Improvement of tsunami countermeasures based on lessons from the 2011 great east Japan earthquake and tsunami
situation after five years

Suppasri, A; Latcharote, Panon; Bricker, Jeremy; Leelawat, Natt; Hayashi, A; Yamashita, Kei; Makinoshima, Fumiyasu; Roeber, Volker; Makinoshima, Fumihiko

DOI
10.1142/S0578563416400118

Publication date
2016

Document Version
Accepted author manuscript

Published in
Coastal Engineering Journal

Citation (APA)
Suppasri, A., Latcharote, P., Bricker, J., Leelawat, N., Hayashi, A., Yamashita, K., Makinoshima, F., Roeber, V., & Makinoshima, F. (2016). Improvement of tsunami countermeasures based on lessons from the 2011 great east Japan earthquake and tsunami: situation after five years. *Coastal Engineering Journal*, *58*(4), 1-30. Article 1640011. https://doi.org/10.1142/S0578563416400118

IMPROVEMENT OF TSUNAMI COUNTERMEASURES BASED ON LESSONS FROM THE 2011 GREAT EAST JAPAN EARTHQUAKE AND TSUNAMI

– SITUATION AFTER FIVE YEARS–

ANAWAT SUPPASRI
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: suppasri@irides.tohoku.ac.jp
PANON LATCHAROTE
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: panon@irides.tohoku.ac.jp
JEREMY D. BRICKER
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: bricker@irides.tohoku.ac.jp
Delft University of Technology, Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA Delft, The Netherlands
Email: jeremy.bricker@gmail.com
NATT LEELAWAT
Department of Industrial Engineering and Management, Graduate School of Decision Science and Technology, Tokyo Institute of Technology, 2-12-1-W9-66 Ookayama, Meguro-ku, Tokyo 152-8550 Japan,
Email: leelawat.n.aa@m.titech.ac.jp, n.leelawat@gmail.com
AKIHIRO HAYASHI
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: hayashi@irides.tohoku.ac.jp
KEI YAMASHITA
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: yamashita@irides.tohoku.ac.jp
FUMIYASU MAKINOSHIMA
Graduate school of engineering, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: makinoshima@tsunami2.civil.tohokua.ac.jp
VOLKER ROEBER
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: roeber@irides.tohoku.ac.jp
FUMIHIKO IMAMURA
International Research Institute of Disaster Science, Tohoku University, 468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-0845, Miyagi, Japan, Email: imamura@irides.tohoku.ac.jp

Abstract

The 2011 Great East Japan Tsunami exposed many hidden weaknesses in Japan’s tsunami countermeasures. Since then, many improvements have been made in both structural measures (numerical simulations, coastal defense structures, building damage assessment and control forests) and nonstructural measures (warning/observation and evacuation). This review summarizes the lessons and improvements in the five-year time period after the 2011 event. After five years, most of the lessons from the 2011 tsunami have been applied, including more realistic tsunami simulations using very fine grids, methods to strengthen coastal defense structures, building evacuations and coastal forests, improved warning content and key points to improve evacuation measures. Nevertheless, large future challenges remain, such as an advanced simulation technique and system for real-time hazard and risk prediction, implementation of coastal defense structures/multilayer countermeasures and encouraging evacuation. In addition, among papers presented at the coastal engineering conference in Japan, the proportion of tsunami-related research in Japan increased from 15% to 35% because of the 2011 tsunami, and approximately 65–70% of tsunami-related studies involve numerical simulation, coastal structures and building damage. These results show the impact of the 2011 tsunami on coastal engineering related to academic institutions and consulting industries in Japan as well as the interest in each tsunami countermeasure.

1. Introduction

Before the 2011 Great East Japan Earthquake and Tsunami, Japan was known as a global leader in tsunami disaster prevention. However, the 2011 tsunami made a serious nationwide impact [Mori *et al*., 2012], mainly in the Tohoku region [Suppasri *et al*., 2012a, 2012b; Gokon and Koshimura, 2012; Kakinuma *et al*., 2012; Mikami *et al*., 2012; Ogasawara *et al*., 2012; Shimozono *et al*., 2012] and in other regions, from Hokkaido in the north [Watanabe *et al*., 2012] Tokyo in the south [Sasaki *et al*., 2012]. This tsunami event exposed hidden weaknesses in Japan's tsunami disaster countermeasures. This review has the objectives of summarizing and discussing the improvements in tsunami-related structural (Section 2: Tsunami simulation, Section 3: Coastal defense structures, Section 4: Building damage assessment and Section 5: Coastal forest) and nonstructural (Section 6: Warning system and Section 7: Evacuation) countermeasures in the five years since the 2011 tsunami. This review study can be beneficial as a general reference for future tsunami research in various coastal engineering and related aspects. The specific points discussed in each section of this review are as follows.

In section 2, numerical tsunami simulations are shown to be much improved, owing to the consideration of previously neglected phenomena, a calculation technique using high-performance computers and high-resolution topographical data. Simulations were also developed and improved for other purposes, such as the analysis of morphological changes and the effect of coastal forests.

In section 3, the failure of coastal defense structures is shown to have led to new concepts for tsunami mitigation countermeasure levels 1 and 2 and their strength even during overflow and turbulence flow conditions. A newly proposed design for coastal embankments and breakwaters is explained.

Section 4 discusses the tsunami fragility functions developed for buildings, land use and topography conditions; however, there is a challenge regarding the proper way to apply these curves to different areas. This section also includes newly proposed design criteria for building evacuation.

Unlike mangrove forests in tropical countries, pine forests are shown in section 5 to have performed rather weakly; most of them were severely damaged, which magnified the damage to downstream buildings via floating debris. Nevertheless, it was shown that coastal pine forests could also reduce the impact of tsunamis. Recent studies focusing on the performance of pine trees, replantation activities and assessment of coastal forests are presented.

Section 6 discusses new observation systems set up in Japan for highly accurate warnings. After the 2011 tsunami, the Japan Meteorological Agency (JMA) modified their tsunami warnings from eight to five levels and created a new type of warning—the so-called emergency warning—for extraordinary disaster events, including tsunamis. These attempts are made to encourage residents to evacuate.

In section 7, many problems related to both inland and offshore evacuation are discussed. Evacuation using vehicles caused serious traffic jams in many areas during and after the 2011 event. For flat areas, such as those in the Sendai Plain, vehicles are now acceptable for evacuation, and there are many ongoing studies on evacuation models. Regulations for offshore evacuation required reconsideration, depending on the coastal topography and difficulty after high-ground relocation.

2. Numerical tsunami simulations

2.1. *Recent development of numerical tsunami simulations*

Numerical tsunami simulations have been developed for the evaluation of tsunami hazards and risks in disaster mitigation. Many numerical models have been proposed to simulate tsunami wave propagation by applying linear long-wave theory in deep seas and nonlinear long-wave theory in shallow seas. After the 2011 Great East Japan Earthquake and Tsunami, numerical tsunami simulations were verified with observed data and then employed to investigate tsunami-induced impacts using numerical modeling codes, such as TUNAMI, MOST [Titov and Gonzalez, 1997], COMCOT [Liu *et al*., 1994, 1995], NAMIDANCE [Yalciner *et al*., 2006], JAGURS [Baba *et al*., 2014], and NEOWAVE [Yamazaki *et al*., 2009]. This section uses TUNAMI as an example of how a model was developed after the 2011 tsunami. TUNAMI was originally developed by Tohoku University in 1995 for the Tsunami Inundation Modeling Exchange (TIME) project, consisting of the series TUNAMI-N1, TUNAMI-N2, and TUNAMI-N3, and was then transferred to countries with tsunami hazards. TUNAMI-N1 is a constant-grid tsunami simulation for investigating near-field tsunamis based on the staggered leapfrog scheme using linear long-wave theory, which is acceptable for the approximation of tsunami wave propagation in deep seas. Based on TUNAMI-N1, TUNAMI-N2 is a constant-grid tsunami simulation using linear theory in deep seas and shallow-water theory in shallow seas and on land. TUNAMI-N3 is a tsunami numerical model with a nested-grid scheme and linear theory. Before the 2011 Great East Japan Earthquake and Tsunami, TUNAMI had been implemented widely to simulate tsunami wave propagation in tsunami hazard areas around the world, as this well-known numerical model is applicable, conventional, and stable. Among other recently developed numerical modeling codes, JAGURS is a nested-grid tsunami simulation for modeling propagation and inundation; it applies either linear or nonlinear shallow-water theory and is numerically based on the uniform finite-difference scheme [Baba *et al*., 2014]. JAGURS-D is a parallel tsunami computation with a nesting algorithm for dispersive propagation of tsunamis using the Boussinesq model [Baba *et al*., 2015]. NEOWAVE is a non-hydrostatic model for calculating tsunami wave propagation and run-up built on nonlinear shallow-water theory, with a vertical velocity term to account for weakly dispersive waves and a momentum conservation scheme to describe bores or hydraulic jumps [Yamazaki *et al*., 2009]. After the 2011 Great East Japan Earthquake and Tsunami, numerical tsunami simulations have continued to improve to achieve reliable prediction via high-performance computing. This section is intended to describe the improvements in numerical tsunami simulations—namely, the dispersive effect, bathymetrical and topographical data, sediment transport, the effect of coastal forest and high-performance computing.

2.2. *Dispersive effect*

For transoceanic tsunamis, numerical modeling of the dispersive effect, including Coriolis force, has been proposed to simulate the wave propagation of a far-field tsunami over a long distance in deep water. In numerical modeling, tsunami wave propagation that considers the dispersive effect can be simulated by using the Boussinesq model, for which a long computation time is required. For example, the TUNAMI-N2 code was modified to consider the dispersive effect, Coriolis force, and sphere curvature, thus resulting in TUNAMI-N2-NUS [Dao and Tkalich, 2007]. Based on a sensitivity study of the numerical simulation for the 2004 Indian Ocean tsunami, dispersion can lead to a notable change in the tsunami amplitude propagating a large distance in deep water; therefore, it needs to be included in trans-ocean tsunami simulations [Dao and Tkalich, 2007]. During the 2010 Chile tsunami, there was a mitigation effect on the Gulf of Arauco due to refraction and dispersion generated by the presence of a submarine canyon [Aranguiz and Shibayama, 2012]. A numerical model of a transoceanic tsunami was developed based on the linear Boussinesq equation; it incorporated Coriolis force and used a spherical coordinate system to assess the tsunami hazards of a far-field tsunami in the South Pacific island countries [Yanagisawa and Shigihara, 2010]. Nonlinear shallow-water equations with a vertical velocity term were built to consider dispersion in tsunami wave propagation by studying the impacts on Hawaii from the 2011 Great East Japan Earthquake and Tsunami [Yamazaki *et al*., 2011]. However, owing to different wavelengths travelling at different speeds, the dispersive effect of tsunami wave propagation can occur in a near-field tsunami in shallow water as well. Numerical modeling of dispersive tsunami waves was developed by solving nonlinear Boussinesq dispersive equations with parallel computing technology and simulating the 2011 Great East Japan Earthquake and Tsunami on the K computer, currently the fastest Japanese supercomputer, in terms of the dispersive propagation of a near-field tsunami [Baba *et al*., 2015].

2.3. *Topographical data and inundation area*

In tsunami inundation simulations, high-resolution topographical data are very important for simulating tsunami wave propagation on land so as to illustrate the inundation area, including inundation depth and velocity, for which reliable prediction is very important for disaster mitigation (Fig. 1). An examination of the improvements in the simulation accuracy and topographic approximation of topographic models was conducted using LIDAR data for the coastal region of the Taro area of Miyako city, in Iwate prefecture in Japan, by comparing the simulation results of numerical analysis with different grids that were spaced from 5 m to 40 m [Murashima *et al*., 2008]. The results from high-resolution tsunami simulations, such as inundation depth and velocity, are necessary to develop a loss estimation function for death, building damage and vessel damage with respect to inundation depth and velocity by using statistical models. In general, before the 2011 tsunami, bathymetrical and topographical data with 50-m grid spacing, provided by the cabinet office of Japan, were widely used for most tsunami-prone areas in Japan. After the 2011 tsunami, 5-m-grid bathymetrical and topographical data, obtained from the Geospatial Information Authority of Japan, are available for simulating tsunami hazards in ports while integrating breakwaters and other built structures around the ports [Oishi *et al*., 2015]. Using high-resolution topographical data, tsunami inundation simulations can be reliably performed for tsunami early warning systems to inform people about a tsunami inundation area. The horizontal and vertical resolutions of the topography data may have a considerable effect on numerical studies of morphological changes due to sediment transport [Udo *et al*., 2012; Sugawara *et al*., 2014b]. The results of tsunami inundation simulations with high-resolution topographical data can provide obvious images of tsunami hazards that aid in developing evacuation guidance and raising awareness among people in possible inundation areas.

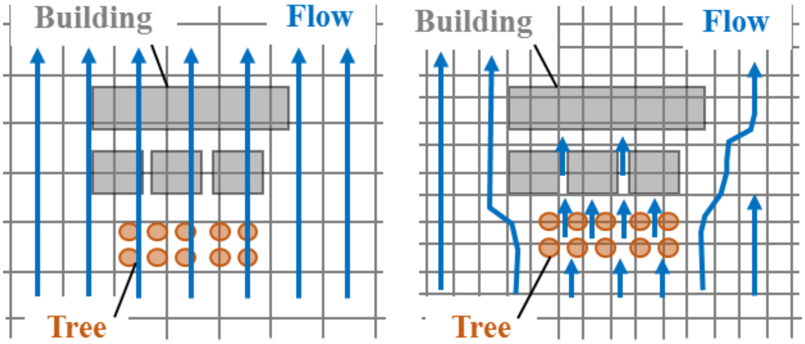

Fig. 1 Equivalent roughness model for buildings and forests (Left) and topographic model for buildings and forests (Right)

2.4. *Sediment transport and morphological change*

Numerical modeling of tsunami sediment transport has been applied to explain bathymetric changes from past events, such as the 2004 Indian Ocean tsunami [Ranasinghe *et al*., 2013]. Numerical models were originally proposed by Takahashi *et al*. [1999] to investigate tsunami sediment transport during tsunami flow and to explain the process of geomorphological changes. The

2011 Great East Japan Earthquake and Tsunami caused massive morphological changes, as reported by Udo *et al*. [2012] and Tanaka *et al*. [2012]. After the 2011 Great East Japan Earthquake and Tsunami, numerical modeling of tsunami sediment transport was performed to investigate how modeled tsunami deposits and erosion corresponded with that observed in the field [Sugawara *et al*., 2014a; Yamashita *et al*., 2016]. Recently, many research studies in the sediment transport field have focused on specific aspects, such as the dynamic behavior of sediment transport and the factors that influence deposition, to improve the sediment transport model. In the sediment transport model, it was found that initial wave amplitudes, beach slopes and grain sizes have a significant effect on tsunami deposit distribution. Based on measurements of distance between tsunami deposits and inundation distributions, historic tsunamis can be simulated to reconstruct earthquake magnitude, run-up height, inundation depth and flow velocity such as in the case of the 869 Jogan tsunami [Sugawara *et al*., 2012] and the 1771 Meiwa tsunami [Miyazawa *et al*., 2012]. The development of an expected ratio between tsunami deposits and inundation distribution was attempted as a way to estimate the inundation areas of future tsunamis by analyzing existing deposits from past tsunamis. For tsunami deposit simulations, forward and inverse modeling represent two opposite approaches aimed at investigating tsunami sediment transport. The forward modeling of sandy deposits can illustrate the process of erosion and deposition of sediment that results in morphological change [Sugawara *et al*., 2014b]. For further improvement, numerical modeling will be developed to investigate the tsunami sediment transport of gravel and muddy deposits.

2.5. *Effect of coastal forests*

Numerical modeling of coastal forests has been developed to simulate tsunami flow in vegetated areas. Using a simple technique similar to that used for buildings where very find grids are not available, the effect of coastal forests can be considered as a roughness coefficient in numerical tsunami simulations. Based on the Morison equation, a roughness coefficient model (Fig. 1) corresponding to inundation depth was proposed [Harada and Imamura, 2003]. The evaluation method for coastal forests using the roughness coefficient can be easily applied to a site for which the physical conditions of the coastal forests are known. Although the physical conditions of coastal forests are considered, they are actually evaluated by ignoring the existing trees. The basic equations of the flood flow in a vegetated region were proposed to consider the shielding effect of existing trees by physical model tests [Matsumori *et al*., 2004, 2006]. For the consideration of branches, an evaluation formula based on experimental values was proposed for the equivalent roughness coefficients of the vegetated area [Imai and Matsutomi, 2006]. After the 2011 tsunami, three-dimensional (3D) modeling of tree shapes was needed to reproduce accurate tsunami flow in vegetated areas. A multiscale 3D numerical analysis was proposed by incorporating the tsunami-damping effect of coastal forests [Nomura *et al*., 2015]. In this multiscale numerical analysis, the tsunami-damping effect of the entire coastal forest can be evaluated by modeling the structure of branches and leaves in a coastal forest. Even without considering the tree shape in detail, the tsunami-damping effect of a vegetated area can be evaluated with high precision via the 3D flow field.

2.6. *HPC and real-time tsunami prediction*

A high-performance computing (HPC) technique has been developed to perform numerical tsunami simulations with high-speed calculations, to contribute to tsunami early warning systems. There are two ways to utilize the HPC technique for tsunami early warning systems. The first is to simulate many thousands of tsunami hazard scenarios from tsunami-induced sources and to then store the resulting database of tsunami inundation simulations. The second is to perform tsunami inundation simulations for real-time tsunami predictions using real-time observation data. For reliable inundation simulations, a large computation time is required to solve nonlinear shallow-water equations using high-resolution bathymetrical and topographical data. Therefore, a parallel programming code for tsunami inundation simulations must be implemented using parallel-processing computers. As two examples of parallel programming models, OpenMPI is used to enable parallel processing on Central Processing Units (CPUs), and CUDA is used to enable parallel processing on Graphics Processing Units (GPUs). Before the 2011 tsunami, a high-performance tsunami prediction system using General-Purpose Graphics Processing Units (GPGPU) with the CUDA application was developed based on TUNAMI-N1 with a large dataset from a bathymetry file [Gidra *et al.*, 2011]. For further improvement of numerical tsunami simulations, a parallel version of tsunami inundation simulations was developed and performed on the K computer at the Advanced Institute for Computational Science of RIKEN. The TUNAMI-N2 code was parallelized using a 1D or 2D domain decomposition scheme, in which load balance among the nested domain and the number of partitions in the x and y directions in each domain are the keys to achieving high performance in real-time tsunami predictions [Oishi *et al.*, 2015; Yamashita *et al.*, 2016]. In addition, it is expected in the near future that accurate real-time prediction with tsunami inundation simulations using parallel massively high-performance computing will be fast enough to inform people about evacuations (i.e., within ten minutes or less), which is very important in disaster mitigation.

2.7. *Multiscale tsunami simulation*

Because the 2011 tsunami destroyed many bridges, breakwaters, and other coastal infrastructure in an unexpected manner, small-scale computational fluid dynamics (CFD) has been applied to determine the mechanisms by which these structures failed and to design countermeasures so that similar destruction does not occur during the next event. To investigate the collapse of a coastal bridge in Minamisanriku, Miyagi Prefecture, Bricker and Nakayama [2014] used a shallow-water model to propagate the 2011 tsunami from its source to the beach; they then manually input the waveform at the beach into a small-scale OpenFOAM Volume of Fluid (VOF) CFD simulation to calculate the forces on the bridge and to thus pinpoint the factors responsible for its collapse. Azadbakht and Yim [2014] applied a similar VOF CFD simulation, while Salem *et al*. [2014] used the Applied Element method (AEM). St-Germain *et al*. [2014] ran CFD simulations using Smoothed Particle

Hydrodynamics (SPH) to determine tsunami-induced forces on structures. Bricker *et al*. [2015] applied Large Eddy Simulation (LES) CFD together with solid body motion to hindcast both the forces on and the resulting displacement of a bridge that collapsed in Noda, Iwate Prefecture. Xu and Cai [2015] used CFD together with a spring-damper model of a bridge to account for fluid-structure interaction.

In addition to bridges, multiscale simulations were used to assess the failure of breakwaters. Bricker *et al*. [2013b] manually combined a shallow-water model with VOF CFD to investigate the failure of the Kamaishi breakwater's caissons. Pringle [2016] and Mori *et al*. [2014] developed a two-way coupled shallow-water (for the far field) and CFD (for the near field) simulation to hindcast the failure of this breakwater. Mitsui *et al*. [2014] used the analytical nappe equations to calculate the geometry and speed of the jet formed during breakwater overtopping and then used VOF CFD to calculate the flow field of the submerged jet and the forces on and within the breakwater's rubble mound foundation and proposed armor units. Nakayama *et al*. [2015] used LES CFD to directly simulate scour trench formation during structure overtopping.

Multiscale simulations have been developed in various forms to resolve actual forces on structures. As described in section 2.6, high performance computing is continuously becoming more available; this will enable more widespread use of 3-dimensional CFD in the design of future coastal structures. Because CFD resolves forces that are often neglected in traditional design [e.g., Bricker and Nakayama, 2014], the proliferation of CFD use in design will result in structures that are less vulnerable to future tsunami events.

2.8. *Tsunami modeling activities in the US and Europe*

In addition to Japan, several other countries have active programs for tsunami hazard mitigation. The US National Tsunami Hazard Mitigation Program (NTHMP) was established in 1995 and is administered by the National Oceanic and Atmospheric Administration (NOAA). The NTHMP includes NOAA, the Federal Emergency Management Agency, the U.S. Geological Survey, and 28 U.S. states and territories, which in turn have initiated state-level working groups to assess potential tsunami hazards and to establish warning and mitigation guidance. In addition, the Mapping and Modeling Subcommittee develops, improves, and standardizes numerical modeling techniques and ensures nationwide consistency of model performance. The 2011 and 2015 Model Benchmarking Workshops [NTHMP, 2012] focused on run-up and inundation scenarios for evacuation purposes and on flow velocity with respect to mariners' and harbor safety, respectively. The benchmarking tests include analytical solutions, laboratory experiments, and observed field data to examine the board selection of numerical codes ranging from full 3D Navier-Stokes solutions to depth-integrated techniques such as the non-hydrostatic, Boussinesq and shallow-water approaches.

In the wake of the Fukushima nuclear disaster, the French nuclear regulation authority (l'Autorité de Sureté Nucléaire française, ASN) established the tsunami modeling program TANDEM (Tsunamis in the Atlantic and English Channel: Definition of the Effects through Numerical Modeling)

[TANDEM, 2014]. Following the NTHMP approach, the effort focuses on model benchmarking and development and investigates potential tsunami threads along the European Atlantic coast with a major focus on the 1755 Lisbon tsunami. The German-Indonesian Tsunami Early Warning System [GITEWS, 2016] uses established and partially commercial numerical models for an early-warning decision-support-system analogous to the DART system.

3. Building damage assessment

3.1. *Building damage assessment by fragility functions*

The tsunami fragility function is a stochastic function that expresses the probability of a building to reach or exceed a predefined damage state for a given tsunami intensity, and it is important for future damage assessment and coastal disaster planning. Before the 2011 tsunami, research on tsunami fragility functions had greatly increased after the 2004 Indian Ocean tsunami in places such as Indonesia and Thailand. Visual detection using high-resolution satellite imagery was applied to the city of Banda Aceh in Indonesia to collect data on damaged buildings [Koshimura *et al*., 2009]. Fragility functions were developed for damaged buildings in Thailand for different types of building materials, such as mixed-type, reinforced concrete (RC), and wood. [Suppasri *et al*., 2011]. For the 2004 tsunami, the data on building damage was merged with the results of numerical tsunami simulations (i.e., flow depth and flow velocity), and regional fragility functions were then developed using linear regression analysis. However, the limitations of studies conducted prior to the 2011 tsunami are a two-level classification of structural damage (surviving or destroyed) and a linear statistical model, which cannot address aggregated data. After the 2011 tsunami, tsunami fragility curves for buildings were developed using least-square regression analysis for different physical properties, such as structural materials and number of stories [Suppasri *et al*., 2013a], land use [Suppasri *et al*., 2015a] and topographic conditions [Suppasri *et al*., 2015a]. An improved statistical method, logistic regression based on the Generalized Linear Model (GLM), was applied [Charvet *et al*., 2014] in addition to the consideration of debris impact [Charvet *et al*., 2015]. Further quantitative refinements remain necessary so that the fragility functions can more realistically represent actual situations.

3.2. *Future application to other countries*

Before the 2011 tsunami in Japan, some existing tsunami fragility functions had been previously developed based on actual damaged building data in Thailand [Suppasri *et al*., 2011], Indonesia [Koshimura *et al*., 2009], Sri Lanka [Murao and Nakazato, 2010 and Leelawat *et al*., 2016] after the 2004 Indian Ocean tsunami and Chile [Mas *et al*., 2012] after the 2010 Chile tsunami. These tsunami fragility functions could also be applicable in other countries around the world if suitable modifications are made. In contrast, the fragility functions developed in Japan have been widely applied in other countries where actual damage data do not exist, such as the west coast of the US [Wiebe and Cox, 2014], New Zealand [Fraser *et al*., 2014] and Portugal, where they are used for tsunami risk assessment, academic research and insurance purposes. However, these countries applied the fragility functions developed in Japan to their target regions directly and without any modification, despite the fact their geographical arrangement, building codes and civil engineering practices are likely to differ from those in Japan. Therefore, it remains a challenging problem to correctly apply existing fragility curves to different countries. The fragility functions developed in Japan must be verified and discussed in terms of their applicability to other countries, given country-specific differences in building performance. Their application can be developed through any collaboration such as among researchers for the Global Tsunami Model (GTM) and coastal engineering organizations [GTM, 2016].

3.3. *Design recommendation for evacuation buildings*

During the 2011 tsunami, RC buildings, such as hospitals, schools, apartments and hotels, served as temporary evacuation shelters for people who lived in these buildings and the surrounding areas. Thus, these types of buildings should be reassessed to ensure the safety of evacuees from future earthquake and tsunami activity. In the evacuation plan of a city, most tall RC buildings are designated as evacuation shelters that cover all of the people in the risk areas. Therefore, it is important to guarantee that these designated evacuation buildings will be secure destinations for the evacuation of disaster victims during tsunamis. Based on the lessons learned from the 2011 tsunami, loss of human life might occur because of unexpected damage [Suppasri *et al*., 2015b], such as buildings overturning [Suppasri *et al*., 2013c], debris impacts [Charvet *et al*., 2015] and fire [Hokugo *et al*., 2013]. Furthermore, overtopping tsunami flow should be considered when establishing the required building height for designated evacuation buildings. Based on observed and possible future damage, new concepts can be proposed for the tsunami design codes of designated evacuation buildings to protect against earthquakes and subsequent tsunamis [Chock *et al*., 2013]. For existing evacuation buildings, strengthening plans should be implemented so that the buildings conform to the design criteria of tsunami design codes.

4. Coastal defense structures

4.1. *Coastal embankments*

During the Great East Japan Tsunami, the cause of most coastal embankment failures was overtopping followed by scouring of the unarmored heel of the embankment [Kato *et al*., 2012]. This was in fact not the first known case of this phenomenon; in 1968, in the case of the Tokachi Earthquake tsunami, a small part of the coastal embankment was scoured by strong overtopping flow [Horiguchi and Yokota, 1968]. However, the lesson of this embankment was not noticed, as the other embankments were of sufficient height, and engineers thought it was necessary only to build the embankments to that sufficient height. After the 2011 tsunami, damaged embankments are currently being reconstructed along the entire Pacific coast of Tohoku, with an array of design improvements aimed at preventing, or at least delaying, embankment failure. The design of coastal embankments that are tall enough to prevent overtopping by the maximum feasible tsunami is financially impractical, and the effects of such tall structures, which would separate the fishing and tourism economies from the sea, are undesirable. Therefore, the new generation of coastal embankments have been designed to prevent a tsunami with a return period of up to 100 years (a so-called “Level 1” tsunami) from overtopping. Tsunamis that are larger than this (“Level 2” tsunamis) are expected to cause overtopping. However, the new generation of nebaritsuyoi (tenacious) embankments and walls under construction along the Tohoku coast has been designed to better withstand the forces induced by overtopping and thus either not fail at all or stand intact for longer than the previous generation of embankments so as to provide the endangered populace more time to evacuate.

New nebaritsuyoi embankments (Fig. 2) have 3 principal differences from their pre-tsunami counterparts: strengthened heel construction, strengthened crest and landside slope armor, and strengthened joints between armor sections [MLIT, 2013b]. Strengthened heel construction is meant to prevent, or slow, failure due to scouring of the earth at the heel of the embankment followed by slumping of the land-side armor into the scour pit and subsequent scour of the embankment material itself. Heel strengthening consists of a combination of measures. One of these measures is a concrete gravity anchor for the land-side armor [Fukushima Prefecture, 2014; Miyagi Prefecture, 2014; Iwate Prefecture, 2014]. This anchor must be either buried more deeply than the expected overtopping scour hole depth, built atop piles that will stand to the designed scour hole depth, or surrounded by a land surface that is resistant to scour. Another measure of heel strengthening is to reinforce the land surface landward of the gravity anchor to make it resistant to scour. This entails extending the landward slope of the concrete armor further landward to prevent the formation of a scour hole and to improve the ground strength (such as with cemented sand and gravel, CSG) below and on the landward side of the armor. This land-side armor is expected to be utilized during normal (non-emergency) times as a local (municipal or prefectural) street.

The second characteristic of a nebaritsuyoi embankment is heavier crest and landside slope armor [Fukushima Prefecture, 2014; Miyagi Prefecture, 2014; Iwate Prefecture, 2014]. Some of the embankments that failed in 2011 were observed to have failed due to the crest and landside slope armor lifting off in zones of low pressure from the overtopping flow [Kato *et al*, 2012]. Heavier armor is expected to mitigate this damage mechanism. The crest armor in most cases is now monolithic to better resist uplift. The third characteristic of a nebaritsuyoi embankment is the improvement of joints between armor sections [Fukushima Prefecture, 2014; Miyagi Prefecture, 2014; Iwate Prefecture, 2014]. This entails either cast-in-place concrete slabs or precast interlocking armor blocks on each slope of the embankment and interlocking joints with the crest armor. Furthermore, the crest armor in most cases extends slightly down the seaward and landward slopes, effectively moving the joint with each slope to a less vulnerable position than the lip of the crest itself. In all cases, expansion joints between the concrete armor units are sealed to be watertight to prevent the scour of fill material during overtopping.

Because overtopping and breaching in some sections is inevitable during a Level 2 tsunami, nebaritsuyoi embankments contain either sheet pile or concrete diaphragm walls at intervals of approximately 50 m. The purpose of these diaphragm walls is to interrupt the propagation of scour along the length of an embankment and thus limit damage to short sections.

Kato *et al*. [2012] showed that parapet toppling often caused bulkhead wall failure during both the incident and drawdown phases of the 2011 tsunami. Because parapet failure was so common, the general guideline for nebaritsuyoi bulkheads and embankments is to avoid the use of parapets at all. However, in locations where parapets are needed (such as recurved parapets for storm wave run-up reflection), the new parapets are less than 1 m high, sufficiently heavy, and tied down properly with rebar to the bulkhead gravity wall and crest armor [Fukushima Prefecture, 2014; Miyagi Prefecture, 2014; Iwate Prefecture, 2014].

4.2. *Breakwaters*

The failure of the Kamaishi bay-mouth tsunami breakwater was estimated by the Port and Airport Research Institute (PARI) [2011] to have been due to scour of the rubble mound foundation when the strong overtopping jet impinged at the heel of the caisson along with rapid flow through the gaps between caissons. Bricker *et al*. [2013a] showed that foundation-bearing capacity (punching) failure might also have contributed to the displacement of the caissons. However, the large-scale hydraulic laboratory experiments of Arikawa *et al*. [2012] showed that sliding of the caissons atop their rubble mound was likely the major cause of failure. MLIT [2013a] agreed with this conclusion, and the Kamaishi breakwater is being rebuilt in nebaritsuyoi fashion, with a friction mat placed between caissons and the rubble mound, to reduce the likelihood of caisson sliding in the future [Japan Dredging and Reclamation Engineering Association, 2013].

The failure of the Ofunato bay-mouth tsunami breakwater was also found to be due to caisson sliding [Takayama, 2015]. Here, the likelihood of sliding during future events is being mitigated by elevating the level of the rubble mound foundation on the harbor side of the breakwater [Iwate Prefecture, 2013]. This elevated portion of the mound will act as a buttress to resist sliding of the caisson into the harbor when the water level on the seaward side is elevated during a tsunami. In addition, the harbor-side elevated rubble mound will be covered with concrete armor blocks to prevent scour during overtopping. Other large breakwaters in Hachinohe, Kuji, Onagawa, and Souma are being rebuilt in similar nebaritsuyoi fashion [Japan Federation of Construction Contractors, 2014; MLIT, 2013b].

In addition to rebuilding the Kamaishi and Ofunato bay-mouth breakwaters with countermeasures so that the caissons are less likely to slide, the central opening in each of these breakwaters is being reinforced with reverse T-walls [Kahoku News, 2015]. These reverse T-walls have not yet been used in submerged structures in the field; however, based on laboratory tests, they are expected to both stand up well to the intense flows generated by tsunamis without toppling or sliding and to reduce the amount of flow passing through the breakwater central openings, thereby reducing the impact of a tsunami event on the protected harbors.

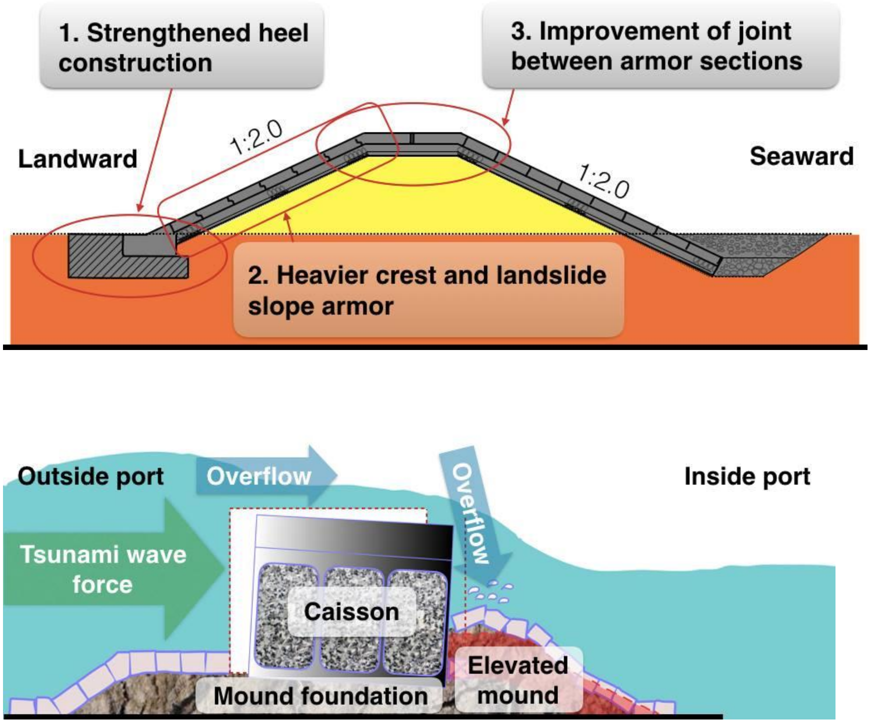

Fig. 2 Example of new coastal embankment and breakwater (Adapted from MLIT [2013b] and the Port and Airport Research Institute [2011]).

5. Coastal forest

5.1 *Damage condition and lessons*

Among the extensive damage of the 2011 tsunami, coastal forests displayed a certain tsunami mitigation effect. For example, the debris flow capture effect was reported in Natori, Iwanuma, and Watari [Sakamoto, 2012] and experienced [Imai *et al*., 2016] along with a reduced inundation height [Sato *et al*., 2012; Noguchi, *et al*., 2014] and less housing damage downstream [Maekawa *et al*., 2013]. Among the lessons of the 2011 tsunami, three reasons were determined to be most important in the damage to the coastal forest. First, a reduction of the binding force of the roots occurred due to land subsidence and liquefaction caused by the earthquake. Second, the relationship between the ground elevation and the groundwater level had an effect. A high groundwater level leads to shallow roots and results in less root-ground binding force [Tamura, 2012; Noguchi, *et al*., 2014]. To mitigate this effect, it has been proposed that the ground elevation be increased by artificial embankment. Third, in the coastal forest, it is difficult, from both landscape and economic viewpoints, to fully stop such large tsunamis by building massive coastal structures.

5.2. *Current situation and remaining problems*

The Reconstruction Agency [2011] has mentioned taking advantage of coastal forests when reconstructing coastal areas in the future. In Sendai Plain, a multilayer countermeasure (Fig. 3) is being implemented to mitigate the tsunami impact by combining a seawall with a coastal forest and elevated land or roadways. Iwanuma city in Miyagi prefecture is one example of this strategy. The plan includes the "Millennium Hope Hills", which include several evacuation hills (TP (Tokyo Peil) +11 m) that make use of tsunami debris, a raised road (TP+4–5 m), a garden path (TP+3 m) and an existing artificial canal (Teizanbori). This is the country's first large-scale social implementation. Therefore, it can also be a model area for multilayer countermeasures against tsunamis. It is important to perform a risk assessment in accordance with the scale of the tsunami. The development of detailed numerical analyses is required to evaluate the specific effect of the coastal forest along with the benefit–cost ratio (B/C) for future replantation. It is also important to promote the shared limitations and damage-reduction effects of the coastal forest.

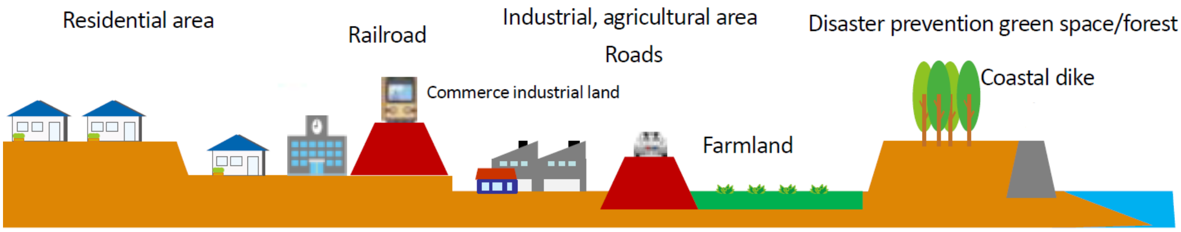

Fig. 3 Image of the multilayer tsunami countermeasure [Miyagi prefecture, 2014].

6. Warning and observation systems

6.1. *Warnings for the 2011 Great East Japan Earthquake and Tsunami and subsequent revisions*

On March 11, 2011, although JMA was able to issue an initial tsunami warning within three minutes of the M9.0 earthquake, the warning was significantly underestimated [JMA, 2013d]. JMA first announced the underestimated tsunami warning at 14:49 JST, with an expected tsunami height of 3 m or Iwate Prefecture, 6 m for Miyagi Prefecture, and 3 m for Fukushima Prefecture, with respect to an estimated JMA magnitude (Mj) of 7.9. The JMA magnitude is a local parameter in Japan that is defined by the JMA and is based on the maximum amplitudes of seismograms [JMA, 2013d; Ozaki, 2012].

Twenty-eight minutes later, thanks to data from the Ports and Harbors Bureau (PHB) GPS buoy 10 km off the coast, which recorded an abnormally rapid change of sea level at approximately 15:10 JST, JMA updated the tsunami warning [JMA, 2013d]. JMA upgraded their tsunami warnings, estimating 3- to 6-m tsunami heights in Iwate Prefecture and Fukushima Prefecture and 6- to over 10-m tsunami heights in Miyagi Prefecture; however, the tsunami had already hit some parts of the area [Ozaki, 2012]. JMA continued to update their warnings following observation data from buoys and tide gauges [JMA, 2013d]. In total, JMA updated the tsunami warnings seven times, until the last update at 03:20 the next day (March 13, 2011) [Ozaki, 2012].

JMA [2013d] summarized the problems of the tsunami warning operation as follows: (1) “The magnitude of Mj 7.9 that was promptly estimated and used in the initial tsunami warning was an underestimation”; (2) “Forecast tsunami heights were also underestimated due to the magnitude underestimation”; (3) “The Mw value was not calculated for approximately 15 minutes due to broad-band seismic data saturation”; and (4) “Minimal tsunami heights announced in Tsunami Observation Information (such as Initial Tsunami Observation: 0.2 meters) may have misled people into thinking that the tsunami would not be large and caused delays or interruptions in evacuation” (p. 8).

6.2. *Improvement after the 2011 Great East Japan Earthquake and Tsunami*

After the event, JMA investigated all their warning strategies to determine how to improve the tsunami warning system [JMA, 2013d]. An advisory meeting for improvement was also held. As a result, various plans were prepared, including (1) “*Direction for JMA Tsunami Warning Improvement*” and (2) “*Recommendation on Tsunami Warning Criteria and Expression of Warning Messages*”; later, (1) and (2) were combined into the “*JMA Tsunami Warning Improvement Plan*” [Ozaki, 2012]. JMA [2013d] summarized three solutions for improving the tsunami warning system: (1) “Basic policy”, (2) “Technical improvements”, and (3) “Improvement of bulletin content and expressions” (pp. 8–10).

6.2.1 Basic policy

Ozaki [2012] summarized the improvements, including that “first warnings have to be disseminated as soon as possible, preferably within three minutes” (p. 442) and that “The first warning issued under such [early stage] circumstances should be made based on the worst possible case within the uncertainty involved” (p. 442). In the case of information updates, previous underestimated values will not appear in the updated bulletin [JMA, 2013d].

6.2.2 Technical improvements

The improvements to technical issues include “Measures for detecting magnitude underestimation”, “Prompt updating of tsunami warnings” and “Enhancement of observation facilities” [JMA, 2013d, pp. 9–10]. For tsunami early warning systems, a 5-m-grid inundation simulation was conducted with the K computer to perform high-resolution inundation prediction, including the effect of highways [Oishi *et al*., 2015].

6.2.3 Content and expression improvements

JMA also attempted to improve the understandability of their warnings. On March 7, 2013, JMA released a modified version of the Tsunami Warning that emphasized “immediate evacuation” [Gyoba, 2014; JMA, 2013d]. A comparison of the tsunami warnings/advisories/forecasts between the old version (eight classes) and the new version (five classes) is shown in Table 1 [JMA, 2013d]. Moreover, not only the quantitative estimated tsunami height but also the qualitative estimated tsunami height is reported (i.e., “Huge” for 5 m, 10 m, and over 10 m; “High” for 3 m; and “(N/A)” for 1 m) [JMA, 2013d]. Because the data from the GPS buoys were found to be useful during the 2011 Great East Japan Earthquake and Tsunami, JMA also started issuing “*Tsunami Information (Tsunami*

Observations at Offshore Gauges)” [JMA, 2013d, p. 11].

Since August 30, 2013, JMA has officially been using the “*Emergency Warning System*” to alert people of the extraordinary magnitude of natural disasters [JMA, 2013c]. With regard to tsunamis, the Emergency Warning System is used for major tsunami warnings. The Emergency Warning System is used to “alert people to the significant likelihood of catastrophes if phenomena are expected to be a scale that will far exceed the warning criteria” [JMA, 2013c]. If an Emergency Warning is issued, people should “evacuate immediately to a safer place such as high ground or a tall building designated as an evacuation center” [JMA, 2013c]. Specifically, JMA [2013e] explains the action to be taken for the Tsunami Advisory as follows: “Get out of the water and leave coastal areas immediately. Do not engage in fishing or swimming activities until Advisories are cleared.” The Tsunami Warning and the Major Tsunami Warning are stated as follows: “Evacuate from coastal or river areas immediately to safer places such as high ground or a tsunami evacuation building. Tsunami waves are expected to hit repeatedly. Do not leave the evacuation location until Tsunami Warnings are cleared.”

As of 2013, there are approximately 660 seismic intensity meters operated by JMA, 777 meters operated by the National Research Institute for Earth Science and Disaster Prevention (NIED), and 2,912 meters operated by local governments [JMA, 2013b]. JMA has approximately 280 seismometers, 27 strain meters (in the Tokai area), and 80 tide gauges/offshore water-pressure gauges [JMA, 2013b]. In addition, there are approximately 1,180 seismometers that belong to academic institutes, NIED, or other related organizations; 40 GPS buoys/offshore water-pressure gauges belonging to the Ports and Harbors Bureau, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), or NIED; and 100 tide gauges belonging to the Ports and Harbors Bureau, the Geographical Survey Institute, or the Japan Coast Guard [JMA, 2013b].

Table 1. Former and Current Tsunami Warning/Advisory Classification[1]

Former classification			**Current classification[2]**		
Estimated tsunami height[3]	**Warning**	**Tsunami warning**	**Estimated tsunami height[3]**	**Warning**	**Tsunami warning**
10 m or more 8 m 6 m 4 m 3 m	Warning	Major Tsunami Warning	$10 \text{ m} < h$ $5 \text{ m} < h \leq 10 \text{ m}$ $3 \text{ m} < h \leq 5 \text{ m}$	Emergency Warning[4]	Major Tsunami Warning
2 m 1 m		Tsunami Warning	$1 \text{ m} < h \leq 3 \text{ m}$	Warning	Tsunami Warning
0.5 m	Advisory	Tsunami Advisory	$0.2 \text{ m} \leq h \leq 1 \text{ m}$	Advisory	Tsunami Advisory
$h < 0.5$ m	Forecast	Tsunami	$h < 0.2$ m	Forecast	Tsunami

		Forecast			Forecast

Notes. [1] Source: JMA [2013a; 2013d]

[2] h denotes height (sea level changes, in m).

[3] The new version as of March 7, 2013.

[4] The Emergency Warning System was launched on August 30, 2013 by JMA.

7. Inland and offshore evacuation

7.1. *Inland evacuation*

A major characteristic of inland evacuation is that residents must travel long distances to shelters. This need to travel caused a large proportion of car use for inland evacuation, resulting in severe traffic jams in many coastal plain areas [The Ministry of Land, Infrastructure, Transportation and Tourism, 2011]. One famous case study on car evacuation is the case in Ishinomaki City, as reported by many researchers. Goto *et al*. [2012] conducted a fact-finding survey in Ishinomaki City and reported that 45% of the respondents were trapped in traffic jams. This suggests that a large number of evacuees used cars for evacuation, which caused severe traffic jams in this area. Hara and Kuwahara [2015] quantitatively determined the actual traffic conditions in the area using probe data. The probe data show that evacuees in central Ishinomaki City experienced severe and wide-scale traffic gridlock, and a large number of evacuees were trapped in the tsunami.

As mentioned above, vehicular evacuations exacerbate the risk of being trapped in traffic jams and hence engulfed by the impending tsunami. However, vehicular evacuation is still effective, especially for elderly evacuees and for evacuees with disabilities who have difficulty completing long-distance inland evacuation routes. Evacuation via car in tsunami disasters had been prohibited as a matter of principle in Japan before the 2011 event [Fire and Disaster Management Agency, 2002]. However, after the March 2011 event, car use in tsunami evacuation has been partly accepted for cases in which vulnerable people cannot evacuate smoothly and in which the cars used in evacuation do not disturb the smooth evacuation of others [National Public Safety Commission, 2014]. Therefore, local governments and residents facing future tsunami risks, including those near the Nankai trough, are struggling with making local rules that facilitate smooth tsunami evacuation.

As a result of their efforts, new approaches for smoother tsunami evacuation in the future have been under development. Watari town, which is located in the southern coastal area of Miyagi prefecture and has a large plain area, is attempting to work with researchers to find a solution involving vehicle use in future evacuations [Sato *et al*, 2014]. They conducted an evacuation drill that intentionally used cars and then developed a macroscopic evaluation method for evacuation planning using cars. Another interesting case study is a new program named “KAKEAGARE JAPAN [2015]”; “KAKEAGARE” means “running up to a higher place”. This is a collaborative project among companies, local governments, local media and Tohoku University. The researchers are now attempting to develop models for evacuation drills so that users can easily plan new evacuation strategies. They have conducted evacuation drills using cars in Yamamoto town and other places.

However, it is very difficult to regulate car evacuation, even after the establishment of local rules. Sun *et al*. [2014] noted the great differences between the behavior established in prior planning and that during the actual event. They conducted two surveys about the planned evacuation behavior and the actual behavior of coastal residents in Kochi prefecture, which faces a tsunami risk induced by the Nankai trough, before and after the 2014 Iyonada Earthquake. The car use ratio in the actual event (73%) was much higher than that established by planning (21%).

To reveal this type of potential risk during an evacuation, tsunami evacuation simulations, which have recently been studied, are essential tools for the quantitative evaluation of future evacuation events, although accurate simulations require further research on human behavioral characteristics during an evacuation [Mas *et al*., 2015; Makinoshima *et al*., 2016]. Every evacuation countermeasure discussed above is important and effective for casualty mitigation during future tsunami events; however, the most important lesson learned from the Great East Japan Earthquake and Tsunami is the strenuous effort required in daily life to prepare for future tsunamis, even when many years have passed since the last event.

Last but not least, shelter-in-place is another option for those who are unable or unwilling to use vertical or horizontal evacuation. In the Tohoku region, the shortest tsunami arrival time is more than 30 min. On the other hand, for areas with high risk and fast tsunami arrival times, i.e., the Tokai tsunami, some shelter-in-places options are located in critical facilities such as schools or nursing homes.

7.2. *Offshore evacuation*

Similar to inland evacuation, the suggested appropriate sea depths for offshore evacuation in cases of announced tsunami heights of 1–2 m, 3–4 m and >6 m are 30 m, 40 m and 50 m or deeper, respectively [Katada *et al*., 2012]. However, the 2011 tsunami was much larger than sizes listed in the regulation. Among fishermen who decided to evacuate offshore, most could not go as far as they expected and felt that they were fortunate to survive and save their boats, despite experiencing various troubles during their overnight stay at sea [Suppasri *et al*., 2015c]. However, what made a difference was how fast they performed their offshore evacuation and their knowledge of tsunami behavior with respect to the bathymetry of their port. For example, a tsunami arrived at a peninsula in the Sanriku areas as quickly as in 30 min or less, as the areas are located in the deep sea near the earthquake epicenter. However, thanks to the influence of the deep sea, boats could reach a safety zone of 50 m or deeper within a short period of time. In contrast, for a plains area such as the Sendai Plain, boats would have to traverse 30 km or more to reach a 50-m sea depth. In other words, the boats would need 1 h or more to evacuate offshore and to survive. After the 2011 tsunami, new regulations were established for offshore tsunami evacuation, and evacuation drills were performed in many locations in different regions [Suppasri *et al*., 2015c]. As part of the reconstruction, it is clear that after 2011, many villages have planned to move to areas more than 30 m higher in elevation and where the village will be farther than 400 m from its original location; such relocation ensures that all villages will be safe from future tsunamis because the villages will be 40–50 m above sea level [Suppasri *et al*., 2014]. In the future, relocation to high ground will definitely affect the evacuation culture of some fishermen who prefer to save their boats from tsunamis, as they would have to perform the offshore evacuation more quickly. This action will be more difficult and risky in future tsunamis. Hence, education for fishermen based on local situations is vital for ensuring survival. Numerical tsunami simulations have been used to create an offshore hazard map as a supporting tool for offshore evacuation [Ohashi *et al*., 2007], together with new tsunami fragility functions for fishing boats based on the 2011 tsunami data [Suppasri *et al*., 2013b] and the development of a tsunami early alert and evacuation support system for fishing boats [Torii *et al*., 2010].

8. Conclusions

To demonstrate another dimension of tsunami research in Japan and tsunami-related countermeasures, a number of research papers presented at the Coastal Engineering Conference of the Japan Society of Civil Engineers (JSCE) were analyzed. It was found that the proportion of tsunami-related papers presented at the conference was approximately 15% in the four years before the 2011 tsunami but increased to 35% during the four years after the 2011 tsunami (Fig. 4). The papers in each category from 2012–2015 were counted, as shown in Fig. 5. These findings indicate that the yearly trend of research in the coastal engineering field in Japan was influenced by the 2011 tsunami. In all, papers on tsunami simulation, coastal structure and building damage composed approximately 65–70% of tsunami-related papers, whereas coastal forests, warning/observation and evacuation constituted approximately 10–15%. Notably, the other papers in 2012 were mostly related to field surveys of the damage and morphological changes along with applied research using satellite imagery or video analysis to determine tsunami flow velocity, building damage and the amount of debris. In 2013, research on multilayer disaster mitigation started to become a main focus. Some research on coastal planning and disaster education was presented. In 2015, interdisciplinary research on social science as applied to tsunami damage was first presented.

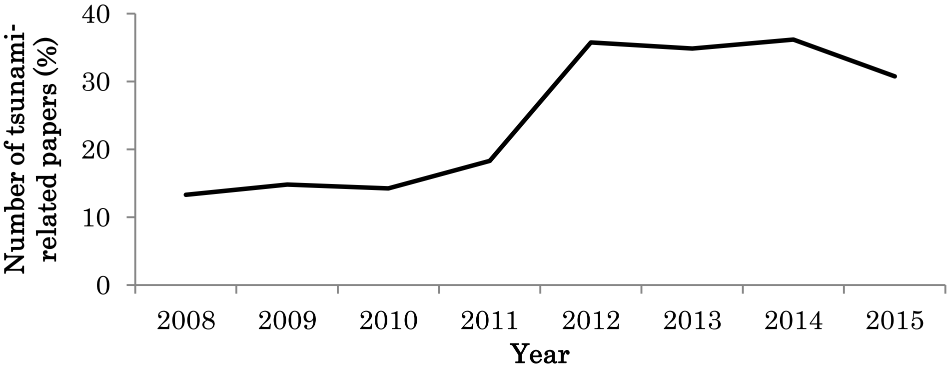

Fig.4 Number of tsunami-related papers four years before and after the 2011 tsunami.

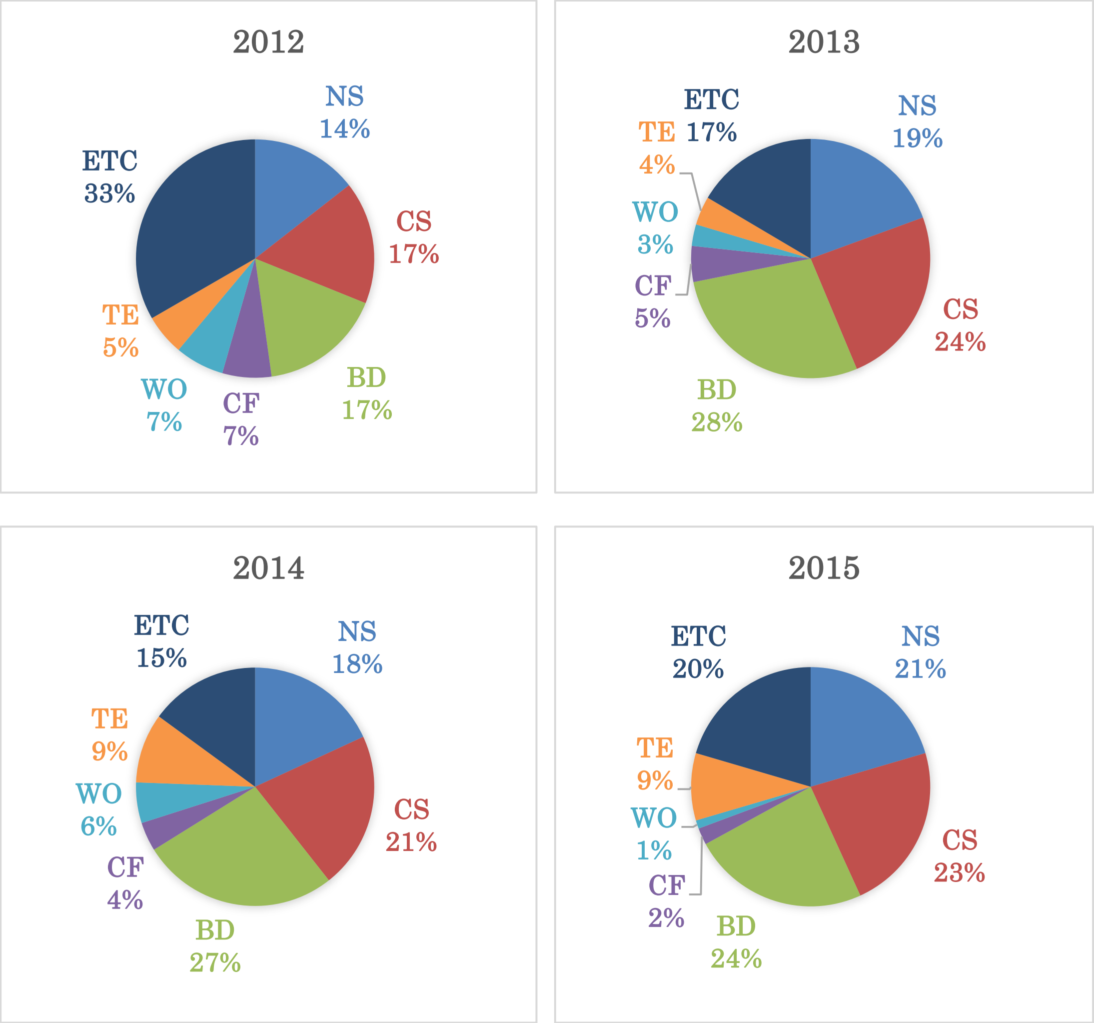

Fig. 5 Summary of research papers presented at the Coastal Engineering Conference of the Japan Society of Civil Engineers (JSCE) from 2012 to 2015. NS = Numerical Simulation, CS = Coastal Structure, BD = Building Damage, CF = Coastal Forest, WO = Warning/Observation, TE = Tsunami Evacuation and ETC = Other.

Improvements pertaining to both structural and nonstructural measures in the five years since the 2011 tsunami are explained and discussed in the preceding sections. They can be briefly summarized for each section as 1) Lessons from the 2011 tsunami, 2) improvements after five years and 3) remaining future challenges, as shown in Table 2.

Table 2. Lessons from the 2011 tsunami, improvement after five years and remaining future challenge for each countermeasure type

Countermeasure type	Lessons from the 2011 tsunami	Improvements after five years	Remaining future challenges
Tsunami simulation	Underestimation of	Real-time tsunami	Real-time inundation

	earthquake and tsunami size	simulation using real-time observation data	mapping with high resolution and its dissemination during an emergency
Coastal structure	Strong turbulence flow causes serious scour and damage at the back side after overtopping	Many proposed techniques to strengthen the back side and build connections that protect the structure from failure	Maintenance of these new types of structures and arguments with a landscape point of view
Building	Many damaged building datasets with details and recommendations for evacuation buildings	Various types of fragility curves and new design codes for evacuation buildings	Application of the developed curves to other regions lacking actual damage data
Coastal forest	Importance of considering depth of tree roots, tree spacing and forest width as well as multilayer countermeasures	Newly proposed idea of tree planting and implementation of multilayer countermeasures	Analysis of benefit–cost ratio and understanding of limitation of the mitigation capacity of coastal forest as well as coastal structure
Warning/observation	Underestimation of earthquake magnitude and complexity of warning content	Revision of warning content, including the new type “Emergency Warning” and developing dense observation systems	Increasing the evacuation ratio by the new warning content and providing enough observation data for real-time tsunami simulation
Evacuation	Known traffic jam route/numbers of evacuees at shelters and more knowledge of human behavior for both inland and offshore evacuation	Evacuation drills using vehicles and evacuation simulations using better known human factors	Greater participant ratios for drills, maintaining high awareness and application of evacuation simulation to different areas

In conclusion, five years of research have applied most of the lessons from the 2011 tsunami, including more-realistic tsunami simulations with a very fine grid; methods to strengthen coastal defense structures, evacuation buildings and coastal forests; improved warning content; and key points to improve evacuations. Nevertheless, there are still some significant challenges for the future, such as the development of an advanced simulation technique and systems for real-time hazard and risk prediction, implementation of coastal defense structures/multilayer countermeasures, and encouraging evacuation.

Acknowledgement

We would like to express sincere gratitude to Emeritus Professor Nobuo Shuto (IRIDeS, Tohoku University), Prof. Kwok Fai Cheung (University of Hawaii at Manoa) and anonymous reviewers for their valuable advice. This research was funded by the Reconstruction Agency of the Government of Japan and Tokio Marine & Nichido Fire Insurance Co., Ltd. through IRIDeS, Tohoku University.

References

Aranguiz, R. and Shibayama, T. [2012] "The effect of submarine canyon on tsunami propagation in the Gulf of Arauco, Chile," *Proceedings of International Conference of Coastal Engineering (ICCE),* 55(4), 1350016.

Arikawa, T., Sato, M., Shimosako, K., Hasegawa, I., Yeom, G.S., and Tomita, T. [2012] "Failure mechanism of Kamaishi breakwaters due to the Great East Japan Earthquake Tsunami," Proceedings of *the 33rd International Conference on Coastal Engineering*, Santander, 1-13.

Azadbakht, M. and Yim, S. [2014] "Simulation and estimation of tsunami loads on bridge superstructures," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **141** (2), 04014031.

Baba T, Takahashi N, Kaneda Y, Inazawa Y, Kikkajin M [2014] "Tsunami inundation modeling of the 2011 Tohoku earthquake using three-dimensional building data for Sendai, Miyagi prefecture, Japan," ln: Kontar YA, Fandino VS, Takahashi T (eds) *Tsunami events and lessons learned: ecological and social significance*, Springer, 35, 89-98

Baba T, Takahashi N, Kaneda Y, Ando K, Matsuoka D, Kato T [2015] "Parallel implementation of dispersive tsunami wave modeling with a nesting algorithm for the 2011 Tohoku tsunami," *Pure Appl. Geophys.*, **172** (12), 3455-3472.

Bricker, J.D., Takagi, H., and Mitsui, J. [2013a] "Punching failure of the Kamaishi breakwater foundation during the 2011 Great East Japan Tsunami," *10th International Conference on Urban Earthquake Engineering*, Tokyo Institute of Technology, Tokyo, Japan. 1875-1882.

Bricker, J.D., Takagi, H., and Mitsui, J. [2013b] "Turbulence model effects on VOF analysis of breakwater overtopping during the 2011 Great East Japan Tsunami," *Proceedings of the 35th IAHR World Congress,* Chengdu, Sichuan, China.

Bricker, J. D. and Nakayama A. [2014] "Contribution of trapped air, deck superelevation, and nearby structures to bridge deck failure during a tsunami," *Journal of Hydraulic Engineering*, **40** (5), 05014002-1-7.

Bricker, J. D., Nakayama, A., Takagi, H., Mitsui, J. and Miki, T. [2015] "Mechanisms of damage to coastal structures during the 2011 Great East Japan Tsunami," Handbook of Coastal Disaster Mitigation for Engineers and Planners (Esteban et al. ed.s), Elsevier, 385-415.

Charvet I., Ioannou I., Rossetto T., Suppasri A., Imamura F. [2014] "Empirical fragility assessment of buildings affected by the 2011 Great East Japan tsunami using improved statistical models," *Nat. Hazards* **73**(2), 951-973.

Charvet I., Suppasri A., Kimura H., Sugawara D., Imamura F. [2015] "Fragility estimations for Kesennuma City following the 2011 Great East Japan Tsunami based on maximum flow depths, velocities and debris impact, with evaluation of the ordinal model's predictive accuracy," *Nat. Hazards* (Published online)

Chock G., Carden L., Robertson I., Olsen M., Yu G. [2013] "Tohoku tsunami-induced building failure analysis with implication for U.S. tsunami and seismic design codes," *Earthq. Spectra*, **29**(S1), S99-S126

Dao M. H. , Tkalich P. [2007] "Tsunami propagation modeling: a sensitivity study," *Nat. Hazards Earth. Syst Sci*. **7**, 741-754

Fraser, S. A., Power, W. L., Wang, X., Wallace, L. M., Mueller, C. and Johnston, D. M. [2014] "Tsunami inundation in Napier, New Zealand, due to local earthquake sources," *Nat. Hazards,* **70** (1), 415-445.

Fire and Disaster Management Agency [2002] "Report of investigation on tsunami countermeasures promotion manual" 139 pages. (In Japanese) Available at: http://www.fdma.go.jp/html/new/tunami1403/tunami_index.html (Accessed 10 June 2016)

Fukushima Prefecture [2014] "On the construction of Tenacious coastal embankments and seawalls," https://www.pref.fukushima.lg.jp/download/1/kaigan-kouzou.pdf (Accessed 5 May 2014)

GITEWS [2016] "German Indonesian Tsunami Early Warning System," Available at: http://www.gitews.org/en/homepage/ (Accessed date: 20 May 2016)

Gidra H., Haque I., Kumar N. P., Sargurunathan M., Gaur M. S. , Laxmi V., Zwolinski M. [2011] "Parallelizing TUNAMI-N1 using GPGPU,." Proceeding of the IEEE 13th *International Conference on High Performance Computing and Communications*, New York, US, Institute of Electrical and Electronics Engineers, 845-850.

Gokon, H. and Koshimura, S. [2012] "Mapping of building damage of the 2011 Tohoku earthquake tsunami in Miyagi prefecture," *Coast. Eng. J.* **52** (1), 1250006.

Goto Y., Mikami T., Nakabayashi I. [2012] "Fact-Finding about the evacuation from the unexpectedly large tsunami of March 11, 2011 in East Japan," Proceeding of the *15th World Conference on Earthquake Engineering*, Paper No. 5140.

Gyoba E. [2014] "Differences in subjective estimation of risks and assessment for the modified tsunami warning system by the Japan Meteorological Agency among university students located in damaged and non-damaged prefectures around the period of the 2011 off Pacific Coast of Tohoku

Earthquake," *J. Disaster Res.* **9**(4), 571-578.

Hara, Y., Kuwahara, M. [2015] "Traffic Monitoring immediately after a major natural disaster as revealed by probe data – A case in Ishinomaki after the Great East Japan Earthquake," Transportation Research Part A: Policy and Practice, **75**, 1-15.

Harada K., Imamura F. [2003] "Possibility of use for evaluation and disaster mitigation of tsunami damping effect of the tide forests," Proceedings of the *Coastal Engineering Conference (JSCE)*, **50**, 341-345. (in Japanese)

Hokugo, A., Nishino, T. and Inada, T. [2013] "Tsunami fires after the Great East Japan Earthquake," *Journal of Disaster Research*, **8** (4), 584-593.

Horiguchi, T. and Yokota, M. [1968] "Field survey of the Tokachi earthquake tsunami," Proceeding of the *Coastal Engineering Conference (JSCE)*, **15**, 243-252. (In Japanese)

Imai, K., Hayashi, A. and Imamura, F. [2016] "Development for the design of colonnade with the capture function of floating objects during tsunami," *Coast. Eng. J.* (This issue)

Imai K., Matsutomi H. [2006] "Hydraulic characteristics on tsunami inundation in a coastal vegetated area," J. Hyd. Coast. Env. Eng. B, (JSCE) **62**(3), 258-269. (in Japanese)

Iwate Prefecture [2014] "Appendix 6, On the construction of Tenacious coastal embankments," http://www.pref.iwate.jp/dbps_data/_material_/_files/000/000/020/028/03_kanmatsusiryou.pdf (Accessed 21 December 2014)

Iwate Prefecture [2013] "Iwate Reconstruction Newsletter," no. 41. https://www.pref.iwate.jp/dbps_data/_material_/_files/000/000/001/828/41fukko_dayori.pdf (Accessed 1 June 2013)

Japan Dredging and Reclamation Engineering Association [2013] "State of Reconstruction from the Great East Japan Tsunami," Item 5, Ports of Kamaishi and Ofunato. Marine Voice 21, **283**, 16-19.

Japan Federation of Construction Contractors [2014] "Engineering structures to survive tsunami," publication 188, http://www.nikkenren.com/publication/pdf/188/05.pdf (Accessed 21 September 2015)

Japan Meteorological Agency (JMA) [2013a] "Criteria for Issuance of Emergency Warnings," http://www.jma.go.jp/jma/en/Emergency_Warning/criteria.html (Accessed 16 September 2015)

Japan Meteorological Agency (JMA) [2013b] "Earthquakes and Tsunamis – Disaster prevention and mitigation efforts," (JMA, Tokyo, Japan).

Japan Meteorological Agency (JMA) [2013c] "Emergency warning system," http://www.jma.go.jp/jma/en/Emergency_Warning/ew_index.html (Accessed 15 September 2013)

Japan Meteorological Agency (JMA) [2013d] "Lessons learned from the tsunami disaster caused by the 2011 Great East Japan Earthquake and improvements in JMA's tsunami warning system," Tokyo: JMA.

Japan Meteorological Agency (JMA) [2013e] "Tsunami Warning/Advisory categories and action to be taken," http://www.jma.go.jp/jma/en/Emergency_Warning/tsunami.jpg (Accessed 16 September 16 2015)

Kahoku News [2015] "New techniques to reduces tsunami-induced flooding in Kamaishi (Reverse T-blocks)," http://www.kahoku.co.jp/tohokunews/201502/20150212_33008.html (Accessed 21 September 2015)

Kakeagare Japan [2015] "Kakeagare Japan," http://kakeagare.jp (Accessed 21 September 2015)

Kakinuma, T., Tsujimoto, G., Yasuda, T. and Tamada, T. [2012] "Trace survey of the 2011 Tohoku tsunami in the north of Miyagi prefecture and numerical simulation of bidirectional tsunamis in Utatsusaki Penisula," *Coast. Eng. J.* **52** (1), 1250007.

Katada, T., Murasawa, N. and Kanai, M. [2012] "Inspection of the rule development effect about Fishing-Boat Evacuation against Tsunami－Example of Correspondence of fishermen belonging to Ochiishi fishery cooperative in Nemuro City in 2011 Tohoku earthquake and tsunami－," *Disaster information,* **10**, 103-112 (In Japanese with English abstract)

Kato, F., Suwa, Y., Watanabe, K., and Hatogai, S. [2012] "Mechanisms of coastal dike failure induced by the Great East Japan Earthquake Tsunami," Coastal Engineering Proceedings, **33**, 1-9.

Koshimura S., Oie T., Yanagisawa H., Imamura F. [2009] "Developing fragility curves for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia," *Coast. Eng. J.,* **51**, 243–273..

Liu, P. L. F., Cho, Y. S., Yoon, S. B., and Seo, S. N. [1994] "Numerical simulations of the 1960 Chilean tsunami propagation and inundation at hilo, Hawaii," *In Recent Developments in Tsunami Research,* Edited by M. I. El-Sabh. Dordrecht, Netherlands, Kluwer Academic Publishers, 99 – 115.

Liu, P. L. F., Cho, Y. S., Briggs, M. J., Synolakis, C. E., and Kanoglu, U. [1995] "Run-up of solitary waves on a circular island," *Journal of Fluid Mechanics*, **302**, 259 – 285.

GTM [2016] "Global Tsunami Model" Available at: http://globaltsunamimodel.github.io/ (Accessed date: 20 May 2016)

Maekawa, T., Nihei, Y. and Nakada, H. [2013] "Study on tsunami mitigation effect of coastal dune and fill," Journal of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering), **69**(4), I_1453-I_1458. (In Japanese)

Mas, E., Koshimura, S., Imamura, F., Suppasri, A., Muhari, A. and Adriano, B. [2015] "Recent advances in agent-based tsunami evacuation simulations: Case studies in Indonesia, Thailand, Japan and Peru," *Pure Appl. Geophy.*, **172**(12), 3409-3424.

Mas, E., Koshimura, S., Suppasri, A., Matsuoka, M., Yoshii, T., Jimenez, C., Yamazaki, F. and Imamura. F. [2012] "Developing tsunami fragility curves using remote sensing and survey data of the 2010 Chilean tsunami in Dichato," *Natural Hazards and Earth System Sciences*, **12** (8), 2709-2718.

Makinoshima, F., Imamura, F. and Abe, Y. [2016] "Behavior from tsunami recorded in the multimedia sources at Kesennuma city in the 2011 Tohoku tsunami and its simulation by using the evacuation model with pedestrian-car interaction," *Coast. Eng. J.* (This issue)

Matsumori H., Onuma K,. Imai K. [2004] "Similarity law of vegetation trees trunk and basic equations of vegetation region flood flow," Proceedings of *Coastal Engineering Conference* (JSCE), **51**, 301-305. (in Japanese)

Matsumori H., Funaki M., Imai K. [2006] "Study on numerical calculation method of vegetation region flood flow," Proceedings of *Coastal Engineering Conference* (JSCE), **53**, 181-185. (in Japanese)

Mikami, T., Shibayama, T., Esteban, M. and Matsumaru, R. [2012] "Field survey of the 2011 Tohoku earthquake and tsunami in Miyagi and Fukushima prefectures," *Coast. Eng. J.* **52** (1), 1250011.

Ministry of Land, Infrastructure, Transpiration and Tourism (MLIT) [2011] "3rd Preliminary result of fact-finding survey" http://www.mlit.go.jp/common/000186474.pdf (Accessed 21 September 2015)

Ministry of Land, Infrastructure, Transpiration and Tourism (MLIT) [2013a] "Committee for the evaluation of coastal works," Item 8, On the construction of Tenacious coastal embankments. http://www.mlit.go.jp/river/shinngikai_blog/kaigan_hyouka/dai01/ (in Japanese).

Ministry of Land, Infrastructure, Transpiration and Tourism (MLIT) [2013b] "Guidelines for breakwaters designed to survive tsunami," 40 pages (In Japanese) Available at: http://www.mlit.go.jp/common/001012142.pdf (Accessed 21 September 2015)

Mitsui, J., Matsumoto, A., Hanzawa, M. and Nadaoka, K. [2014] "Stability of armor units covering rubble mound of composite breakwaters against a steady overflow of tsunami," Proceedings of Coastal Engineering. **34**, structures.34.

Miyagi Prefecture [2014] "Report on Tenacious coastal embankments," http://www.pref.miyagi.jp/uploaded/attachment/287153.pdf (Accessed 21 September 2015)

Miyazawa, K., Goto, K., Imamura, F. [2012] "Re-evaluation of the 1771 Meiwa Tsunami source model, southern Ryukyu Islands, Japan". In: Yamada, Y.; Kawamura, K.; Ikehara, K.; Ogawa, Y.; Urgeles, R.; Mosher, D.; Chaytor, J.; Strasser, M. (Eds.), Advances in Natural and Technological Hazards Research, Submarine Mass Movements and Their Consequences, Springer, **31**, 497-506.

Mori, N., Takahashi, T. and the 2011 Tohoku earthquake tsunami joint survey group [2012] "Nationwide post event survey and analysis of the 2011 Tohoku earthquake tsunami," *Coast. Eng. J.*, **52** (1), 1250001.

Mori, N., Yoneyama, N., Pringle, W. J. [2014] "Effects of the offshore barrier against the 2011 Off the Pacific Coast of Tohoku Earthquake Tsunami and lessons learned," Post-Tsunami Hazard. Volume **44** of the series Advances in Natural and Technological Hazards Research, Springer, Pp 121-132.

Muhari A., Charvet I., Tsuyoshi F., Suppasri A., Imamura F. [2015] "Assessment of tsunami hazards in ports and their impact on marine vessels derived from tsunami models and the observed damage data," *Nat. Hazards*, **78**, 1309-1328

Murao, O. and Nakazato, H. [2010] " Vulnerability functions for buildings based on damage survey data in Sri Lanka after the 2004 Indian Ocean Tsunami," *Proc. 1st Int. Conf. Sustainable Built Environment*, Kandy, Sri Lanka, pp. 371–378.

Read More: http://www.worldscientific.com/doi/ref/10.1142/S1793431116400017

Murashima Y., Takeuchi H., Imamura F., Koshimura S., Fujiwara K., Suzuki T. [2008] “Study on Topographic model using Lidar for tsunami simulation,” Proceeding of ISPRS XXXVII(B8), 223-228.

Nakayama, A., Bricker, J. D. and Francis, M. (2015) Large Eddy Simulation of scour due to tsunami flow overtopping seawall and revetment. Journal of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering), **71**, I_811-I_1816. (In Japanese)

National Public Safety Commission [2014] “Instruction of transportation,” Available at: https://www.npa.go.jp/koutsuu/kikaku/kyousoku/index.htm (Accessed 10 October 2015)

National Tsunami Hazard Mitigation Program [2012] “Proceedings and results of the 2011 NTHMP model benchmarking workshop,” NOAA special report, 437 pages. Available at: http://nws.weather.gov/nthmp/documents/nthmpWorkshopProcMerged.pdf (Accessed date: 20 May 2016)

Noguchi, S., Niiyama, K., Tamura, H., Tanaka, S., Kubota, T., Yasuda, Y. [2014] “Variation of the ground water level in a coastal forest in Miyagino-ku, Miyagi prefecture, Japan, *Journal of the Japanese Forest Society,* **96** (3), 150-154. (In Japanese)

Nomura R., Takase S., Terada K., Moriguchi S. [2015] “Multiscale Numerical Experiment for Evaluating Tsunami Damping Effects of Coastal Forest,” *Proceedings of the Conference on Computational Engineering and Science* (in Japanese)

Ohashi, T., Koshimura, S. and Imamura, F. [2007] “Design of a tsunami hazard map on the sea to reduce fishing boat user’s damage,” In proceeding of the *Coastal Engineering Conference* (JSCE), **54**, 1351-1355. (In Japanese with English abstract)

Oishi Y., Imamura F., Sugawara D. [2015] “Near-field tsunami inundation forecast using the parallel TUNAMI-N2 model: application to the 2011 Tohoku-Oki earthquake combined with source inversions,” *Geophys. Res. Lett.* **42**(4):1083-1091.

Ogasawara, T., Matsubayashi, Y., Sakai, S. and Yasuda, T. [2012] “Characteristics of the 2011 Tohoku earthquake and tsunami and its impact on the northern Iwate coast,” *Coast. Eng. J.,* **52** (1), 1250003.

Ozaki, T. [2012] “JMA’s tsunami warning for the 2011 Great Tohoku earthquake and tsunami warning improvement plan,” *J. Disaster Res.*, **7**(sp), 439-445.

Pringle WJ, Yoneyama N, Mori N. [2016] “Two-way coupled long wave-RANS model: Solitary wave transformation and breaking on a plane beach,” *Coast. Eng.*, **114**, 99-118.

Ranasinghe D. P. L., Goto K., Takahashi T., Takahashi J., Wijetunge J. J., Nishihata T., Imamura F. [2013] “Numerical assessment of bathymetric changes caused by the 2004 Indian Ocean tsunami at Kirinda Fishery Harbor, Sri Lanka,” *Coast. Eng.,* **81**, 67-81.

Reconstruction Agency [2011] “Basic Guidelines for Reconstruction in response to the Great East Japan Earthquake”, 42 pages. Available at: http://www.reconstruction.go.jp/topics/000052.html (Accessed 10 October 2015)

Sakamoto, T. [2012] “Disaster mitigation effect of coastal forests in capturing floating debris” *Forest*

Science, **33**, 13-16. (In Japanese)

Salem, H., Mohssen, S., Kosa, K. and Hosoda, A. [2014] "Collapse analysis of Utatsu Ohashi bridge damaged by Tohoku Tsunami using applied element method," *Journal of Advanced Concrete Technology*, Japan Concrete Institute, **12**, 388-402.

Sasaki, J., Ito, K., Suzuki, T., Wiyono, R. U. A., Oda, Y., Takayama, Y., Yokota, K., Furuta, A. and Takagi, H. [2012] "Behavior of the 2011 Tohoku earthquake tsunami and resultant damage in Tokyo Bay," *Coast. Eng. J.*, **52** (1), 1250012.

Sato, H., Torita H., Masaka, K., Abe, T., Noguchi, H., Kimura, K. and Sakamoto, T. [2012] "Relationship between treefall damage and forest structure of Pinus thunbergii coastal forest by the 2011 Tohoku earthquake tsunami disaster : An example of Misawa City of Aomori Prefecture, *Journal of the Japanese Society of Coastal Forest*, **11**(2), 41-45.

Sato, S., Imai, K., Ohno, S., Sai, M., Matsuo, T., Itahara, H., Imamura, F. [2014] "A Planning Process of Tsunami Evacuation Plan for Local Government with Combination of Walking and Cars –Implementation in Watari Town, Miyagi Prefecture–", Annu. J. Coast. Eng., JSCE 70, I_1371-I_1375 (in Japanese)

Shimozono, T., Sato, S., Okayasu, A., Tajima, Y., Fritz, H. M., Liu, H. and Takagawa, T. [2012] "Propagation and inundation characteristics of the 2011 Tohoku tsunami on the central Sanriku coast," *Coast. Eng. J.*, **52** (1), 1250004.

St-Germain, P., Nistor, I., Townsend, R. and Shibayama, T. [2014] "Smoothed-particle hydrodynamics numerical modeling of structures impacted by tsunami bores," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, **140** (1), 66-81.

Sugawara D., Goto, K., Imamura, F., Matsumoto, H. and Minoura, K. [2012] "Assessing the magnitude of the 869 Jogan tsunami using sedimentary deposits: Prediction and consequence of the 2011 Tohoku-oki tsunami", *Sedimentary Geology*, **282**, 14-26.

Sugawara D., Takahashi T., Imamura F. [2014a] "Sediment transport due to the 2011 Tohoku-oki tsunami at Sendai: results from numerical modeling," *Mar. Geol.*, **358**, 18-37.

Sugawara D., Takahashi T., Imamura F. [2014b] "Numerical models of tsunami sediment transport: current understanding and future directions," *Mar. Geol.*, **352**, 295-320.

Sun, Y., Nakai, F., Yamori, K., Hatayama, M. [2014] "Tsunami Evacuation Behavior of Coastal Residents in Kochi Prefecture during the 2014 Iyonada Earthquake," *Journal of Japan Society for Natura Disaster Science*, **33**(1), 53-63.

Suppasri A., Koshimura S., Imamura F. [2011] "Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand," *Nat. Hazards Earth. Syst. Sci.*, 11, 173–189.

Suppasri, A., Koshimura, S., Imai, K., Mas, E., Gokon, H., Muhari, A. and Imamura, F. [2012a] "Damage characteristics and field survey of the 2011 Great East Japan tsunami in Miyagi prefecture, " *Coast. Eng. J.*, **52** (1), 1250005.

Suppasri, A., Mas, E., Koshimura, S., Imai, K., Harada, K. and Imamura, F. [2012b] "Developing tsunami fragility curves from the surveyed data of the 2011 Great East Japan tsunami in Sendai and Ishinomaki Plains," *Coast. Eng. J.,* **52** (1), 1250008.

Suppasri A., Mas E., Charvet I., Gunasekera R., Imai K., Fukutani Y., Abe Y. and Imamura F. [2013a] "Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami," *Nat. Hazards,* **66**, 319–341.

Suppasri, A., Muhari, A., Futami, T., Imamura, F. and Shuto, N. [2013b] "Loss functions of small marine vessels based on surveyed data and numerical simulation of the 2011 Great East Japan tsunami," *J. Waterw., Port C-ASCE,* **140** (5), 04014018.

Suppasri, A., Shuto, N., Imamura, F., Koshimura, S., Mas, E. and Yalciner, A.C. [2013c] "Lessons learned from the 2011 Great East Japan tsunami: Performance of tsunami countermeasures, coastal buildings and tsunami evacuation in Japan," *Pure and Applied Geophysics,* **170** (6-8), 993-1018.

Suppasri, A., Yasuda, M., Abe, Y., Fukutani, Y., Imamura, F. and Shuto, N. [2014] "Relocation after tsunamis in the Sanriku area and the condition of fishing villages two years after the 2011 Great East Japan tsunami," *Post tsunami hazard reconstruction and restoration,* Springer Monograph, **44**, 47-58.

Suppasri A., Charvet I., Imai K., Imamura F. [2015a] "Fragility curves based on data from the 2011 Great East Japan tsunami in Ishinomaki city with discussion of parameters influencing building damage," *Earthq. Spectr*a, **31**(2), 841-868.

Suppasri, A., Charvet, I., Macabuag, J., Rossetto, T., Leelawat, N., Latcharote, P. and Imamura, F. [2015b] "Building damage assessment and implications for future tsunami fragility estimations," Handbook of coastal disaster mitigation engineers and planners, Edited by Esteban, M., Takagi, H. and Shibayama, T., Elsevier, 147-178.

Suppasri, A., Nguyen, D., Abe, Y., Yasuda, M., Fukutani, F., Imamura, F. and Shuto, N. [2015c] "Offshore evacuation of fishing boats – Lessons from the 2011 Great East Japan tsunami and its future challenge–" *Tsunami Engineering Technical Report,* **32**, 33-45.

Takahashi, T., Imamura, F. and Shuto, N. [1999] "A movable bed model for tsunami with exchange rate between bed load layer and suspended layer," In proceeding of the *Coastal Engineering Conference* (JSCE), **46**, 606–610 (in Japanese).

Titov, V.V. and F.I. Gonzalez [1997] "Implementation and testing of the Method of Splitting Tsunami (MOST) model," NOAA Technical Memorandum ERL PMEL-112, 11p.

Port and Airport Research Institute (PARI) [2011] "Early report on the survey of earthquake and tsunami damage to ports, coastlines, and airports by the Great East Japan Earthquake of 2011," Technical note of the Port and Airport Research Institute, No. 1231, 200p.

Takayama, T. [2015] "Mechanisms of and countermeasures against damage to facilities. Reconstruction after the Great East Japan Tsunami: Current Status and Future Plan," *Journal of Coastal Development Institute of Technology,* **43**, 24-26. (In Japanese)

Tamura, H. [2012] "Uprooted damage in the coastal forest of Sendai Plain", *Shinrin Kagaku*, **66**, 3-6. (In Japanese)

Tanaka, H., Tinh, N. X., Umeda, M., Hirao, T., Pradjoko, E., Mano, A. and Udo, K. [2012] "Coastal and estuarine morphology changes induced by the 2011 Great East Japan earthquake tsunami," *Coast. Eng. J.*, **52** (1), 1250010.

Torii, H., Sawamoto, J., Segawa, N., Sugino, E. and Nomura, Y. [2010] "Tsunami early warning and evacuation support system for fishery workers by mobile phones," In proceedings of the *2010 IEEE 24th International Conference on Advanced Information Networking and Applications Workshops*, Perth, WA, 20-23 April 2010, 704-709.

TANDEM [2014] "Tsunamis in the Atlantic and the English Channel definition of the effects through numerical modeling," Available at: http://www-tandem.cea.fr/ (Accessed date: 20 May 2016)

Udo, K., Sugawara, D., Tanaka, H., Imai, K. and Mano, A. [2012] "Impact of the 2011 Tohoku earthquake and tsunami on beach morphology along the northern Sendai coast," *Coast. Eng. J.*, **52** (1), 1250009.

Watanabe, Y., Mitobe, Y., Saruwatari, A., Yamada, T. and Niida, Y. [2012] "Evolution of the 2011 Tohoku earthquake tsunami of the pacific coast of Hokkaido," *Coast. Eng. J.*, **52** (1), 1250002.

Wiebe, D. M. and Cox, D. T. [2014] "Application of fragility curves to estimate building damage and economic loss at a community scale: a case study of Seaside, Oregon," *Nat. Hazards*, **71** (3), 2043-2061.

Xu, G. and Cai, C. S. [2015] "Numerical simulations of lateral restraining stiffness effect on bridge deck-wave interaction under solitary waves," *Engineering Structures*, **101**, 337-351.

Yalciner, A. C., Pelinovsky, E., Zaytsev, A., Kurkin, A., Ozer, C., and Karakus, H. [2006] "NAMI DANCE Manual," Middle East Technical University, Civil Engineering Department, Ocean Engineering Research Center, Ankara, Turkey.

Yamashita, K., Sugawara, D., Takahashi, T., Imamura, F., Saito, Y., Imato, Y., Kai, T., Uehara, H., Kato, T., Nakata, K., Saka, R. and Nishikawa, A. [2016] "Numerical simulations of large-scale sediment transport due to The 2011 Tohoku Earthquake Tsunami in Hirota Bay, Southern Sanriku Coast", *Coast. Eng. J.* (This issue)

Yamazaki Y., Kowalik Z., and Cheung K. F. [2009] "Depth-integrated, non-hydrostatic model for wave breaking and runup." *Int. J. Numer. Methods Fluids*, **61**(5), 473–497.

Yamazaki Y., Roeber V., Cheung K. F., Lay T. [2011] "Modeling the 2011 Tohoku-oki tsunami and its impacts on Hawaii," Proceeding of OCEANS2011, 1-9.

Yanagisawa, H. and Shigihara, Y. [2010] "Tsunami hazards of far-field tsunamis in the South Pacific Islands," In proceeding of the *3rd International Tsunami Field Symposium*, 10-11 April 2010, Sendai, Japan, 109-110.