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ENGINEERING SIGNIFICANCE AND LESSONS OF THE MARCH 11, 2011 TOHOKU TSUNAMI - TSUNAMI IMPACTS ON STRUCTURES

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ABSTRACT: The paper will present results collected by the first international forensic engineering research team composed of four engineers (three from US and the author, from Canada), who surveyed the affected area approximately four weeks after the 2011 Tohoku Tsunami to conduct reconnaissance work on behalf of the American Society of Civil Engineers (ASCE). The paper will present findings and observations on the performance of particularly buildings and the general damage caused by devastating tsunami waves on infrastructure. On March 11, 2011, a magnitude 9.0 earthquake occurred along the Sanriku Coast, offshore northeast Japan, at 3:46 p.m. local time. The quake resulted in several massive tsunami waves that hit the Japanese coast, often reaching runups of up to 10 to 30 meters in height along the coast and even in excess of 45 meters locally in several areas. Consequently, significant damage affected engineered and non-engineered structures located in several coastal towns that were largely destroyed. The paper presents a brief description of some of the structures affected by the tsunami inundation. The field survey and the subsequent analysis outlined the need for new, mandatory design standards that would account for the tsunami-induced loading.

1. Introduction

Tsunami waves are catastrophic events which can adversely impact communities located in often heavily populated coastal areas around the world, including Canada (Clague et al., 2003; Satake et al., 2003; Nistor & Murty, 2009, Etkin 2010). Tsunami-induced coastal flooding often leads to numerous casualties and significant economic losses (Saatcioglu et al., 2006, Koshimura et al., 2009). Such extreme waves can propagate thousands of kilometers away from their generating source. Since 80% of tsunamis in the world have occurred in the Pacific Ocean, the western coast of Canada is particularly susceptible to the threat of tsunami waves attack. Seismological features off the coast of British Columbia are similar to those in the Indian Ocean, which generated the recent Tsunami of December 2004, to those off the coast of Chile that triggered the 2010 Earthquake and Tsunami and particularly to those off the north-eastern coast of Tohoku which generated the March 2011 Tohoku Tsunami. From northern Vancouver Island to northern California, the Cascadia Subduction Zone delineates the boundary between the smaller offshore Juan de Fuca Plate that is sliding under the much larger North American Plate. Research demonstrated that tsunami-generating earthquakes of magnitude 9.0 or greater have occurred in the past: recent seismological research (GSC, 2010) indicates that such an event has an average return period of approximately 500 years, with the shortest gap between events being less than 300 years. The 1700 Cascadia Earthquake of magnitude 9.0 was generated by a fault rupture over a length of approximately 1000 km and subsequently triggered a massive tsunami wave which, based on paleo-geological evidence (Clague et al., 2003), showed that the western coast of Vancouver Island was severely affected by tsunami flooding. More recent damaging tsunamis affected the western coast of Canada in 1899 (Northern Georgia Strait, BC), 1964 (Port Alberni, BC), 1994 (northern coast of BC), and the Canadian eastern coast in 1929 (Burin Peninsula, NF). Ultimately, a massive earthquake occurring along the Cascadia Fault, which constitutes the focus of intense research for earthquake and structural engineers in Canada, will, most probably, be accompanied by a major tsunami event that could significantly affect large cities such as Victoria, Tofino, Port Alberni and, with lesser intensity due to its sheltered geographical location, Vancouver.

Events which occurred during the past decade, including the December 2004 Indian Ocean Tsunami with approximately 230,000 victims (the second deadliest natural disaster in the history of mankind - Etkin et al., 2010), the April 2007 South Pacific (Solomon Islands) Tsunami, the February 2010 Chile Tsunami, and the March 2011 Tohoku Tsunami (the costliest natural disaster in the history of mankind with 300 billion US dollars' worth of damage – Shibayama and Nistor 2012), reinforced the importance of understanding the effects of tsunami-induced forces and the need for design guidelines for structures located near shorelines in tsunami-prone regions (Yamamoto et al., 2006; Nistor et al., 2009, Chock et al. 2012). Understanding the impact mechanisms and properly understanding the nature of tsunami-induced extreme hydrodynamic forces on coastal infrastructure and quantifying them is essential because of the enormous economic and social consequences generated by such disasters. An extensive literature review of the state-of-the-art research on tsunami forces on structures (Nistor et al., 2009) suggests that, to date, design documents or building codes that specifically address tsunami loading on near-shoreline structures are lacking. Moreover, existing documents, such as FEMA 55 (2000), were primarily developed for offshore coastal structures or coastal flooding due to storm surges. The only other two recent documents, Okada et al. (2006) and FEMA P646 (2012), while making some provisions for tsunami loading of structures, employ design parameters, such as (1) tsunami inundation flood velocity and (2) fluid pressure distribution and associated forces, that were recently shown to be either inaccurate or incorrectly estimated (Palermo et al., 2012). Additionally, from a structural engineering viewpoint, the influence of structural response on the time-history and magnitude of the extreme hydrodynamic forces has not yet been investigated (Yeh et al., 2005).

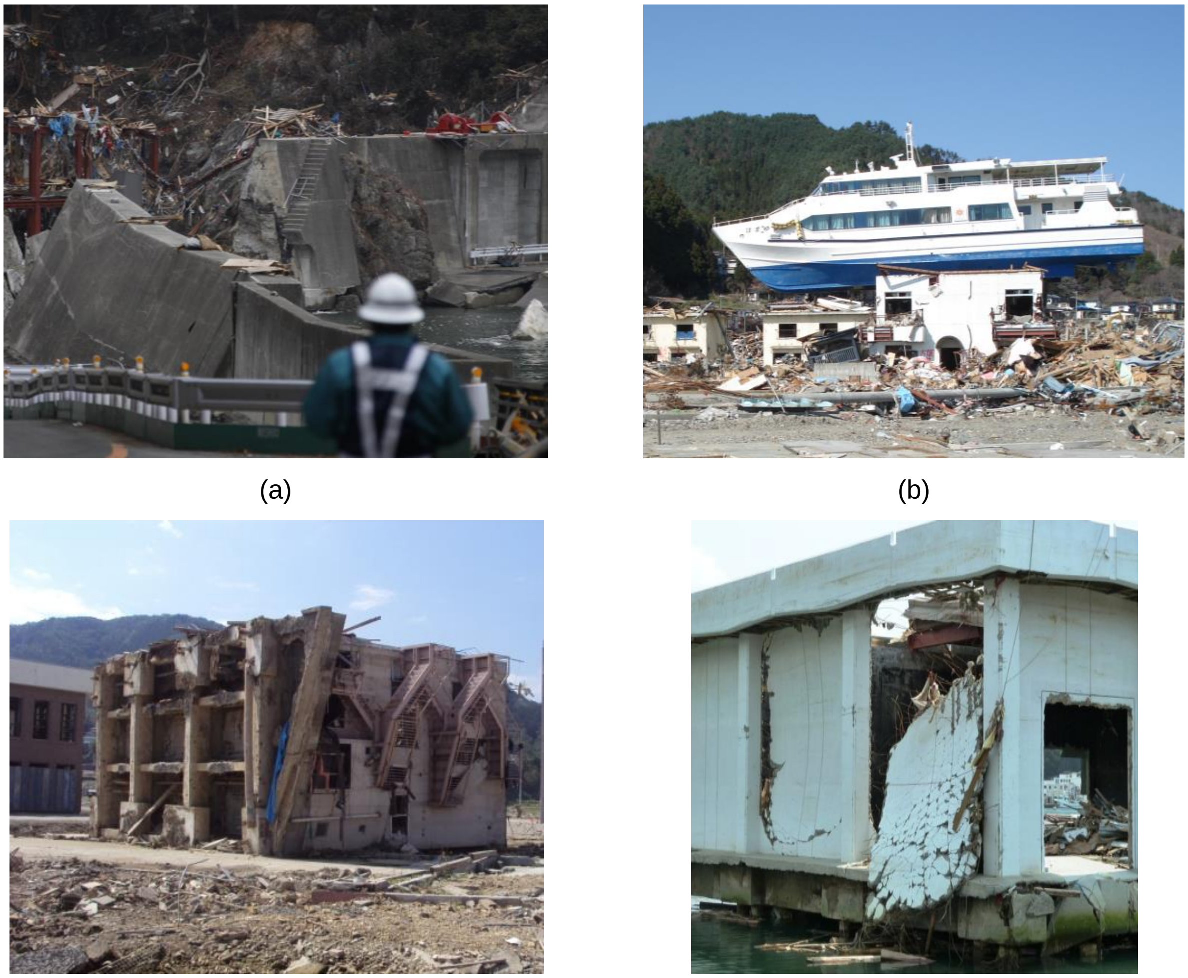
Post-tsunami field surveys represent unmatched opportunities to understand and quantify the impacts that tsunamis have on coastal communities, by conducting measurements, collecting unique field data, and by interviewing local inhabitants and authorities. Information and data collected can be further used to develop preventive measures and engineering solutions required to protect the population and infrastructure against such devastating phenomena. The author's focus during the post-tsunami surveys in which he participated was on field measurements of the spatial tsunami-generated flood parameters (inundation depth and inland flood extent) and particularly on the quantitative assessment of damage to infrastructure. As part of several interdisciplinary international teams, the has carried out the post-tsunami surveys following the December 2004 Indian Ocean Tsunami, in Thailand (in Phuket, Phi-Phi Island, and Khao Lak) and in Indonesia (Banda Aceh) (Ghobarah et al., 2006), the 2010 Chile Tsunam, and the 2011 Tohoku Tsunami. Using data collected from these surveys, aside from a qualitative damage assessment, the author performed quantitative analysis to assess the validity of the few available formulas used to estimate tsunami-induced hydrodynamic forces (Saatcioglu et al., 2006, Chock et al. 2012).

2. The Great Tohoku Tsunami of March 11, 2011

A massive earthquake of moment magnitude of 9.0 on the Richter scale occurred at 14:46 JST (05:46 UTC) under the Pacific Ocean, near the northeast coast of Japan, with the epicenter located approximately 129 km east of Sendai, Honshu, with coordinates of 38.322 N latitude and 142.369 E longitude and at a depth of 32 km. The subsequent tsunami arrived on the northeastern coast of Japan approximately 15 minutes thereafter, giving little warning time for many villages and communities. Local runup heights of up to 48 m were estimated (Chock et al. 2012). As of June 2013, This event was responsible for approximately 15,867 deaths, 6,109 injuries, and 2 909 people missing. The Japanese Cabinet Office estimated direct losses of more than $309 billion due to damage to housing, roads, utilities, and businesses, making it the most expensive natural disaster on record.

In terms of lessons learned with respect to the occurrence of such events, this massive tsunami has brought to fore the memory of a significant similar event, the July 13, 869, Jogan Sanriku Earthquake and Tsunami which occurred in the same offshore area along the northeast coast of Honshu and whose magnitude was estimated to have been magnitude 8.6. It was suggested by Japanese researchers that the March 2011 tsunami may be the indication of a 1,000-year return period megathrust subduction earthquake (Minoura and Imamura, 2001). The probability of this seismic source zone generating an earthquake of Mw 8.1 to 8.3 had been estimated to be 99% by 2037 (Satake et al., 2007). The March 11, 2011 Mw 9.0 megathrust earthquake was therefore the fourth largest earthquake in the world since 1900, and surpassed in magnitude the 869 Jogan Earthquake as the largest earthquake known to have ever affected Japan.

The destruction caused by this tsunami was extensive and somehow surprising given that Japan is a most equipped and trained country when it comes to protection against tsunami. However, tsunami waves displaced, overtopped and destroyed large structures, including seawalls, which were initially constructed to mitigate the impact of tsunami waves on local communities. The designs of these structures were based on historical tsunamis and were not necessarily sufficient considering probabilistic-based tsunami events. Figure 1 illustrates the effects of the 2011 Tohoku Tsunami, including breaching and overtopping of large concrete sea walls, displacement of floating vessels, overturning of a concrete building, and punching failure of a reinforced concrete wall panel.



(a) (b)

(c) (d)

Figure 4. Effects of 2011 Japan tsunami on structures (Nistor, 2012): a) breaching and overtopping of concrete sea walls in Taro; b) impact loading from large vessel in Otsuchi; c) overturning of reinforced concrete apartment building in Onagawa; and d) punching failure of reinforced concrete walls in Onagawa

3. Joint ASCE/JSCE Survey of the Tohoku Region Tsunami

The ASCE-SEI Tsunami team comprised two groups seven engineers and researchers who were selected from the 30-plus members of the Tsunami Loads and Effects Subcommittee (TLESC) responsible for the development of tsunami design provisions to be introduced into the ASCE 7-2016 Standard, Minimum Design Loads for Buildings and Other Structures. All team members had experience with post-tsunami damage assessments and earthquake reconnaissance efforts conducted abroad. The ASCE-SEI tsunami reconnaissance and damage assessment was significantly helped by the collaboration with the Japanese researchers in tsunami design. In this sense, the UNESCO-NOAA

International Tsunami Information Center (ITIC) and the Japan Society of Civil Engineers set up a recommended survey protocol and point of contact for international research teams seeking to enter the tsunami-damaged area. The ASCE-SEI team traveled with teams of at least two Japanese collaborators at all times. The ASCE-SEI team was issued UN-credentialed ID badges per the standing practice of the ITIC.

The principal coordinator of the Japanese collaborators was Prof. Tomoya Shibayama from Waseda University, Tokyo, who was, at the time, the Chair of the Ocean Engineering Committee (OEC) of the Japan Society of Civil Engineers. Several Japanese engineers and researchers further assisted the ASCE-SEI team with travel and logistic arrangements within the affected region.

An important lesson from all previous tsunami field forensic surveys conducted by the author was that is essential to capture tsunami damage evidence before they were remove since it is difficult to understand the circumstances to which a particular structure was subjected. The ASCE-SEI Tohoku Tsunami Reconnaissance Team conducted field surveys starting on April 16, 2011, which was the first day officially recommended by JSCE for international tsunami teams to conduct field work. The ASCE-SEI team participated in an in-brief meeting with Dr. Shibayama and other collaborators upon arrival in Tokyo, during which Japanese data on tsunami height, inundation extent, and runup height were discussed. Maximum runup heights and inundation limits were extensively measured by Japanese researchers during the month following the tsunami. After waiting for immediate emergency assistance to be conducted, JSCE researchers had mounted a well-coordinated national survey of tsunami inundation and runup heights during the second half of the month of March and the first half of April, 2011.

The ASCE-SEI Tohoku Tsunami Reconnaissance Team performed the tsunami damage survey as two groups, with a short overlap for Group 1 to brief Group 2 before they started their own survey. Group 1 was composed of Gary Chock (Team Leader and ASCE TLESC Chair – structural; engineer), David Kriebel (US Naval Academy – coastal engineer), Ian Roberson (University of Hawaii structural engineer) and the author of this paper, Ioan Nistor (University of Ottawa – coastal engineer). Group 2 was composed of Dan Cox (Oregon State University – coastal engineer), Mathew Francis (URS Corporation – geotechnical engineer) and Solomon Yim (Oregon State University – structural engineer). Each of these two groups had several Japanese collaborators from universities and private industry assisting with the survey. Prof. Tomoya Shibayama (Waseda University – coastal engineer) and Dr. Nobuhito Mori (Kyoto University – coastal engineer) were the leaders of the two Japanese teams helping Groups 1 and 2, respectively. While the focuses of the two survey groups were similar, the present paper will mainly focus on some of the results of the survey carried out by Group 1.

4. Pre-Survey Planning of the 2011 Tohoku Tsunami Forensic Engineering Campaign

Based on the experience of previous surveys carried out by the members of the research group, a significant effort was invested into preliminary organization and research work carried out in preparation of the post-tsunami forensic engineering survey. As mentioned, the main goal of the survey work of Group 1 focused on the investigation of the impacts and effects of tsunami on onshore built infrastructure. In this sense, while some of the coastal structures like breakwaters were surveyed during the survey, the main effort was directed towards inland-built structures which were damaged or affected by the tsunami. These included, but were not limited to: (1) onshore tsunami seawalls; (2) engineered and non-engineering concrete structures, (3) engineering and non-engineered steel structures, (4) bridges and (5) buildings designated as tsunami shelters.

The preparatory and research work conducted in advance of this tsunami survey included several steps, which greatly helped the efficiency of the fieldwork. These steps are briefly described below.

4.1. JSCE Tsunami Inundation and Runup

Immediately following the tsunami, several teams organized by the Japan Society for Civil Engineering have conducted extensive field surveys of all sectors of the coastline affected by the tsunami, from Hokkaido in the north to the southern shores of the Honshu Island. The main effort was focused on the Tohoku area, all the way down south to Ibaraki Prefecture. Based on this continuously-updated, excellent quality field data, the ASCE-SEI Groups 1 and 2 were able to identify the regions of highest interest in terms of location of the field surveys to be carried out at macro scale.

An example of the data collected by the JSCE survey groups is presented below in Fig. 2.

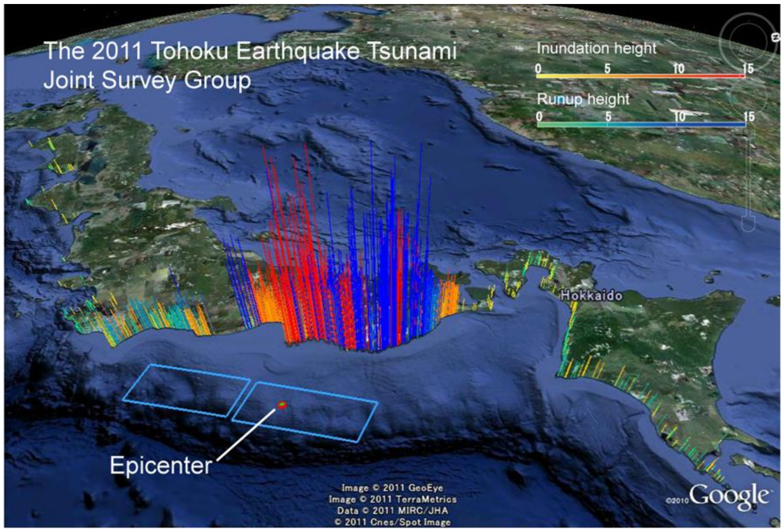


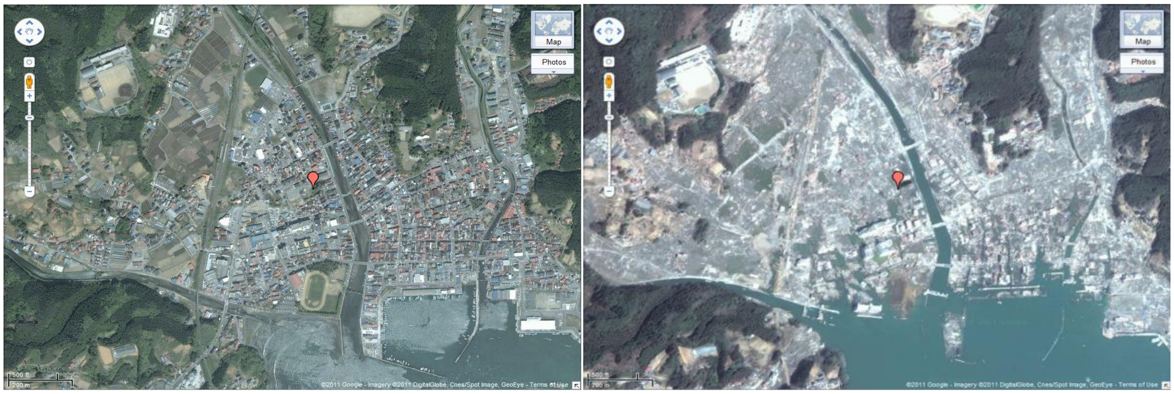
Fig. 2 - Example of the tsunami runup and inundation field data prepared by the 2011 Tohoku Earthquake Tsunami Joint Survey Group of JSCE

Particularly the coastline along the Honshu Island from Hachinohe to Ibaraki was hence identified as the main priority region to be surveyed.

4.2. Mapping of Survey and Infrastructure Locations

As soon as the region to be surveyed was established at macro-scale, the next step was to identify the communities to be surveyed as well as the structures located inside these communities to be surveyed.

One of the major sources of information was provided by the Japan Meteorological Agency website which featured tsunami warning documentation and initial offshore tsunami information. Aerial photography provided by JSCE as well as satellite images posted on the Google Earth Crisis Response (Fig. 3)., and by Digital Globe, as well as status maps prepared by the Joint Research Centre of the European Commission were very helpful in verifying areas of interest for structural evaluations.



(a) (b)

Fig. 3 – GoogleMap satellite image of the Town of Minamisanriku (a) before and (b) after the 2011 Tohoku Tsunami (GoogleMap, 2011)

In addition, the Japanese government posted a kml file of damaged and destroyed bridges and railroads for emergency management of transportation routes. Tsunami inundation limit maps produced by the Geospatial Information Authority of Japan were also electronically acquired and used by the ASCE-SEI survey groups. Information from the Asian Disaster Reduction Centre was helpful as an overarching summary developed over time.

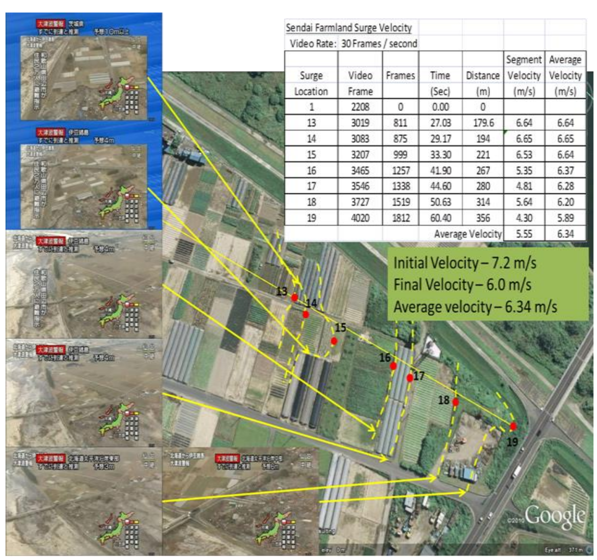
Asia Air Survey performed aerial surveillance with high-resolution cameras shortly after the tsunami as shown in Fig. 4 for the Town of Minamisanriku. On these maps, the members of the ASCE-SEI survey teams were able to identify structures, which they further surveyed during the tsunami forensic field survey.

Fig. 4 – Aerial photograph of the Town of Minamisanriku after the 2011 Tohoku Tsunami (Asia Air Survey Co., Ltd.)

By using this approach, the location and designation of many of the structures to be investigated was obtained for most of the local communities surveyed.

4.3. Video analysis and overland inundation flow velocity

The 2011 Tohoku Tsunami was one of the first events for which, due to its time of occurrence and Japan's extensive media coverage, significant video footage from various sources was available. This information was reviewed in preparation for the reconnaissance survey. NHK TV and other news media had standard operating procedures for immediate news crew deployment after major earthquakes. As a result, helicopters equipped with video cameras were airborne above the Tohoku coastline in time to record the initial tsunami waves. Numerous other videos taken by the news media and the Japanese public were archived and made available online. The frame-by-frame analysis of video was used to estimate flow velocities at various locations of interest, as shown in Figure 5.



Surge Location	Video Frame	Frames	Time (Sec)	Distance (m)	Segment Velocity (m/s)	Average Velocity (m/s)
1	2208	0	0.00	0		
13	3019	811	27.03	179.6	6.64	6.64
14	3083	875	29.17	194	6.65	6.65
15	3207	999	33.30	221	6.53	6.64
16	3465	1257	41.90	267	5.35	6.37
17	3546	1338	44.60	280	4.81	6.28
18	3727	1519	50.63	314	5.64	6.20
19	4020	1812	60.40	356	4.30	5.89
				Average Velocity	5.55	6.34

Fig. 5 – Pre-analysis of aerial video to determine Natori River bore velocity (Chock et al., 2012)

The 2011 Tohoku Earthquake Tsunami Joint Survey Group website was maintained by the Coastal Engineering Committee of the Japan Society of Civil Engineers for months, providing useful updates on tsunami inundation and runup heights. Tohoku University was among the first groups to provide structural damage photos from the Sanriku coast, most notably the Town of Onagawa. The Shibayama Lab at Waseda University also focused its Tohoku Tsunami website on field surveys of buildings and coastal structures in addition to tsunami runup. The Port and Airport Research Institute (PARI) issued a number of overview reports on tsunami effects on coastal and harbor structures. The above resources were used to digitally preview the affected region and plan the ASCE-SEI team's field survey itinerary.

5. 2011 Tohoku Tsunami-Induced Damage to Onshore Structures

Tsunami inundation height was in the range of 5 to + 30meters along the Tohoku coastline. Most of light-frame residential construction subject to about a story height or more of inundation collapsed. Therefore, complete collapse of residential light-frame construction occurred in nearly 100% of all affected areas up to the edge of the inundation limit. In commercial and industrial areas, low-rise building collapses occurred in the approximate range of 75% towards 95%, with the higher collapse rate occurring as tsunami height reached the upper range (Fig. 6).

Fig. 6 – Infrastructure damage due to tsunami inundation in Minamisanriku

In many of these inundated coastal zones, buildings taller than 5 stories were rare. Despite this devastation, a number of these multi-story buildings survived the tsunami impact without loss of structural integrity of their vertical load carrying system or foundation. In fact, a significant proportion of the surviving buildings did not appear to have significant structural damage. This provides some assurance regarding the potential resilience of larger modern buildings with robust seismic designs and scour and uplift-resistant foundations.

The ASCE-SEI two groups, on behalf of the ASCE7 Tsunami Loads and Effects Subcommittee, tried to accomplish the followings objectives:

- Understand infrastructure failure due to tsunami loading
- Collect and record basic data and field information required to evaluate mechanisms that generated damage to the infrastructures, with particular emphasis on buildings and bridges
- Contribute to tsunami load and tsunami-resistant designs for buildings such as tsunami evacuation buildings.

The damage to structures due to tsunami varied widely depending on structures' type, characteristics, location, and spatial exposure to the incoming flood. The structures investigated in detail were selected based on observed damage and likely cause of failure. Two important facts were considered in the process of selecting the structures to be investigated:

- *Complete structural failure* only indicated that the load exceeded the structure’s capacity
- *Undamaged structures* indicated potential for success as their capacity was larger than the loading.

Hence, members of the ASCE-SEI Group 1 were mainly interested in *near-collapse or partial failure of structures* which indicated in fact that the tsunami-induced load was equal to the capacity of the structure. In such cases, by careful measurement of the geometry and identification of the structure’s material properties one can calculate its capacity. Subsequently, using the collected information on the maximum inundation depth, one could back calculate the speed of the flow, be it at inflow or outflow of the tsunami inundation. The participants hence conducted detailed investigation of the structures during the field survey operations and continued their analysis during post-survey work.

Fluid and impact loads and scouring during tsunami inundation and drawdown pose a significant risk to coastal buildings and infrastructure. The Tohoku Tsunami generated all types of loading and effects:

- *Hydrostatic Forces*: Buoyant forces, additional loads on elevated floors, unbalanced lateral forces
- *Hydrodynamic Forces*: Lateral and uplift pressures of tsunami bore and surge flow
- *Debris Damming and Debris Impact Forces*: External and internal debris accumulation and striking
- *Scour Effects*: Shear of cyclic inflow and outflow, and transient liquefaction.

5.1. Buildings performance

Structural failures of low to mid-rise building components of any structural material were observed as a result of either loads above alone or in combination with the others. Building performance was not guaranteed simply by the generic choice of structural material and structural system. Lateral strength and element resistance to impact were critical to avoid local damage, while resistance to progressive collapse was effective at preventing local member failures from precipitating disproportionate structural collapse.

Generally, modern, mid-rise reinforced concrete (RC) buildings with deep pile foundations resisted the tsunami hydrodynamic and debris loading. It should be also noted that these RC structures surveyed during this forensic engineering survey were properly designed to withstand seismic loading. Figure 7 exemplifies cases of building performance for buildings surveyed in Minamisanriku.

(a) (b)

Fig. 7 – (a) Minamisanriku Hospital – RC building withstood tsunami loading (Chock et al., 2012); (b) RC building with collapsed steel trusses top floor

Several building were overturned and displaced on their side, while remaining nearly structurally complete from foundation to roof. These buildings either floated due to the hydrostatic forces and then were carried away by the lateral hydrodynamic loading, or they were simply overturned by hydrodynamic forces of the tsunami inflow or outflow, or a combination of both (Fig. 8). The contribution of these effects to the failures depended on the degree of openness of the building structures.

(a) (b)

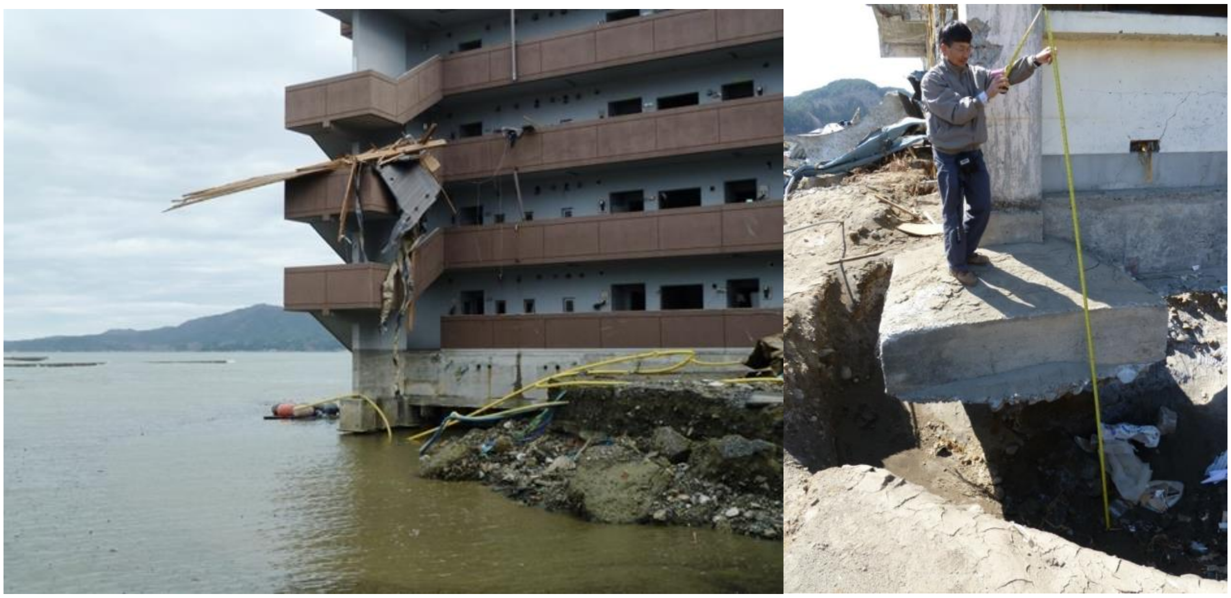
Fig. 8 – (a) Overturned RC building in Onagawa with pile foundation; (b) Overturned masonry bearing wall apartment building in Otsuchi with shallow foundation

Tsunami flooding generates massive debris from failed building components, street infrastructure, and natural material stripping. Moreover, this debris load increases with each passing cycle of inflow and outflow (Fig. 9). Debris are not carried away but are hence recycled in the debris flow. Additionally, buildings always have contents that act as internal debris loading elements subject to hydrodynamic forces when tsunamis flow enters the structure; such debris then transmits additional hydrodynamic load to the structure even when the exterior envelope has opened to allow water to flow through.

(a) (b)

Fig. 9 – (a) Three stories steel moment-resisting building in Otsuchi with debris damming; (b) Overturned masonry bearing wall apartment building in Otsuchi with shallow foundation

Building foundations are often also affected and subsequently undermined by erosion due to the overland tsunami-induced flow. This was observed to typically occur at the corners of building as flow accelerating around or between or over any bluff body obstructions generated scouring of the soil. Typical examples of scouring around building are shown in Fig. 10.



(a) (b)

Fig. 9 – (a) Scour due to return flow around apartment building in Minamisanriku; (b) Foundation scour at the corner of reinforced concrete building in Taro (Chock et al., 2012)

6. Lessons from the 2011 Tohoku Tsunami

A number of *critical engineering lessons* with direct application to buildings subjected to tsunami impact were drawn from the 2011 Tohoku Tsunami forensic engineering survey conducted by the ASCE-SEI Group 1:

- Historical tsunamis provide valuable information with respect to the magnitude of possible future events. However, recorded history may not always provide a good measure of the potential inundation and run-up heights generated inland due to extreme tsunamis events. The experience of the 2011 Tohoku Tsunami particularly demonstrated that historical events need to be carefully assessed.
- Probabilistic Tsunami Hazard Analysis should be implemented as a method to determine the maximum considered tsunami event for a particular location in an area prone to tsunami impact. The probabilistic analysis should consider different scenarios for the specific geographic location and the earthquake intensity of tsunamigenic sources for a scientifically justified return period.
- In addition to evacuation, losses to buildings and critical infrastructure can be mitigated. While coastal vegetation and sand dunes appeared to have provided some level of protection for the case of the 2004 Indian Ocean Tsunami (Sri Lanka and Tanzania) or in the case of the 2010 Chile Tsunami (Peluhe), their effect in coastal areas exposed to massive tsunami waves such as the 2011 Tohoku Tsunami showed minimal protective effectiveness.
- Coastal dikes designed to protect against storm waves generally performed poorly against the high loading generated by the overtopping tsunami waves, which resulted in scour either to the front or at the back of these structures leading to failure of many of the sections of the dikes.
- Future tsunami breakwater design should avoid potential catastrophic failures and provide some degree of resilience However, considering the present experience with such structures, it is not clear what level of protection these structures can successfully provide.

- Damaging tsunamis can travel far inland due to the long period of the tsunami surge, and sites should be studied for unfavourable topographical conditions that can generate high outflow velocities.
- Flow diversion and acceleration around large buildings significantly focus flow on downstream buildings.
- Foundation systems should consider uplift and scour effects, particularly at corners.
- Structures of all construction and material types can be subject to general and progressive collapse during tsunami.
- Overturning should be considered as a tsunami design condition for the foundation and the superstructure.
- Wood-frame construction in nearly all cases and locations were quickly destroyed to the foundation.
- High seismic design may not assure sufficient tsunami resistance, particularly for low-rise buildings.
- Debris accumulation in tsunami inflow occurs rapidly. Loads on structures must consider debris damming and blockage.
- Buildings should have sufficient openings to alleviate buoyancy. The advantages of breakaway cladding may be more beneficial to prevent buoyancy rather than to drastically reduce hydrodynamic forces (due to debris accumulation).
- Structurally boxed-in areas should be avoided in the design of structures since they would be subject to hydrodynamic pressurization.
- Mid-to-high-rise reinforced concrete buildings with robust shear walls appear to survive structurally, even for cases where a number of walls are located at the perimeter, and can be successful evacuation structures if tall enough.
- Protection structures can be designed to mitigate damaging effects for the case of small to medium size tsunamis, but are difficult to design and implement for regions affected by large tsunamis.

At the same time, *some societal and hazard mitigation and awareness lessons* were also learned as a direct results of this field survey:

- Soft measures, such as evacuation plans, require residents to be able to access higher ground. If such higher elevations are not located within a reasonable distance, residents will need to proceed to Tsunami Shelters or Evacuation Buildings, which must be designed to be tsunami-resistant (Shibayama et al., 2013). In fact, the Japanese tsunami planners and coastal engineers are now considering the multi-level tsunami protection planning: this would account for different emergency measures to be implemented depending on the level of magnitude of tsunami event.
- Emergency managers need to establish a classification of the Evacuation Areas that would provide residents with guidance to the safest places to seek shelter once a tsunami warning has been issued. In the event of an impending tsunami, residents should proceed to the safest points. If they determine that sufficient time is not available to reach such points, then residents should proceed to Evacuation Areas which are considered less safe. Since coastal areas are often characterized with drastic differentiation in the topography of the land and urban development, careful consideration should be given to the implementation of such plans which need to be sufficiently detailed and may require periodic review.
- Tsunami Shelters and Evacuation sites should be selected considering conservative elevations and design.
- An accurate forecast of the spatial and temporal extent of the tsunami impact based on a probabilistic earthquake and tsunami scenario is extremely important in disaster management

and mitigation. This is an ongoing area of research, where tools available at present must be significantly improved.

- For the case of the 2011 Tohoku Japan Tsunami, in spite of the large number of casualties, the loss of lives could have been significantly higher without the intense awareness and educational efforts of the Japanese society with respect to the danger of tsunamis.

Finally, some *lessons related to how to conduct a successful tsunami forensic field investigation* were also drawn:

- Tsunami reconnaissance should be conducted with the intent to gain hard data sufficient for subsequent tsunami inundation studies and structural analysis. Actual tsunamis represent full-scale study cases which could not be reproduced at physical model scale.
- Data from structural reconnaissance should then help resolve, validate, or refine solutions to major questions in tsunami design provisions regarding flow velocities and momentum of tsunami surges over land, fluid hydrodynamic forces on structural elements, debris flow, debris strike effects, and erosion and scouring of foundations.
- The time of conducting post-disaster field surveys is more critical for the case of tsunamis than for other natural disaster as field evidence will be rapidly disappear during debris clearing and demolition/recovery operations.
- It is crucial to enlist an experienced multi-disciplinary engineering reconnaissance team to evaluate a broad range of tsunami effects and to *a priori* establish clear responsibilities for each team member and expertise resource. Coastal engineers with experience in tsunami physics and mechanisms, structural engineers experienced with both forensic analysis and hydrodynamics, and geotechnical engineers with experience with hydrodynamic scour are essential members of any reconnaissance team concerned with evaluating tsunami effects.
- It is important to develop joint collaborations with national experts to avoid duplication of work, especially in the case of countries with advanced tsunami warning and education systems.
- Before departure, tsunami teams need to review all available information on the tsunami effects including, but not limited to: (1) review of all existing local information from government and local specialist; (2) review of aerial and satellite imagery, existing videos of tsunami, and photographs of damage which should be used to select objectives of interest.
- It is required to independently evaluate available quantitative data on local conditions and avoid using immediate mass media reports since these are often speculatively and prepared by unqualified correspondents.
- Survey teams should carry instrumentation for quantitative data and collect, whenever possible, physical samples for subsequent laboratory testing and further analysis. Such instruments may include, for example, bar cutters for reinforcing steel samples, impact hammer to estimate the concrete strength, and gauges for metal thickness measurements.
- Survey teams must document details of both surviving and failed buildings and structures in order to perform structural analysis of failure modes. Additionally, the evaluation of the performance of essential and critical facilities should be given high priority.

7. Conclusions

The March 11, 2011 Tohoku Tsunami was an extraordinary opportunity to understand the tsunami loading mechanisms and draw lessons about the effects of a maximum credible tsunami that was greater than the maximum considered historical tsunamis for the area investigated. The purpose of the ASCE-SEI tsunami reconnaissance of the 2011 Tohoku Tsunami was to investigate and document the performance of buildings and other structures in greater detail, with the direct intent to use this experience for the ongoing work of developing the new Tsunami Loads and Effects structural design provisions for the ASCE 7 Standard, Minimum Design Loads for Buildings and Other Structures. Until recently, tsunami surveys have focused primarily on gathering information and conducting measurements on the spatial extent of the tsunami-induced coastal inundation. While this is important, one should understand that post-tsunami surveys involve more than measuring the spatial extent of the tsunami inundation and that a multi-disciplinary engineering/economical/societal approach is important, especially when there is significant damage to infrastructure and major loss of life.

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