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Tsunami damage to coastal defences and buildings in the March 11th 2011 M_w9.0 Great East Japan earthquake and tsunami

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Abstract On March 11th 2011 a M_w9.0 mega-thrust interface subduction earthquake, the Great East Japan Earthquake, occurred 130 km off the northeast coast of Japan in the Pacific Ocean at the Japan Trench, triggering tsunami which caused damage along 600 km of coastline. Observations of damage to buildings (including vertical evacuation facilities) and coastal defences in Tōhoku are presented following investigation by the Earthquake Engineering Field Investigation Team (EEFIT) at 10 locations in Iwate and Miyagi Prefectures. Observations are presented in the context of the coastal setting and tsunami characteristics experienced at each location. Damage surveys were carried out in Kamaishi City and Kesennuma City using a damage scale for reinforced concrete (RC), timber and steel frame

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buildings adapted from an earlier EEFIT tsunami damage scale. Observations show that many sea walls and breakwaters were overtopped, overturned, or broken up, but provided some degree of protection. We show the extreme variability of damage in a local area due to inundation depth, flow direction, velocity variations and sheltering. Survival of many RC shear wall structures shows their high potential to withstand local earthquake and significant tsunami inundation but further research is required into mitigation of scour, liquefaction, debris impact, and the prevention of overturning failure. Damage to steel and timber buildings are also discussed. These observations are intended to contribute to mitigation of future earthquake and tsunami damage by highlighting the key features which influence damage level and local variability of damage sustained by urban coastal infrastructure when subjected to extreme tsunami inundation depths.

Keywords Great East Japan tsunami · Vertical evacuation · Field observations · Tsunami fragility · Flow velocity estimates · Damage scale

1 Introduction

On March 11th 2011 at 14:46 local time (05:46 GMT), a M_w9.0 mega-thrust interface subduction earthquake, officially named as the Great East Japan earthquake, occurred 130 km off the northeast coast of Japan in the Pacific Ocean at the Japan Trench, triggering tsunami that caused damage along a 600 km stretch of coastline in the Tōhoku region. Coupled co-seismic rupture (lasting approximately 5 min) of several major fault segments in an area of prior slip deficit resulted in a large fault plane 400–500 km in length by 100–200 km in width (Geo-Spatial Information Authority of Japan 2011a; Shao et al. 2011). The rupture process resulted in significant deformation of the sea bed over a large area, which generated the tsunami. This deformation occurred as close as 70 km to the Tōhoku coastline, leading to relatively short tsunami arrival times in the three worst-affected prefectures: Iwate, Miyagi, and Fukushima.

Tide gauge records show that the first small tsunami waves with amplitudes of tens of centimetres arrived at the coastline within 10 min of the earthquake (Okumura 2011), while the most damaging waves arrived after only 25 min in some locations in Iwate Prefecture. Maximum run-up of 40.545 m was recorded at Omoe Aneyoshi in Miyako City (The 2011 Tohoku Earthquake Tsunami Joint Survey Group 2011), while inundation heights of between 5 and 15 m occurred in many locations. At Onagawa Town, Miyagi Prefecture, the tsunami had a maximum inundation height of 18.4 m (Takahashi et al. 2011a) and resulted in overturning of reinforced concrete (RC) buildings, discussed in Sect. 6.6. Over 1 million buildings suffered earthquake or tsunami damage and as of the same date 19,185 people are confirmed dead or remain missing (National Police Agency of Japan 2012).

Coastal populations of Tōhoku were among the best prepared in the world with respect to tsunami, with extensive sea defences (including sea walls and breakwaters constructed specifically for protection against tsunami), comprehensive earthquake and tsunami warning systems, evacuation planning and public education. With wave heights sufficient to overtop and breach coastal defences, the tsunami caused extensive damage to residential areas, commercial and industrial facilities, agricultural land and infrastructure. Evacuation plans and placement of tsunami mitigation infrastructure (defences, evacuation structures) had been developed according to expected tsunami scenarios and previous events; however, in many areas the expected inundation height and extent were exceeded in this event.

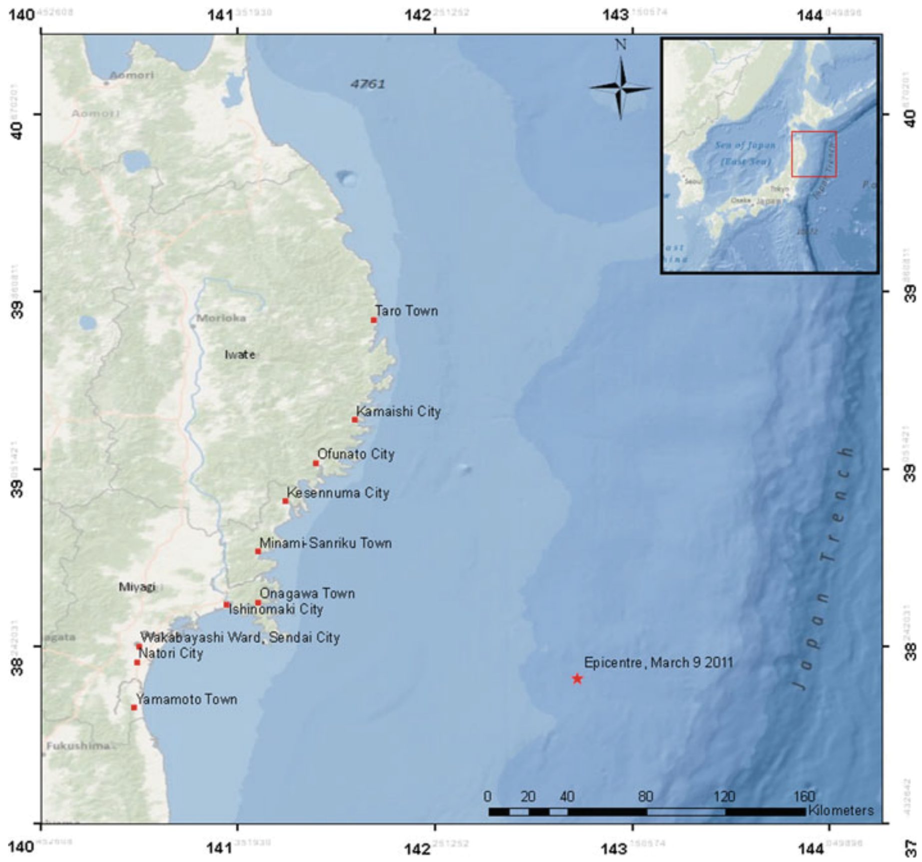

Fig. 1 Locations of tsunami damage investigations carried out by EEFIT, with an indication of the extent of plains and rias coastline

A post-tsunami field mission was conducted by the authors representing the Earthquake Engineering Field Investigation Team (EEFIT) of the Institution of Structural Engineers (IStructE) between May 28th and June 3rd 2011 in Iwate and Miyagi Prefectures. Our investigations covered the coastline between Tarō Town in the north and Yamamoto Town in the south (Fig. 1), while observations of ground shaking damage (Goda et al. 2012) also incorporated inland areas. The full mission field report (EEFIT 2011) presents comprehensive field investigation results from all locations visited and includes observations on ground shaking, tsunami damage, and emergency response and recovery.

The mission was conducted as early as possible following the event, considering requests from host-country organisations that international reconnaissance teams wait until adequate transport, accommodation and fuel supplies became available to support investigations. The delay ensured our investigation did not impede the emergency response and was intended to minimise any additional burden placed on host researchers. The authors recognise that due to the delayed reconnaissance, a large degree of debris clean-up and demolition had occurred in the three months between March 11th and our field mission. Despite this impressive progress, at the time of our visit there remained substantial amounts of in-situ debris and large numbers of buildings unaffected by post-event activity, which warranted our investigation and presentation of observations. We make no assumptions of building damage or tsunami characteristics where it was apparent that post-event debris clearance had taken place.

Post-event damage observations such as those presented here are vital to record and understand the performance of defence infrastructure and buildings for loss estimation and development of effective mitigation strategies. Inundation depth and velocity data must be collected in the field to aid validation of numerical tsunami inundation modelling, and these data combined associated assessments of damage are used in establishing tsunami fragility curves, such as in the methods applied by Koshimura et al. (2009). The objective of our field mission was to record and present such observations to supplement findings by Japanese and international researchers, and contributed to the already existing body of data on tsunami fragility in Japan (e.g. Hatori 1984 and Shuto et al. 1986, in Shuto 1993). Primary field observations presented in this paper, notably building damage surveys relating inundation depth to damage level enabled us to refine the EEFIT tsunami damage scale for reinforced construction (EEFIT 2006) and propose new damage scales for steel frame and timber frame buildings for use in damage assessment following future events (Tables 3, 4, 5).

The paper provides an overview of the March 11th tsunami, its severity and effects (Sect. 2), and a brief comparison with previous tsunami in Tōhoku (Sect. 3). Section 4 describes coastal defences in place in the Tōhoku region, while Sect. 5 briefly discusses the provision of vertical evacuation structures in this region and their efficacy on March 11th. EEFIT observations are then discussed for 10 locations (ordered from north to south) in Sect. 6, where we present details of 2 building damage surveys, 3 updated tsunami damage scales (revised scale for RC, new scales for steel and timber frame buildings) and further interpretation of our observations. In order to place the damage in context with the characteristics and severity of the event, damage observations of defences and buildings in each location are preceded by a short description of the location and summary of casualty figures. A summary of observations is provided in Sect. 7, with conclusions on the use of such information in enhancing tsunami mitigation strategies in the future.

2 The Great East Japan tsunami of March 11th 2011

Following the occurrence of the M_w 9.0 earthquake at 14:46, wave heights of 6.7 m (recorded at 15:12, 18 km off Kamaishi) and 5.6 m (at 15:14, off the coast of Rikuzentakata) were detected by offshore GPS tsunami monitoring buoys (Fujita 2011). Considering the effects of shoaling as the wave enters shallow water, this suggested that the tsunami wave height could be up to 10 m once it reached the shoreline. Within 10 min of the earthquake the initial waves, only tens of centimetres in height, had reached 3 tide gauges between Choshi, Ibaraki Prefecture and Miyako, Iwate Prefecture (Okumura 2011). More significant waves exceeding 3 m in height began to reach the coast from about 25 min after the earthquake (e.g. Ōfunato City, IOC/UNESCO 2011). The tsunami caused damage along 600 km of coastline, with estimates of area inundated between 400 and 500 km^2 (300 km^2 of this in Miyagi Prefecture) and affecting some urban areas particularly badly—Ishinomaki City and Yamamoto Town both suffered inundation of 46 % of their total area (CEDMHA 2011).

The east coast of the Tōhoku region comprises two very different forms which significantly affected tsunami inundation extent and run-up: rias to the north of Ishinomaki Bay, and plains to the south (Fig. 1). The rias are drowned river valleys, open to the sea and characterised by a jagged-shaped coastline; neighbouring rias are separated by steep ridges that extend inland. In rias, the shape of the valley slows and constrains the incoming wave, amplifying the wave height and leading to significant run-up; inundation extent is limited by

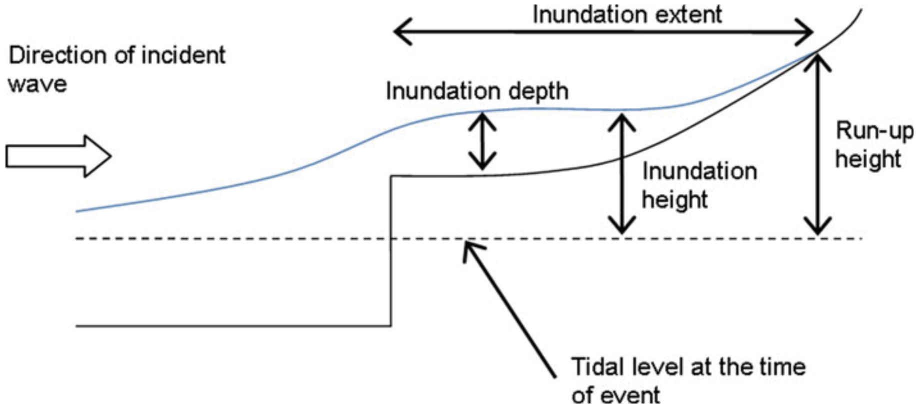

Fig. 2 Schematic diagram defining tsunami terminology used in this paper (after Port and Airport Research Institute 2011)

steep topography except where tsunami propagates up a river valley or channel. In contrast, the coastal plains are extensive areas of flat land often used for agriculture, and experienced substantially lower run-up values but greater inundation extent (up to 7 km in this event; Geo-Spatial Information Authority of Japan 2011b), as there is less steep topography to restrict tsunami flow. Tsunami terminology used in this paper is defined in Fig. 2.

The location of greatest run-up and inundation height occurred in the rias: the maximum recorded value of tsunami inundation height was 40.545 m at Omoe Aneyoshi (The 2011 Tohoku Earthquake Tsunami Joint Survey Group 2011). This exceeds the previous highest ever recorded wave height in Japan, of 38.2 m at Ryori Bay, Iwate Prefecture in 1896 (United States Geological Survey 2011). Additional observations of inundation height greater than 30 m were recorded to the north of Tarō Town, in Miyako City. Elsewhere in the rias coastline, inundation height of around 10 m was common and our surveys in Kamaishi City showed inundation heights of 7.0 to 9.0 m (Sect. 6.2). Inundation height of 9.5 m was measured in the inner port area of Ōfunato City and in Onagawa Town, inundation height of 14.8 m was measured in the port area and 18.4 m immediately to the west of the port (Takahashi et al. 2011a). The coastal plains experienced inundation heights of 4.1–5 m in the port of Ishinomaki City, 7.3–8.0 m in Sendai Port and 9.7 m at Arahama Beach. Inundation height was 5.7 m at Sendai Airport terminal (Port and Airport Research Institute 2011).

3 Comparison of tsunami with past significant events

There have been several previous catastrophic tsunami in the Tōhoku region. The Sanriku coast (roughly corresponding to the extent of the rias, north of Ishinomaki City) has suffered repeated damage, particularly from the local 1896 Meiji-Sanriku (22,000 deaths; Tanaka et al. 2008), 1933 Showa-Sanriku (3,064 deaths; Takata 2009) earthquakes and the distal 1960 Chilean earthquake (142 deaths; Takata 2009). During each of these events, Iwate Prefecture experienced tsunami heights exceeding 10 m, and the 1896 event was comparable with the 2011 event (Earthquake Research Institute 2011). Minor damage was recorded in Ōtsuchi and Kuwagasaki (near Miyako City) due to the 1700 Cascadia event (Atwater et al. 2005).

Further south in Miyagi Prefecture, however, previous tsunami have previously resulted in inundation heights <5 m and further south from Sendai, generally <2 m (Watanabe 1998).

Therefore, in Miyagi and Fukushima Prefectures, inundation heights of 4–7 m (and greater) experienced on March 11th 2011 far exceeded experience of the last 120 years. However, tsunami further back in history are believed to have occurred with tsunami heights similar to the Great East Japan tsunami. In the 1611 Keicho earthquake, which caused fatalities estimated up to 5,000 mostly due to tsunami (Utsu 2002), a 6–8 m high wave devastated the Sendai Plain. Satake et al. (2008) modelled the 869 Jogan earthquake and tsunami, generating estimates of inundation extent of 1–3 km inland on the Sendai and Ishinomaki Plains, and 1.5–2 km inland further south in Fukushima Prefecture. These are comparable to, or exceed the inundation of the Great East Japan tsunami. It is possible that the 869 earthquake had a similar location and magnitude to the March 11th earthquake (Simons et al. 2011).

4 Coastal defences in Japan

Japan has a very high proportion of coastline to unit area of land and has relied heavily on a limited amount of flat coastal land for development, with 75 % of its assets in the 10 % of the total land area that is flat coastal plain (Kokusai Kogyo Group 2011). In the region affected by the Great East Japan tsunami, four cities are classified as 'major ports' (Miyako, Kamaishi, Ōfunato, and Ishinomaki) and Sendai-Shiogama as one of Japan's 23 'specially designated major ports' serving international marine networks. The ports are centres of production and import/export, passenger transport hubs, and provide business activities, housing and recreation and as a result, tsunami damage to ports has a knock-on effect beyond the immediate location. In addition to this importance of coastal land and facilities, the frequent occurrence of typhoons, storm surges and tsunami led to the development in Japan of some of the most extensive coastal defences in the world. Typical coastal structures of jetties, groynes, and breakwaters (both detached and submerged) may be seen along the coastline, in addition to significant land reclamation projects. Tsunami-specific breakwaters and walls have been built along vulnerable coastlines, often at those locations badly affected by previous events, such as Tarō Town, Kamaishi City and Ōfunato City.

On March 11th a total of 8,500 m of breakwaters collapsed (Yagyu 2011), including the newly-completed tsunami breakwater in Kamaishi City designed to withstand a tsunami of 5–6 m. Many coastal protection structures along the Sanriku coast were designed based upon the Meiji Sanriku tsunami, which was considerably smaller than the Great East Japan 2011 event. As a result they were not effective in stopping the waves from overtopping, and in many situations suffered catastrophic failure. Takahashi et al. (2011b) suggested that in future, rather than building even bigger structures, coastal defences should remain of similar size, but with special attention given to their stability in order that they survive even a huge tsunami despite being overtopped. The rationale for this is that a defence that is overtopped but survives is better than no defence at all. The observed performance of individual defence structures is described in Sect. 6.

5 Vertical evacuation structures

Japan has over 70,000 designated tsunami evacuation sites (The Japan Times 2011), comprised of areas of land or buildings either located on high ground or considered far enough inland to avoid inundation. Other buildings are designated as vertical evacuation structures,

Table 1 Number of people surviving on the upper storeys of buildings in 5 municipalities on the Sendai Plains (Iwate Nichi Nichi Shinbun 2011)

District	Survivors on upper storeys	Number of evacuation facilities
Sendai City	2,139	4
Natori City	3,285	5
Iwanuma City	2,095	5
Watari	2,102	5
Yamamoto Town	91	1

located in the expected tsunami inundation zone but designated according to government guidelines (Cabinet Office Government of Japan 2005) to withstand tsunami loading and to have enough vertical height to provide safe refuge above estimated tsunami inundation level. Observations from the March 11th 2011 tsunami have shown the importance of vertical evacuation structures in providing refuge in the inundation zone.

At least 9,700 people in 5 towns in the Sendai Plain survived the tsunami by evacuating to the upper storeys of RC buildings (Table 1; Iwate Nichi Nichi Shinbun 2011). Loss of life was significantly reduced in Natori City and Iwanuma City through the use of vertical evacuation structures, while in areas such as Yamamoto Town there was a lack of suitable structures on the coastal plain. In Yamamoto Town, only 1 % of residents living in the inundation zone were able to survive by entering such a building as opposed to 27 % in Natori City, 26 % in Iwanuma City, 15 % in Watari and 8 % in coastal areas of Sendai City. An absence of vertical evacuation facilities was apparent in the tsunami affected wards of Sendai—Wakabayashi-ku and Miyagino-ku.

EEFIT observations of vertical evacuation structures in the tsunami affected areas suggest inconsistencies between municipalities in the planning and designation of evacuation structures. Designated vertical evacuation structures performed well structurally (observed damage was generally limited to scour, debris strike, glazing and contents damage). However, additional research shows that many of these structures were close to being overtopped in this event, and that there are many issues around the provision of welfare and access which must be improved in future (Fraser et al. 2012). In addition to the tsunami and earthquake impacts on such structures, concurrent or subsequent fire is a significant hazard that must be considered to ensure safety of evacuees taking refuge. Some evacuation centres, such as Kadonowaki School in Ishinomaki City, were affected by fire which spread as burning debris or spilled fuel floated on the water surface.

6 Field observations of tsunami damage

This section describes observations made at 10 locations investigated during the EEFIT mission. For each location fatality rates are quoted; the full figures and data sources are presented in Table 2 for comparison between locations. Damage levels referred to in this section relate to the EEFIT tsunami damage scales adapted from that used by EEFIT (2006). These scales range from D0 (no damage) to D4 (collapse) according to descriptions of damage, occupancy suitability, and level of required repair for timber frame, steel frame and RC buildings. The individual scales are presented in Tables 3, 4 and 5 and are proposed for use in future post-tsunami damage surveys. These scales are demonstrated in our Kamaishi and Kesennuma damage surveys.

Table 2 Death toll and fatality rate at locations visited by EEFIT during the reconnaissance

Location	Coordinates	Casualties as of August 25th (Fire and Disaster Management Agency of Japan 2011)	Fatality rate		Proportion of population living in inundation zone (Japanese Ministry of Internal Affairs and Communications 2011) (%)
			As a proportion of total city population (%)	As a proportion of people living in the inundation zone (Geo-Spatial Information Authority of Japan 2011b) (%)	
Kamaishi City	39° 16′ 32.77″ N, 141° 53′ 8.63″E	883 dead, 299 missing	3.0	9.0	33
Ōfunato City	39° 4′ 54.80″ N, 141° 42′ 30.79″ E	336 dead, 116 missing	1.1	2.5	47
Kesennuma City	38° 54′ 29.02″ N, 141° 34′ 11.98″ E	1,007 dead, 399 missing	1.9	3.5	55
Minami-Sanriku Town	38° 40′ 38.46″ N, 141° 26′ 46.93″ E	551 dead, 437 missing	5.7	6.9	82
Onagawa Town	38° 26′ 43.64″ N, 141° 26′ 39.80″ E	547 dead, 414 missing	9.6	11.9	80
Ishinomaki City	38° 26′ 3.55″ N, 141° 18′ 9.68″ E	3,158 dead, 849 missing	2.5	3.6	69
Wakabayashi-ku	38° 14′ 39.08″ N, 140° 54′ 2.56 E	* July 8th, 375 dead, 28 missing	0.3	4.3	7
Natori City	38° 10′ 17.49 N, 140° 53′ 30.69 E	911 dead, 76 missing	1.4	8.1	17
Yamamoto Town	37° 57′ 45.31″ N, 140° 52′ 39.29″E	670 dead, and 22 missing	4.1	7.7	54

* This is the latest available data at ward resolution.

6.1 Tarō Town, Iwate Prefecture

Tarō Town is situated in an east-facing bay where two rivers flow from the north and west and is confined by steep hills. Sea walls designed for tsunami and standing 10 m high dominate the landscape of Tarō, with an original wall and two new sections forming 4 divided areas of the town, connected by tsunami gates. The concrete blocks of the newest

Table 3 EEFIT tsunami damage scale for RC frame or RC shear wall buildings of EMS-98 structural vulnerability class D and E, i.e. moderate and high earthquake resistant design respectively, of up to 6 storeys height (adapted from EEFIT 2006)

Damage level	Description
No damage (D0)	No visible damage to the structure observed during the survey. Suitable for immediate occupancy
Light damage (D1)	Flood damage to contents. Some non-structural (fittings, windows) damage. Damage is minor and repairable. Suitable for immediate occupancy
Moderate damage (D2)	Out-of-plane failure or collapse of parts of or whole sections of masonry infill walls and windows at ground storey. Repairable damage from debris impact to structural members (columns, beams, walls). No structural member failure. Scouring at corners of the structures leaving foundations partly exposed but repairable by backfilling. Unsuitable for immediate occupancy but suitable after light repair
Heavy damage (D3)	The structure stands but is severely damaged. Infill panels above the 1st storey have been damaged or have failed. Structural and non-structural members have been damaged. Failure of a few structural members which are not critical to structure stability (e.g. failure of infill concrete walls). Roofs are damaged and have to be totally replaced or repaired. Significant scouring at corners of the structures leaving foundations exposed, with minor repairable tilting. Structure requires extensive repair and is unsuitable for immediate occupancy
Collapse (D4)	Partial or total collapse of the building. Collapse of large sections of foundations or structure due to heavy scouring or debris impact. Excessive foundation settlement and tilting beyond repair. Damage to the structure cannot be repaired and must be demolished

section of wall contained sand infill and were apparently constructed without reinforcement or interlocking blocks. As a result, they were almost all toppled from their positions and the only parts of this section of wall left standing were some buttress supports and blocks around the gates. The breakwater at the mouth of the bay showed signs of severe damage, while the sluice gates on the river were undamaged. The mean value of the inundation depth and run-up height measurements was 21.47 m (The 2011 Tohoku Earthquake Tsunami Joint Survey Group 2011). In front of the tsunami walls (along the quay), only two buildings survived: an RC frame building with significant tsunami damage to the lower 4 storeys and a steel-frame building whose structure appeared to be intact despite removal of cladding. Between the new and old sections of wall the village was completely destroyed and only two buildings remained standing at the time of EEFIT survey (May 31st). A 7-storey steel-frame hotel had sustained damage up to the 4th storey, with cladding entirely removed at the lowest 2 storeys. One storey of an RC structure remained standing but its additional storeys of timber construction had been washed away. The tsunami overtopped all sections of wall and most timber structures had been washed off their foundations even behind the oldest section (furthest inland) wall. Significant amounts of debris had been washed into this area and became trapped behind the walls as waters receded.

Table 4 EEFIT tsunami damage scale for timber frame buildings of EMS-98 structural vulnerability class D

Damage level	Description
No damage (D0)	No visible damage to the structure observed during the survey. Suitable for immediate occupancy
Light damage (D1)	Flood damage to contents. Some damage to the exterior of the building's cladding above foundation level and windows/fittings at ground-floor level. Damage is minor and repairable. Suitable for immediate occupancy
Moderate damage (D2)	Ground-floor cladding has been destroyed partially but structure is standing and may be reoccupied after substantial repairs. Contents and fittings in the ground-floor level will need to be replaced. Not suitable for immediate occupancy, but in most cases damage is repairable
Heavy damage (D3)	Ground-floor cladding has been destroyed, and there may be some damage to cladding at the 2nd storey. The load-bearing timber frame has been damaged by water flow or debris impact, but the building is still standing. In many cases these buildings will have to be demolished, as damage to the timber structure is too extensive. Not suitable for occupancy
Collapse (D4)	The building has extensive structural damage due to flow or debris impact, has collapsed partially or totally, or has been washed away. The building will require demolition if still standing. Tsunami flow in these buildings is usually above 3 m (measured from ground-floor level)

6.2 Kamaishi City, Iwate Prefecture

Kamaishi City is situated in an east-facing bay, with urban development concentrated along a river valley 1.1 km wide at the port and bounded by steep hills to the north and south. Approximately 33 % of Kamaishi's population lived in the inundation zone, and the city suffered 9 % fatality rate within the inundated zone (Geo-Spatial Information Authority of Japan 2011b; Japanese Ministry of Internal Affairs and Communications 2011).

The tsunami on March 11th overturned the north section (990 m in length) of the newly-completed offshore breakwater and although the south section (670 m in length) survived mostly intact, it was left inclined (Yagyu 2011). The Port and Airport Research Institute (PARI) (Fujita 2011) ran numerical simulations which estimated that the tsunami height was 10.8 m on the offshore face but only 2.6 m on the onshore side. This difference in water depth created a large hydrostatic force on the wall and along with water flowing through gaps between blocks of the breakwater causing scour, led to collapse of the wall (Kazama 2011). Despite the fact that the breakwaters were severely damaged, it is estimated that the breakwater reduced the height of the tsunami by 40 % (from 13.7 to 8 m), delayed the tsunami arrival time onshore by 6 min allowing more time for evacuation, and reduced run-up from (a simulated height of) 20.2 m to the observed 10 m (Kazama 2011). Analysis of inundation and run-up heights by Mori et al. (2011) supports these simulation results.

EEFIT carried out a building damage survey on May 31st 2011 along 1 km of a road at an elevation of <5 m above mean sea level, comprising 2- to 3-storey mixed-use commercial

Table 5 EEFIT tsunami damage scale for steel frame buildings of EMS-98 structural vulnerability class E

Damage level	Description
No damage (D0)	No visible damage to the structure observed during the survey. Suitable for immediate occupancy
Light damage (D1)	Flood damage to contents. Some non-structural (fittings, windows) damage. Damage is minor and repairable. Suitable for immediate occupancy
Moderate damage (D2)	Out-of-plane failure or collapse of parts of or whole sections of infill walls, cladding and windows at ground storey. Repairable damage from debris impact to structural members (steel columns and beams). No structural member failure. Scouring at corners of the structures may leave foundations partly exposed but repairable by backfilling. Unsuitable for immediate occupancy but suitable after repair
Heavy damage (D3)	The steel frame is still standing, structural columns and beams are in their pre-tsunami position despite some damage due to pressure or debris impact, damming. Non-structural steel members may be buckled or fractured. The interior of the building and the cladding have been destroyed, washed-away, at 2nd storey or above. Scouring at corners of the structures may leave foundations partly exposed but repairable by backfilling. The building may be re-occupied after reconstruction of all the non-structural elements and fittings
Collapse (D4)	The building has partially or totally collapsed due to debris impact or debris damming effects. Multiple structural columns are buckled or fractured and cannot be replaced without loss of stability, even though the building is still standing. Building will have to be demolished

and residential buildings and a few commercial buildings of over 5 storeys. Land-use seaward of the survey area was industrial, including the large Nippon Steel Factory. Inundation depth of 8 m was recorded by EEFIT at the eastern end of the survey, decreasing gradually to around 2 m at the western end where the river flows towards the north-east (Fig. 3). The survey included 154 buildings (51 % steel frame, 32 % timber frame, 15 % RC, 2 % unconfirmed steel frame or RC). Examples of buildings at different levels of damage as observed in our tsunami damage survey in Kamaishi City at each level are shown in Fig. 4.

Observed failure modes included (i) out-of-plane failure of infill walls and panel walls in all construction types but particularly steel frame structures; (ii) debris impact damage (from minor damage of exterior cladding to major damage of non-structural components of steel frames); (iii) extensive glazing damage at ground-floor level, some damage to 1st and 2nd storey glazing; and (iv) soft-storey failure of several timber structures (Fig. 5).

Regarding the observed soft-storey failure, short period component ground motions recorded at K-NET station IWT007, 1.5 km west of Kamaishi port, were of sufficiently magnitude and duration to cause deformation in these structures, indicating that the soft-storey failure of some 2-storey timber frame buildings could be due to ground shaking. However, in areas that were not inundated, timber buildings performed well with respect to ground shaking. This suggests that, in this case, this style of failure may be due to tsunami loading rather than ground shaking, despite the apparent sheltering of these timber buildings. Over

Fig. 3 Damage survey in Kamaishi City with individual buildings plotted to show construction and damage level. Construction type is indicated by shape, EEFIT tsunami damage level by colour: *Diamonds* denote timber frame; *squares* denote RC; *circles* denote steel frame. *Blue* denotes D0, *green* denotes D1, *yellow* denotes D2, *orange* denotes D3, *red* denotes D4. Inundation depths, the collapsed section of Nippon Steel Factory building (red polygon), and vertical evacuation building are also shown. *White letters* show the position of buildings shown in Fig. 4

half of the surveyed timber frame buildings experienced damage level D4 (partial or complete collapse) and where they survived with less damage it was due to significant sheltering by other more resistant structures.

No steel frame or RC structures suffered partial or complete collapse in the survey area, and a limited number suffered heavy damage (D3): 15 % and 4 % respectively. Most steel frame (77 %) and RC (83 %) buildings suffered heavy non-structural damage but the structural frames or walls were often only lightly damaged (D1–D2). At the eastern end of the survey area most timber buildings suffered complete collapse and several had been washed away or cleared away, while steel frame buildings suffered damage level D1–D3, and RC buildings D1–D2. The survey indicates a general reduction in damage with distance from the port and increase in ground elevation towards the west, although variable levels of local sheltering were also observed due to the dense nature of development. There is some indication of sheltering provided by the large trussed steel portal frame building (red polygon in Fig. 3), the eastern-most (structurally isolated) end of which suffered partial collapse. At the western end of the survey transect (inundation depths of 2.5 to 3 m, adjacent to the river) timber frame structures generally sustained damage D1–D2, while one building at an exposed street corner sustained damage of D3. Evidence suggests that flow velocity was low at this end of the transect; plastic shop signs and some glazing remained undamaged despite being submerged.

EEFIT investigated a designated vertical evacuation structure (8-storey RC shear wall construction) situated 40 m from the harbour (39° 16′ 26.7″ N, 14° 53′ 17.6″ E), with vertical evacuation signage at building entrances. This mixed-use office and apartment building was oriented perpendicular to the harbour front and had a steel-frame car parking structure attached to the seaward face (Fig. 6). Although it is unlikely that this steel structure was deliberately designed as a sacrificial structure, it was lightly damaged by debris impact up to a height of about 9 m and prevented damage to the main building behind. The ground floor (1st storey) was partially open-plan for use as a car park, with walls comprising cast-in-situ

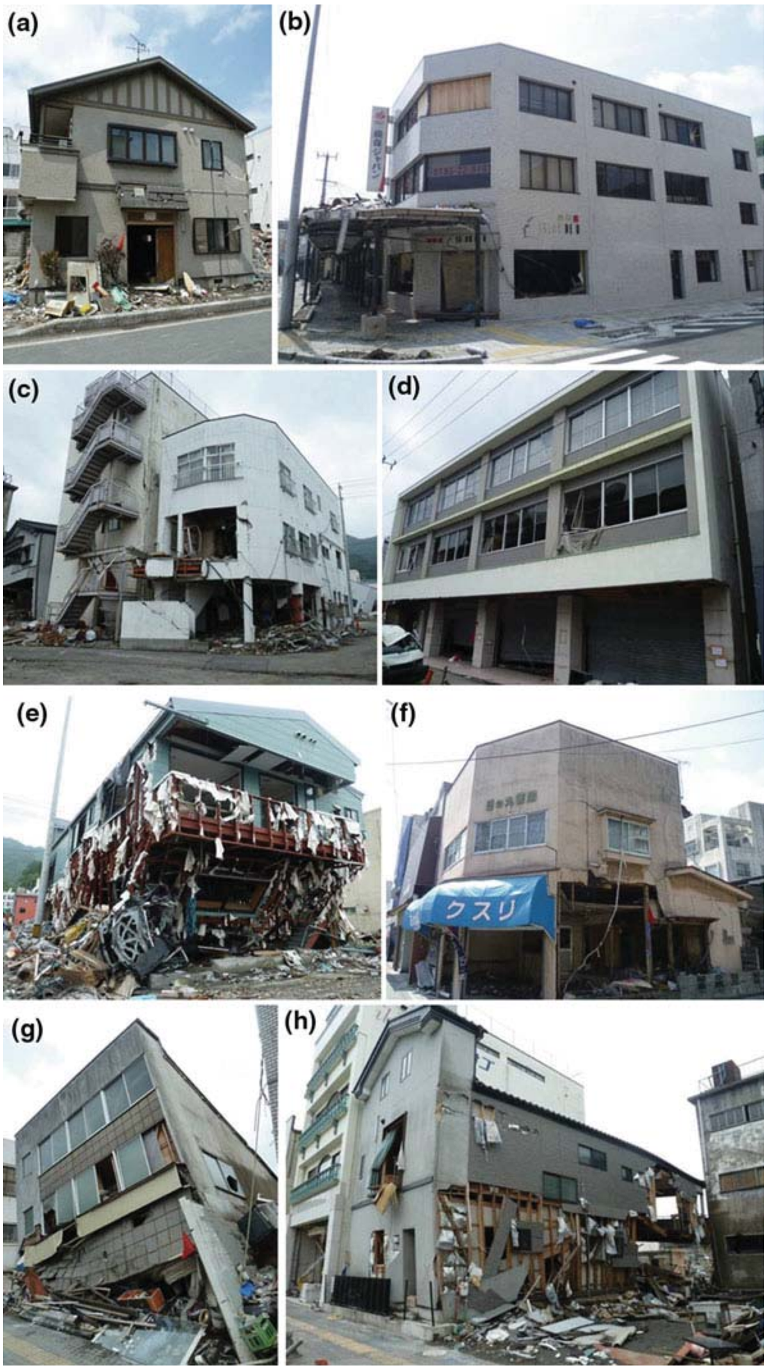

Fig. 4 Photographs of structures surveyed in Kamaishi City, providing examples of the EEFIT tsunami damage scale applied for different structure types: **a** Timber frame structure, observed damage level D1; **b** Steel frame, D1; **c** Steel frame, D2; **d** RC shear wall, D2; **e** Steel frame, D3; **f** Timber frame, D3; **g** Timber frame, D4; **h** Timber frame, D4. The position of each photograph is indicated on Fig. 3 by the photograph letter

Fig. 5 Soft storey collapse of a timber structure observed in Kamaishi City. The 2nd storey appears to have remained intact due to central steel beam supporting the second storey

Fig. 6 Eight storey un-braced RC shear wall apartment block and designated evacuation building in Kamaishi City. A steel frame structure is located on the seaward face and sustained minor damage from debris impact. Two external staircases to the 4th floor exist on the other side of the building. This building was inundated to the 3rd storey

RC infill panels which were severely damaged. The building was inundated to the 3rd storey, but adequate elevation and absence of structural damage meant that occupants were able to evacuate to the designated evacuation area on the 4th storey and above.

6.3 Ōfunato City, Iwate Prefecture

Ōfunato City is situated within a narrow south-facing bay bounded by steep hills on either side. The bay is 5.7 km long from the port to the Ocean, and 1.1 km wide at the harbour front. Prior to the tsunami there were two breakwaters at the mouth of the bay, 540 m in combined length, which collapsed completely on March 11th (Yagyu 2011). Funnelling of the tsunami

Fig. 7 Apartment building of RC shear wall construction in Ōfunato City. Seaward side of the building is shown. Inundation reached the ceiling of the 3rd floor, but the structure remained intact. This landward side of the building was sheltered from debris impact during the tsunami return flow

wave contributed to a wave height measured at 11.8 m at the harbour. The fatality rate (2.5 % of the population living in the inundated area, Table 2) was among the lowest in the rias coastline, despite almost half of the population living in the area inundated, and was similar to that of Miyako (3 % of population living in inundated area; Geo-Spatial Information Authority of Japan 2011b; Japanese Ministry of Internal Affairs and Communications 2011).

From the tide gauge record obtained in the port, initial tsunami arrival at Ōfunato City occurred 25 min after the earthquake and took just 6 min to reach a height of 8 m, at which point the gauge stopped recording (IOC/UNESCO 2011). There was a drawdown phase of the sea here prior to the tsunami arrival, and the 1st tsunami wave was the highest. The city experienced 0.78 m co-seismic subsidence (Geo-Spatial Information Authority of Japan 2011c), resulting in frequent flooding since the event.

Following the 1960 Chilean tsunami, when inundation depths of 5.6 m occurred in Ōfunato, some residents reconstructed their homes as 3-storey RC structures in the belief that these would survive future tsunami. However, on March 11th the tsunami inundated many of these buildings up to the roof level. There was almost total collapse of timber buildings in the area investigated. Many steel frame and RC buildings remained structurally intact but in the case of the steel buildings there was heavy damage to non-structural elements such as removal of cladding, consistent with observations elsewhere.

EEFIT inspected a 3-storey RC shear wall apartment building (39° 3′ 49.09″ N, 141° 43′ 12.74″ E; Fig. 7). Maximum water levels reached the top of the 3rd storey level and possibly overtopped the building. The structure remained intact as it avoided major debris impact, despite its proximity to the sea and its relatively exposed position. Many windows in this building remain unbroken and water marks in line with the top of the window openings were seen in all rooms on the top storey, suggesting air void formation in the building. A distinct water mark with a well-defined upper limit and deposition of sediment below on the inland side of the building suggests a sustained period of standing water before recession of flood waters slow enough to deposit sediment during recession. During the return flow this building was sheltered by a 3-storey RC shear wall apartment building on its inland side, which had sustained damage from debris impact.

6.4 Kesennuma City, Miyagi Prefecture

Kesennuma City is situated in a long, 1 km wide south-facing bay with most development on the west side and at the northern head of the bay. The bay appears somewhat sheltered from the Ocean by Ōshima Island and headland to the east. The tsunami at Kesennuma flowed north up the bay, arrived at the harbour as a fast-flowing rising tide (Japan Coast Guard 2011) and overtopped harbour walls and river defences. Significant damage was sustained along the western shore of the bay (on the eastern side of the river) and in the northern area of the city at the head of the bay. Inundation height measurements of 7–8 m were recorded by EEFIT at approximately 500 m inland in the survey area at the head of the bay. Kesennuma City was severely affected by fire which appears to have started at the marine oil terminal in the south of the city and spread extensively on floating debris. At the time of our visit, there were damaged fuel tanks and burned propane cylinders among the debris. Although there were many casualties in Kesennuma, this translates to relatively low a fatality rate of 3.5 % of the population in the inundated zone (see Table 2).

An extensive area of damage was surveyed in the northern part of Kesennuma City from 450 m inland to 1.1 km inland (Fig. 8). Flooding associated with 0.74 m of co-seismic subsidence (Geo-Spatial Information Authority of Japan 2011c) prevented closer access to the shoreline. Timber frame structures suffered heavy damage to collapse (90 % sustained damage level D4), 60 % of steel frame structures registered moderate to heavy damage (D2–D3), and 78 % of the surveyed RC structures sustained light damage (D1). A large number of timber frame buildings had been washed away or destroyed by fire and the building footprints were not visible during the survey. Field observations have therefore been augmented with building footprint data to estimate the total original number of buildings. Steel frame and RC buildings remain standing in areas most affected by fire, therefore all buildings identified from the GSI building footprints with no corresponding surveyed building are assumed to be timber frame, damage level D4 (collapse).

Highly variable damage was induced by flows of similar depths in this survey area. Although many timber frame structures are in a state of partial or complete collapse, there were a significant number which remained standing (with damage level D1–D3) in flows of 5–7 m depth, which is inconsistent with the 2 m wash-away threshold for Japanese timber houses observed in the 1960 Chilean tsunami (Sasaki 1960, in Shuto 1993). A comprehensive report into building damage from all affected areas by the Japanese Ministry of Land Infrastructure Transport and Tourism (2011) (MLIT) shows a clear threshold for heavy damage or collapse to buildings at around 2.0 m: at 1.0–1.5 m inundation height, only 9 % of buildings were washed away or rendered unrepairable, while this increases to 31 % at 1.5–2.0 m. At 2.0–2.5 m 66 % of buildings were washed away or not repairable. The inconsistency between this and the EEFIT survey highlights the importance of local effects on influencing damage levels to individual buildings.

A number of timber frame dwellings constructed with an RC ground-floor structure (Fig. 9), or on artificially raised land were present in the surveyed area. The impact of raising residential timber frame buildings was generally positive, with the majority sustaining light to moderate damage depending on tsunami inundation depth or debris impact, as opposed to suffering heavy damage or collapse when built on concrete ring foundations just above ground level.

Embankments provided a large degree of protection to some parts of the survey area: the railway running north is situated on an embankment approximately 4 m high, and Highway 4 (traversing the northern valley) is situated on a 6 m high embankment. No scour or slope failure was observed at these embankments and in both cases tsunami damage to buildings

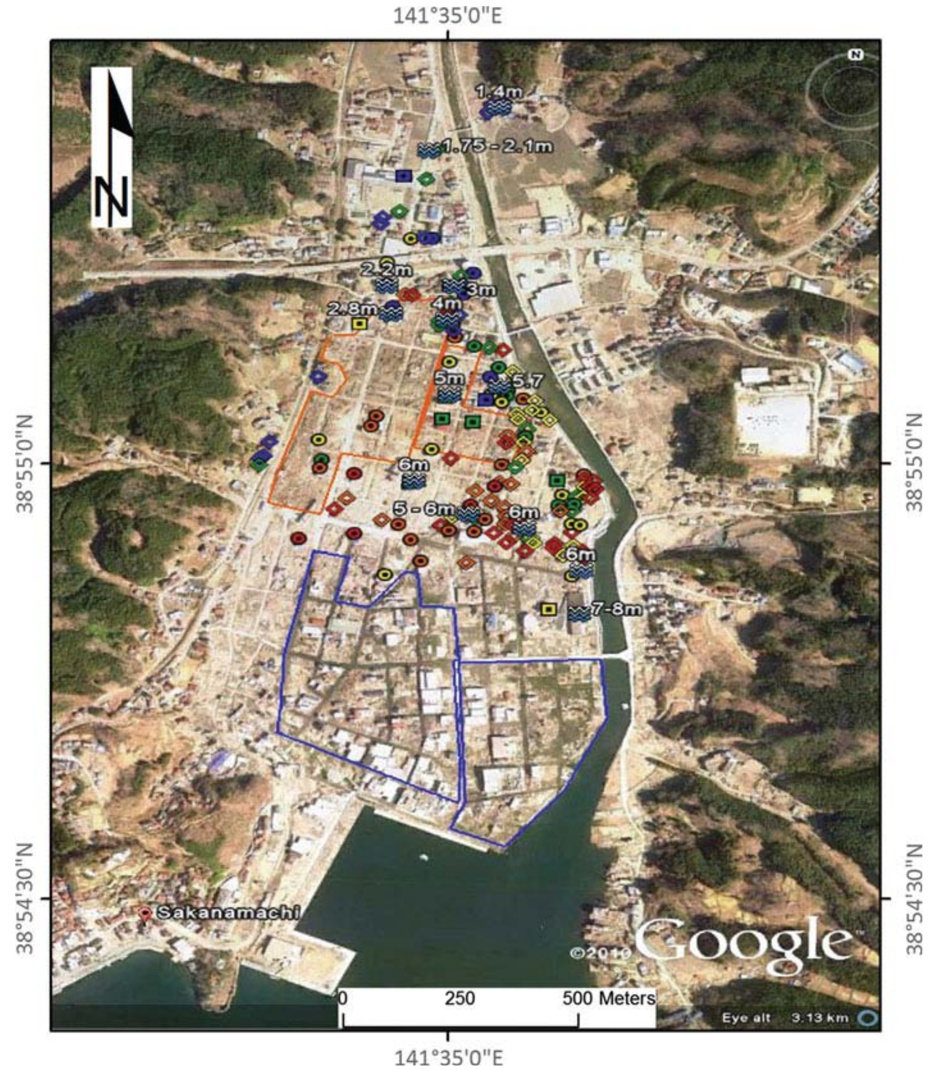

Fig. 8 Damage survey in Kesennuma City with individual buildings plotted to show construction and damage level. *Diamonds* denote timber frame construction, *squares* denote RC, *circles* denote steel frame. Damage level is indicated by colour—*Blue* D0, *green* D1, *yellow* D2, *orange* D3, *red* D4. Inundation depths, heavily fire damaged areas (*orange* outline) and subsided area (*blue* outline) are also shown. The subsided area was flooded at the time of survey. Inset shows survey location in the context of Kesennuma Bay

behind the embankments was substantially lower than in front. Damage was not entirely prevented north of the Highway 4 embankment, as the tsunami flowed along a road which runs north under the highway. The railway embankment, although overtopped, blocked floating debris and prevented fire spreading to structures west of the railway. Tsunami impact west of the railway was limited to flood-damaged contents in modern timber dwellings. Clearly, the impact of embankments was entirely related to their position and height relative to tsunami inundation depth; however, these observations provide evidence that in low to moderate

Fig. 9 An example of a timber frame dwelling constructed with an RC ground floor structure. The main house is 3 m above ground level, 780 m inland and 60 m from the river. Despite inundation depth of approximately 6 m in this area, the house had sustained very little non-structural damage

inundation depths, placement of infrastructure on embankments can limit damage to both infrastructure and structures in the lee of the embankment.

6.5 Minami-Sanriku Town, Miyagi Prefecture

Minami-Sanriku Town is in a south-east facing bay at the junction of 3 river valleys (Fig. 10). The bay is broad, the mouth measuring 1.7 km across with little narrowing to the harbour front (1.1 km across) and further inland, where urban development extends to 1.5 km inland up the rivers. Despite less opportunity for wave amplification in this bay compared with some of the more narrow rias, tsunami height at the shore was estimated at 16 m (Take and Yamaya 2011) and observed by EEFIT to be at least 11 m at Shizugawa Hospital, 300 m inland. Inundation heights and inundation extent here far exceeded those experienced during the 1960 Chile event, or that expected from the anticipated offshore Miyagi-ken-oki earthquake (around M 7.4 with recurrence interval of <40 years). More than 82 % of the town's population resided within the area that was inundated and the fatality rate in this area was 6.9 % (Table 2; Geo-Spatial Information Authority of Japan 2011b; Japanese Ministry of Internal Affairs and Communications 2011).

The coastal defences in this town consisted of a sea wall and two flood gates across the two river channels; the concrete pillars of these gates remain standing although the attached steel operating components were washed away. Long sections of the tsunami wall collapsed and evidence of inadequate interlocking of adjacent blocks in the concrete sea walls was observed, with the blocks relying on self-weight for stability.

Steel frame buildings sustained heavy damage and EEFIT observed collapse of several 2- to 3-storey RC buildings from debris impact and significant scour. The 3-storey steel frame Crisis Management Department (CMD) building (38°40′ 40.06″ N, 141° 26′ 46.82″ E; 470 m from the harbour front) remained standing with heavy damage after being inundated to its roof at 10 m above ground level (Fig. 11).

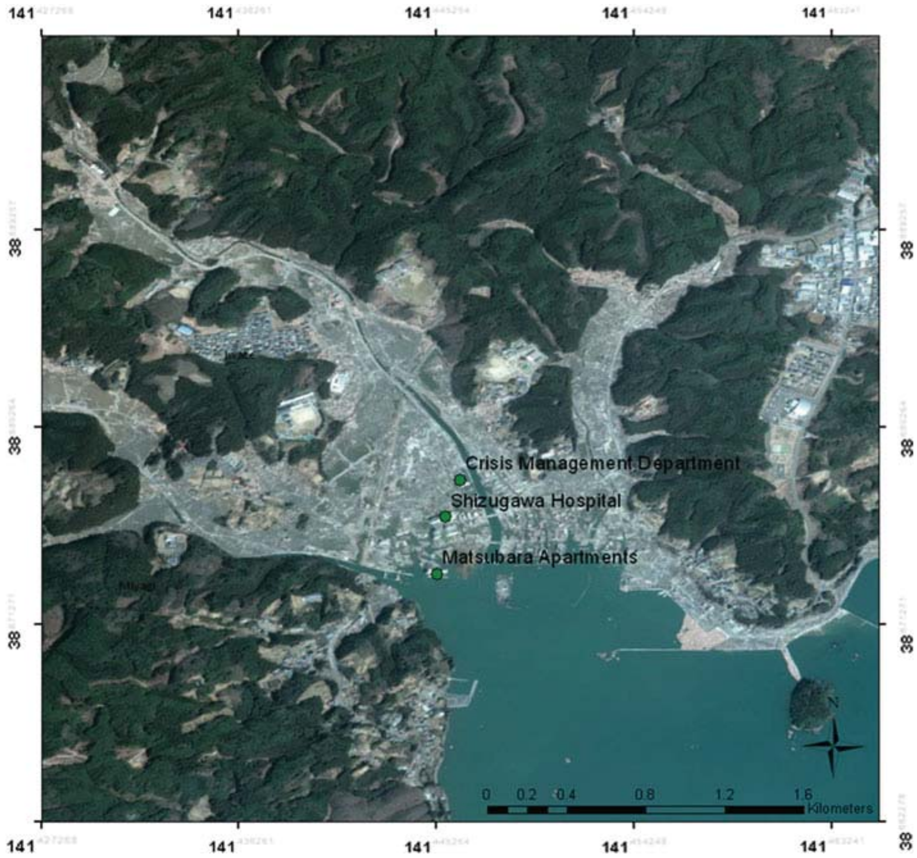

Fig. 10 Satellite image showing Minami-Sanriku town in its coastal situation. Key buildings discussed in the text are marked: Crisis Management Department, Shizugawa Hospital and Matsubara community housing apartment block, also designated as a vertical evacuation building

Several large RC buildings, including vertical evacuation structures, survived but sustained moderate to heavy damage. In the area up to 500 m from the port front, almost all timber frame structures suffered collapse and many steel frame and RC structures sustained moderate to heavy damage (D2–D3). Several RC structures within 300 m of the coast suffered collapse due to extensive scour and/or debris strike (Fig. 12). The 4-storey RC Matsubara community housing apartment block at the harbour front (38° 40′ 25.10″ N, 141° 26′ 42.93″ E; Fig. 13), constructed in 2007, was designated for vertical evacuation. The structure was built parallel to the harbour front in the longitudinal direction, which did not appear to have affected its structural performance despite inundation to the 4th storey and scour of the piled foundations to at least 2 m below previous ground level. The building was protected on the seaward side by a sea wall, which failed during the tsunami return flow; directly in front of this building this wall remained intact, but had failed where it was not sheltered in the return flow. Shizugawa Hospital (38° 40′ 34.44″ N, 141° 26′ 44.99″ E; Fig. 14) is a 4-storey RC shear wall construction with steel bracing, and showed significant non-structural damage from debris impact including parts of the steel bracing.

Fig. 11 The 3-storey steel frame Crisis Management Department (CMD) building, located 470 m from the harbour front. This building was inundated to the roof (at 10 m elevation above ground level) and sustained loss of all cladding although the structure remains standing. Damage to this building and the deaths of CMD staff resulted in the loss of crisis management facilities and expertise in the immediate aftermath of the tsunami

6.6 Onagawa Town, Miyagi Prefecture

Onagawa Town is situated in a narrow valley exposed to the Ocean to the east, with an estuary at the western end of the valley (Fig. 15). Maximum inundation depths here exceeded 16 m due to flow from the east. The town suffered a high fatality rate (11.9 % of the population living in the inundated zone, see Table 2), which was greater than the rate in Minami-Sanriku for a similar level of population in the inundated area, and similar magnitude of tsunami inundation height. These figures suggest important differences in evacuation response between these towns.

The ground-floor of the hospital, 145 m inland from the harbour (38° 26′ 36.17″ N, 141° 26′ 43.19″ E), was inundated despite being located on a hill 16 m above the harbour. Inundation was sufficient to float cars in the hospital car park (also at 16 m elevation), while vehicles had been deposited on rooftops of two 3-storey buildings in the low-lying main area of the town. Onagawa Town had two breakwaters situated 1 mile east of the harbour at the mouth of the bay, each 300 m long with a maximum depth of 28 m and a 150 m gap between, constructed following the 1960 Chile tsunami (Noh 1966); post-tsunami aerial photographs indicate that the breakwaters were destroyed by the tsunami and only a few caissons remain

Fig. 12 RC building in Shiomi-cho, Minami-Sanriku, 100 m from the sea (38° 40′ 29.10″ N, 141° 26′ 44.96″ E) showing collapse of upper storeys. Several other RC buildings in the immediate vicinity of this building had suffered collapse with evidence of severe scour and debris impact

Fig. 13 The Matsubara apartment block and designated vertical evacuation building in Minami-Sanriku. This photograph shows the landward side of the building with scour of at least 2 m at it northern end (a similar amount of scour was also observed at the southern end). Observations of this side of the building show little structural damage despite 16 m inundation height

visible above water level on the south section. In the urban area up to 400 m inland, timber buildings had all collapsed (D4) and most steel frame buildings suffered moderate to severe damage and collapse (D2–D4). Many RC buildings sustained moderate damage (D2), and a few were severely damaged (D4) through overturning.

Onagawa Town provided some of the most unexpected observations of this event: 5 RC shear wall buildings and 1 steel frame building, all of 2- to 3-storeys height, were overturned and moved from their original positions during the tsunami (movement indicated by arrows in Fig. 16). This type of failure had not been previously observed for RC shear wall or steel frame buildings subject to tsunami loading. The aspect ratio of these buildings may have been

Fig. 14 Shizugawa Hospital, Minami-Sanriku, which was inundated to 11 m depth but was used in evacuation to the roof. This photograph shows the landward side of the building with evidence of damage to the balcony at the 4th storey

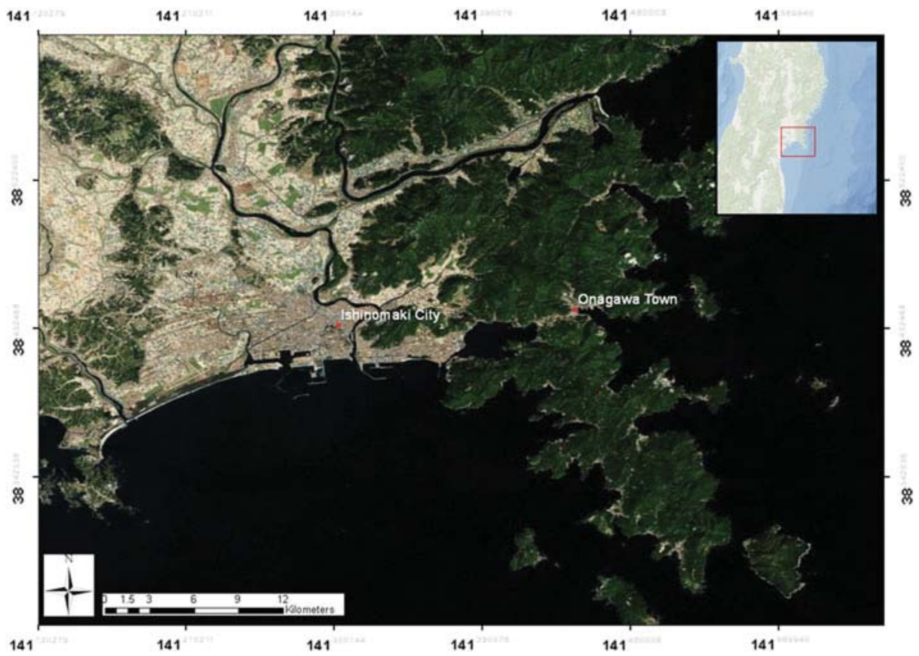

Fig. 15 Satellite image showing Onagawa Town and Ishinomaki City, showing the transition between plains coastline to the west and rias to the east. Figure 16 shows a close up of the eastern harbour of Onagawa Town

higher than other nearby buildings and all had a small building footprint. Some had piled foundations, others were on raft foundations—descriptions of each building are provided below. Witnesses described that the 1st incoming wave knocked over these buildings (Read 2011). Potential explanations for the overturning of these structures are offered below.

Fig. 16 Satellite image of the harbour in Onagawa Town, indicating the (i) final locations of overturned RC and steel frame buildings (*blue points*, marked with building tag A–E) as observed by EEFIT; (ii) the track of building movement from the original position indicated by *arrows* (Tokimatsu et al. 2011); and (iii) positions of two velocity estimations made for return flow velocity using video footage

A 2-storey RC shear wall office building with piled foundations was overturned landward during tsunami inflow (‘Building A’; Fig. 17). The structure had one pile at each corner, and three closely spaced piles at each of the central pile caps. The rebar in each pile did not extend very far down the pile and they appeared quite lightly reinforced at the top, suggesting they were designed only for shear, rather than also for tension. The uppermost (originally seaward) piles remained connected to the pile cap and were relatively straight, suggesting that they had been pulled out of the ground and then failed in tension. In contrast, the bottom (originally landward) piles were sheared off closer to the foundation and were all bent downwards; this suggests the lateral forces imparted by tsunami flow were concentrated on the landward piles, which became the pivot point in the overturning motion. Overturning in this case may have been initiated by debris strike, evidence of which was observed at the top of the structure.

The final location of a 2-storey RC shear wall structure with raft foundation (‘Building B’; Fig. 18) implied the building overturned seaward, however, it is expected that the initial failure was landward (consistent with other structures) and the building had then been moved during tsunami return flow to its final position. The raft foundation of this structure was inadequate for resisting the effects of scour and the lateral forces imparted by tsunami flow.

A 3-storey hotel (with 4th storey appendage) of RC shear wall construction (‘Building C’), on raft foundation with evidence of a failed pile was moved approximately 30 m from its original position (Shuto 2011) until it rested against the steep reinforced wall of the hill where the hospital is situated. This building had been removed by the time of our visit to allow free flow of traffic.

Fig. 17 Foundations of an overturned two-storey RC shear wall structure with piled foundations in Onagawa Town—'Building A'. Evidence of impact at the roof of the building on its seaward side indicates that this failure may have been initiated by debris strike

Fig. 18 An overturned two-storey RC shear wall structure with raft foundations at the harbour edge in Onagawa Town—'Building B'

Overturning was also seen at 3-storey steel frame structure on piled RC foundation with 2–3 piles at each of 8 pile caps ('Building D'; Fig. 19). Only one of the 20 RC piles remained attached to the foundation beams by only reinforcement bars. All cladding at the ground-floor was removed exposing an open lattice-type structure suggesting that buoyancy could not have had a significant impact on the building displacement.

A 3-storey RC shear wall structure ('Building E'; Fig. 20) had shallow pad footing with ground beams of small dimensions, with one of the corner pads effectively acting as a pile cap rather than pad footing, possibly due to locally weak soil. No piles remained connected to the pile caps in this case, suggesting a higher level of shear in the overturning motion than experienced at the other piled buildings.

Fig. 19 An overturned 3-storey steel frame building (‘Building D’) on piled RC foundation with evidence of debris impact on the (originally) seaward face of the building. This photograph was taken from a neighbouring building during tsunami inundation, courtesy of Miyagi Prefectural Office

Fig. 20 A 2-storey RC shear wall structure with shallow pad footing foundation (‘Building E’). Evidence of small piles on at least one of the corner columns can be seen, but no piles remained attached at the time of our visit. The building has also sustained out-of-plane failure of an infill wall at the ground floor

Although any evidence of liquefaction had been washed away in the tsunami, this may have also contributed by loosening the soil around piles prior to the overturning motion. During liquefaction soil shear strength is decreased, thereby decreasing shaft resistance between the pile face and the soil around it. This would allow greater lateral movement of the piles while in the ground, and enable the piles to be extracted more easily from the ground when the building was subjected to uplift or lateral forces (due to tsunami flow or debris impact), which were significant in Onagawa due to the extreme inundation depth. Similar overturning failures of RC buildings were observed in at least one case in Ōtsuchi (Chock 2011) and Miyako City.

Despite extreme hydrodynamic forces in this area, many buildings survived due to dense urban development affording a certain degree of sheltering. A 4-storey harbour-front complex of 2 buildings suffered extensive glazing damage, limited damage to masonry cladding, and the loss of an elevated walkway that connected the buildings. Smaller buildings in the lee of these substantial structures were sheltered on the inflow of tsunami, and remain standing despite sustaining heavy non-structural damage on the return flow. While observations from Onagawa and many other sites in this and previous extreme tsunami events (EEFIT 2006; Borrero 2005) showed that RC structures are effective in withstanding tsunami loading, it is now clear that there are additional failure modes to consider in their resistance to tsunami loads in high velocity flows exceeding 15 m depth. This has vital implications for the selection of appropriate RC structures to use in vertical evacuation strategies.

6.7 Ishinomaki City, Miyagi Prefecture

Ishinomaki is the 2nd-largest city in Miyagi Prefecture and has approximately 12 km of south-facing coastline (Fig. 15), much of which is dedicated to warehouses and industrial sites associated with the fishing port and commercial port. Inland of the ports, the densely built-up urban area extends 4.8 km inland at it furthest point; the 400 m closest to the harbour is commercial and industrial land use, with residential and smaller commercial land use further inland. The death toll in Ishinomaki City was the highest of all tsunami affected cities and towns and as of August 25th 2011, stood at 3,158 dead and 849 missing (Fire and Disaster Management Agency of Japan 2011). This was a relatively low fatality rate of 3.6 % relative to the population living within the inundated area, when compared to other locations which also had 70–80 % of the population was living in the inundated area (i.e. Rikuzentakata, Ōtsuchi, Onagawa, and Minami-Sanriku).

Inundation simulations based on a Miyagi-ken-oki earthquake of JMA magnitude 8.0 multiple source zone rupture estimated that 164 people would be killed in Ishinomaki (Miyagi Prefectural Government 2004). Maximum estimated inundation height from the subsequent tsunami was 3 m along the port front, and 1 m at a distance of 500 m inland. Our surveys showed that the inundation height on March 11th was at least 4 m at several locations over 470 m inland, while measurements by The 2011 Tohoku Earthquake Tsunami Joint Survey Group (2011) indicate tsunami height at the Ishinomaki fishing port was around 4 times higher than the above modelled estimates.

Aerial photographs show that the majority of structures remained standing in the inundated area of Ishinomaki City, although there were some areas of almost entire destruction observed around the mouth of the Old Kitakami River where significant co-seismic subsidence of up to 0.78 m occurred (Geo-Spatial Information Authority of Japan 2011c). Flooding of subsided land adjacent to the river mouth and along the port front now occurs at high tide. There was evidence of fire damage in this area, with Kadonowaki School building showing significant external fire damage.

General observations of damage levels were made along two transects in the eastern part of the city. The survey indicated no structural damage at distances greater than 850 m inland, although there was evidence of motor vehicle floatation at this distance. During this rapid survey, timber frame buildings showed extremely variable damage, from light damage to collapse (D1–D4). Steel frame buildings showed light to heavy damage (D1–D3), while RC buildings showed light to moderate damage (D1–D2). At 420 m inland a lorry had been deposited on the 1st storey roof of a residential building, but despite the 3 m inundation depth, several adjacent timber frame houses remained standing with light damage (D1), suggesting low flow velocity. In the immediate vicinity of these houses, heavy damage to a steel frame building, moderate damage to RC buildings and collapse of other timber structures shows high local variability of tsunami damage. Observations of damage at the port front included impact of large debris, causing significant bending of the structural columns of a large 1-storey steel frame warehouse.

6.8 Sendai City coastal areas, Miyagi Prefecture

Sendai City is divided into 5 wards, including Miyagino-ku and Wakabayashi-ku which are coastal, and Taihaku-ku which spreads across the whole of the southern part of the city with its borders reaching up to 3 km inland from the shore. In Miyagino-ku and Wakabayashi-ku 630 people died. The dense urban area of the city is over 4 km inland and the city centre is 12 km from the coast; the majority of land between the coast and the Tōhoku Expressway, which dissects the eastern part of the city from north to south, is agricultural land. Inundation reached up to 5.7 km inland in Wakabayashi-ku and up to 7.5 km where the tsunami flowed up the Natori River at the southern limits of the city.

EEFIT investigated damage to residential properties in the Arahama District of Wakabayashi-ku, which suffered severe damage and a fatality rate of 4.29 % from the tsunami. The coastline is east-facing with localised use of 6 offshore breakwaters; the main defence being concrete block revetments along Arahama Beach. A pine forest immediately inland of the revetments provided additional protection. The flat low-lying terrain contributed to inundation of up to 5 km inland.

The concrete defences at Arahama Beach had failed in several places and the sand infill had been washed out (Fig. 21), while concrete blocks had been removed and washed up to 100 m landward into the coastal pine forest. Many residential properties of timber frame construction suffered complete collapse or had been demolished by the time of our investigation. Significant scour of the sandy soil (old beach deposits) on the seaward side of buildings had caused tilting and exposure of foundations in some buildings. Out-of-plane failure of infill

Fig. 21 Failure of a concrete block revetment at Arahama Beach. Sand fill had been washed out of the revetment, causing collapse of the concrete blocks and pathway along the crest of the defence

Fig. 22 The south side of Arahama Elementary School, which was successfully used for vertical evacuation. Timber-clad steel bracing is visible in windows of the lower floors. Damage to non-structural components at the ground floor is shown, along with debris at the seaward end of the building on the second floor. The roof shows evacuation infrastructure including warning sirens and fencing around an evacuation area. There is external access to the roof on the north side of this building

walls at several RC and reinforced masonry structures was observed approximately 100 m landward of concrete sea defences. Scour up to 3 m deep resulted in the collapse of a tsunami warning siren at the beach.

This area was notable for two contrasting examples of evacuation structures. A pre-cast concrete gymnasium building (38° 15′ 39.30″ N, 141° 00′ 53.61″ E) close to Sendai Port was indicated by a damaged road sign as an evacuation site. This structure was 380 m from the open ocean with a small estuary (150 m wide) on the inland side of the beach. A series of dikes separated part of the estuary into individual ponds—the dikes were breached by the tsunami and had been repaired with sandbags at the time of investigation. Due to its function as a sports hall (single storey, high ceiling) the building had no upper storey in the main part of the building, and very little floor space at the 2nd storey of the adjoining building, making it unsuitable for vertical evacuation. There was also a lack of external access to the roof (only a small maintenance ladder). Only non-structural damage was apparent: glazing, damaged wall cladding, minor scour and lifting of the gymnasium floor.

Arahama Elementary School (38° 13′ 20.52″ N, 140° 58′ 49.88″ E; Fig. 22), performed its secondary function as a vertical evacuation refuge well during this event. The 4-storey pre-2001 RC structure comprised shear walls on the narrow external seaward and landward faces. The building had been previously retrofitted with steel bracing members to strengthen its central section. The bracing was situated only on one side of the central shear walls and only at the lower 3 storeys. The lowest 2 storeys of the building were flooded up to ceiling level. The building had rooftop railings, direct external roof access via a large brightly painted steel staircase to the rear and two sets of rooftop sirens. No vertical evacuation signage was clearly displayed on the building. Debris had entered the building in the longitudinal (perpendicular to the shoreline) direction, with timber and 3 cars inside the central ground-floor corridor indicating significant flow velocity through the central corridor that ran the length of the building. All other observed damage was non-structural: glazing and contents, and

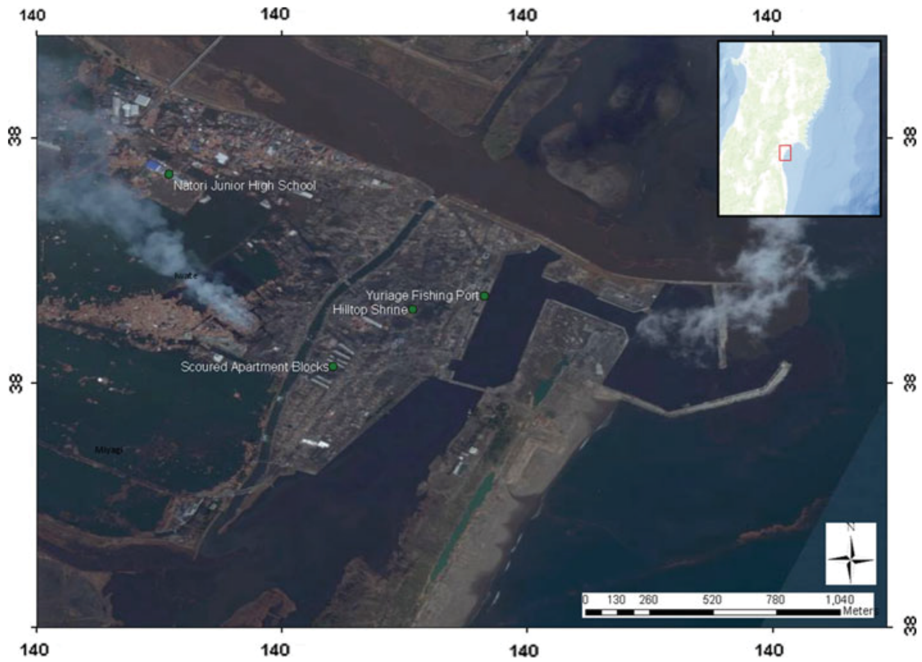

Fig. 23 Post-tsunami aerial photograph of Yuriage District, Natori City, showing almost complete destruction of this residential area, although the part of Yuriage adjacent to the river embankment (northern edge of this image) sustained less damage

small debris strike at the seaward end. A successful evacuation was carried out at this site: 380 people survived by evacuating to the roof (Iwate Nichi Nichi Shinbun 2011).

6.9 Natori City, Miyagi Prefecture

Natori City is located on the Sendai Plains and is predominantly low-lying flat agricultural land, with 2 main population centres—the main city situated at least 5 km inland and Yuriage District at the coast, adjacent to the mouth of the Natori River (Fig. 23). Coastal defence in Yuriage comprised pine coastal forest with concrete harbour walls at the Yuriage Port (38° 10′ 21.63″ N, 140° 57′ 23.51″ E). The tsunami arrived in Yuriage approximately 65 min after the earthquake and inundated up to 5.2 km inland, close to the embankments of the Tōhoku Expressway, where floating and burning wooden houses, cars, boats and other debris were deposited. Natori City officials advised EEFIT that Yuriage sustained a greater number of casualties than seaward of Sendai Airport, further south. The fatality rate was high compared to other areas (8.1 %), and as was the case in many other areas in this event, predominant casualties were people over 65 years of age (Fire and Disaster Management Agency of Japan 2011).

Almost all timber frame residential buildings in Yuriage sustained complete collapse (D4). Steel and RC structures sustained damage ranging from light (D1) to collapse (D4). The RC port building sustained out-of-plane failure of all hollow concrete block masonry infill walls and partial collapse, and the wharf itself suffered significant scour and partial collapse. The majority of reinforcement in the concrete block infill walls was un-deformed rebar. Consistent failure direction of columns immediately inland of the port structure indicates flow

Fig. 24 View along the north side of one apartment block in Yuriage, illustrating scour at the seaward end of one apartment building. Loss of soil providing bearing capacity to support the footings resulted in tilting of this building

direction from the east, which indicates that the wave arrived approximately perpendicular to the coastline, directly into the river mouth and across Yuriage harbour, where there were no significant coastal defences.

Significant scour of sandy soil was observed at a row of four apartment blocks (all 2- to 3-storey RC shear wall construction) in Yuriage. Scour occurred to up to 2 m deep around the eastern (seaward) ends and northern sides of the two of these buildings, causing severe tilting of one (Fig. 24). The position of the most severe scour implies that scouring at this location most-likely occurred during the return flow of the tsunami. Another building had severe debris impact damage on the 2nd storey level on the seaward side RC shear wall, likely due to impact from the floating fishing vessel that still lay in front of the building at the time of our visit (June 1st).

At Sendai Airport, the tsunami broke close to the shore and overtopped a 5–10 m high sand dune before flowing several kilometres inland through paddy fields. The airport terminal building, 1 km inland (38° 8′ 17.13″ N, 140° 55′ 48.88″ E), is a 4-storey steel and RC construction with a significant amount of exterior glazing on all storeys. The tsunami inundated the 1st storey of the terminal building—internal steel frame partition walls had been bent by debris strike. Airport staff reported that external windows broke only when struck by debris, not due to wave loading alone.

Five vertical evacuation structures in Natori City saved 3,285 lives in this event (Table 1; Iwate Nichi Nichi Shinbun 2011). EEFIT investigated the performance of Yuriage Junior High School (38° 10′ 38.70″ N, 140° 56′ 42.30″ E); the building suffered non-structural earthquake damage at seismically-designed separation joints, but remained effective as a vertical evacuation structure throughout tsunami inundation. The school was 1.5 km from the shoreline and only 320 m from the river to the north. Constructed on a 1.8 m high embankment, the school was raised above the level of surrounding rice fields, reducing the inundation depth at the eastern (seaward) end of the school buildings to 1.76 m. Flow velocity was low around the school building, with only flood damage to contents, and no debris impact or glazing damage as recorded at other locations. Natori City officials reported that this building

Fig. 25 A steel frame agricultural building located 1 km inland at Yamamoto Town, Miyagi Prefecture. A tree trunk, apparently from the damaged coastal pine forest, struck a structural column on the south-east (seaward) corner of the building, buckling the structural and non-structural members. Tsunami flow has removed cladding to a height of over 4 m

provided refuge to approximately 800 people who had to remain there for 2 days following the tsunami.

6.10 Yamamoto Town, Miyagi Prefecture

Yamamoto Town has very similar low-lying topography to the Yuriage and Arahama districts, and suffered a similar fatality rate (7.7 %) as Natori City. The beach had large periodically-placed groynes and a concrete block revetment, with pine coastal forest immediately inland. Both sides of the revetment comprised a concrete lattice in-filled with concrete blocks and natural vegetation. The revetment had a sand core and a concrete and bitumen pathway along its crest. The groynes were constructed of slim concrete armour units aligned with the slope and appeared largely intact. At several locations along the revetment, there were breaks in the reinforced lattice and most of the concrete blocks were missing. Scour on the leeside was a main cause of embankment failure. Pine trees of the coastal forest were largely destroyed by the tsunami: they had bent over and trunks were snapped very close to the base. The coastal forest provided substantial amounts of debris which was seen to cause structural damage to a steel frame agricultural building located 1 km inland (37° 57′ 26.39″ N, 140° 54′ 18.44″ E; Fig. 25). This building was struck during tsunami inflow by a tree trunk which bent structural members.

7 Summary and conclusions

The M_w9.0 Great East Japan earthquake and tsunami of March 11th 2011 caused extensive damage along the Tōhoku coastline, damaging coastal defence structures and hundreds of thousands of buildings. The affected region had an extensive array of coastal defences of all types—some specifically designed to mitigate tsunami damage. This event rigorously tested these defences, and where they failed to protect the coastal communities it was primarily because the wave heights experienced in this event far exceeded the design values, which were based on the expected Miyagi-ken-oki event or inundation levels experienced in the 1896, 1933 and 1960 tsunami. Sea walls and breakwaters were overtopped, overturned, or broken up by hydrostatic and hydrodynamic forces and scour on a large scale, but did provide some degree of protection despite this damage. Trees (from the coastal protection forest) and concrete blocks (from coastal revetments) proved to be damaging debris sources, contributing to structural damage and collapse of buildings in several locations.

Numerous evacuation refuges and other critical infrastructure (such as hospitals, crisis management and police headquarters) were inundated in this event resulting in significant loss of life. Estimation of tsunami hazard in this region had been underestimated, and many evacuation centres were inundated. The network of vertical evacuation structures should be expanded for use in future events, particularly in the Sendai Plains where there is no access to high ground. Further work is required in future to ensure refuges are properly designated in terms of location and structural suitability; both of these issues are a product of adequate hazard estimation and mapping.

EEFIT tsunami observations show that damage can be extremely variable in a local area and it is clear that inundation depth, direction of flow, local flow velocity variations, sheltering during the inflow and return flow, and debris entrainment must all be considered for a complete assessment of tsunami fragility. RC shear wall structures are again confirmed as able to withstand tsunami loading and should form the primary construction type for critical infrastructure in tsunami risk areas, but further research is required into mitigation of scour, liquefaction, debris impact, and the prevention of overturning failure as these features caused failure of RC buildings in several observed cases.

Our surveys show that the structure of steel frame buildings often remain standing following a tsunami but significant damage to non-structural components, primarily removal of cladding, renders this type of structure unsuitable for use as critical infrastructure. Debris impact is a key factor in structural damage of steel frame structures—while tsunami flow alone is shown to cause significant non-structural damage, it is debris impact which most often caused heavy damage to the structural members and collapse of the building.

Our surveys have suggested that significant local variability in damage, even to timber frame structures, occurs due to local flow characteristics and that many timber frame buildings can survive in areas experiencing low flow velocity, however, there remains no doubt that timber frame buildings generally cannot withstand tsunami flow forces, particularly in the near shore area. Raising timber structures on RC open-structure ground-floors can mitigate damage in inundation depths of up to 6 m, as observed in Kesennuma City. This should be a consideration in reconstruction of residential areas as long as potential soft-storey effects during ground shaking are adequately addressed, and where it is appropriate to the level of tsunami hazard.

As a result of our observations and damage surveys in Tōhoku, EEFIT have further developed separate tsunami damage scales for timber, steel frame and RC buildings. These scales have been demonstrated in this paper, and provide a consistent basis for completion of future post-tsunami damage assessments, enabling comparison of damage across different areas and events.

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