in order to evaluate loadings being considered for a new chapter on Tsunami Loads and Effects in the ASCE 7 Standard, Minimum Design Loads for Buildings and Other Structures. A subsequent survey captured detailed LiDAR data of selected structures. The powerful 3D data provides a virtual world that enables many types of analyses, including deformation maps of partial concrete wall blow-outs, scour depths and volumes, displacements of damaged steel frame structures, bridge collapses, and other failures. This is valuable information to validate numerical models and theories, enabling the quantification and understanding of tsunami forces, failure mode, and for validation of non-linear structural response analysis. This paper discusses the methodology used to evaluate tsunami loading provisions being considered for adoption using these full-scale tsunami damage field observations. In addition, the contribution of seismic maximum inelastic capacity to the successful performance of multi-story buildings subjected to tsunami loads was further evaluated. The authors will discuss how these findings may influence the performance objectives of the new chapter on Tsunami Loads and Effects in the ASCE 7 Standard.

TSUNAMI RECONNAISSANCES AFTER THE GREAT EAST JAPAN EARTHQUAKE

Tohoku Tsunami Reconnaissance Objectives

The reconnaissance teams had several principal objectives in the post-tsunami evaluation:

1. Collect detailed structural data for specific structures as input for case studies of loading,
2. Perform detailed, 3D laser scan of selected buildings for use in the validation of analysis, and
3. Use findings to develop improved building codes for USA regions with tsunami hazards.

ASCE/SEI Tohoku Tsunami Reconnaissance Team

There is great interest in the United States in studying the effects of the Tohoku Tsunami, due to the analogous threat posed by the Cascadia subduction zone to the Pacific Northwest of North America. In 1700 it is estimated that this subduction zone generated a tsunami-genic earthquake of magnitude 9. The Tohoku Tsunami provided substantial information regarding tsunami impacts to structures in a high seismic region of a developed country with uniform design standards and a variety of tsunami failure loading conditions, both observed and analytically derived. The ASCE Structural Engineering Institute (ASCE SEI) will be incorporating tsunami design provisions in the national load standard, ASCE 7, and the principal author led the ASCE Tsunami Team to Japan a month after the Tohoku Tsunami of March 11, 2011, working with members of the Japan Society of Civil Engineers. Field work (extent shown in Figure 1) concentrated on identifying structures of interest, local tsunami inundation depths, and researching the probable flow velocities either by video analysis or by analysis of failure mechanisms of “flow surrogate” structural elements.

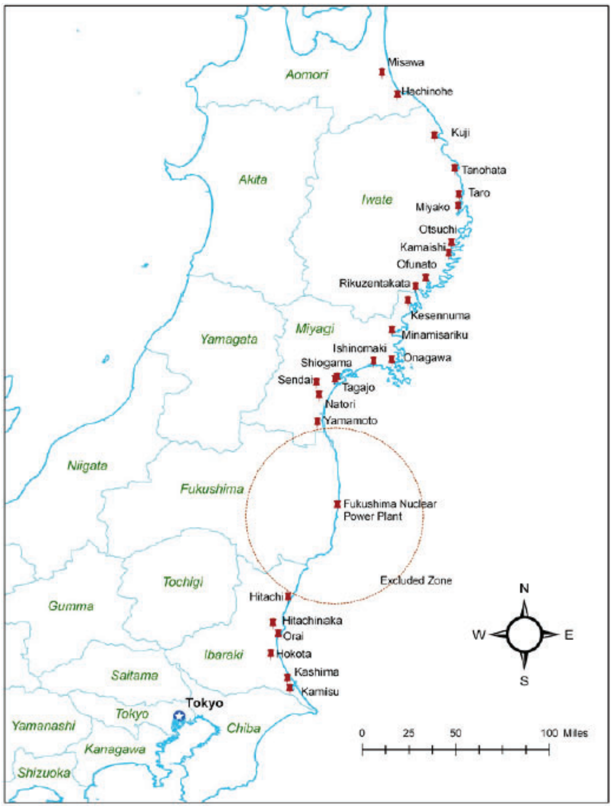


Fig. 1 Extent of the ASCE SEI Reconnaissance

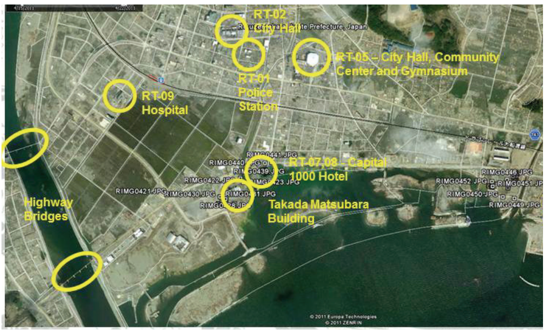
A full report by ASCE/SEI is in publication (Chock, Robertson, Kriebel, Francis, Nistor, 2012).

National Science Foundation 3D laser scanning

Scanning technology provides an invaluable resource to digitally preserve a scene so that engineers and scientists can virtually visit the scene repeatedly to validate models and theories. Light Detection and Ranging (LIDAR) 3D laser scanning is a line of sight technology that emits laser pulses at defined, horizontal and vertical angular increments to produce a point cloud, containing XYZ coordinates for objects that return a portion of the light. The point cloud must be processed to remove noise, debris and sporadic points from the dataset. Tripod mounted systems are often called terrestrial laser scanners (TLS) or ground-based LIDAR. Details of typical 3D laser scan acquisition and processing can be found in Olsen et al. (2010). The 3D laser scan survey sponsored by the National Science Foundation was performed in June and July 2011 in the areas summarized in Table 1, scanning sites of interest based on surveys made by the ASCE and Building Research Institute (BRI) and National Institute of Land and Infrastructure Management (NILIM). Buildings were selected that would result in optimal case-studies for use in modeling hydrodynamic forces in both steel frame and reinforced concrete structures. This survey combined the 3D laser scanning with traditional structural measurements of: overall building geometry, and where accessible; concrete member sizes, reinforcing sizes and layout; structural steel sizes and plate thicknesses; and other pertinent structural information and damage Measurements made within an aligned 3D scan dataset can generally be obtained at sub-centimeter level accuracies. The 3D laser scan data, as such, allows for virtual reconnaissance efforts where the user can make measurements without being present at the site and at points that would be inaccessible in the real world. The measurements extracted from point clouds of the buildings can be used to validate the failure analyses for these structures.

Table 1 Locations surveyed with 3D laser scanning and example of Rikuzentakata sites

Site	**Prefecture**	**Emphasis**	**Scans**
Yuriage\Natori	Miyagi	Structural	20
Onagawa	Miyagi	Topography	30
Minami-Gamou (Waste- water Treatment Plant)	Miyagi	Structural	10
Minamisanriku	Miyagi	Structural	5
Rikuzentakata	Iwate	Structural & Topographic	38
Totals			**103**



DATA ANALYSIS

Estimation of Tsunami Flow Velocities

In order to estimate the hydrodynamic forces applied to structures during a tsunami it is necessary to estimate the flow depth and velocity that caused the observed damage. The Tohoku tsunami provided an unprecedented opportunity to analyze tsunami flow conditions based on video and field evidence. Much of this analysis can be performed remotely using just the captured videos and satellite imagery tools such as Google Earth. However, field verification of dimensions provides valuable confirmation of the assumptions made during video analysis. Field investigation is also necessary to determine flow depth which may be difficult to estimate from the video evidence alone. Video evidence of tsunami flow characteristics is only available at certain locations depending on where helicopters or observers were located at the time of the inundation. Because of the variability in tsunami flow characteristics from location to location due to changes in bathymetry, topography, and physical obstructions, it is not always possible to base flow characteristics at one location on those determined for another location. If video evidence is not available at a location of interest, it is possible to estimate the flow characteristics by failure analysis of a "flow surrogate" structure. Utilizing both video and "flow surrogate" analysis, we have been able to ascertain flow velocities at numerous sites of interest. As shown in Tables 2 and 3, the tsunami flow velocities were typically found in the range from 5 to 8 m/s. However, there is evidence that flow velocities reached 10 m/s in areas of concentrated flow.

Table 2 Summary of the tsunami flow velocities determined using video analysis.

Location	**Wave form**	**Tracking object**	**Est. velocity (m/s)**
Natori River	River bore	Leading edge of bore	6.89
Sendai Airport	Sheet flow surge	Leading edge of flow	3.75
Kamaishi	Surge	Leading edge of flow	3.75
	Surge	Debris in flow	5.17
Kesennuma	Surge	Debris in flow between buildings	4.74 – 5.0
Onagawa	Initial sheet flow surge	Sheet flow over port streets	2.92
	Inflow at 50% inundation	Debris in flow	3.91
	Outflow between Marine Pal Bldgs	Debris in flow	7.43 – 8.19
Minamisanriku	Incoming river surge	Debris in flow	5 – 8.73
Noda Tamagawa	Harbor bore	Leading edge of bore	9.78
	Unbroken swell	Leading edge of swell	13.4
Kuji Port	Unbroken swell	Leading edge of swell	12.3

Table 3: Summary of flow velocities determined from flow surrogate structures

Location	Flow surrogate	Est. velocity (m/s)	Evaluation
Yuriage, Natori	Concrete utility room	7.75	Minimum velocity
Sendai Park	Flag poles	3.5 – 4	Varies with aluminum strength
Onagawa	Street sign	>3	Minimum drawdown velocity
Tarou	Hillside handrail	4	Assumed steel strength
	2-story steel frame	5.75	
Hotel Ragaso	Concrete Trellis	4.5	
Rikuzentakata	Large light pole	7.25	
	Bridge guardrail	7.25 – 7.75	
Otsuchi	Steel bollards	10	Breach focused flow from river bank

Flow Characteristics at the Takada Matsubara Building in Rikuzentakata

The utility of “flow surrogate” simple structures adjacent to a more complex building failure is illustrated by the case of a large-scale wall blowout in the Takada Matsubara building in Rikuzentakata. Two large light standards stood on either side of the building, and a section of undamaged bridge was also nearby (Figure 2). The maximum inundation depth measured by fishing debris on the building was less than the elevation of the light fixture on top of the pole. Based on structural analysis, the pushover of the light standards during the 10 meter deep inflow had the following sequence. Under flexural bending, an initial buckling of the thin pipe walls above the base plate stiffeners resulted in rotation of the pipe until the initially dry light fixture frame at the top of the pole was lowered into the flow and captured debris. This debris load at the top of the pole greatly increased the moment at the base and initiated much more rotation until it generated tensile rupture of the anchor bolts. The bolt anchorage group had higher moment capacity than the flexural local buckling strength of the pole. A depth-averaged flow velocity of at least 7.25 m/s was determined from structural analysis of the pole in order to create the initial buckling. In the same vicinity, the undamaged railings of a bridge were analyzed to provide an upper bound for the flow velocity of 7.75 m/s at this location. Thus, at this location we have estimates that the flow velocity to be greater than 7.25 m/s but less than 7.75 m/s.

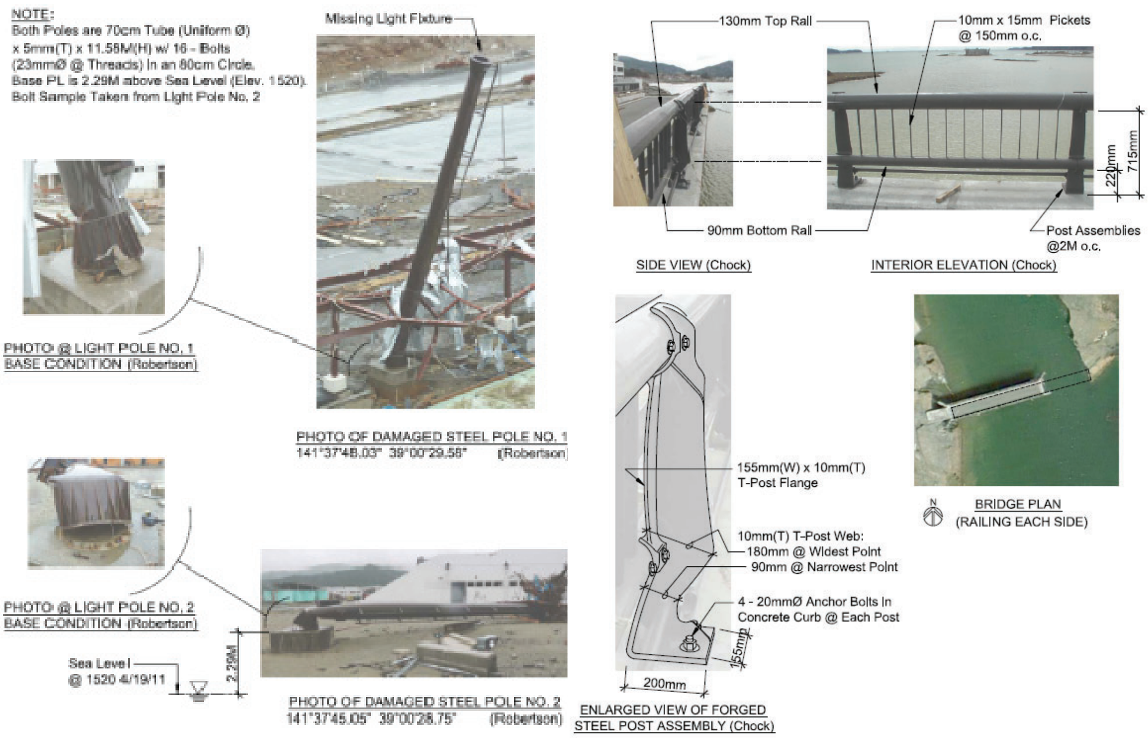


Fig. 2 Flow “surrogate structures” next to the Takada Matsubara Building in Rikuzentakata

Flow Velocity derived from Concrete Wall Failures during Inflow at Yuriage Fish Market

A large morning fish market building was located directly at the wharf area at the harbor of Yuriage (Figure 3). The building consisted of a large 120 m long by 20 m wide steel-truss framed single story high-bay building with a smaller attached one-story single bay of reinforced concrete bearing walls and concrete roof slab. The steel-framed main building was stripped off. A reinforced concrete utility closet for equipment had its sole door opening oriented towards the incoming tsunami, and was thus subjected to the internal pressure resulting from stagnation of the flow. Reinforcing bar samples tested to be equivalent to JIS G3112 SD 390 with 400 MPa average yield strength. In order for the failures shown here to have occurred, flow velocity would have been at least 7.5 meters/second.

Fig. 3**:** Wall corner joint and flexural failure by internal hydrodynamic pressurization

Flow Characteristics derived from a concrete warehouse in Onagawa

This case study was used to estimate flow velocity during the drawdown phase of the tsunami at Onagawa. The concrete warehouse building shown in Figure 4 had three sides enclosed and became internally pressurized by flow stagnation during tsunami drawdown. The 3D laser scan shows large deformations of over 0.5 m in the larger wall panels, while the smaller panels had negligible lateral deformations. Analysis based on a stagnated hydrodynamic load was able to show that the larger panels in the exterior walls failed after flexural yielding of the panels followed by formation of a catenary membrane, then shear failure around the perimeter of the wall. The flow velocity for such a condition was at least 5.5 m/s. Some cracking due to yielding around the perimeter of the walls was observed in the smaller wall segments, but the segments did not fail. The shorter vertical spans resulted in reduced bending moments in these wall segments. It was calculated that a flow velocity of around 7.5 m/s would have been required to fail the smaller wall segments.

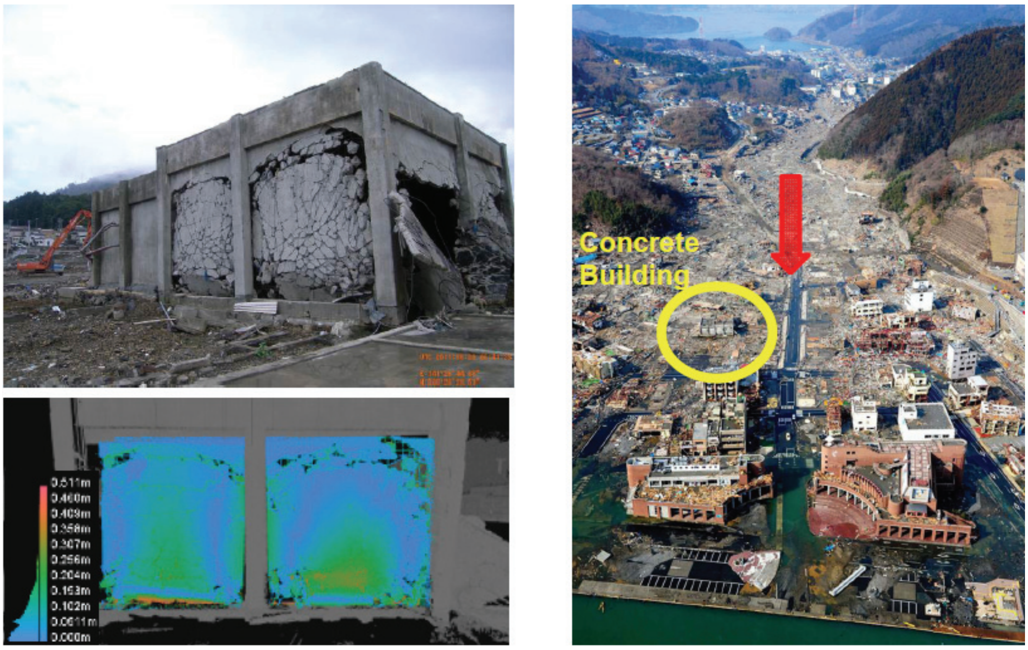


Fig. 4 Concrete warehouse wall failure due to internal pressurization in Onagawa. (a) Photograph, (b) 3D laser scan model (c) Building location

STRUCTURAL ANALYSIS

The ASCE Tsunami Reconnaissance Team selected a number of representative cases for failure mode analysis. In this section, cases studies of hydrostatic and hydrodynamic loading are further evaluated. The loading equations discussed by Chock (2011) and Robertson (2011) were the basis for this analysis.

Onagawa Two-Story Cold Storage Building Buoyant Uplift

The building shown in Figure 5 was lifted by hydrostatic buoyancy off of its pile foundation, which did not have tensile capacity. This building was approximately 22 meters by 8.7 meters by 12 meters tall. Based on extensive field measurements and a concrete density of 2400 kg/m^3, the total deadweight of the structure was 8995 kN. The refrigerated space on the ground floor was effectively sealed off, leading to a neutrally buoyant condition as soon as the water inundation depth reached 7 meters. The building was lifted off its original site and carried over a low wall (photograph on the left), before being deposited about 15 meters inland from its original location. It was apparently flipped over by contact with the top of the wall that it damaged in the process. The low wall had its top edge broken off. A large opening was chipped into the wall to access the interior of the building after the tsunami.

Fig. 5 The ASCE Tohoku Tsunami Reconnaissance Team at the Onagawa uplifted and overturned 2-story reinforced concrete cold-storage building

Onagawa Three-Story Steel Building Lateral Pushover

The three-story steel moment-resisting frame in Figure 6 was exposed to flow returning to the ocean estimated from video analysis at about 8 m/s. This flow was sufficient to yield the top and bottom of the second story columns and top of the first story columns with an estimated 67% blockage of the original enclosure, either from cladding still intact or debris damming. At the first yield point of the system, the calculated lateral drift at the third floor would be about 30 cm. Subsequently sustained flow induced further displacement. A subsequent LiDAR scan of the frame shows a third floor drift of up to 50 cm. Therefore, it is proposed that once yielding of the structure had occurred, with significant inelastic deformation, the blockage percentage reduced until loss of all cladding reduced the building's projected area , relieving the structure of much of the lateral pressure. Without such load shedding, collapse would have occurred.

Fig. 6 Onagawa 3-Story Steel Frame Pushover

Minami Gamou Wastewater Treatment Plant Bore Impact

The Minami Gamou Wastewater Treatment plant building shown in Figure 7 is a three-story reinforced concrete building, located on the Sendai coastline south of the main port and approximately 350 meters from the coastline. Video of this facility in Sendai showed a tsunami bore directly striking the longitudinal walls of buildings. The ocean facing wall of a two story high-bay on one side of the building failed through out-of-plane flexure due to the large hydrodynamic forces.

Using inundation depth estimates by the Joint Survey Group and video footage, the resulting pressure distribution was applied to a nonlinear finite element model (FEM) of the reinforced concrete wall. A tsunami bore travelling over standing water and striking a wall is addressed by the method of Robertson, Paczkowski, and Riggs (2011) for structural walls oriented perpendicular to the flow direction with a width greater than $3h_b$ or $3h_j$, whichever is smaller, as shown in Figure 8. The transient lateral load per unit width of wall is given by Eq. (1).

$$F_w = k_s \rho_{sw} \left(\frac{1}{2} g h_b^2 + h_j v_j^2 + g^{1/3} (h_j v_j)^{4/3} \right) \qquad (1)$$

This force acts at $(h_b+h_r)/3$ from the base of the wall, where h_r.is given by Eq. (2)

$$h_r = g^{-\frac{1}{3}} (v_j h_j)^{\frac{2}{3}} \qquad (2)$$

Structural drawings for the damaged buildings were obtained from the plant management. The bore forces were found to be sufficient to create the mid-height and top and bottom flexural yielding (Figure 9). The bore impact forces were also found to exceed the surge and hydrostatic forces resulting from the rising tsunami surge. It is concluded that repeated bore impacts were likely to be responsible for the amount of deformation found in this wall and another building nearby.

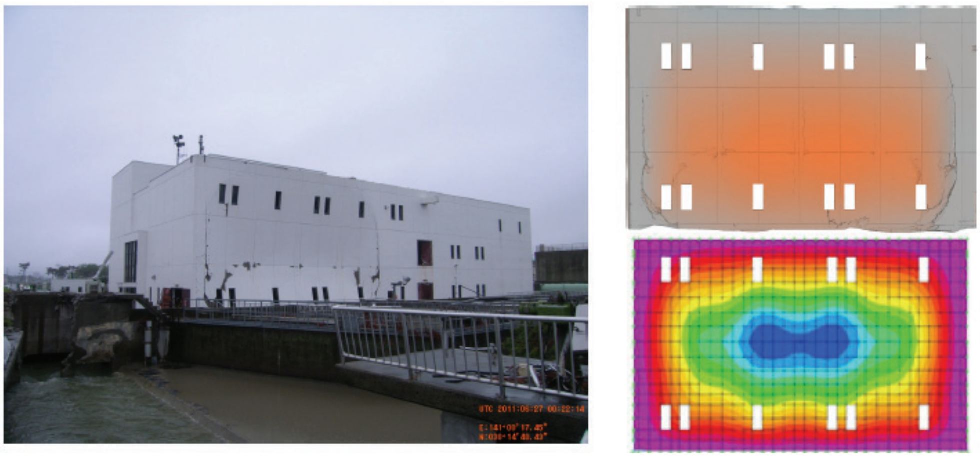


Fig. 7 Reinforced concrete wall at the Minami Gamou Wastewater Treatment Plant Pump Station damaged by direct strike from tsunami bore (a) exterior view, (b) LiDAR view (c) Analysis Plot

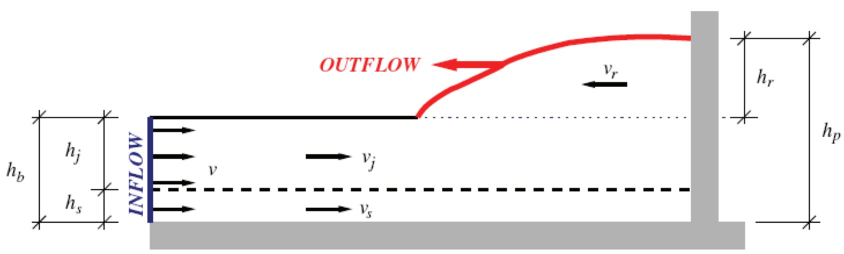


Fig. 8 (a) Parameters for a tsunami bore travelling over standing water and striking a wall

Rikuzentakata Tourist Center Concrete Wall Failure due to Inflow Loading

The Takada Matsubara Road Station in Rikuzentakata shown in Figure 9 endured a 10.5 meter tsunami inundation depth with flow of about 7.5 meters/second, but suffered a failure of its principal transverse shear wall due to unbalanced hydrostatic and hydrodynamic forces of the incoming tsunami. The wall was at the rear face of a three-sided concrete box with the opening in the fourth side being a main entrance into the building at the front facing the ocean. Reinforcing steel was sampled and tested at 510 MPa average yield strength, consistent with JIS G3112 SD 490.

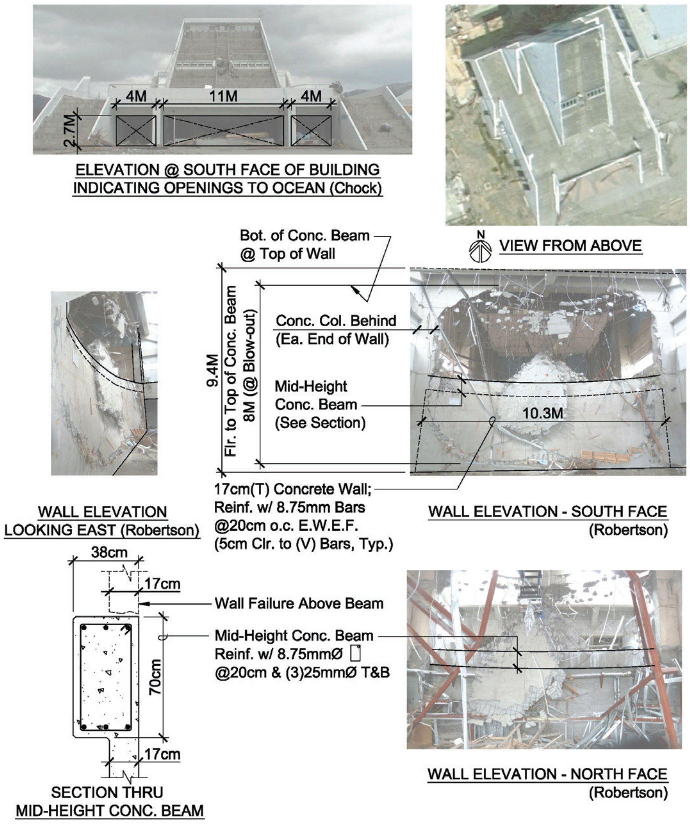


Fig. 9 Large Wall Failure in the Takada Matsubara Building in Rikuzentakata

The probable sequence of nonlinearities ultimately leading to failure was found by stepwise nonlinear analysis of the progression of unbalanced hydrostatic and hydrodynamic loading to be:

1. Flexural yielding of the base of the wall as soon as the flow level reached 1.6 meters.
2. Bottom half of side edge supports of the wall and the two ends of the horizontal beam yield when the flow level reached 2.2 meters.
3. The top and upper portions of the side supports of the wall yield and concrete shear cracks occur at the bottom when the flow reaches 2.7 meters. Shear friction of the double dowels from the wall base foundation maintains stability of the bottom portion the wall.
4. Side supports and horizontal beam supports reach concrete shear failure cracking when the flow reaches 7.2 meters. The flexurally yielded wall essentially became a membrane.
5. The top and upper portions of the side supports reach concrete shear failure cracking when the flow reaches 9.5 meters. The top half of the wall is hanging in tension from the top beam.
6. At 10.5 meters, the upper portion of the concrete walls hanging in tension drops down and relieves further loading increase; the unbalanced hydrostatic forces are relieved.

COMPARISON OF TSUNAMI FORCES WITH SEISMIC DESIGN CAPACITIES

We compare tsunami loading to the ultimate inelastic structural capacity of buildings designed to current seismic codes in the USA and Japan. While they have essential common features, there are many procedures on which the U. S. and Japanese seismic designs differ.

1. The U. S. seismic provisions are based on Maximum Considered Earthquake. The Japanese seismic designs are based on two levels of earthquakes (i.e., moderate and severe).
2. In the U. S. seismic loads are adjusted based on Occupancy Category. For essential facilities, seismic forces could be 50% higher than a building with standard occupancy. Japanese designs don’t have an importance factor to adjust seismic loads based on occupancy.
3. Japanese design response spectrum (severe earthquake) is higher than the U. S. for a building with a very short period or long period. They are similar for structures with a short period.
4. Japanese seismic design code adopts a two-phase design procedure which checks both serviceability and ultimate limit states. The U. S. seismic design provisions do not require that structural members be checked for serviceability.
5. The U. S. seismic designs use *R*-factor to account for both the structural ductility and overstrength of a lateral system. The *R*-factor ranges from 1.5 to 8.0. The Japanese seismic code uses a constant factor equivalent to *R*= 4.0 for all systems.
6. The drift limits specified by the Japanese code may be more stringent than the U. S. for a ductile system and vice versa for a non-ductile system.

Larger scaled and taller buildings will be inherently less susceptible to tsunamis, provided adequate foundation anchorage for resistance to scour and uplift is present. The Japanese seismic design code (Kuromoto, 2006) generally results in greater lateral forces and stiffer systems for reinforced concrete and steel buildings than in the USA. Seismic designs in the USA (Chock, 2010) utilize greater reduction of the elastic design force, and this may also result in an impairment of capacity from earthquake damage prior to the arrival of the tsunami. Parameters for this comparison to tsunami loading are as follows: 1) the prototypical building is 120ft long and 90ft wide and is 25% open; 2) it is located in high seismic zones (for Japan, in Seismic Zone A; for U.S., Ss = 1.5 and S1 = 0.6); 3) connections develop the inelastic capacities of the members; 4) tsunami flow velocity is 8m/s, 5) each tsunami inundation load curve represents the sequence of hydrodynamic loading effects as inundation increases to the maximum depth, and 6) maximum seismic inelastic capacity is utilized with the overstrength Ω factor.

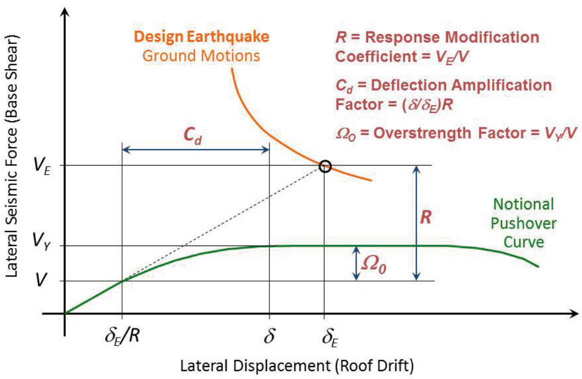


Fig. 10 Illustration of USA Seismic performance factors based on inelastic response capacity

Figure 11 shows a comparison using a prototypical steel building of various heights. Figure 12 shows a comparison of a prototypical reinforced concrete building. We present three- and four-story deep tsunami inundations as load histories in the depth and load domain. Mid -rise reinforced concrete buildings with shear walls appear to survive structurally without collapse. Japanese steel buildings appear to have similar capability, but USA steel buildings would need to be strengthened at their lower stories beyond seismic code in order to have the necessary structural integrity for tsunami resistance.

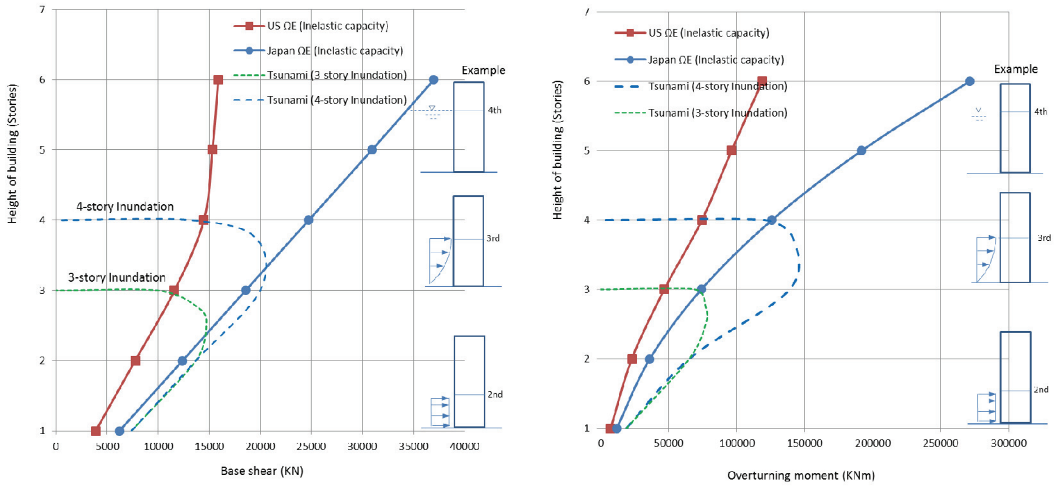


Fig. 11 Comparisons of seismic & tsunami actions for USA and Japanese special steel moment-resisting frame buildings based on drift-governed member sizes

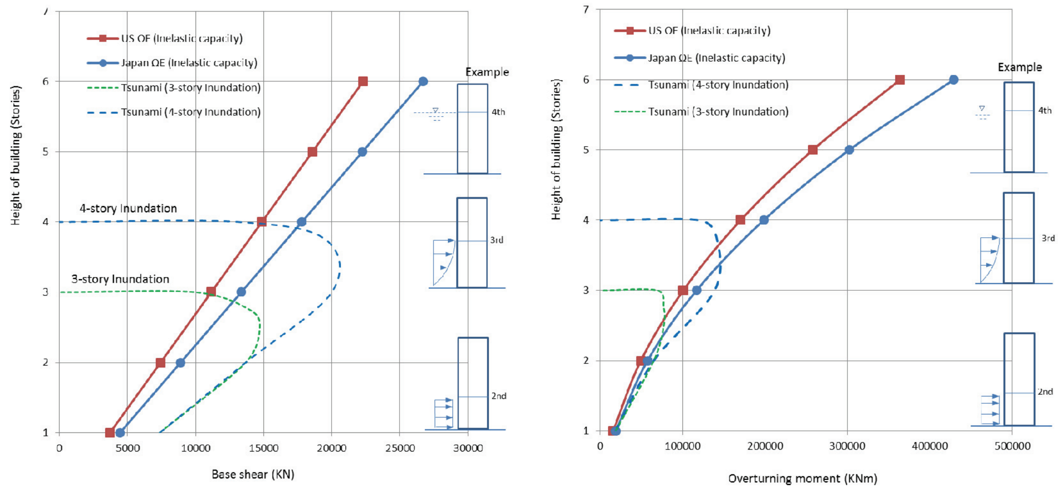


Fig. 12 Comparisons of seismic and tsunami actions for USA and Japanese concrete structural walls

CONCLUSIONS

Tsunami Lessons for the Design of Buildings and Other Structures

Structures of all material types can be subject to collapse during tsunami, but it is feasible to design taller buildings to withstand large tsunami. Building lateral strength and local element resistance to impact are keys to survivability. Seismic design does have a beneficial effect that increases with the height, size, and seismic design level of the building, and expected maximum inelastic capacity can be used to find the height of archetype structures with inherent tsunami resistance. For Japanese designs, modestly-sized buildings one story taller than the inundation may have adequate structural integrity. For USA designs of similar height, sufficient structural integrity may not be reached for steel moment frame systems. Foundation anchorage needs to consider overturning under buoyancy as well, and having sufficient openness in buildings will alleviate buoyancy. Conversely, structurally boxed-in areas will be subject to hydrodynamic over-pressurization. Loads on structures must consider debris damming and blockage; complete breakaway cladding should not be relied upon to relieve loads. Foundations should consider scour effects particularly at building corners.

Tsunami Design Performance Objectives Proposed for Tsunami Design Provisions in ASCE 7

The provisions will most likely have differing requirements based on height, seismic base shear, and the Risk Category of Building defined in ASCE 7 per Table 4. In Figure 13, the key performance levels are shown for two return periods, the 100-year period and a maximum considered 2500-year event consistent with existing seismic provisions. Buildings would be designed for structural elevation above the 100-year tsunami inundation height, similar to coastal storm flooding. The design limit for the 2500-year event would be based on the inelastic capacity of structural behavior.

Table 4 Risk categories of buildings and other structures per ASCE 7

Risk Category I	Buildings and other structures that represent a low risk to human
Risk Category II	All buildings and other structures except those listed in Risk Categories I, III, IV
Risk Category III	Buildings and other structures with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.
Risk Category IV	Buildings and other structures designated as essential facilities

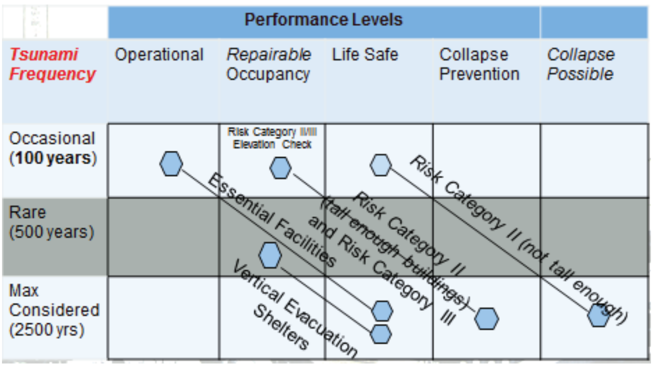


Fig. 13 Proposed Tsunami Design Performance Objectives

ACKNOWLEDGMENTS

We greatly appreciate the quick decision of the ASCE Board to fund the ASCE/SEI Tohoku Tsunami Reconnaissance on which data this study is based. Funding for the LiDAR survey was provided by the National Science Foundation through a NSF Rapid Grant (1138710 and 1138699).

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