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Y. Kaneda *Editors*

Post-Tsunami Hazard

Reconstruction and Restoration

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The present publication is dedicated to all those who have directly or indirectly suffered from the effects of tsunamis. We hope that the advancement of science and knowledge together with the implementation of appropriate policies will help in reducing vulnerability in populations of coastal areas while enhancing resilience against tsunami hazards.

Foreword

Few natural phenomena are as devastating as a tsunami. People, buildings, infrastructure, and vehicles in the hazard path rarely come out unscathed. While the width of this path of destruction is typically measured in hundreds of meters to a few kilometers, its breadth can extend from hundreds to even thousands of kilometers, crossing towns and countries and even traversing an entire oceanic basin at high speed. The almost binary nature of tsunami impacts can also present some unique recovery and rebuilding challenges, and these are the primary subjects of this book. For survivors, the psychological trauma lasts a lifetime and can motivate survivors to relocate homes, jobs, and even whole communities to safer ground, sometimes at tremendous social and financial costs. For governments, the level of concentrated devastation usually exceeds the local capacity to respond and thus requires complex intergovernmental arrangements with regional, national, and even international partners to support the recovery and rebuilding of impacted communities, infrastructure, and economies.

Starting with the catastrophic 2004 Indian Ocean tsunami, a sequence of devastating tsunamis in the first decades of the twenty-first century have taken the lives of more than 300,000 people worldwide along the shores of Indonesia, Sri Lanka, India, Thailand, Chile, Japan, and elsewhere across the Indian and Pacific Oceans. While most common in these two oceanic basins, tsunamis can also occur in the Atlantic Ocean, Caribbean and Mediterranean seas, and other large water bodies.

Images of the massive tsunami resulting from the Mw9.0 Great East Japan Earthquake of March 11, 2011, rolling across the coastal plains of northeast Japan engulfing trees, roads, cars, homes, industries, ships, and even aircraft and crippling the Fukushima Daiichi nuclear power plant, will never be forgotten. The tsunami inundated more than 561 sq km of land, contaminated soil and croplands, destroyed fisheries and coastal ecosystems like rias and lowlands, reshaped the coastline in some places, displaced nearly half a million people, and damaged or destroyed more than 390,000 residential buildings as well as infrastructure, commerce, and public-serving facilities. A total of 15,833 people lost their lives and an additional 2,656 people are still listed as missing.

The widespread devastation caused by the 2011 tsunami prompted Japan's government to establish the Reconstruction Agency to guide the investment of more than 25 trillion yen (approximately US$ 250 billion) of restoration and rebuilding funds into the impacted region and, in less than 3 years, much has already been accomplished. Working with scientists, residents, and other decision makers, four prefectures and 81 local governments have developed recovery plans that provide an array of strategies to mitigate the effects of more common but less damaging tsunamis as well as the less frequent but potentially devastating mega-tsunamis like the one that occurred in 2011. Researchers have also been able to analyze the performance of different tsunami protection systems in place in the region—both natural, such as dunes, and man-made, such as levees, seawalls, and offshore breakwaters—and incorporate lessons into the repairs and rebuilding designs. Recovery projects include collective relocations and elevating the lands underlying communities; restoring infrastructure, ports, and maritime commerce; and designing and constructing enhanced tsunami protection systems, shelters, and evacuation routes as well as scores of temporary and permanent housing. These and other efforts to enhance the long-term community resilience and sustainability have the potential to reverse decades of population loss and economic decline and induce an air of optimism in many parts of the region.

Nonetheless, the social and financial pressures continue to be immense for many residents, and getting community consensus for the rebuilding efforts has proven to be difficult in some areas. As of March 2014, about 267,000 people are still living in temporary housing oftentimes at great distances from their former homes, livelihoods, and towns. In some instances, the psychological stress of being displaced for so long, particularly among the elderly, has sadly proven too great to bear. While efforts are under way to decontaminate areas of Fukushima Prefecture, former residents of some towns may never be able to return to their homes and are beginning to rebuild their lives and community ties elsewhere.

With time's passing since the deadly 2004 Indian Ocean tsunami, there is also an opportunity to look at the longer-term outcomes of recovery and resilience policies, programs, and funding implemented in Indonesia, Thailand, and elsewhere. Studies in Indonesia have shown that the natural recovery of protective mangrove forests in coastal areas has fared far better than many of the mangrove plantings introduced by various organizations post tsunami. Also, in Banda Aceh, a longitudinal study of post-disaster reconstruction in two impacted villages offers strong evidence that innovative, community-led reconstruction approaches resulted in greater hazard resilience and social viability than the externally led reconstruction approaches more traditionally employed by international aid organizations. Nonetheless, as demonstrated by a longitudinal study of recovery in two small villages of Thailand, sustained external support from national and international agencies and the private sector is invaluable to individuals and communities facing such immense recovery challenges.

This volume presents a unique collection of papers, presented by researchers from Japan, Indonesia, Thailand, and elsewhere, considering the major lessons in rebuilding resiliently and sustainably following the 2004 Indian Ocean and 2011

Great East Japan tsunamis and also looking back through history at rebuilding following the tsunami devastation in Japan in 1896 and 1933 and in Peru in 1746. These insights can help advance disaster risk reduction and recovery planning efforts in tsunami-vulnerable coastal communities around the world, while also benefitting urban and emergency planners, engineers, and policy makers in other regions prone to natural hazards or dealing with community sustainability issues in the face of climate change and other urban challenges. It is also the second publication within the Springer Advances in Natural and Technological Hazards Research focusing on specific tsunami-related topics. The first, *Tsunami Events and Lessons Learned* (Kontar, Santiago-Fandiño, and Takahashi, Eds., 2014), focused on the assessment, evaluation, forecast, policy, and lessons learned as well as environmental and societal impacts of the 2004 and 2011 tsunamis as well as that of the Central Pacific Ocean in 2012.

Just as the 2004 and 2011 catastrophes sent waves of shock across the globe, they also helped, in part, to heighten public awareness and preparedness efforts for tsunami hazards that hopefully will ensure that the human suffering and losses caused by these and other disasters have not been in vain. Authors in this volume also describe some of the major advances made in recent years to implement real-time monitoring and warning systems, enhance the characterization of tsunami sources and inundation mapping, and improve the design and construction of coastal protections, buildings, and infrastructure.

This book will be of interest to researchers, graduate and undergraduate students, planners, engineers, and policy makers involved in disaster recovery and urban planning, tsunami and coastal engineering, hazard mitigation, risk assessment, and environmental science.

Co-Chairs of California's Ad hoc Tsunami Policy Working Group, San Francisco, CA, USA
June 2014

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Contents

Chapter 1
Long-Term Recovery from the 2011 Great East Japan Earthquake and Tsunami Disaster

Maki Norio

Abstract Because national and local governments completed the Recovery Planning process for the areas impacted by the East Japan Earthquake Disaster in 2011, the recovery phase is currently being implemented. The physical recovery of the tsunami-impacted areas considers policies related to land use changes and the relocation of affected people. Due to the periodic tsunamis in the Tohoku area, part of the recovery process is relocating people from tsunami-prone areas. Land use regulations in coastal areas and people's resettlement to higher ground are usually discussed after each tsunami disaster. However, these policies usually fail because people return to vulnerable areas. This paper discusses the damage suffered from the East Japan Earthquake Disaster in the resettlement areas from the Meiji (1896) and Showa (1933) Sanriku Tsunami disaster based on historical documentation and field survey undertaken in 2011. Four types of damage patterns emerged: (1) No damage: Aneyosi, a well-known location where a stone-monument indicates that villagers should not live below the site, did not sustain damage despite of highest tsunami inundation. (2) Slight damage: Some resettlement sites of the Meiji tsunami, which remained on higher ground, did not suffer major damages. (3) Severely damaged low lands: Resettlements where the community expanded to low land areas sustained significant damage. (4) Major damage: Some sections of the Showa resettlements were badly damaged due to the unexpected scale of the tsunami.

Issues related to recovery after a disaster are discussed based on studies conducted at the Showa resettlement site.

Keywords Long-term recovery • Tohoku earthquake • Resettlement

This chapter is an updated and revised paper by the author: Maki N (2012) Long Term Recovery from the 3.11 East Japan Earthquake Disaster -Moving to Higher Ground?-: Disaster: Earthquake Disaster: Evaluating Resettlement Projects after Tsunami Disasters, Proceedings of 15th World Conference on Earthquake Engineering, CD-ROM, 2012.

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1.1 Introduction

The East Japan Earthquake Disaster on March 11, 2011 (EJED) resulted in 18,916 dead or missing, 129,472 buildings with severe damage, and 255,977 with minor damage. Most of the damage was due to the tsunami. The Iwate, Miyagi, and Fukushima Prefectures were especially impacted (Level 1 Disaster Response Headquarter 2012).

After this catastrophe, the national government established two categories of tsunami hazards: level 1 and level 2. A level 1 tsunami occurs once every 100 year statistically. The strategy for a level 1 tsunami is to “prevent damage” through activities such as constructing sea walls at the height of a level 1 tsunami. In contrast, a level 2 tsunami occurs once every 1,000 years statistically. The strategy for a level 2 is to “mitigate damage”. To save lives, the comprehensive disaster reduction plans include land use regulations and tsunami warning systems.

The recovery project from the EJED was undertaken considering these two levels of tsunamis. Resettlement to higher ground or creating mounds on lower land is now planned in the impacted areas. Figure 1.1 shows the concept of the land use plan for recovery projects.

The area impacted by the EJED has been hit by a tsunami every 30–50 year, including the 1896 Meiji Tsunami Disaster, the 1933 Showa Tsunami Disaster, and the 1960 Chili Tsunami Disaster. After every disaster, residents in the impacted area move to resettlement sites on higher ground. However, over time people return to the low land near the sea due to variety of reasons, such as population growth or the

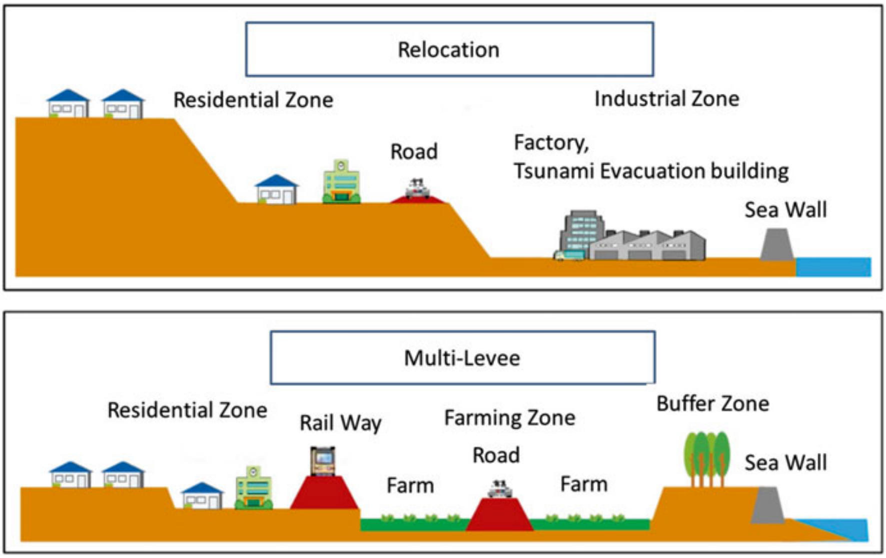

Fig. 1.1 Land use plan concept (Source: Miyagi Prefecture Recovery Plan)

inconvenience to fishing businesses, and are inevitably victims of another tsunami. Thus, as the recovery phase of the EJED is implemented, it is important to monitor the history and damage of resettlement sites since the Meiji and Showa Disasters. This paper discusses damages at the resettlement sites from the Meiji (1896) and Showa (1933) Tsunami Disasters via a historical document review, a field survey of the resettlements after the EJED, and the recovery policies in the Meiji and Showa resettlement sites.

1.2 Resettlement After the 1933 Showa Tsunami Disaster

This section explains about the recovery project after the 1933 Showa tsunami disaster from the analysis of historical documents.

1.2.1 Recovery Plan from the 1933 Showa Tsunami Disaster

The 1933 Showa Tsunami Disaster killed 4,007 people, and destroyed 4,453 buildings in Miyagi and 4,932 housing units in Iwate. The national government established a recovery plan that called for resettlements at 102 villages in the Miyagi and Iwate Prefectures. The Department of Urban Planning, Ministry of Interior published a report about recovery (Department of Urban Planning, Ministry of Interior 1934), which included two types of recovery plans: one for urban areas and one for fishing and farming villages (Table 1.1). The recovery plan for urban areas consisted of (1) location, (2) roads network, and (3) tsunami protection, whereas that for fishing and farming villages consisted of (1) location, (2) resettlement site, (3) road network, and (4) tsunami protection.

The EJED recover plan is very similar to the 1933 Showa Tsunami Disaster recovery plan. One difference is the sea wall in the EJED is intended to prevent a level 1 tsunami in the future, whereas the Showa recovery used resettlements to higher ground as a disaster reduction tool. Figure 1.2 shows example drawings of resettlement sites.

1.2.2 Implementation of a Recovery Plan

Municipality governments implemented the 1933 Showa Tsunami Disaster Recovery Plan. The two major projects were (1) road recovery projects and (2) construction of resettlement sites. The total cost of these projects amounted to JPY 675,879 (It will be JPY 479 million of 2012 currency, Bank of Japan 2014), which

Table 1.1 The 1933 Showa Tsunami Recovery Plan

	Location	Road	Tsunami protection	Resettlement site
Urban Area	Recovery at original location. Residential area move to higher ground. Storage, and transportation industry stays at sea side	Road network with the other cities and villages is necessary. Width of road should consider for tsunami evacuation and fire protection. Road from resettlement site to the sea side should be constructed	Mound will be constructed in minor impacted areas. Sea wall and sea reclamation will be done for tsunami protection. Tsunami and shaking proof structure will be constructed at sea front to prevent wooden structure building behind	
Fishery and Farming village	Villages move to higher ground near from original location. Condition of resettlement site should be as follows: (1) Near from the sea, (2) Higher than tsunami inundation heights, (3) Sea view, (4) South facing hill, (5) Drinking water	Road network between villages need to be tsunami safe heights to prevent isolation of villages	Sea wall, buffer zone, and evacuation road will be installed for non-resettled villages	Public facilities such as village office, schools, police, temples should be located at the highest location in the site. Community park locates at the center of resettlement site, and meeting hall and public bath will be constructed around the park. Resettlement site should accommodate all the villagers who would like to move to higher ground in the future. Tsunami inundation area will be used for common working space for village

Source: Department of Urban Planning (1934)

was 49 % of the annual budget for all the corresponding municipality governments. The national government supported the municipality governments through the following measures. (1) The national government covered 85 % of road recovery project costs. (2) Low-interest loans for resettlement site construction projects were established, and the national government paid the interest of these loans.

Resettlement sites were located on acquired private lands along with municipality government–owned and community-owned lands. Residents at the resettlement

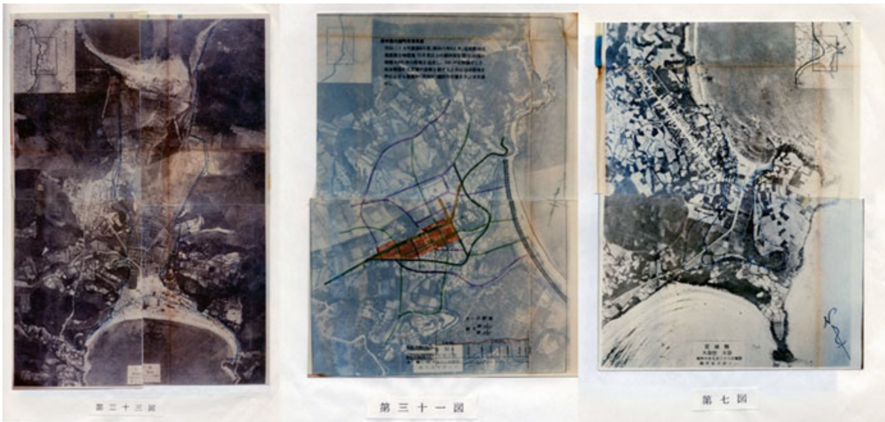

Fig. 1.2 Site plan of the resettlements: *Left*: Funakoshi, Yamada, Iwate, *Middle*: Kirikiri, Ootsuchi, Iwate, and *Right*: Ootani, Motoyoshi, Kesennuma, Miyagi (Source: Department of Urban Planning 1934)

sites were able to own their land after 15 years of payments (20 years later: 5-year moratorium + 15 years of payments). The price of the resettlement site was calculated as: (Cost of land actuation + Construction cost of resettlement)/Portion of occupied land. After the 1939 Showa Tsunami Disaster, 60 villages (11 community resettlements, 49 individual resettlements) in Miyagi and 38 villages (all community resettlements) in Iwate conducted resettlement. All recovery projects were completed within 1 year.

1.3 Damage Due to the EJED at Resettlement Sites

This section explains about the field survey results on the damage about the Showa resettlement sites, and damage pattern classification and recovery scheme from the EJED.

1.3.1 Damage at Resettlement Sites

A field survey of resettlement sites from the Meiji and Showa Tsunami Disasters was conducted after the EJED using 21 large-scale resettlement sites as the targets. Table 1.2 shows the results. Figure 1.3 shows the location of several resettlement projects. Four types of damage patterns were clarified. Damage classification of resettlement site is field observation bases, which does not based on quantitative data.

Table 1.2 Damage and recovery of resettlement sites for the EJED

Village	Size	Summary	Damage	Recovery
Onappe (Sakiyama, Miyako, Iwate)	Small	Residential area have stayed in higher ground and no damage for housing. Fishery facilities at sea side got damage	○	Mound
Aneyoshi (Shigemori, Miyako, Iwate)	Small	No damage in spite of the highest inundation reaching to 40 m. Famous village for stone monument saying no residents under the monument	◎	–
Funakoshi (Yamada, Iwate)	Medium	Though Sea wall got damage, Minor damage to residential area because people have stayed in resettlement site of Meiji and Syowa recovery	○	Relocation (lower part residents)
Tanohama (Yamada, Iwate)	Medium	Damage at sea wall and residential area in lowland got severe damage. Resettlement site of Syowa recovery survived without minor damage	Δ	Relocation (lower part residents)
KiriKiri (Ootsuchi, Iwate)	Medium	Resettlement site of Syowa recovery got damage but housing in higher ground survived	Δ	Relocation and mound
Ryouishi (Kamaishi, Unozumai, Iwate)	Small	Sea wall was destroyed. Resettlement site of Syowa recovery got severe damage	×	Relocation
Hongo (Karani, Kamaishi, Iwate)	Small	No damage in resettlement site of Syowa recovery, but expanded lowland residential area got severe damage	Δ	Relocation (lower part residents)
Koshirahama (Karani, Kamaishi, Iwate)	Small	Sea wall was destroyed, and residential area in lowland got severe damage. Resettlement site of Syowa recovery was safe	Δ	Relocation (lower part residents)
Hondo (Yoshihama, Sanriku, Oofunato, Iwate)	Medium	No damage	◎	–
Urahama (Okirai, Oofunato, Iwate)	Small	All the village got severe damage. Resettlement of Syowa recovery also got severe damage	×	Relocation
Minato (Ryori, Sanriku, Oofunato, Iwate)	Small	Residential area in low land got severe damage. Resettlement site of Syowa recovery did not get any damage	Δ	Relocation (lower part residents)

(continued)

Table 1.2 (continued)

Village	Size	Summary	Damage	Recovery
Syuku (Akazaki, Oofunato, Iwate)	Small	Residential area in low land got severe damage, and slight damage in resettlement site of Syowa recovery	Δ	Relocation (lower part residents)
Hosoura (Suezaki, Oofunato, Iwate)	Small	Residential area in low land got severe damage. Resettlement site of Syowa recovery did not get any damage.	Δ	Relocation (lower part residents)
Tomari (Suezaki, Oofunato, Iwate)	Small	Residential area in low land got severe damage. Resettlement site of Syowa recovery stays in minor damage	Δ	Relocation (lower part residents)
Tomari (Rikuzentakada, Iwate)	Small	Resettlement of Syowa recovery was safe. Minor damage in residential area in sea side	Δ	Relocation (lower part residents)
Osabe (Rikuzentakada, Iwate)	Medium	Reclaiming land and sea wall of Syowa recovery did not work. All the villages got severe damage	×	Relocation
Oosawa (Karakuwa, Kesennuma, Miyagi)	Small	Resettlement and lower land housing got severe damage	×	Relocation
Tadakoshi (Karakuwa, Kesennuma, Miyagi)	Small	Housing in lowland got severe damage No damage in resettlement of Syowa recovery	Δ	Relocation (lower part residents)
Ooya (Motoyoshi, Kesennuma, Miyagi)	Medium	No damage in resettlement site of Meiji and Syowa recovery. Mainer damage at houses near from the sea	○	Relocation (lower part residents)
Aikawa (Kitakami, Ishinomaki, Miyagi)	Small	Residential area in lowland got damage. No damage in resettlement of Syowa recovery	Δ	Relocation (lower part residents)
Tanigawa (Ojika, Ishinomaki, Miyagi)	Small	Resettlement site of Syowa recovery got severe damage	×	Relocation
Okatsu (Ishinomaki, Miyagi)	Medium	Severe damage at residential area in lowland. Minor damage in resettlement site of Syowa recovery	Δ	Relocation

No damage (◎); *Minor damage* (○); *Major damage in expanded low land settlements* (△); *Major damage in resettlement sites* (×)

Fig. 1.3 Location of resettlement sites (Edited on Google Map)

1. *No damage* (◎): Aneyosi settlement, which is famous for a stone monument indicating that villagers should not live below this monument, did not sustain any damage despite having the highest tsunami inundation.
2. *Minor damage* (○): A few buildings near from the sea got damage. Resettlement sites from the Meiji tsunami that remained on higher ground sustained minimal damage.
3. *Major damage in expanded low land settlements* (△): All the buildings at expanding low land area were washed away by tsunami Showa resettlement communities that expanded their settlement, and low land areas sustained damage, but the original resettlement site did not.
4. *Major damage in resettlement sites* (×): All the buildings including resettlement site at higher ground were washed away by tsunami.

Although the Showa resettlement sites were on higher ground, major damage occurred due to the unexpected scale of the tsunami.

1.3.2 Resettlement Sites Without Damage

In Miyako, only Aneyoshi did not sustain damage. Although the name Aneyosi is not expressly listed in Table 1.2, this community is famous for a stone monument stating, “You shall not live below this monument” (Yamaguchi 1943), and people in this community individually moved to higher ground. Although Aneyoshi sustained the highest tsunami inundation height in the EJED of 38.9 m, the tsunami did not reach the monument.

1.3.3 Resettlement Sites with Slight Damage

Communities remaining at the original resettlement sites and did not expand to lower ground sustained minor damage due to the EJED because the elevation of the resettlement sites were determined based on previous tsunamis. Damage in these communities is very limited, but some houses near the sea were damaged. Two of the resettlement sites from the Meiji and Showa Tsunami Disasters correspond to this type of damage: Funakoshi (Yamada, Iwate) and Ootani (Kesennuma, Miyagi). Photo 1.1 shows damage in these communities.

These two communities resettled on higher ground after the Meiji Tsunami. After the Showa Tsunami, the damage was limited to low land residents (24 housing units at Funakoshi and 27 housing units in Ootani). People have remained on higher ground since the Meiji recovery. Another point about these communities is the location of the community center. These communities face a national highway, which runs on higher ground, and the business area is located along the highway. Business areas on higher ground and residents remaining in the original resettlement sites may have successfully reduced the damage from the EJED.

Photo 1.1 Meiji resettled community; (**a**) Funakoshi, no residential use in low land, (**b**) Funakoshi community after the EJED; (**c**) Ootani community (Source: Miyagi Prefectural Government)

1.3.4 Major Damage in Expanded Low Land Settlements

Large-scale Showa resettlement sites correspond this type of damage. Although resettlement sites on higher ground did not sustain damage, expansion of residential areas to low land resulted in devastating damage due to the EJED. Figure 1.4 shows the site plan of these Showa resettlements and the impact of the EJED.

Yaichiro Yamaguchi, an anthropologist monitoring the resettlement sites in this area, points out reasons why people live in the lower land near the sea (Yamaguchi 1943). One is shortage of land after the World War II. People returning to Japan settled in low land areas because they did not have housing in a resettlement site. The other reason is economic. Those, who were successful fishing and earned a lot of money, had the means to construct their new houses on their original lots near the sea.

The resettlement sites from the Showa Tsunami Disaster have about an 80-year history. The environmental condition of the resettlement sites looks nice. For example, the lower part of the Tanohata community (Fig. 1.4 upper left) sustained severe damage, but the main part was unaffected. The basic layout has been maintained and several shops exist in the resettlement site. The situation in Hosoura (Fig. 1.4 upper right) is similar to Tanohata.

Moreover, the Hongo community has an excellent layout. Cherry trees were planted at the boundary of the resettlement site and the lowland. However, several

Fig. 1.4 Showa resettlement; (**a**) Tanohama, Yamada, Iwate; (**b**): Hosoura, Oofunato, Iwate; (**c**) Hongo, Karani, Kamaishi, Iwate; (**d**) Aikawa, Kitakami, Ishinomaki, Miyagi (Maps Source: Department of Urban Planning 1934)

houses in the low land were damaged in the EJED. An interesting feature of Aikawa is that the bus stop is still named "resettlement site".

1.3.5 Major Damage to Resettlement Sites

Some resettlement sites from the Showa recover plan, even those on higher ground, suffered devastating damage. Figure 1.4 shows the recovery projects and damage from the EJED. Ryoishi in Kamaishi (Fig. 1.5 left), Urahama in Okirai, Oofunato, Tanigawa in Ojika, and Ishinomaki correspond to this damage type. Run up height from the EJED at Ryoishi was 21.2 m, though that from the 1933 Syowa was 9.5 m. (Iwate Prefecture). Moreover, neither the mound nor the sea wall for tsunami protection after the Showa Tsunami Disaster in Osabe in Rikuzentakada (Fig. 1.5 right) could save the community. The tsunami of the EJED greatly exceeded the height of Meiji and Showa Disasters in these communities.

1.3.6 Recovery Plan for the Showa Resettlements

Many recovering communities from the Showa Tsunami also suffered from the 2011 tsunami. In particular, expansion areas to lower land from the original resettlement sites sustained severe damage. After the EJED, new resettlement sites on higher ground are planned in many communities. For example, Onappe and Kirikiri have opted to create mounds to raise the elevation.

There are two issues regarding resettlement projects for the 2011 tsunami recovery. One is the scale of the resettlement sites. Five parcels are a minimum size of the resettlement site. The way towards recovery is based on individual decisions taken by each family and not the community. Consequently, the EJED newly developed small-scale resettlements are scattered around the area (Fig. 1.6). However,

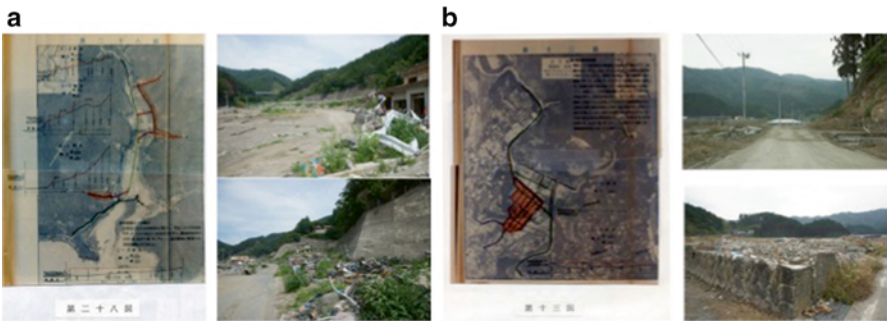

Fig. 1.5 Showa Resettlement suffered devastating damage. (**a**) Ryoishi, Kamaishi, Iwate; (**b**) Osabe, Rikuzentakada, Iwate (Source: City of Oofunato)

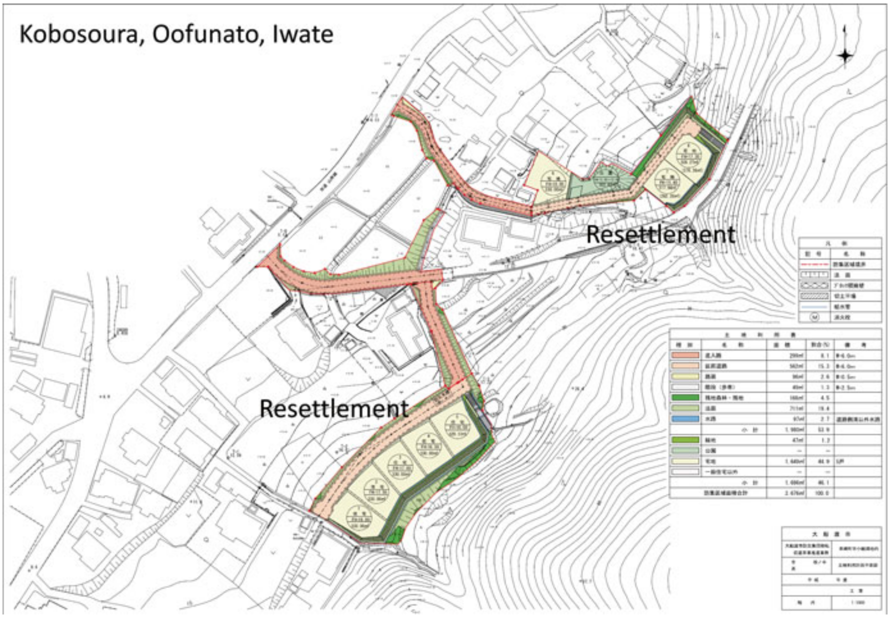

Fig. 1.6 Infill Resettlement Development type (Source: City of Oofunato 2014)

some small-scale resettlements are infill development at an existing settlement. Those infill development type resettlement projects are preferable.

The other issue is the buffer zone. In the Miyagi prefecture, a buffer zone was also set in the surviving Showa resettlement sites based on tsunami simulation results. The Ooya community in Miyagi was minimally inundated by the EJED tsunami at the Showa resettlement site, but housing was not damaged. It is a success story of resettlement to higher ground. The inundated area was designated as a buffer zone, and the construction of new houses will no longer be permitted. Comparing to Iwate prefecture, the buffer zone setting in Miyagi is a radical. In Iwate, a buffer zone is set referring to a land use planning for a recovery project.

1.4 Discussions and Conclusions

The concepts in the EJED recovery plan are not new. Because most are from the scheme of tsunami recovery in Showa, it is important to learn from the damage due to the EJED in resettlement sites. One point for a successful recovery is how to regulate the expansion of residential areas to low lands. As part of the Showa recovery, the Miyagi prefecture set an ordinance to regulate the construction of houses in lower lands. Despite this land use regulation, people move back to lower land near the sea, and suffered tsunami damage again in 2011.

One interesting example of a resettlement project is the resettlement site of the Meiji Tsunami Disaster. Due to the construction of a national highway, the community center moved to higher ground and people did not move back to lower ground. The national highway developed new business opportunities, demonstrating the importance of creating new business opportunities in resettlement sites as a thriving local economy may keep people in the resettlement site.

Tsunami impacted area of the EJED is tsunami prone area. Soon after disaster, people moved to higher ground but come back to lower land. It is clear that daily life is more important than safety at the time of tsunami with several decade interval. It means that the 100-year and the 1,000-year design standards do not work sense. Resettled communities in 1933 have moved back to lower area and hit by 2011 tsunami. However, lessons in several communities that have stayed in higher ground are interesting. Combination with daily life convenience and disaster safety is important.

A new issue is about the EJED is the aging population. Many of those who have moved to resettlement sites and constructed new houses or moved into public housing are elderly people. Depopulation means that the probability of expanding these communities to lower land is low. On the other hand, sustainability of these communities is a serious issue because if no one migrates into these communities, they may be vacant in the near future. For the recovery from the 2011 tsunami, many communities decided to create new residential resettlement sites on higher ground. Although the probability of expanding these communities to lower land is low, a serious issue is the sustainability of these communities. Because it is critical to solicit new community members to create a sustainable community, new business opportunities are important for communities within these recovery projects. The issues will be discussed in another article.

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Chapter 2
Reconstruction Plans and Planning Process After the Great East Japan Earthquake and Tsunami

Michio Ubaura

Abstract This paper aims at showing the numerous gaps between the ideal concept and reality in the reconstruction process after the Great East Japan Earthquake and the following tsunami within 2 years from the disaster. The gaps are mainly attributable to the misunderstanding or incomprehension of spatial planning by the local government, which puts too much weigh on acceleration of the planning process and lacks in preparation to deal with the disaster in the ordinary time.

Keywords Great East Japan Earthquake • Spatial planning • Disaster prevention planning • Reconstruction projects

2.1 Introduction

Three years have passed since the Great East Japan Earthquake, and it is noteworthy that most of the municipalities in the affected area had made reconstruction plans within the first year after the disaster caused by the natural calamity. Since these plans contain only general policies about the recovery from the disaster and often have abstract contents especially as for land use, the municipalities have decided to tackle the problems associated with the implementation of the plan and the related projects. However, many of them are facing difficulties and the recovery planning process is proceeding very slowly compared with those of previous disasters that have occurred in Japan, such as the Great Hanshin Earthquake in 1995 or the Niigata Prefecture Chuetsu Earthquake in 2004.

This paper aims at clarifying the reconstruction planning process and its problems by comparing the theory with the actual situation according to the following aspects; relationship between spatial planning and disaster prevention planning, necessity of additional plans on district level, importance of planning with a time perspective, citizen's participation, and role of experts.

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2.2 Problems of Provincial Areas Before the Disaster

A preliminary discussion of the general problems faced by provincial municipalities in Japan before the disaster is important, as many of the problems that occurred after the disaster can be ascribed to these issues (Fig. 2.1).

Two major issues are population decline and aging society. Although the Japanese population began declining since 2005, the provincial municipalities registered a declining population earlier in comparison. In Ishinomaki city, which is the municipality most affected by the Tsunami, the population declined from approximately 182,900 in 1990 to 161,600 in 2010 (Fig. 2.2), at a rate of approximately 12 % in 20 years.

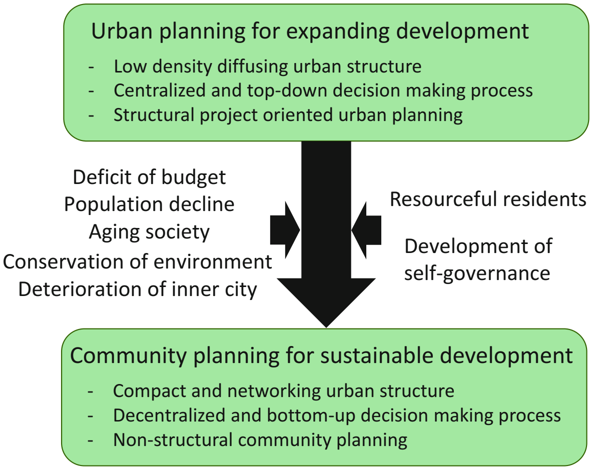

Fig. 2.1 Problems and future perspectives in Japanese provincial cities

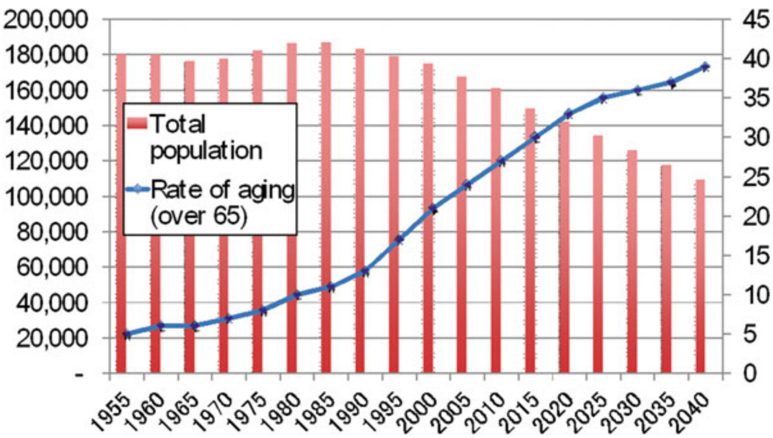

Fig. 2.2 Changes in Population and aging rate in Ishinomaki city (Actual number until 2010, prediction from 2015) (Source: Ishinomaki city government)

On the other hand, the population of the elderly people (i.e., over 65 years old) has been increasing from approximately 14 % in 1990 to 27 % in 2010. This trend is much more noticeable in the small municipalities.

Another important issue that should be mentioned is the fiscal problem of the local municipalities, as this is linked to spatial planning. The real debt expenditure burden ratio of Ishinomaki city is 14.3 % in 2010, and other municipalities are also in a similar situation. When exceeding 18, municipalities must obtain permission of the national government for municipal bond issue, this situation can be estimated to be severe. This also reveals the importance of a planning process that emphasizes on efficiency.

Regarding spatial planning, urban sprawl and deterioration of the inner city have been significant issues in the provincial cities. The maintenance of small settlements along the coast, where the presence of industrial depression is evident, has also caused severe problems. In recent years, additional problems occurred due to the "reverse sprawl," a typical timeless, geographic phenomenon of generation of vacant lots during population decline.

Based on these premises, it is recognized that the spatial planning in Japan should shift its paradigm from an expanding, low density structure with a centralized top-down decision making process a sustainable and compact, networking structure with a decentralized bottom-up decision making process. However, effective solutions for realization of new paradigm of spatial planning have not been developed yet.

In addition to this, the Great East Japan Earthquake has raised the question of resilience of urban and rural areas. In Japan, both structural and non-structural counter measures have been taken to tsunami hazard, construction of levee, evacuation training in the school and local communities for example. This achieved some positive results, such as lower death rate compared to other areas, Banda Aceh in Indonesia for example (TTILIT 2012). However, the size of the number of the GEJE tsunami victims shows the room for improvement to enhance resilience to natural disasters. Some of those countermeasures are closely- linked to spatial planning.

Therefore, it is important to coordinate with it and to realize in the framework of the new paradigm of spatial planning.

2.2.1 Summary of Reconstruction Plans

According to a general survey on the affected municipalities, the content of the reconstruction plans can be summarized as follows.

Land protection, through coastal levees, should take place against the "level 1" tsunami, occurring with frequencies in the range between once every several decades and a hundred years ("tsunami protection level"). Protection against the largest-scale tsunami, "level 2" tsunami, which occurs once every several hundred or more years, should be guaranteed from both structural and non-structural aspects ("tsunami diminishing level"). The inhabitable area is limited to an expected inundation height of less than approximately 2 m in the case of “level 2” tsunami. The area with expected inundation higher than 2 m, is designated as disaster hazard area, and its residential use is forbidden.

Reconstruction land use plans, which are made to ensure this safety level, can be categorized into five typical patterns according to the investigation of the national government (TTILIT 2012)[1]:

(a) “Relocation”: part of the inundated area, with expected inundation height of more than 2 m of “level 2” tsunami, is designated as disaster hazard area, and the settlements must be relocated outside the inundated territory.
(b) “Aggregation on site”: the settlement is to be aggregated to the on-site area, where safety is ensured by a coastal levee or a secondary levee.
(c) “Land Raising”: part of the inundated area is to be raised, and the settlement must be aggregated there.
(d) “Relocation + Land Raising”: combination of Relocation and Land Raising
(e) “On site reconstruction with defense facilities”: the inundated area must be reconstructed when the safety is ensured by structural protection facilities.

2.3 Relationship Between Spatial Planning and Disaster Prevention Planning

2.3.1 Conflicts Between Objective and Subjective Safety in Reconstruction Plans

The height of the levee planned by the government corresponds in principle, as abovementioned, to the height of Level 1 tsunami. This reaches into, in some cases, as many as more than 10 m. However, the height of it required by the local residents is in some cases lower than that because of the influence on fishing, landscape or tourism. These cases occurred mainly among the fishing villages along the ria coast, where people’s life is closely linked to the ocean through fishing, representing both a regular vocation and a tourist industry.[2] The planned tsunami protection system is excessive for those people, hindering their comfort and convenient daily life or smooth industrial activities and it is considered responsible for accelerating the decline of the village. It is also, in some cases, criticized to be inefficient, for there is no land use to be protected in the hinterland, such as farmland or even uncropped farmland.[3]

In other cases, the height of the levee required by local residents is higher than that planned by the government. Moreover, the designation of the disaster hazard

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[1] More than 31,000 people were killed by the tsunami after 2004 Indian Ocean earthquake, which correspond to more than 10 % of the whole population of the city.

[2] We can take the following cases as typical examples; Moune district, Motoyoshi district and Shibitachi district in Kesennuma city. (from Aug. 13th to 18th, *Kahoku Shimpo Newspaper*).

[3] Is levee needed in inhabited island!? (2013, Nov. 09) *Mainichi Shimbun*, p. 21.

area, where they can relocate with subsidies, is too narrow for those who want to live outside the area. These cases are observed mainly near or in the city, where most residents are paid workers, whose economy and lifestyle remotely relate to the ocean. They are generally afraid to take a risk of a tsunami, no matter how low it is in theory.

Both conflicts can be ascribed to the gap between objective safety level, which is defined based on scientific analyze and subjective safety level, which is requested by local residents. That nature is deeply connected with the characteristics of the settlements. It demonstrates the necessity of the flexible planning of the levee or the land use, especially in the case of a requested lower levee, which is not a big fiscal issue (Ubaura 2012).

2.3.2 Ideal Relationship Between Spatial Planning and Disaster Prevention Planning

A crucial issue in the spatial reconstruction planning process is the safety of the city or village, for the disaster, which triggered the planning, occurred for this very reason. However, safety is not the only important factor to be considered in the planning process, and it should not always be prioritized over other interests. For example, the safety level will increase if a higher levee is constructed. However, the latter will block the view of coastal landscape, thereby negatively impacting the tourist and fishery industry, which needs regular observation of sea conditions. This, in turn, represents a "risk" of declination for the villages, whose economy is based on these industrial activities.

The same arguments applied to land use. New settlements often locate on the hills or inland, where the risk of tsunami is extremely low. However, they will be sometimes scattered due to the limited availability of hilly land for building construction, with the consequent dispersion of the communities of inhabitants, who will suffer a great discomfort in their daily life.

These example show how the construction of tsunami protection facilities or the change in land use and building relocation can bring as many advantages as disadvantages in terms of safety, comfort, amenity, efficiency, and landscape. Therefore, all these factors should be taken into account during the planning process integrating the needs of safety with all the other aforementioned aspects within a comprehensive relocation plan.

A committee of the national government, "Exploratory Committee of Countermeasures against Tsunami in the Coastal Area (*kaigan ni okeru tsunami taisaku kentou iinkai*)" takes the similar stands: In the report of the committee, "The basic concept on reconstruction of coastal levee suffered from the Great East Japan Earthquake and Tsunami in 2011 (*heisei 23 nen touhoku chihou taiheiyouoki jishin oyobi tsunami ni yori hisai sita kaigan teibou touno fukkyuu ni kansuru kihonteki na kangaekata*)", the necessity of comprehensive planning is cited as follows; "The crown of the levee should be decided on the premise of the water level of planned tsunami or high tide. During the planning process, care for the diversity of coastal function, environmental protection, blending in with the landscape, economical efficiency… should be comprehensively taken into account."

2.3.3 Actual Situation

However, Miyagi prefecture, the most affected by the tsunami, persists with constructing the highest levee permitted by the fiscal legislation. It decides the height of coastal levee only by the necessity of tsunami and high tide protection, whichever is higher.[4]

One of the reasons for such a policy might be the regretful will of the prefectural governor to be officially responsible for the safety of present and future generation of local residents.[5] Another possible reason is the vertical administrative structure with members of the division of levee construction "doing their best" with little concern for the structural and non-structural urban aspects.

2.4 Integration of Plans on District Level: Ideal, Reality and Gap

2.4.1 Project Coordination on the District Level

(a) Necessary adjustment of projects
The reconstruction of the settlement in the affected area occurs with different projects under the jurisdiction of different departments and agencies being planned at the same time and in the same place: road, levee, and public housing construction, land readjustment, and collective relocation projects for disaster prevention are all planned simultaneously. In this scenario, it is ideally imperative to set the time schedule, the areas and the contents of each project on a working level that can promote all of them.

(b) Elimination of waste
Many public facilities were damaged by the disaster, and most of them need to be reconstructed. Furthermore, new tsunami protection facilities are needed to guarantee the safety of citizens. Those facilities should be constructed as soon as possible and with minimum waste. Most of the recovery and new construction projects will be financed by the national government, in other words, the national taxes. These costs represent a burden on the young generation, and hence they need to be minimized. In addition, the finances from the national

[4] http://www.pref.miyagi.jp/uploaded/attachment/43036.pdf

[5] Press conference of Miyagi prefectural governor on July 8. 2013.

government should not cover the whole cost of the project, and some expenses, some of the construction cost as well as the most of the maintenance cost, should be covered by the local governments.

However, these reconstruction projects are sometimes not well coordinated and it arises many problems. The following examples illustrate the barriers that hinder smooth project coordination.

One barrier is between the vertically divided administrative organizations. In Minamisanriku town, for example, the coastal levee and the mounded national road are planned to run parallel to each other, in close vicinity of about 100 m. The road, planned to be behind the levee, is even higher than the levee and the local government is planning to fill the resulting dips between the two infrastructures. Although the construction of a road that also functions as levee might present an economic advantage, it is hard to coordinate the two projects because the prefectural government plans the levee and the road is by the national government. Each section is overloaded with such enormous tasks that the active coordination between the two is completely neglected.[6]

The other barrier is the time sequence. Each section of the project works with its own time schedule, which means that while one project proceeds with the construction phase, the other is still at the basic design stage. In these cases, it is almost impossible to coordinate these two projects.

(c) Contribution to creation of new attractive place

A coordination of the projects contributes not only to waste reduction, but also to creation of a new attractive space for the future generation.

In Ishinomaki city, for example, the construction of the embankment on Kitakami River is planned to take place in the central part of the city. Ishinomaki city was historically developed as a port along the river. After the disaster, the national government has planned to construct the embankment, while the prefecture is in charge of rebuilding the bridge, and the city of redeveloping the site along the river for commercial use. If those projects proceed uncoordinated, the city center will be separated from the river and will be an ordinary stereotypic center.

Therefore, at the moment members of the national, prefectural and local government arrange regular "working-level" meetings with academic experts and consultants to coordinate time, space and budget while explaining the projects to the local residents about the conformation of areas where the city and river will be structurally and non-structurally closely connected with each other (Fig. 2.3).

2.4.2 Blank Area of the Projects

There are many projects for the requalification of the affected area such as land readjustment, urban redevelopment, and projects promoting the group relocation for disaster mitigation. All of them present several problems in the planning and implementing phases.

[6] Interview to an administrative officer of Minamisanriku Town on May 15. 2013.

Fig. 2.3 Image of unified plan along Kitakami River (Source: Urban and Regional Planning Lab., Tohoku University and Geospatial Information Authority of Japan)

Photo 2.1 Situation of Watanoha district, Ishinomaki city, 2 years after the disaster

Furthermore, the areas severely damaged by the tsunami, for which these reconstruction projects have not been planned yet since the safety measures against tsunami will be ensured by constructing levee and since there is no need to improve urban facilities of the district, are also waiting for problems to be solved: although there is no local regulation for reconstruction of houses, most of the residents are anxious, and not willing to have their houses rebuilt in the same place as before. For this reason, this land is still vacant even 2 years after the disaster as is typically seen in Watanoha district in Ishinomaki city (Photo 2.1). The situation is worsened by the indifference of the local government towards the residents, who feel abandoned, since it gives information or expenses man power and money only through concrete reconstruction projects.

Although it is difficult to plan and implement large scale projects in those areas, there is an urgent need for the improvement of the district through implementation of small scale structural projects, such as small residential district improvement project based on Building Standard Law, or non-structural projects, such as evacuation drill and promotion of community activities.

2.5 Time Sequence and Planning

2.5.1 Attention to the "Past" in the Planning Process

Most of the buildings in these urban and rural areas were washed out by the tsunami or demolished afterward. Many of the Kura storehouses could have been conserved, but were demolished because of the high cost of reconstruction and maintenance. Even in such a situation, however, there are still many structural and non-structural infrastructures that should be saved. Considering the history and characteristics of the area, it is important to preserve these facilities for the future generations.

Roads are an example of such type of infrastructure. Particularly in the areas where land readjustment is planned, it could be a good option to preserve the pathway and width of the roads in order to maintain the original landscape. Otherwise, the new road network will be planned as a grid-like structure typical of a new suburban, residential area.

On the other hand, not everything should be restored as it used to be before the disaster. In fact, one possible reason for the decline of the settlements might have been the irregular form of the sites and the narrow roads, which were inconvenient for car users. In such cases, preserving the old style may not be attractive features of the district and may accelerate the decline of the area.

Hence, every infrastructure should be carefully evaluated to determine what should be preserved and what to be changed.

In the present situation, however, new reconstruction is often preferred to restoration of old infrastructures, leading to standardized settlements with limited features. In the case of Kadonowaki district in Ishinomaki city (Fig. 2.4), local government plan attempted, within a certain degree, to preserve the old configuration of the streets (Fig. 2.5).

However, a long time will be required by authorities to investigate the area and for the local residents to understand the characteristics of the area and importance of it. Therefore, this way of elaborate planning is hardly compatible with the needs of a prompt recovery planning process in order to measure up to the expectations of the people affected by the disaster.

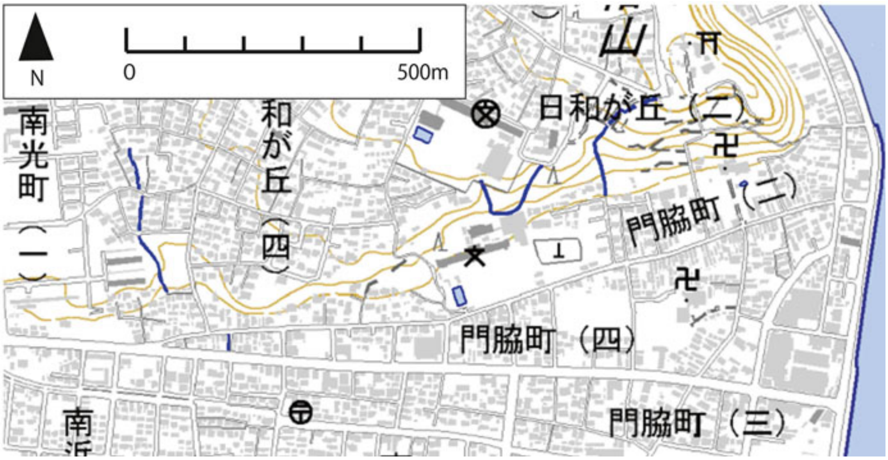

Fig. 2.4 Present situation of Kadonowaki district, Ishinomaki city (Scale 1:25,000) (Source: Geospatial Information Authority of Japan)

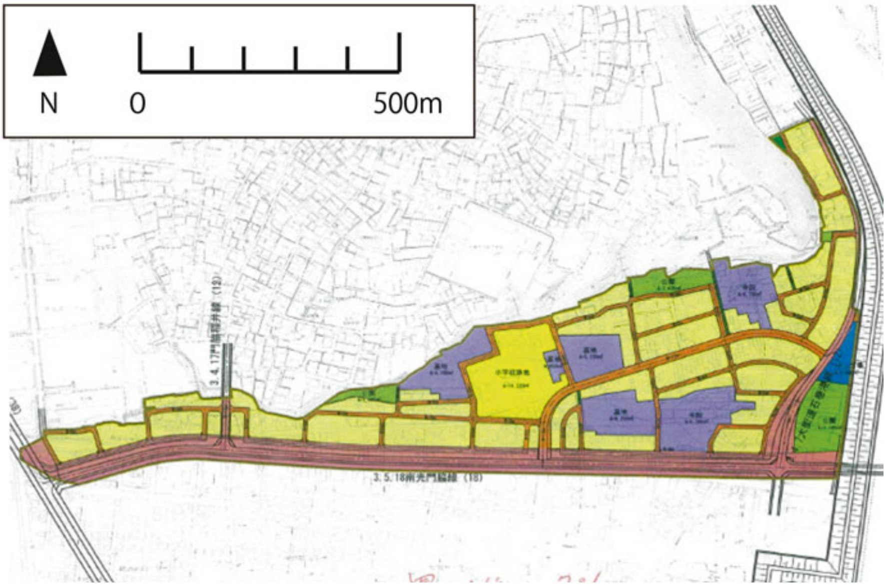

Fig. 2.5 Plan of land readjustment in Kadowaki district, Ishinomaki city (*no scale, no direction*) (Source: Ishinomaki city)

2.5.2 Attention to the "Present" in the Planning Process: Ensuring Quantitative and Qualitative Adequacy

The level of housing expectations for the affected people by the disaster varies drastically with time and conditions, and these ultimately affect both the future land use and the size of new settlements. Municipalities therefore conduct meticulous and frequent surveys about people's expectations.

Many projects were planned in the chaotic and uncertain period shortly after the disaster. Some of them demonstrated that the size of the new settlements is excessive with respect to the real demand, especially in the case of on-site land readjustment projects. In Ishinomaki city, for example, these sorts of projects are planned in four districts. However, most of the local residents want to sell their land and move to the inland, which is safer considering future tsunamis. Only 20–30 % of them want to rebuild their houses where they lived.[7] It is thus foreseen that many lots will remain vacant after the accomplishment of the project and the improvement of the urban facilities with considerable expense. This will lead to new inefficient settlements with extremely low density of scattered houses.

New sort of project, which will solve such a problem, should have been developed before the disaster and, at least in the planning process of the project, the preferred developing areas should have been selected with a strategy of "selective concentration" in order to prevent useless public investment in infrastructures.

In addition to the quantitative aspects mentioned above, there are also some problems in the qualitative aspects of the planning process. An aforementioned inadequacy is the insufficient attention to the historical aspects. However, the municipal authorities do not intend to modify the contents of the plans with the excuse of the first, provisory stage that is the same plan already explained to the local residents and one, which will never be modified.

Although speed is a very important factor to be considered in the reconstruction planning process, especially in the case of industrial recovery, the adequacy in the size of the settlements and their quality is sometimes underestimated.

2.5.3 Attention to the "Future" in the Planning Process

Those settlements, developed by the reconstruction projects, will be likely to decline shortly after their accomplishment, as the population of the region will decrease and this trend will even accelerate because of an aging society. It is therefore important to consider the shrinkage of the population since the beginning of the planning process.

From this perspective, the first step should be the development of existing sites in the undamaged settlements, as many of these sites are already witnessing a declining process with many vacant lots and houses available to host people. If a relocation site is planned out of the undamaged settlement, both new and old settlements will eventually remain with many vacant lots and houses.

In some cases, they made well-planned relocation project in with this concept meaning. Norinowaki district in Miyako city, is a clear example of this case (Fig. 2.6). It will not move to the higher land independently, but move to the

[7] Interview to an administrative officer of Ishinomaki city on Dec. 25. 2013.

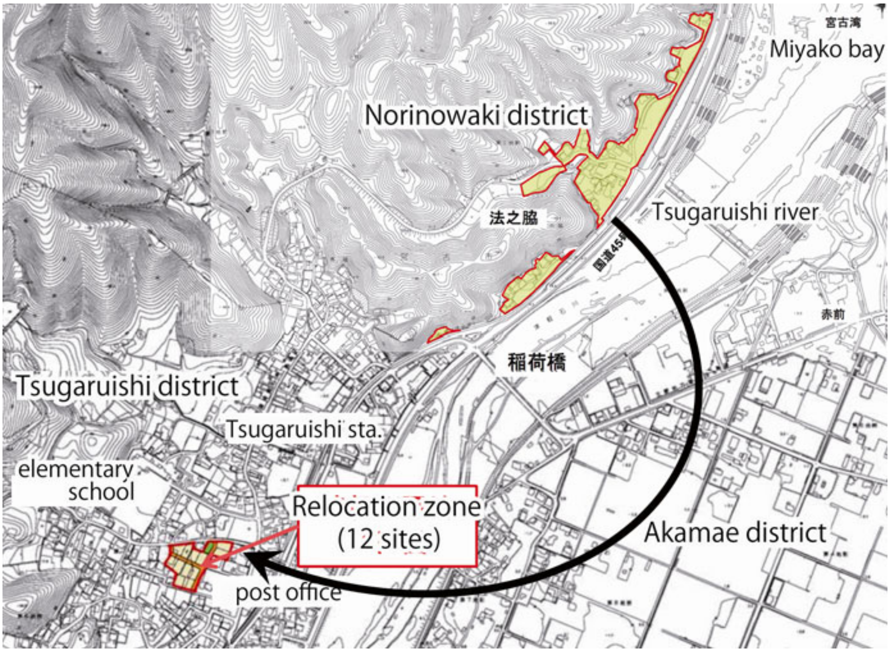

Fig. 2.6 Relocation plan of Norinowaki district to Tsugaruishi, Miyako city. Material used for the explanation meeting for local residents (Source: Geospatial Information Authority of Japan)

farmland inside the neighboring Tsugaruishi district. The main reasons for this are that the number of the households to move is not many, around 30,[8] the aged people occupying the greater part of the inhabitants were reluctant to live in isolation and inconvenience.

On the contrary, the relocation project of Akamae district in the same city has planned a new relocation site mainly distributed outside the district (Fig. 2.7), although there are many vacant lots and houses in this settlement. The reasons for that are as follows; the unwillingness of the victims to live in the village with unaffected residents, the unwillingness of land owners to sell their land to local government, and the impossibility of expanding the narrow roads of the unaffected settlement, because it concerns many land owners and may result in complex and long-term projects.

Moreover, it is also important to consider shrinking processes in land use or architectural plans of the new settlements. One of the typical examples is the conversion from the public housing to nursing home after the residents get older. Another example can be the land use plan with consideration of use program of vacant lots before they generate (Ubaura 2013).

However, the local municipalities cannot afford to consider the future implications as the target of their planning is mainly limited to the accomplishment of the project.

[8] Interview to an administrative officer of Miyako city on June.

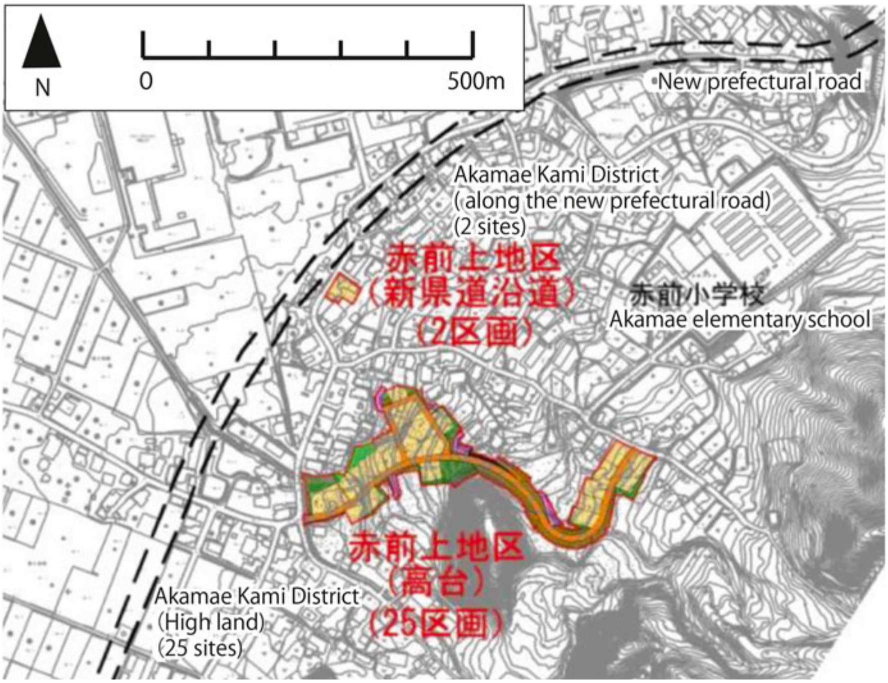

Fig. 2.7 Relocation Plan of Akamae district, Miyako city. Material used for the explanation meeting for local residents (Source: Geospatial Information Authority of Japan)

2.6 Conclusions

This article depicts several gaps existing between the ideal concept and the reality in the reconstruction process after the Great East Japan Earthquake and the following tsunami. Besides the misunderstanding or incomprehension of the spatial planning by the local government, some of the gaps are caused by excessive timer-related limitations in the planning process. This aspect is strongly linked to the qualitative and quantitative lack of manpower shown by the local administration despite the help of many supporting officers from all over Japan. It is important to accelerate the reconstruction work, as most of the victims hope to put their lives back together as soon as possible. In particular, industrial activities should start again soon so that people can the earn money needed for their recovery. However, this article illustrates that time limitations may also have a side effect and claims that different problems may need different plans, some that are quick and others with a more elaborate and careful processing.

Other problems originate because they are not dealt with steadfast commitment before the disaster, i.e., during normal time. A disaster rapidly and drastically worsens the problems existing before it. There is a necessity to theoretically and systematically develop new planning methods that suit the current trends such as population decline, shrinking settlements. Hence, completely tackling the current problems before a disaster is one of the most important countermeasures for recovery from the disaster.

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Chapter 3
Three Years After a Mega-disaster: Recovery Policies, Programs and Implementation After the Great East Japan Earthquake

Kanako Iuchi, Elizabeth Maly, and Laurie Johnson

Abstract Since March 11 2011, the national government of Japan has invested significant resources to aid recovery in the Tohoku region, devastated by the Great East Japan Earthquake (GEJE) and tsunami. Thus far, 25 trillion yen (approximately US$ 250 billion) has been committed, a 10-year national Reconstruction Agency has been established to guide the process, and many planning policies and rebuilding programs have been developed and implemented. During this time, four Prefectures and 81 local governments have also crafted recovery plans, and identified national rebuilding programs for use in implementing their plans. The first sites for permanent relocated settlements have been completed, and some residents have already moved into permanent disaster recovery public housing. At the same time, approximately 267,000 people are still displaced and living in temporary housing as of March 2014.

This chapter provides an overview of policies and programs for rebuilding from the GEJE that have a strong emphasis on reducing risk for future tsunamis, along with the awareness of the need for both physical and non-physical aspects of disaster mitigation. Focus is given to describing policies and programs for land use, temporary housing and the current conditions of disaster survivors in regaining stability in their lives. Also, the progress of program implementation and livelihood rebuilding in communities is clarified, to explain the unprecedented challenges and emerging opportunities that affected localities and communities are experiencing due to the unique nature of the tsunami impacts.

Keywords Great East Japan Earthquake and Tsunami • Rebuilding policies and programs • Temporary and permanent housing • Land use and rebuilding for risk reduction

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3.1 Introduction

The Mw9.0 Great East Japan Earthquake (GEJE) and tsunami of March 11, 2011 instantly disrupted lives in coastal communities of the Tohoku region in northeast Japan. The subsequent damage and losses were devastating: the total number of dead and missing in 12 prefectures surpassed 20,000, including 1,600 people who died in the following weeks and months; more than 390,000 residential buildings were totally destroyed (33 %) or partially damaged (67 %); approximately 561 square kilometers (km) of land was inundated; 237 out of 352 local government buildings in the severely affected region were seriously damaged; and at the peak, 470,000 people were displaced (Cabinet office 2012a; Geospatial Information Authority of Japan 2011; Reconstruction Agency 2014a). Moreover, the tsunami damaged nuclear power plants causing a meltdown at the Fukushima Daiichi plant in Fukushima Prefecture, and exposing nearby communities to a plume of radiation. Early on, residents within a 20 km zone were forced to evacuate. Later, people were evacuated from even more distant areas that were also contaminated by radiation, adding to the displaced population. The evacuation order lasted for about 6 months. After several revisions, contamination areas have been separated into three zones based on the level of radiation and their future potential for reoccupancy.

A tremendous level of resources have been invested by different levels of government and other actors in the first 3 years of the region's recovery. Thus far, Japan's national government has committed 25 trillion yen (approximately US$ 250 billion) and has established a national Reconstruction Agency with a 10 year mandate to guide the rebuilding process. Many national-level planning policies and rebuilding programs have also been developed and implemented. Four prefectures and 81 local governments have crafted recovery plans and identified national rebuilding programs for implementing these plans. By the third anniversary of the GEJE, the first sites for permanently relocated settlements had just been completed and some residents had been able to move into newly constructed disaster recovery public housing.

Affected populations have gone through several stages of displacement during the first 3 years of recovery. As aftershocks and blackouts continued after March 11, more than 470,000 people initially took shelter in evacuation centers – 150 % more than the number of evacuees after Japan's 1995 Kobe Earthquake. One week later, this number dropped as people returned to houses that were at least partially inhabitable. The first temporary housing units were completed in April 2011, a total of 53,000 units were constructed in a year, and almost all evacuation shelters were closed by the end of 2011 (Kan 2012; MLIT 2012b). As of March 2014, about 267,000 people are still living with temporary housing assistance, waiting for permanent homes to be rebuilt (Reconstruction Agency 2014a). Figure 3.1 shows the general location and distribution of the remaining displaced population. Evacuees from Fukushima Prefecture face a more complicated recovery, a longer-term evacuation, and a more uncertain future.

This chapter considers the policies and programs related to land use, temporary housing and housing recovery in the Tohoku region during the first 3 years after the

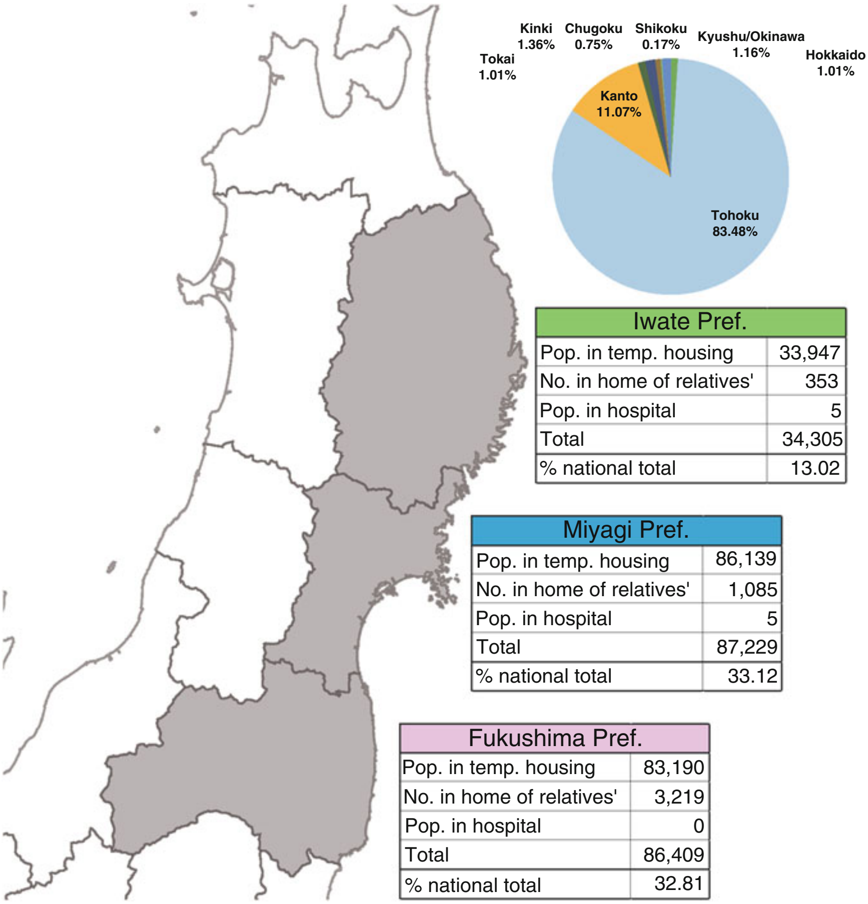

Fig. 3.1 Distribution of the displaced population (Source: Data from the national Reconstruction Agency on the number of displaced residents as of April 10, 2014) (Source: National Reconstruction Agency of Japan)

GEJE and the current status of their local implementation. Particular attention is given to considerations of risk reduction from future tsunamis as part of the recovery and rebuilding as well as the level of awareness of the need for both physical and non-physical approaches to future disaster mitigation.

3.2 Recovery Planning Policies and Programs to Reduce Future Tsunami Risk

There has been an array of planning processes, decisions, and implementation efforts in the first 3 years of recovery following the GEJE and when considered collectively roughly define 3 year-long phases in the rebuilding process (Fig. 3.2). The first phase, which lasted approximately a year after the disaster, was a time

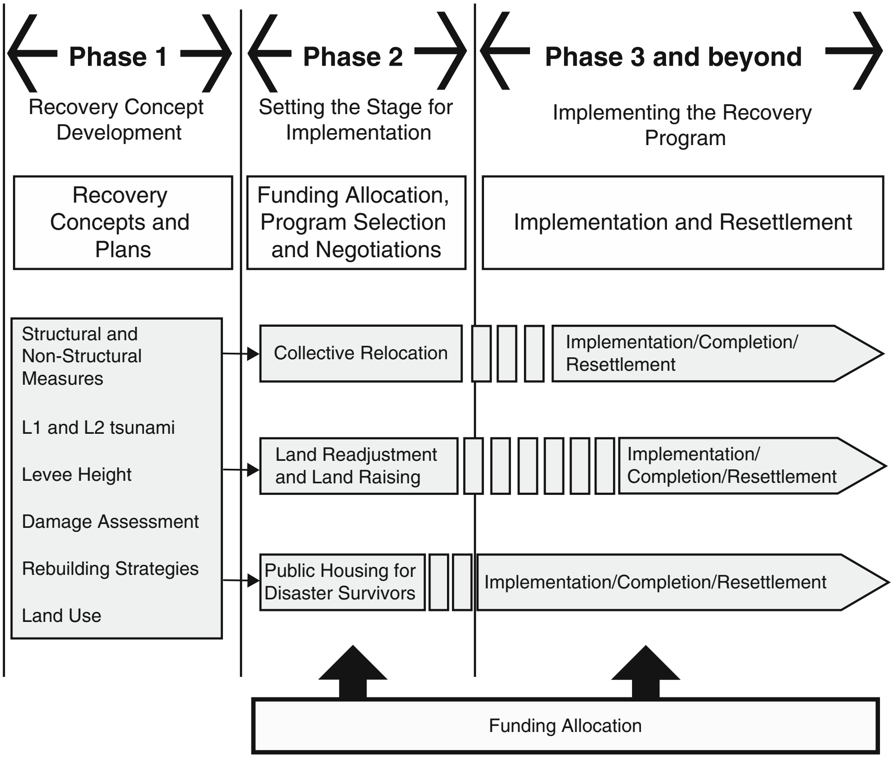

Fig. 3.2 Three rebuilding phases after the GEJE

when all levels of government, decision makers and scholars were developing rebuilding concepts, policies and strategies. In this stage, visions and plans for recovery that incorporate resilience against future tsunamis were created. At the same time, a national ministry carried out damage assessments in the affected areas in order to suggest rebuilding strategies that fit local conditions. The second phase, in the second year of recovery, was a time during which systems for implementing recovery and consensus on rebuilding approaches were publicly established. In this phase, the national Reconstruction Agency became operational, a system was established for local governments to request national funding, and details about the implementation of rebuilding became clearer. Finally, in the third phase in the third year, the majority of recovery programs were selected by the local governments, including collective relocation, land readjustment and raising, and public housing projects, and implementation of these have begun. Also in this phase, the reconstruction of coastal protection, including levees and breakwaters, have progressed considerably.

3.2.1 Recovery Phase One: Recovery Concept Development

In the first year after the GEJE, key decision makers and several government bodies devoted their energies to develop basic rebuilding concepts and strategies. At the national level, the Reconstruction Design Council was established a month after the earthquake to initiate recovery and craft a national recovery vision. Entitled "Toward Reconstruction: Hope beyond the Disaster (Reconstruction Design Council 2011)", the vision was published in June 2011 and included five core principles for the reconstruction as well as a series of basic strategies to rebuild safer from future tsunami risk. Then, a Tohoku-wide survey was carried out for 10 months, under the leadership of the Ministry of Land, Infrastructure, Transportation and Tourism (MLIT), to assess the overall damage and develop rebuilding strategies to fit local conditions. Tsunami simulations incorporating different potential designs for coastal protection infrastructure were also conducted as part of this survey, to define tsunami-vulnerable areas in each locality.

Later in this phase, affected prefectural and local governments developed and published initial recovery plans that closely mirrored the national recovery visions. The four prefectures of Aomori, Iwate, Miyagi, and Fukushima announced their plans in December, August, October and December 2011, respectively. At the same time, because prefectural governments are responsible for coastal management, levee and breakwater heights in each bay were also developed for use in local land use planning for rebuilding. The three most devastated prefectures of Iwate, Miyagi, and Fukushima announced these in September and October of 2011. Likewise, local governments prepared municipal recovery plans that included basic strategies and programs for rebuilding. The timing when plans were publicized varied by local government; some of the earlier plans were announced in the first 2 months after the GEJE, while others were developed gradually in the next 10 months. By the end of the first year after the tsunami, 59 local governments had their plans ready (Cabinet office 2012b); and that number continued to rise to a total of 81 in the second and third years.

3.2.1.1 Rebuilding Concepts

One of the key achievements in this phase was the development and refinement of rebuilding concepts that aim to make Tohoku's coast more resilient against tsunamis. The vision created by the national Reconstruction Design Council served as a foundation for this recovery concept, together with rebuilding plans based on future tsunami risk simulations and studies

Fundamental element of the Tohoku recovery plans: Combining structural and non-structural measures. The national recovery vision developed by the Reconstruction Design Council suggested that along with five other principles, prioritizing safety and resilience against disasters in rebuilding are critical (Reconstruction Design Council 2011). Concurrently, the Reconstruction Design Council (2011) emphasized the need for a combination of structural and non-structural measures to minimize future disaster impacts and the proactive adoption of an array of components, such as levees, sea walls, relocation to higher ground, well-considered land use and building code enforcement, for a sustainable recovery in the Tohoku region. To be specific, the Council presented five schematics of future land use patterns for future tsunami impact reduction, each reflecting different geographical and damage characteristics, with a mix of relocation, land raising, and levee strategies. The land use patterns were offered for consideration in areas where: (1) urban functions were totally destroyed in low elevation areas; (2) urban functions were partially destroyed in low elevation areas, but others had been saved in higher elevation areas; (3) urban functions are concentrated in flatlands and surrounded by hilly geography; (4) flatland areas along the coast; and (5) inland areas that were destroyed and experienced liquefaction.

Level one and two tsunami protection: Minimizing future tsunami damage. The concept of level one (L1) and level two (L2) tsunamis and the ways to protect inland assets and lives were also discussed and defined during this phase. First, the frequency of different magnitude tsunamis was differentiated between L1 and L2 by the Japan Society of Civil Engineers (2011) and MLIT. Based on historic tsunamis in the Tohoku region, a L1 tsunami was defined as an event occurring once every ten to one hundred years (or having less than a one percent annualized probability of occurrence), and an L2 tsunami was described as an event that happens once every several hundred to one thousand years (or having a greater than one percent annualized probability of occurrence). The tsunami caused by the GEJE was classified as a L2 tsunami since similar magnitude tsunamis had occurred with less frequency historically than the L1 tsunamis. A policy consensus also emerged that structural measures, i.e. levees, would be designed and built to defend and protect land and people against L1 tsunamis, while non-structural measures, mainly land use patterns and evacuation plans, would be implemented in addition to levee defenses to secure human lives against L2 tsunamis.

Prefectures are the government level responsible for coastal management and they had responsibility for deciding levee heights after the L1 and L2 concepts were developed. In the end, Iwate Prefecture established levee heights for rebuilding in 24 bays, Miyagi Prefecture in 22 bays, and Fukushima Prefecture in 14 bays (MLIT 2011). Mainly, L1 tsunami heights were used as the basis for the decisions, unless other historic storm surge heights were found to be higher than a L1 tsunami. Levee heights in many bays turned out to be higher than the heights of levees that existed prior to the GEJE. In some cases, the recommended levee heights were as high as 15.5 m in Iwate Prefecture and as low as 2.4 m in Fukushima Prefecture (MLIT 2011).

Land use policies for rebuilding. The Tohoku-wide damage assessment and land use survey led by MLIT targeted 62 disaster affected local governments in six prefectures and developed basic land use recommendations for rebuilding for 32 local coastal governments. National consultants were hired to support the local governments in developing land use plans that incorporated the L1 and L2 tsunami protection concepts, together with the spatial strategies envisioned in the national recovery vision. The work mainly proceeded in two steps. First, the national consultants ran tsunami simulations to identify potential inundation areas from L2 tsunamis. Then, the prefecture-designated levee heights were taken into account, and the potential inundation areas from tsunamis overtopping the proposed levees were also calculated. Second, with this result, a land use plan was developed for each local government to avoid rebuilding residential areas in possible inundation areas. Industrial and recreational uses, such as parks, were proposed instead for these areas. Thirty-two land use recommendations were then aggregated into five land use patterns, which are to: (1) relocate inland away from the tsunami inundation areas; (2) consolidate residential areas in nearby safer locations; (3) consolidate residential areas on artificially raised lands; (4) partially relocate residential areas inland and partially consolidate residential areas on raised lands; and (5) rebuild on site (MLIT 2012a).

3.2.1.2 Programs for Rebuilding

The national Reconstruction Agency developed a set of recovery programs ahead of the timeframe in which most local governments were making land-use-related decisions as part of local recovery planning. The key programs that addressed the physical rebuilding of local areas included the collective relocation program, the land readjustment and raising program, the public housing program and the special tsunami recovery zone program (Iuchi et al. 2013).

The *collective relocation program* was initially established in 1972 under the "Act on special measures for national finance regarding the collective relocation program for disaster prevention" and has traditionally been used to promote the relocation of disaster-prone communities prior to disasters (Mitsui 2007). In some post-disaster environments, including this one, the program has been used to relocate communities to less hazardous areas. In this case, it was used to relocate communities from areas defined as tsunami hazard zones to less hazardous areas. On a similar note, the *land readjustment and raising program*, is being used for areas where rebuilding occurs at the prior location, but the land is elevated to a higher level. The program originally was established in 1954 under the "Land Readjustment Act" and in principle has no relation to disasters. It aims to reallocate land parcels in certain areas for better and more efficient use and anticipates an increase in land values by investing in public facilities and public spaces (MLIT 2014). While the first two programs were available for use in the past few decades, the *special tsunami recovery zone program* was established specifically for this recovery process. This program funds redevelopment of the basic urban systems in devastated localities, if facilities that help reduce future tsunami impacts are also built there (Reconstruction Agency 2012c). This program also aims to reduce complex land use procedures by allowing urban development on agricultural land. Finally, the *public housing program for disaster victims*, originally established under the "Act on Public Housing" of 1951, was listed as one of the national recovery programs so that local governments could provide subsidized rental public housing for those disaster survivors without the financial capacity or ability to rebuild their own houses.

3.2.2 Recovery Phase Two: Setting the Stage for Implementation

In February 2012 – 11 months after the GEJE and tsunami disaster – the national Reconstruction Agency took over the responsibility of leading recovery as the successor to the Reconstruction Design Council. The Agency is authorized to operate for 10 years, and is primarily responsible for coordinating the recovery budget and reconstruction procedures among various national-level ministries that oversee different reconstruction projects (Reconstruction Agency 2012a). It also aims to serve as a focal agency in administering recovery activities so that the administrative procedures to implement the different reconstruction programs could be reduced for affected local governments.

The Reconstruction Agency supervises two types of reconstruction approaches used by local governments. The first type includes 40 selected programs that relate to basic infrastructure rebuilding and are monitored by five relevant national-level ministries. The collective relocation program, land readjustment and raising program, and public housing program for disaster victims are all included in this type (Reconstruction Agency 2012b). The second type allows local governments to apply to the Agency with different ideas that are related to the 40 defined programs (Cabinet office 2013). This type of approach was introduced in early 2013 as a response to criticism about the inflexible nature of the national recovery funds. Since then, local governments have been applying for and implementing this type of approach for projects such as evacuation route construction, rebuilding workshop activities, and any other programs necessary for the local areas. Local governments, however, need to bear 20 % of the total cost used for implementing projects through this approach. At the same time, the cost cannot exceed 35 % of the budgets allocated though the principal programs. The Reconstruction Agency also manages recovery funds for other types of programs, in collaboration with responsible ministries. Construction of levees and break waters are examples of these. In January 2013, the Reconstruction Agency estimated that project implementation in the first 5 years of recovery would cost about 23.5 trillion yen (US$ 235 billion). Based on this figure, the national government has committed about 25 trillion yen (US$ 250 billion) for rebuilding in the 5-year period (Reconstruction Agency 2013a).

During this phase, a system to apply and receive national recovery funds was also established. The procedure includes several exchanges among local governments, relevant ministries, and the Reconstruction Agency. Local governments submit applications to the Reconstruction Agency and to qualify for evaluation these applications need to include detailed designs and implementation plans for the targeted programs. The Reconstruction Agency facilitates the funding decisions and allocations with relevant ministries, and notifies local governments about the approval decisions and funding amounts. There are no limitations on the number of applications local governments can submit. So, the additional experiences, even if they are rejected, have helped local governments learn techniques for getting approval. The application window has been opened nine times so far, and the most funding was granted in 2012. Through this system, recovery funds totaling 581 billion yen (US$ 5.81 billion) as of August 2013 have been allocated to 92 local governments in 11 prefectures (Reconstruction Agency 2013b).

Intensive negotiations between local governments and communities also occurred during this phase of recovery. In communities aiming for *the collective relocation program*, details about the potential sites for relocation and participating members were carefully discussed and identified. Negotiations took place between local governments and land owners, including those who decided to sell their land to the government to be used for collective relocation sites and those participating in buyouts of their tsunami-inundated property. In communities adopting *land readjustment and raising programs*, local consensus on levee height and land use behind the levee had to be negotiated. Some localities made quick decisions either because of the existence of good decision making systems or because of a total lack of community involvement; whereas, some other localities have faced continuing difficulties in reaching consensus because of opposing interests. Lastly, plans for the *public housing program* have attempted to incorporate user needs in some areas. By the end of the second year after the GEJE, the majority of recovery programs were approved for implementation, including agreement on 100 % of collective relocation programs and authorization of 75 % of the land readjustment and raising programs. Also, with time, programs have been linked better spatially and in relation to the levees and other local considerations. There has also been more spatial planning that has included scenic preservation. For example, in some coastal communities, the concrete levees shown in the original plans have now turned into green recreational trails that can help unify neighboring communities and create a stronger sense of place for residents.

3.2.3 Recovery Phase Three: Implementing the Recovery Programs

By the spring of 2013, local governments were accelerating rebuilding projects with funds allocated by the national Reconstruction Agency. By this time, 23 % of all the collective relocation projects, 46 % of all the land readjustment and raising projects, and 41 % of all the public housing construction projects had broken ground (Reconstruction Agency 2013c). Implementation has been proceeding relatively quickly once these projects began construction. By the end of the third year in March 2014, 70–90 % of all the projects were under construction, and 15 % of the collective relocation projects and 10 % of the public housing projects were completed (Reconstruction Agency 2014b). Some community members who took part in collective relocation program are ready to build their new homes on the new sites, and many households have begun moving into public housing. The Reconstruction Agency (2014b) also reported that 68 % of the total planned levee reconstruction managed by the prefectural governments had begun construction by March 2014.

Nevertheless, the fundamental issue of balancing future tsunami risk and livelihood restoration persists. Levee reconstruction to defend land, assets and lives against a L1 tsunami extends for about 400 km along the Tohoku coast in 600 locations, and is estimated to cost one trillion yen (US$ 10 Billion) (NHK Special 2014). There have been delays in levee reconstruction in some communities, caused mainly by the lack of consensus and conflicting tensions between reducing future tsunami risk and sustaining livelihoods. On one hand, at the community level, some members are willing to accept the highest possible levees to avoid future tsunami risk. On the other hand, some members are demanding the lowest possible levee heights in order to maintain the seaside aesthetic and support related elements of community life, such as recreation, fishing, aquaculture, and maritime shipping.

Similar discussions are ongoing between governments and communities around levee heights, land use, and the type of programs to use. For example, in the northernmost city of Kesennumana in Miyagi Prefecture some communities prefer to secure livelihoods and environmental assets by lowering the prefecture's defined levee heights. However, the prefectural government is not proactively changing the levee heights that they previously adopted. Kesennuma City's younger generation have established several civic groups that work to more actively engage residents and others in discussions related to levee construction, land use, and community redevelopment. They are concerned about protecting the local culture, scenery, and life styles which they fear might disappear if all the government-led projects and programs are accepted and implemented. Having a new wave of activism is particularly notable for this city, as Kesennuma's younger population had been moving away to larger cities for the last several decades.

In other communities such as Natori City, located in southern Miyagi Prefecture, the city and community members have not yet established a consensus on whether to select the collective relocation or land readjustment/raising programs. While the City is in favor of rebuilding on site by raising the height of coastal lands, the majority of community members are hoping to relocate inland away from the ocean. Since the City wants one standard approach, either to relocate or rebuild on site, this dispute has not yet been solved.

3.3 Displacement and Resettlement

3.3.1 Housing Issues in the Recovery Phases Following the GEJE

Housing recovery after the GEJE is occurring in parallel with the development and implementation of the recovery programs described in previous sections and it is inextricably linked to the same decision making processes. The unprecedented and large scale nature of the recovery planning and tsunami risk reduction activities after the GEJE have required considerable time to develop new concepts, policies, and programs. On the other hand, there are well developed precedents in

Japan for the underlying policies related to post-disaster housing reconstruction even if the housing issues are also large and complex. Unlike planning related programs, the organization of government programs and funding processes for temporary housing were already established and it was possible to start the process for planning temporary housing almost immediately after the disaster. However, the final permanent housing reconstruction phase depends on land use planning and land preparation, and therefore is directly impacted by the time requirements and delays in recovery planning and implementation.

Mirroring housing recovery phases theorized by Quarantelli (1995), government support for housing recovery in Japan normally comes in three phases: (1) provision of shelters for immediate evacuation and occupancy, (2) provision of temporary housing, and (3) support for permanent reconstruction in the form of grants for housing damage, provision of land in relocation areas, and construction of public subsidized rental housing for survivors. According to the Act Concerning Support for Reconstructing Livelihood of Disaster Victims of 1998, depending on the level of damage, homeowners can receive up to three million yen (about U.S. $30,000) for houses damaged by a natural disaster. This policy was first created after the 1995 Kobe Earthquake when homeowners lacked rebuilding funds and it has been used in recent disasters such as the 2004 Niigata Chuetsu Earthquake. This support has been crucial to assist households in rebuilding.

After the GEJE, the evacuation shelter phase began immediately on March 11 and continued through the first year. The temporary housing phase started about a month after the disaster and has continued for the first 3 years and will continue at least a few more years in most impacted areas, and longer in Fukushima Prefecture. Because of limitations and complications of land availability, it took longer than hoped to erect all the temporary housing needed in the GEJE disaster area. To be more responsive to the situation, some policies were implemented at a large scale for the first time in Japan, such as the use of wooden temporary housing, and the use of private rental apartments as "designated" (*minashi*) temporary housing.

Many displaced residents continue to wait in temporary housing as land reconstruction negotiations and decisions continue and sites for permanent housing are constructed. Most permanent housing reconstruction, both private homes and government-constructed public housing, are being built in areas where new lots have to be created as part of recovery projects. For the collective relocation program, affected residents can sell their land in hazardous areas, and in turn, buy or rent new residential lots in higher elevation areas and rebuild private homes on the new lots prepared through the program. Residents participating in the land readjustment and raising program face a similar process to reconstruct their houses on raised land after new lots are prepared. Most of the more than 20,000 planned public housing units will also be built in new higher elevation areas. The first public housing units have already been completed. However, construction of public housing is planned to continue for 5 years, and in Fukushima Prefecture it will take longer. In many places, permanent housing reconstruction depends upon the completion of the land use planning and implementation of recovery projects. Early observation suggests that permanent housing reconstruction takes longer with relocation projects than for in-situ reconstruction.

3.3.2 The Provision of Temporary Housing

3.3.2.1 Japan's Approach to Temporary Housing

In Japan, temporary housing is funded by the national government, constructed by the prefectural government, and managed by local government. Local governments also select the beneficiaries. Most units are smaller than 30 square meters and intended for 2 years of use, although this can be extended. After the 1995 Kobe Earthquake, many people lived in temporary housing for 5 years. After the GEJE, the limit has already been extended several times, currently until March 2015; and in Fukushima Prefecture it has already been extended until March 2016. Since temporary housing is intended to provide for housing needs before permanent housing is rebuilt, the long time required for the large scale reconstruction in the Tohoku region means displaced residents will continue to live in temporary housing for a number of years to come.

Lessons from past temporary housing experiences after the 1995 Kobe and 2004 Niigata Chuetsu earthquakes. The temporary housing challenges following the 1995 Kobe Earthquake are well known. In Kobe, temporary housing was awarded using a lottery system with priority given to the elderly and other vulnerable residents. This intention to support vulnerable people is commendable, but caused a scattering of former communities and a separation of residents from pre-existing local support systems. Built on land available to Kobe City, much of the temporary housing was located some distance from former communities and inconvenient for school, work and daily life routines. Many of the younger, working age people and families chose not to move into temporary housing, which together with the priority system, resulted in a concentration of largely elderly and vulnerable people. One troubling phenomenon was 'solitary death', where disaster survivors withdrew from society entirely, and died without anyone noticing; it persisted even after residents moved into permanent public housing. Efforts were made to provide social services and address these issues in Kobe. Following the 2004 Niigata Chuetsu Earthquake which struck a rural mountainous area in Niigata Prefecture, local and regional governments made a concerted effort to keep residents together throughout the recovery process, from evacuation, temporary housing, and into the permanent reconstruction phase.

3.3.2.2 Temporary Housing Challenges in the Tohoku Region

Providing large numbers of temporary housing units after the GEJE has been a complex challenge spanning many municipalities and multiple prefectures, and occurring in the context of a vast area and scale of disaster damage and a limited availability of buildable land. Multiple governments involved at different levels and varied social and geographical contexts have resulted in a wide variety of temporary housing.

Before the GEJE, all 47 prefectures in Japan had pre-existing agreements with the Japanese Association of Prefabricated Builders (*prekyo)* to construct temporary housing following a natural disaster. Even with these agreements, it was difficult for the member companies to quickly provide all the temporary housing needed following the GEJE. In addition, among prefabrication companies, some were more familiar with residential construction than others, and levels of quality varied widely between different temporary housing in different areas.

Based on the lessons from the Kobe and Chuetsu earthquakes, attempts have been made to keep communities together and relocate them collectively to nearby temporary housing when possible. However, even when such attempts were made, they were not always successful due to time pressures and land constraints. As in Kobe, entry into temporary housing was often decided by lottery. Residents also made choices between time and selection. People who wanted to move into temporary housing more urgently might settle for less desirable locations.

3.3.2.3 Temporary Housing Innovations After the GEJE

Providing the temporary housing needed after the GEJE was a massive project carried out on a town by town basis throughout the disaster area. The large scale and complexity resulted in a wide variety of temporary housing outcomes. However, there were several improvements that emerged, including two specific programs used on a large scale for the first time after this disaster: the use of privately owned rental units known as "designated" temporary housing, and the use of wooden temporary housing. In addition, there were also improvements in the form of well-designed community spaces, and an example of multi-story temporary housing.

'Designated' temporary housing using private rental housing units. In the "designated" temporary housing system, the government pays rent for disaster survivors to live in privately owned rental apartments. Following the GEJE, this system was used on a large scale for the first time, and there are more people living in 'designated' temporary housing than newly built temporary housing (Reconstruction Agency 2014b). The introduction of the new system represents an innovation in the housing provision process. It may also be an improvement for the lives of displaced residents, as it uses existing housing stock, and can be more comfortable and more convenient for residents if they can find preferable locations. However, there are some challenges: the system makes keeping track of disaster survivors and insuring their access to government support and recovery information more difficult. It may also speed up depopulation of rural areas and movement of young people to cities as the system requires having some available vacant housing stock, which often is concentrated in urban areas. Since this is the first time it has been used on such a large scale, the final outcome and long term impact is not yet clear. However, in areas with available vacant housing, designated temporary housing appears to be an efficient use of resources, provides access to higher permanent quality housing, and allows residents to be in control of the choices that affect their housing recovery.

Wooden temporary housing. The use of timber to construct high quality temporary housing is another housing innovation. There are examples of wooden temporary housing in Iwate and Miyagi Prefectures, and the largest amount has been used in Fukushima Prefecture. Before the GEJE, Fukushima Prefecture already had an organization promoting the use of local timber materials. After the GEJE, Fukushima Prefecture took a proactive role in providing wooden temporary housing. After the prefab association stated they could only provide 10,000 of the 14,000 needed units, Fukushima Prefecture decided to build the remaining 4,000 units (later increased to 6,000 units) using timber construction. In Fukushima Prefecture, where residents will be displaced longer because of the radiation issues, wooden temporary housing also can provide a more comfortable living environment over the long-term.

Multi-story temporary housing in Onagawa. Three-story temporary housing made from shipping containers in Onagawa Town is another new type of project in Japan. Temporary housing regulations do not require single story construction, but it is the typical style because of the ease of construction and reduced cost. Although it is more expensive, multi-story temporary housing is one solution for limited land areas like much of the coastal areas in the Tohoku region. Most of Onagawa Town was inundated by the tsunami and many residents had to move to temporary housing in other towns. As residents from the multi-story container temporary housing move into recently completed public housing, vacancies in the container temporary housing are quickly filled by residents who have been living outside Onagawa and want to return.

Considering social aspects in planning for temporary housing. With the awareness to provide psycho-social care, design efforts to improve livability took place in many temporary housing settlements and included aspects of both physical design and social networks. Through design efforts, meeting and community spaces were built along with each temporary housing settlement based upon a minimum number of units. Additionally, many small scale design activities, including the addition of porches, outdoor benches and other furniture, were introduced to improve the living conditions in temporary housing settlements (Archi Aid 2014; Public Shelter 2014). With support from local governments, NGOs, or private foundations, various programs have provided on-site staff to check on residents and coordinate other social networking events and services at temporary housing settlements. Efforts have been made to reduce solitary deaths, and to address the special needs of vulnerable and elderly residents.

3.3.3 Displaced Population in the Third Recovery Phase

While various reconstruction projects are underway to complete the preparation of land for new housing in collective relocation and land raising areas, life in small and cramped temporary housing is uncomfortable for many displaced people. There have been almost 100 cases of solitary death among the elderly in temporary housing settlements after the GEJE, even with dedicated efforts to improve the quality of life and regularly check on residents (Yomiuri Shinbun 2014).

Communities are also facing disintegration. Over time, some residents are moving out of temporary housing settlements to rent or buy their own permanent housing. Other residents have left their former hometowns to live in temporary housing in other areas. Opportunities for former community residents to meet and discuss the future – of their town and also their own recovery choices – are increasingly rare. This scattering of residents will have long term impacts on the future of many towns, as well as residents' decisions to return and their ability to have a voice in future town planning.

The issue of community disintegration is also becoming very serious in Fukushima Prefecture. Whether they were ordered to evacuate from certain areas, or self-evacuated from other areas, many Fukushima residents who fled radiation contamination are likely to face a much longer displacement than those other disaster survivors whose homes were destroyed by the earthquake or tsunami. Currently, contaminated areas are separated into three zones based on their level of radiation and likely ability to be reoccupied at some point. They are: (1) Areas where evacuation orders are ready to be lifted; (2) Areas in which the residents are not permitted to live; and (3) Areas where it is expected that residents will have difficulties in returning for a long time (METI 2013). Even in the areas where the radiation measurements may be low enough to be officially designated as "safe" and the government eventually lifts the evacuation order, residents and especially families with young children may not chose to return. This creates an untenable future for these towns, and presents some difficult long-term challenges – both for those residents who chose to return and those who do not – in sustaining connections between residents, and also integrating residents into the new communities that are hosting long-term evacuees.

3.4 Discussion and Conclusion

The Great East Japan Earthquake and tsunami damaged a vast area and caused a complex series of disasters that continue to have cascading effects even today, more than 3 years later. Planning and implementing recovery and rebuilding of the impacted region has involved a massive amount of resources and sustained coordination and intervention. A multitude of recovery programs and related relocation projects are happening simultaneously and require multi-institutional collaboration and management by an array of institutions and agencies. Residents must also reach consensus on the proposed recovery plans and projects in order to help ensure their implementation. Thus, there are many stakeholders in the Tohoku region's recovery with a wide variety of recovery interests continually facing new challenges to build and sustain consensus on key decisions and implementation processes.

Several key insights have emerged from this review of the recovery and rebuilding activities following the GEJE. First, it takes a long time to develop the overall recovery concepts and build the necessary consensus and support to transform these concepts into actionable programs and projects, especially when the scale and complexity of the disaster and devastation are beyond the capacity of the existing recovery system. Almost the entire first year following the GEJE was spent developing recovery concepts, plans and policy directions that reflect local characteristics. A large portion of the second year was also spent negotiating with relevant local stakeholders, establishing the financial systems to fund the proposed recovery projects and programs, and gearing up for implementation. These time requirements were probably unavoidable given the disaster's complexity, the vast area affected, and the many different cultures and institutional arrangements that needed to be involved. Existing systems, programs, and plans simply could not manage such a large-scale recovery and rebuilding effort.

These challenges also likely resulted in a series of innovations that did not exist pre-disaster. For instance, ongoing negotiations between governmental institutions and communities in Kesennuma and Natori City have likely led to the creation of new citizens' organizations and also motivated residents to more carefully consider long-term risk and sustainability issues. In these and other communities, the return of younger community members has provided a renewed sense of optimism after decades of population loss and decline.

On a similar note, the recovery process has introduced more flexibility into the pre-existing housing recovery policies and programs. After the 1995 Kobe Earthquake, Japan's housing recovery policy was a "one-track" policy, providing a single option – pre-fabricated temporary housing – for the temporary housing phase and a single option of government-subsidized rental public housing for permanent housing recovery (Koshiyama 2011). Back then, those who did not follow this singular track received very little governmental support for housing. Following the GEJE and tsunami disaster, there have been a variety of temporary housing solutions including the "designated" temporary housing program and wooden temporary housing along with the more typical pre-fabricated temporary housing. Furthermore, public housing reconstruction after the GEJE includes various types, both single family detached housing as well as multi-family housing, and public housing built with wooden construction and local companies.

Also following the GEJE, the extended length of time necessary to assess damage, determine alternatives for managing future tsunami risk, and design and implement solutions has not always been an attractive situation for communities and residents anxious to recover and rebuild their lives. However, these time delays have also provided some windows of opportunity to rebuild better, at least spatially, in some local areas. Initially, all programs related to collective relocation, land adjustment and raising, as well as public housing, were laid out as individual programs without much consideration for linkages within the local context. With time, however, programs have been linked better spatially and in relation to the levees, scenic preservation, and other local considerations.

The GEJE and tsunami disaster has had a devastating impact on the Tohoku region of northeast Japan – a region already struggling with an aging and declining population and other economic issues before the disaster. Even while the recovery challenges endure and are certainly immense, there are signs that a stronger sense of community resilience, sustainability and viability is emerging at least in some communities as part of the reconstruction efforts.

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Chapter 4
Relocation After Tsunamis in the Sanriku Area and the Condition of Fishing Villages Two Years After the 2011 Great East Japan Tsunami

Anawat Suppasri, Mari Yasuda, Yoshi Abe, Yo Fukutani, Fumihiko Imamura, and Nobuo Shuto

Abstract The 2011 Great East Japan tsunami severely damaged or destroyed most of the fishing ports and facilities along the Sanriku coast. Reconstruction is ongoing, and a relocation plan has already been enacted. Interviews with fishermen in three fishing villages were performed to obtain reports on current situations as well as opinions and problems. For each village, information regarding reconstruction after historical tsunamis and the 2011 tsunami were obtained, and comparisons were made amongst the target villages. A land ownership problem was found in Tadakoshi village. Moving to high ground was proposed for the first time after the 2011 tsunami in Niranohama village. Housing relocation occurred in some parts of Tadakoshi and Yagawa after historical tsunamis in the Sanriku area, but the whole village will be relocated to high ground in the future, as lessons from the 2011 tsunami revealed that the tsunami inundation area was much larger. In general, all of the villages are still facing problems resulting from land subsidence where the ports are partly submerged during high tide. Although there are some small differences in detail, the three villagers have the same desire to move the entire community to high ground, making high seawalls unnecessary because there will be no more houses on the low land area. Some disagreement regarding the height of seawalls remains between coastal residents and local governments.

Keywords 2011 Great East Japan tsunami • Sanriku areas • Reconstruction • Fishing Villages

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4.1 Introduction

Sanriku is well known as one of the areas in Japan most frequently hit by tsunamis, having experienced two great local tsunamis in 1896 (Meiji-Sanriku) and 1933 (Showa-Sanriku) as well as the far-field tsunami from Chile in 1960. Figure 4.1 shows recorded historical tsunami heights (two events in 1896 and 1933) in the south of the Sanriku area of approximately 10 m or less (Suppasri et al. 2013). In contrast, the 2011 Great East Japan tsunami reached as high as 20 m and was higher than 10 m in most areas. Furthermore, the tsunami inundation area caused by the 2011 tsunami was particularly large compared to the impact from the tsunamis in 1896 and 1933. As a result, many areas were greatly damaged by the 2011 tsunami (Suppasri et al. 2013). Based on a study of the Government of Japan's Cabinet office (2011a), relocation was one countermeasure implemented after the 1896 tsunami, with seven of the 43 villages reported as having implemented group relocation. After the 1933 event, all 38 villages in Iwate prefecture relocated as a group, whereas 11 of 60 villages were reported to have relocated in Miyagi prefecture. In addition, land elevation was increased in one village after the 1960 Chile tsunami.

The objective of this chapter is to examine relocation efforts in the Sanriku area following the 2011 tsunami, including a comparison with the area's past experience. We focused on interviewing fishermen as aquaculture is the main productivity in these small villages. In addition, fishermen are more vulnerable to tsunami because they work at the sea and many of them are likely to drive their boats off shore to save their boats against tsunami. Based on contact availability and participation, interviews of 20 fishermen were conducted during June and July of 2013 in three target villages: Tadakoshi (Kesennuma city), Nirahohama (Minami-Sanriku town) and Yagawa (Ishinomaki city), as shown in Fig. 4.1.

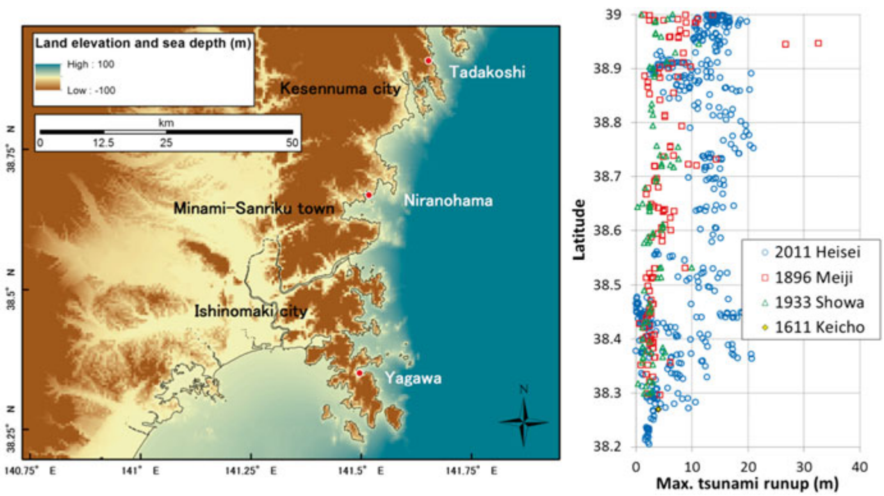

Fig. 4.1 Study areas in the southern Sanriku area and maximum tsunami runup heights

4.2 Relocation After Historical Tsunamis in the Sanriku Area

This section summarizes the adaptation of reconstruction for about a century of historical tsunamis that affected the Sanriku area—particularly the local tsunamis in 1896 and 1933. Table 4.1 is a summary of the experience of moving to high ground following historical tsunamis in the Sanriku area among the 2011 tsunami-affected areas (Cabinet office 2011b).

In the study, there were a total of 30 villages that had experience in relocation; five villages could not relocate due to limitations but performed a combination of other structural measures (seawalls and breakwaters) and non-structural measures (land use management and planning) instead. Among the 30 relocated villages, nine experienced no serious damage from the 2011 tsunami; four of these nine villages relocated once; and the remaining five villages relocated twice. Twenty-one villages were seriously damaged by the 2011 tsunami despite having relocated after past tsunamis. Fifteen of these villages had relocated once and the remaining six had relocated twice. The 1896 Meiji-Sanriku tsunami killed over 22,000 people and had a maximum tsunami run-up of 38.2 m (Yamashita 2008). As mentioned earlier, moving to high ground was the only countermeasure for this tsunami. However, some returned to low land for reasons summarized by Tanakadate and Yamaguchi (1938): (i) Beaches were too far for fishermen; (ii) Drinking water was insufficient on high ground; (iii) People were strongly attached to their ancestral lands; and (iv) Tsunamis were considered rare compared to other disasters.

Yamaguchi (1972) concluded that the tendency of moving back to lowland areas increased if the height difference between residence and beach was larger than 15 m and if the horizontal distance was longer than 400 m; the rate of return to low land after 10 years was especially remarkable. Another great tsunami occurred just 37 years after the great one in 1896. This time, the run-up was as high as 28.7 m, and the tsunami claimed approximately 3,000 lives (Yamashita 2008). Relocation to high ground was one option among other new countermeasures:

Table 4.1 Summary of relocation of villages affected by tsunamis in the Sanriku area

Past experience of moving to high ground	Villages that were affected by the 2011 tsunami		Number of villages that moved to high ground after historical tsunamis		
	Damage	Number of villages	1896 Meiji	1933 Showa	1960 Chile
Yes	No	9	5	9	0
	Yes	21	7	19	1
No	No	1	0	0	0[a]
	Yes	4	0[b]	0[c]	0

[a]Construction of 15.5 m tsunami gate
[b]Combination of construction of seawalls and land use management
[c]Combination of construction of seawalls, breakwaters and land use management

(i) Defensive structures, including coastal dikes and seawalls; (ii) Town planning, including relocation to high ground, buffer zones, control forests and evacuation routes; and (iii) Disaster prevention systems, including tsunami warnings, tsunami evacuation and memorial events.

4.3 Relocation and Recovery in the Study Areas

4.3.1 Tadakoshi Village, Kesennuma City

Area map of Tadakoshi village is shown in Fig. 4.2. A tsunami with a peak height of 8.3 m hit Tadakoshi village in 1896, causing 237 deaths and destroying 51 houses (Meiji University 2011). Although there was a plan for moving to high ground, the villagers instead only constructed evacuation routes because of the mountain's hard foundation rock (Cabinet office 2011b). A tsunami in 1933 with a peak height of 6.6 m reportedly resulted in ten deaths, 135 minor/moderately damaged houses and 39 majorly damaged or washed away houses (Meiji University 2011). After this event, 32 households were individually relocated. Relocated areas after the 1933 tsunami were outside the inundation limit of the 1933 tsunami. However, most of the areas were not far or high enough to avoid damage from the 16.3 m high 2011

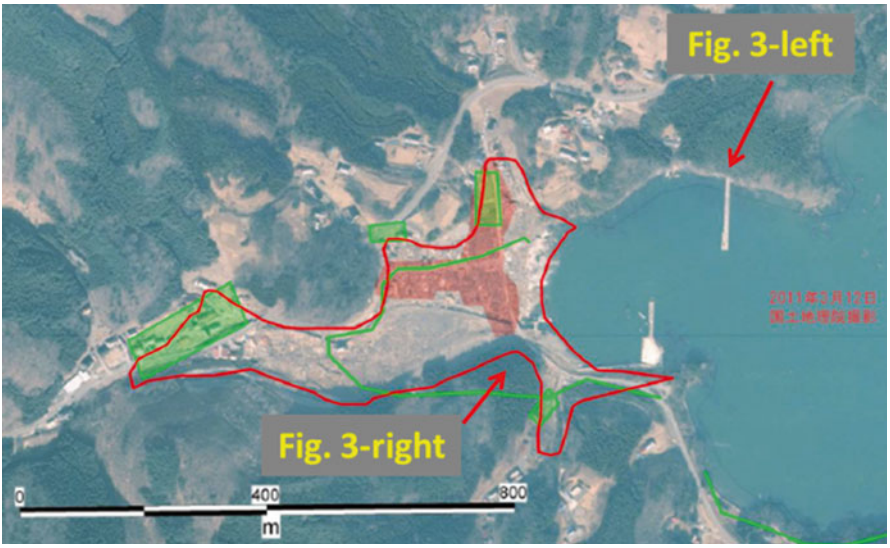

Fig. 4.2 Area map of Tadakoshi village (Cabinet office 2011b). The *green line* is the inundation limit of the 1933 tsunami. The *green box* is the relocation area after the 1933 tsunami. The *red line* is the inundation limit of the 2011 tsunami. The *red area* is the building damage area (Source: Cabinet Office, Government of Japan)

Fig. 4.3 Damaged seawalls and area for relocation in the mountain (*left*). Forests in the mountain that were cut for personal purposes (*right*)

tsunami. Two years after the 2011 tsunami, the village's port is still suffering because of land subsidence as a result of the port being submerged during high tide. Most fishermen still have to anchor their boats at other ports because the fishing port in Tadakoshi is not yet fully reconstructed.

Aquaculture activities of the port have recovered to some extent. For the view of village reconstruction, the villagers realized the level of devastation, and all residents agreed to move their homes to high ground. According to the current reconstruction plan, part of the mountain near the port will be cut and approximately 25 households will be moved by 2015 (Fig. 4.3-left). An example of a new adaptation following the 2011 tsunami in many villages of the Sanriku area is the posting of signs showing the elevation above sea level in many places. This information may help support an evacuation decision following a tsunami warning. There was one problem found in this area during the survey: a large numbers of trees in the forest were cut in a private mountain behind the village (Fig. 4.3 right) and the owner did not agree to see his land for the purpose of the high ground residents (Suppasri and Yasuda 2013). The removal of trees will lead to a high risk of landslides triggered by large earthquakes or heavy rainfall to the lowland area below.

4.3.2 Niranohama Village, Minami-Sanriku Town

According to the reconstruction plan of Minami-Sanriku town (2011), Niranohama village was hit by a tsunami with a peak height of 4.3 m in 1896 and one with a peak height of 2.4 m in 1933. Nevertheless, the tsunami height of the 2011 event reached as high as 12.2 m. According to the interview, there were eight deaths among the village population of 361, which can be interpreted as a 2.22 % fatality ratio (Suppasri 2013). This low ratio is likely due to a tsunami evacuation drill performed in the village just 4 months before the 2011 tsunami. The reconstruction plan of this

Fig. 4.4 Area map of Niranohama village (Miyagi Prefecture 2012). The *blue area* is the inundation area of the 2011 tsunami. The *red area* is the relocation area of both villages

village after the 2011 tsunami is to move as a group (20 households) to high ground, and the space is to be shared with another tsunami affected village (Yoriki village, 25 households) nearby (Fig. 4.4). A report by the Tohoku Regional Bureau (2013) mentioned that leaders of both villages did well in discussing the plan with each resident individually. As a result, everyone agreed to the reconstruction plan with no conflict. After 2 years, the reconstruction situation of the fishing port in this area is similar to Tadakoshi; Fig. 4.5-left shows some boats anchoring in the port in the background. One problem noticed during the survey involves the designated tsunami evacuation shelters. Two of the three shelters are located on high ground, as shown in Fig. 4.5-right. The shelters were effectively used during the 2011 tsunami event, but the evacuation routes leading to them were poorly maintained and may cause difficulty in evacuating for future events.

4.3.3 Yagawa Village, Ishinomaki City

Area map of Yagawa village is shown in Fig. 4.6. Although the maximum tsunami height of the 1896 event was only 2.5 m with one death and 17 destroyed houses reported, the maximum tsunami height of 3.95 m of the 1933 event killed 21 people

Fig. 4.5 *Left*: A fishing port is submerged during high tide, but some aquaculture activities were observed (*left*). View of evacuation shelters located behind the high ground from the fishing port (*right*) (Source: Cabinet Office, Government of Japan)

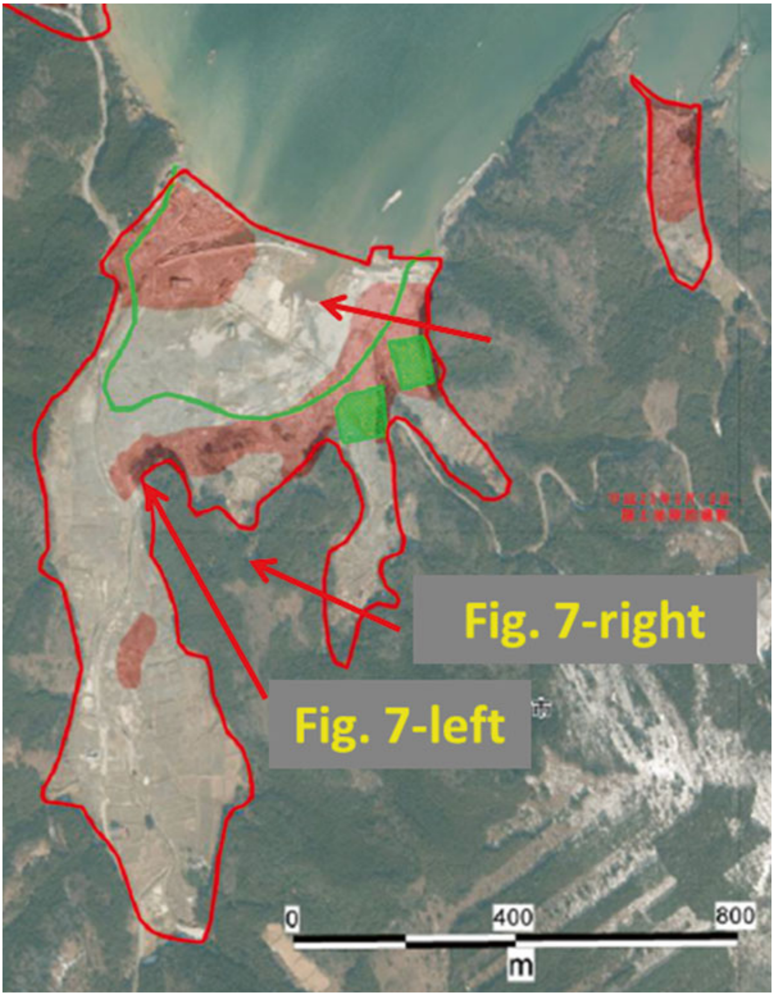

Fig. 4.6 Area map of Yagawa village (Cabinet office 2011b). The *green line* is the inundation limit of the 1933 tsunami. The *green box* is the relocation area after the 1933 tsunami. The *red line* is the inundation limit of the 2011 tsunami. The *red area* is the building damage area

Fig. 4.7 Tsunami memorial of the 1933 tsunami with warning messages (*left*). Relocation area on top of the mountain in Yagawa village (*right*)

and damaged or destroyed 165 houses (Meiji University 2011). Consequently, the relocation plan was implemented after the 1933 event. There were 19 households relocated as a group to two locations outside the 1933 tsunami inundation limit. The only house that survived the tsunami did so because the first floor of the house was higher than usual, as the house was built with wood taken from an unused fishing boat whose planks was longer than usual for house construction at that time.

Figure 4.7-left is a memorial rock plate of the 1933 tsunami in Yagawa village with three warning messages: (i) Be aware of a tsunami after occurrence of an earthquake; (ii) Go higher than this point if a tsunami comes; and (iii) Do not live in the tsunami danger zone. Despite these measures, the 2011 tsunami was much higher, measuring 18.5 m (Cabinet office 2011b), and the tsunami inundation area was extremely large. As a result, the 2011 tsunami claimed 8 lives from the population of 167, equal to a fatality ratio of 4.79 %—higher than that of Niranohama village. The damage also includes the only house that survived from the 1933 tsunami, which later became one of the relocated houses after the 1933 tsunami but finally washed away by the 2011 tsunami (Suppasri and Abe 2013). Unlike the two above examples, recovery of aquaculture activities in Yagawa is still slow after 2 years. The fishing port is deeply submerged even when the tide is not high as Yagawa is located closer to the earthquake epicenter. This village has a similar reconstruction plan to the others; its residents will move to high ground by excavating part of the mountain (Fig. 4.7-right).

4.4 Discussion

4.4.1 The Seawalls Controversy

There is one point to be mentioned here concerning moving to high ground: most villagers feel that it is not necessary to build a high seawall in their village because

Fig. 4.8 *Left*: View of the Millennium Hope Hills from the ground. *Right*: View of the Millennium Hope Hills from the top

there will be no more residences in the lower area. This is still a typical issue for most areas, and discussion between local governments and local residents are very important during the reconstruction process. However, Iwanuma city is an example of a city that successfully constructed a seawall. In fact, the city officially started a project in June 2013, called "Millennium Hope Hills" (Fig. 4.8-left). The project involves building 15 hills as seawalls approximately 8 m high around the city using tsunami debris as filler and various kinds of trees on the surface. Therefore, behind small concrete seawalls, there will be 8 m high nature-like embankments in front of the city (Fig. 4.8-right) (Iwanuma city 2013). Due to the landscape and the hills' added function as a tsunami memorial and recreational park during non-tsunami times, the project has garnered strong support from local residents and volunteers and often appears in the media. Such a successful project that clearly presents the city's consideration of the environment and landscape may be applied in other areas.

4.4.2 Comparison Among the Three Villages and Other Areas in Miyagi Prefecture

Although the three villages are similar in terms of their decision on relocating to high ground, there are some differences that can be mentioned in this section. There was no relocation record in Niranohama but according to the interviews, the relocation after the 2011 tsunami seems to be the first time. However, both Tadakoshi and Yagawa had experience in relocation after the 1933 tsunami. In addition, (MLIT 2012) mentioned that there was one house that relocated to high ground after the 1896 tsunami in Yagawa where the rest and the whole village of Tadakoshi did not. After the 2011 tsunami, Kawakura faced the land occupation problem as mentioned in the previous section but Niranohama could solve their relocation issue by the group relocation with another nearby village. According to the interview, fishermen in both Niranohama and Yagawa said that they will surely evacuate to high ground soon after they feel the shake as their lives are more important than their boats. On the other hand, in Karakuwa most fishermen told us that they insist to evacuate offshore with their boat in case of future tsunamis. The situation we learned from fishermen in Karakuwa is quite unique in comparison to other villages in Miyagi prefecture too.

4.4.3 Difference in Altitude and Distance of the Relocation Areas

From the examples introduced in the previous section, it is clear that all three villages had experienced large tsunamis due to their location along the Sanriku area. They also had experience in individual or group relocation that proved to be insufficient for the 2011 tsunami. Reports from past events also showed that the residents moved back to low land for various reasons and the villages suffered again following the 2011 tsunami. The 2011 tsunami was the event that led the villagers to agree to move the entire residential area to high ground for the first time. Figure 4.9 shows the average differences in distance and altitude of relocating to high ground after the 1933 Showa-Sanriku tsunami as reported by Yamaguchi (1972). This distribution is consistent with the study by Tanakadate and Yamaguchi (1938) in that most of the data are clustered around a distance shorter than 400 m and altitude lower than 15 m. Data from the three villages affected by the 2011 tsunami interviewed in this study were added to the same figure. It is clear that all villages have planned to move to areas where the altitude difference is higher than 30 m and the distance is longer than 400 m; such relocation to ensure that all villages will be safe from future tsunamis because their destination point will be 40–50 m higher than sea level.

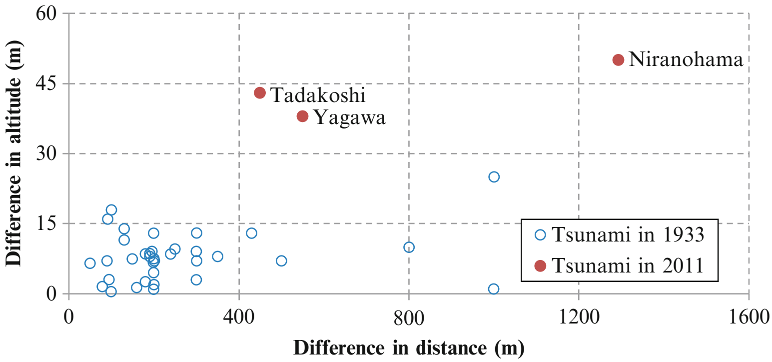

Fig. 4.9 Comparison of the difference in distance and difference in altitude between moving to high ground after the 1933 Showa-Sanriku and after the 2011 Great East Japan tsunami

4.5 Conclusions

From our interviews and field visit, we found that land subsidence was the most common problem even almost 3 years after the 2011 tsunami. For locations where aquaculture is the main productivity, the land subsidence problem especially in fishing ports should be solved as soon as possible. Nature-like embankments that can serve as recreation park may be adapted in some areas but they require more space. However, this might help preventing villagers to move back to low land and build their houses again. Villagers in three areas have the same future plan because they decided to relocate high ground. Nevertheless, some small differences were observed according to their respective historical tsunami experiences, geographical setting and local problems. Relocation to high ground will definitely affect the evacuation culture of some fishermen who still prefer to save their boats from tsunamis because they should perform the evacuation faster. This action will be more difficult and risky for future tsunamis. Although for other areas, most of the fishermen who generally prefer to live near the sea, the 2011 event was so large that they must consider the most important aspect—their lives—rather than convenience. Maintaining their awareness and transmitting this experience to future generations so that they will not move back to low land will be one of the biggest challenges.

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Chapter 5
Lessons Learned from Two Villages in the Tsunami Most Affected Area of Banda Aceh City; A Review of the Housing Reconstruction and the Current State of Village Development

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Abstract This paper discusses two approaches to post-disaster housing reconstruction in Banda Aceh, the Indonesian area that was the most affected by the Indian Ocean Tsunami in 2004. The two villages discussed in this study are Alue Deah Tengoh and Lambung, both located in Meuraxa sub-district. The village of Alue Deah Tengoh represents the common approach to post-disaster reconstruction within in Aceh with the construction of housing carried out by several external benefactors. It is referred to as the donor driven approach. In contrast, the reconstruction of the village of Lambung was based on its community's involvement. Contrasting these two approaches, this study analyzes time series satellite images, housing and other reconstruction archives. It also conducted site evaluation and depth interview with their leaders in order to evaluate the conditions of each village prior to tsunami as well as its current state of development. Our aim is to unravel the process of housing reconstruction in these respective locations village. Drawing from this analysis, our results evaluate these two distinct approaches to housing reconstruction in post-disaster Aceh. On the one hand, it reveals that the community-based approach

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adopted in Lambung enabled the successful use of land consolidation (LC) and the total makeover of village layout and housing plot arrangement. On the other hand, our study reveals that the donor approach in Alue Deah Tengoh resulted in a heterogeneous landscape with several types of houses contributing to social inequality and disparity. Moreover, the reconstruction of Alue Deah Tengoh did not include LC and kept the village old layout with its meandering narrow streets and poor accessibility. These features are bond to hinder the upgrading and maintenance of urban utility services as well as the evacuation process during future disasters. In the light of this study, we thus recommend that community driven approach should be implemented in post-disaster reconstruction programs.

Keywords Housing reconstruction • Housing provision approach • Land consolidation • Post-disaster village development

5.1 Introduction

5.1.1 Background

The Indian Ocean tsunami of 26 December 2004 damaged almost the entire coast of Aceh Province and its most affluent cities, Banda Aceh and Meulaboh. This event is one of the largest tsunamis recorded on the coasts of Indian Ocean and the Bay of Bengal (Liew et al. 2010). The tsunami inundation in Banda Aceh reached as far as 5 km inland (Prasetya et al. 2011; Paris et al. 2007), taking some 120,000 lives within Banda Aceh. It was assumed that around 88,000 housing units in Aceh had to be replaced, and some 71,000 units needed to be rehabilitated. It also became evident that the residential infrastructure (water, sanitation, roads, electricity, etc.) as well as social facilities, had been affected and that the overall infrastructure of Aceh's coastal villages and settlements required substantial investment for their reconstruction (Steinberg 2007).

Post disaster development in Banda Aceh was initially conducted by the central government and the Indonesian army. Due to their limited capacity and resources, they soon conceded their leadership to international and national NGOs with regards to vital aid, rehabilitation and housing reconstruction. In May 2005, the Indonesian government established Rehabilitation and Reconstruction Agency (BRR). It mandated the BRR to implement rehabilitation and reconstruction programs as well as coordinate the effort of donors and international agencies. However, the overload of responsibilities onto the BRR furthered the lack of coordination and engendered greater confusion among bilateral, multilateral agencies and NGOs. Due to the absence of central administration, the BRR practically gave a free hand to all NGOs (Steinberg 2007) leading to an eclectic post disaster development in Aceh.

The two main strategies towards reconstruction were the donor-driven and the community-driven approaches. The donor-driven reconstruction pursued contractor-built implementation for housing reconstruction (Chang et al. 2011) while the community-driven approach consisted in the empowering and participatory of local people. In the latter, communities have come together to determine their needs and priorities, choose its leadership for the recovery, acquire labor and construction materials, and supervise the reconstruction process (Chang et al. 2011; Steinberg 2007).

In this paper, we discuss and contrast these two approaches in two specific villages, which we believe represent best the two general trends that took place during the reconstruction of Banda Aceh City. These two villages are Alue Deah Tengoh and Lambung both located in Meuraxa sub-district. Alue Deah Tengoh constitutes the common approach to reconstruction where the provision of housing was based on the initiative of several donors. This donor-driven approach was implemented due to the low number of survivors that returned to the village after the disaster and yet needed housing. In contrast, the reconstruction program in Lambung extensively involved the community. This process was initiated before discussions took place between donors and community leaders. The aim of the study is to find out what resulted from these two approaches and evaluate the current state of development of each village.

5.2 Study Area and Method

5.2.1 Study Area

The study was located in Meuraxa, a sub-district of Banda Aceh city (Fig. 5.1). This area was selected because it was heavily damaged by tsunami 2004 and is often labeled as "the ground zero area of tsunami 2004". Since it is located in the strategic part of the city, many recovery efforts started with emergency operations followed by the re-initiation of medium and long-term development plans. This area epitomizes the coordinated efforts that took place in the context of post disaster Aceh and makes it a valuable source of data for the evaluation of the reconstruction process. It is also where many lessons learned for future environmental recovery.

5.2.2 Method

This research analyses time series satellite images, reviewed housing and other reconstruction archives, conducted questionnaire survey for residents (45 household respondents in Lambung and 62 respondents in Alue Deah Tengoh representing about 15 % of house owners) and interviews with key village informants revealing the village situation prior to tsunami and its current state of development. For the satellite images, we used three sets of *Quickbird* images taken on 23 June 2004, 28 December 2004 and *Worldview* images 2 March 2011. The pre-tsunami situation studied from the *Quickbird* images of 23 June 2004 and 28 December

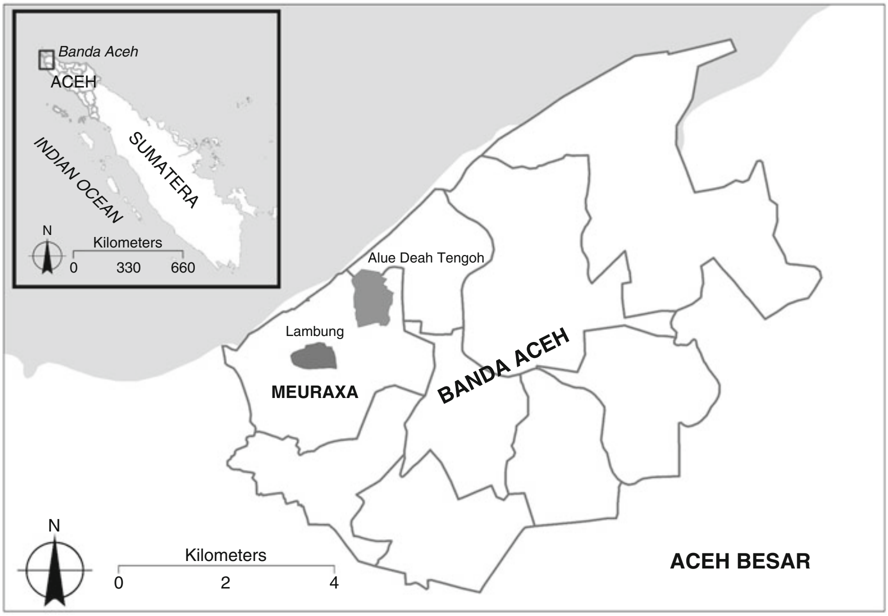

Fig. 5.1 Location of study, Lambung and Alue Deah Tengoh villages (shaded), Meuraxa sub-district of Banda Aceh city

2004 recorded effects of the tsunami; and the image 2011 revealed the current state condition (The pre-tsunami and post-tsunami images were accessed from the archives of the GIS and Remote Sensing Development Center, Syiah Kuala University with courtesy from ReGID Laboratory IRIDeS, Tohoku University and BAPPEDA Banda Aceh city).

5.3 Results and Discussions

The results indicate the value of these two distinct approaches to housing reconstruction in post-disaster Aceh in terms of the type of houses built, the village layouts and the villages' current levels of development.

5.3.1 Housing Reconstruction Approach

The provision of housing for the survivors of the tsunami was the main task of the reconstruction program led by Badan Rehabilitasi dan Rekonstruksi (BRR), which attempted to coordinate 463 organizations (Masyrafah and McKeon 2008). Housing type as defined by the BRR had to be of a minimum size of 36 square meters. The sheer number of organizations conducting the reconstruction and the lack of basic standards resulted in a myriad of designs and structures (White 2009). Lubkowski et al. (2009) divided housing types in Aceh into three main categories, namely: "permanent" houses, which are built from brick and often with reinforced concrete frames, "semi-permanent" houses, which made of brick and timber, and "traditional" houses with timber structures. In Aceh, most houses or "core" house are of a minimum size of 36 square meters. In addition, they frequently have veranda and/or kitchen extensions increasing the inhabitable space to 48 square meters. Most people in Aceh lived in "permanent" houses prior to the tsunami, many of which were larger than those being provided after the disaster. In the case of Alue Deah Tengoh and Lambung villages, we found only two types of housing, permanent and semi permanent.

5.3.1.1 Lambung Village

Villagers of Lambung have rebuilt their community with the support of the Multi Donor Fund (MDF). Two of the MDF's Community Recovery programs, the Community-based Settlement Rehabilitation and Reconstruction Program (CSRRP, Indonesian acronym Rekompak) and the Kecamatan Development Program (KDP), financed a community-driven process through which the villagers of Lambung designed their houses and community infrastructure. The CSRRP program provided led to a community-driven approach (MDF 2011). As part of this scheme, the village was subject to land consolidation before the construction of new houses. Land consolidation consisted in a planned readjustment and rearrangement of land parcels and their ownership. Such strategy is usually carried out in order to form larger and more rational land holdings. Land consolidation was also used to improve the rural infrastructure and to implement regional developmental and environmental policies (Pasakarnis and Maliene 2010).

The reorganization of the village layout was initiated through discussions between the donor representatives and the head of the community. Our interviews suggest that during the process of land consolidation many problems aroused among landowners, especially those whose land was divided for the widening and construction of new roads. The implementation of the new layout occupies between 10 and 15 % of the communal land. During the negotiation process, village leaders have conducted (1) regular meeting with the people of their community; (2) invited facilitators to explain and convince villagers of the importance of rearrangement of village with land consolidation; (3) engaged with individuals who refused the concept of land consolidation; and (4) met intensively with the stakeholders related to the activities of land consolidation. Finally, after almost 2 years of extensive discussions and public assembles, everyone finally agreed upon the new planning. In other words, the leadership of village leaders played a critical role in making people endorse the new concept of Lambung including the total change of the village's layout and its housing plot arrangement (Fig. 5.2). Despite their relative success, we found that the present plot could better accommodate urban utility services as well as disaster mitigation plan.

Fig. 5.2 Lambung Village, latest development on 2 March 2011 (Source: Worldview image (BAPPEDA Banda Aceh city))

The Lambung housing reconstruction project started at the beginning of 2005 and finished by the end of 2007. All of the houses provided by MDF in Lambung were of the 36 square meters permanent type with additional terrace (Fig. 5.3). This project helped the villagers to rebuild their houses and revamp the drainage system and public washing areas. During project implementation, the beneficiaries worked hard to plan and carry out the construction works themselves. In this community-driven approach, the villagers worked in groups and everyone was involved at every step of the process, attributing their success to hard work and cooperation (MDF 2011).

A better layout of its streets and houses, the development of its road network and a new drainage system made Lambung village one of the pilot villages for Aceh's reconstruction. The MDF through the BRR later supported a 70 billion IDR (about 7.7 millions USD) to develop 42 roadblocks in the village with a sewer system, a telephone network, and public and social facilities. These roads measured between 6 and 15 m wide (Mahdi 2007). Following the land consolidation, 297 houses were built by the MDF under the Rekompak project, thus equating the number of houses existing prior the tsunami. Both the local government of Banda Aceh and the BRR celebrated Lambung's successful redevelopment making it an icon for Aceh's reconstruction.

Fig. 5.3 Permanent house built by MDF in the village of Lambung

Table 5.1 Donor support houses in Alue Deah Tengoh

Donor name	Type of house	Number of houses
Oxfam	Permanent house with tile floor, including kitchen, terrace, bath room inside	81
Yayasan Berkati Indonesia (YBI)	Semi-permanent, half concrete brick and half wood, non-tile floor, bath room out side, terrace	119
Caritas	Permanent house with kitchen, terrace, non-tile floor, bath room inside	50
BRR	Permanent houses with kitchen, terrace, non-tile floor, bath inside	159
Total		409

5.3.1.2 Alue Deah Tengoh Village

The approach found in the village of Alue Deah Tengoh was radically different. The housing reconstruction was realized by several donors, namely Oxfam, YBI, Caritas and BRR (Table 5.1). This program resulted in several types of houses with different design and level of quality (Fig. 5.4). Such a donor-driven approach was commonly found in Aceh reconstruction program.

Following the tsunami, the survivors of Alue Deah Tengoh initially found shelter in the IDP camps located in the villages of Panteriek and Tanjong. A month following the tsunami, some started to return to the village in order to clean it from the debris and build new barracks. However, their precarious and harsh living conditions required new houses to be built as promptly as possible. To this effect, donors came

Fig. 5.4 Different type of houses built by different donors resulting different design and quality at Alue Deah Tengoh (**a**) "Permanent house" built by BRR (**b**) "Permanent house" built by Caritas (**c**) "Semi permanent house" built by YBI (**d**) "Permanent house" built by Oxfam

to villages and offered their support in order to build new houses. With a single donors being unable to assume the reconstructions of the entire village, each organization was responsible to rebuild a certain number of houses while being supervised by the local government and the BRR.

The physical construction was carried out by contractors directly appointed by the donors. The members of the community were not consulted by the donors and could only 'monitor' the building of their houses on a voluntary basis. The beneficiaries of this new housing who were not staying in the village could not monitor the construction process of their houses at all.

The YBI, one of the donors, built almost 30 % of the new houses using the local contractor. The 119 houses erected were of the semi-permanent type with half of the houses made of wood.

The result of the questionnaire-based survey and other interviews suggest that almost all of the inhabitants who received semi-permanent houses from YBI were unsatisfied (the questionnaire surveyed 10 % of total YBI beneficiaries). They felt that their condition was unfair when compared with that of those people who received permanent houses built by other donors within the same village.

Another example is Oxfam building 81 semi-permanent houses made of mix concrete brick and wood materials, later to be remodeled into permanent structures. During the reconstruction process, Oxfam faced difficulties in getting supplies of

Fig. 5.5 Alue Deah Tengoh Village, the latest development of the village taken on 2 March 2011 (Source: Worldview images (BAPPEDA Banda Aceh city))

wood and saw the construction of its houses delayed extensively. This situation made some of Oxfam housing beneficiaries become disillusioned until all semi-permanent houses were finally completed in 2005. Later, the beneficiaries of Oxfam' houses felt at a loss in comparison to their neighbors got permanent houses provided by other donors, i.e. BRR and Caritas. Those beneficiaries then tried to negotiate their upgrading to permanent houses with Oxfam. After many discussions Oxfam agreed to replace all semi-permanent houses with permanent houses (Fig. 5.4d). The modifications and entire project were completed at the end of 2007.

This kind of approach without conducting LC prior housing reconstruction had the benefit of providing new house more speedily than other community-based reconstruction programs. In the long-term, however it also resulted in social inequalities as different types and quality of houses emerged randomly within the old layout of the village (Fig. 5.5).

5.3.2 Pre and Post Tsunami Development Situations in Alue Deah Tengoh and Lambung

A summary of the different situations pre and post tsunami conditions is given in Table 5.2

Table 5.2 Comparative profile between Alue deah Tengoh and Lambung villages. Pre and post tsunami situation

Description	Alue Deah Tengoh	Lambung
Location from the coast line	700 m	800 m
Village surface area	60 Ha	52 Ha
Public infrastructure	Mosque, schools, Escape building, health clinic	Mosque, schools, Escape building, health center
Population before tsunami	1,492	1,780
Occupation	Fishermen, civil servant, traders, businessmen, policeman, teachers, etc.	Fishermen, civil servant, traders, businessmen, teachers, etc.
Population after tsunami Jan 2005	410	440
Population as of Dec 2012	1,161	592
Current Population composition	1,161 people with mix of native and new comers	592 people with 90 % are native inhabitants
Damage by tsunami 2004	Totally damage, 100 % building damaged	Totally damage, 100 % building damaged
Number of houses constructed	409	297
Housing provider	Oxfam, YBI, Caritas, BRR	MDF
Type of houses	Mix permanent and semi-permanent	Permanent
Housing reconstruction approach	Donor-driven	Community-driven
Applying land consolidation prior housing reconstruction	Without Land Consolidation	With land consolidation
Degree of satisfaction	Permanent (67 % satisfy, 33 % unsatisfied)	82 % satisfy
	Semi-permanent (100 % unsatisfied)	18 % unsatisfied
Village layout and road condition	Old village layout with some narrow and winding road	New village layout with straight and wide road

Although they both share similarities in term of distance from the coastline, surface area, initial population, occupation, basic infrastructure while equal damage caused by the tsunami, 8 years after tsunami various changes and development have been observed in these two villages as seen in Table 5.2.

Its important to note that none of the two villages have regained its initial population and that housing located closer to downtown area was less affected by the tsunami attracting a higher number of returnees.

Based on field survey and interview with village leaders and both native and new comers, it was found that the population of Alue Deah Tengoh increased more rapidly than Lambung's. The new inhabitants of Alue Deah Tengoh are not originally from the area but new comers who either rent the newly built houses or bought lands and properties (JICA 2012). The price of land and properties was significantly reduced after the disaster due to people's fear in living within an area prone to tsunamis. After the reconstruction program had been implemented and the redevelopment

Fig. 5.6 *1–3* Lambung Village. (1) Pre-tsunami condition (23 June 2004); (2) Destruction after the tsunami (28 December 2004) and (3) Redevelopment (2 March 2011) (Source: Quickbird and Worldview images (BAPPEDA Banda Aceh city))

completed, however, the value of the land increase gradually. In average, the price of the land in Alue Deah Tengoh is cheaper than Lambung's; yet the successful implementation of LC in Lambung made the new village layout with straight and wide roads more attractive and increased the value of its land. The new layout can be identified from the satellite image of 2011 as shown in Figs. 5.6 *1–3* and 5.2.

Some 90 % of people in Lambung are native of the village. The others have become members of the village through marriage, not merely by moving into it. Most villagers are related to one another through family ties, fitting the traditional concept of kinship in Aceh known as "*kawom*". Among other social traits, this filial custom has always constituted the strength of community and formed strong social ties among villagers (Mahdi 2007). Eight years after the disaster, the Government and the local community have worked closely together to restore the village's main facilities, such as its mosque, health center, and schools.

The village of Alue Deah Tengoh where the LC was not adopted and several types of houses were built, had its the old layout with meandering narrow street and poor accessibility kept (Fig. 5.7 *4–6*). However the community now faces great challenges in order to upgrade and maintain utility services as well as planning disaster evacuation.

Meuraxa sub-district lost over 50 % of its total vegetation cover as a whole and in many villages the loss reached 100 %. After 8 years of reconstruction vegetation cover in Lambung and Alue Deah Tengoh has regrowth. Percentages of tree coverage towards area size reported by Agustina et al. (2012) were 27 % in Lambung and 5 % in Alue Deah Tengoh. The percentage of tree coverage in Alue Deah Tengoh is smaller because about 30 % of the village is water bodies, such as fish pond, river and lagoon.

5.3.3 Community Satisfaction on Housing Reconstruction

People living in Lambung and Alue Deah Tengoh villages expressed different level of satisfaction with regards to their new housing. Based on our survey in Lambung, about 83 % of house owners are satisfied with the house provided by MDF. In contrast, only 17 % responded that they were not satisfied essentially because of the provision of relatively small kitchens and bathrooms.

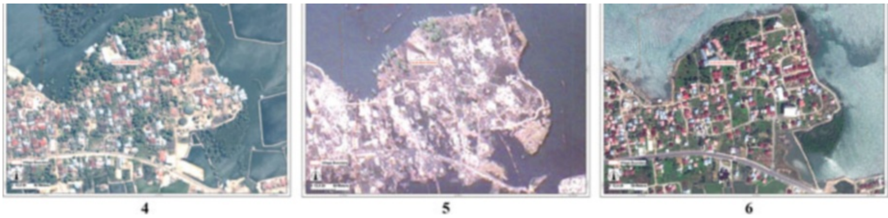

Fig. 5.7 *4–6* Alue Deah Tengoh Village. (4) Pre-tsunami condition (23 June 2004); (5) Destruction after the tsunami (28 December 2004); (6) Redevelopment (2 March 2011) (Source: Quickbird and Worldview images (BAPPEDA Banda Aceh city))

Table 5.3 Beneficiaries comparative satisfaction percentage by provider and housing type in Alue Deah Tengoh

		Response of respondent (%)	
Provider	House type	Satisfy	Unsatisfied
Oxfam	Permanent house	75	25
YBI	Semi-permanent house	0	100
Caritas	Permanent house	63	37
BRR	Permanent house	63	37

In contradiction with Lambung, overall more house owners in Alue Deah Tengoh village were discontent with their new living conditions provided by the donors (Table 5.3). People who received semi-permanent houses by YBI shown to have the highest unsatisfied percentage with the facilities of their houses.

The current situation is likely to be due to lack of uniformity in the housing as provided by the donors. Moreover, about 33 % of permanent houses' beneficiaries are also not happy with their houses due to the characteristics of the floor, the reduced size of their kitchen and the poor quality of wood materials.

5.4 Conclusions

The different approaches have resulted in different of houses and state of village development with varied results. Lambung village successfully conducted LC and resulted in a total change of village layout and the arrangement of its housing plots. The latter could better accommodate urban utility services. While in Alue Deah Tengoh where LC was not adopted and several types of houses, the village traditional layout with meandering narrow streets and poor accessibility was left unchanged. This lack of improvement hinders the maintenance and improvement of the village's utility services and will certainly cause problems during evacuation process should another tsunami take place. The downside of LC was the time it needed to be completed amid the pressing need to build houses as fast as possible after disaster.

The difference type and quality of houses causes resulted in different level of satisfaction by the beneficiaries in the disaster-affected villages, bringing in mix feelings and unhappiness in an important percentage of the population. On the other hand, it is important to highlight the successful achievement and critical role by the community leaders during reconstruction and planning process in Lambung as they were able to bring together different opinions, discuss and reach an agreement between the affected community and the stakeholders resulting in making the people to endorse the total change of the village's layout and its housing plot arrangement.

The present research has shown that depending on the approach taken the reconstruction, planning and housing process results in the two study villages largely differ with mixed results. It is important to highlight that this study has only analyzed one example of the housing and development strategy in two villages of Banda Aceh, therefore its findings cannot be generalized or be applied to other situations. Moreover, further research must be carried out in consultation with post-disaster communities in the studied villages as well as in others to better ascertain the results of the post tsunami reconstruction process in this devastated city.

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Chapter 6
Accomplishments in the South Coastal Thai Communities After the 2004 Tsunami in the Restoration Process, A Case Study in Ranong Province

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Abstract The 2004 tsunami caused by the great Sumatra earthquake devastated a large amount of the local communities along the coastline of the Andaman Sea in the southern Thailand. Since then most communities have been gradually recovered from this disaster through various restoration processes. This chapter presents a case study of the post-disaster recovery processes for two small local villages: the Nua and the Hat Sai Khao villages in Suk Samran district, Ranong province, compared with those of the government organizations, the Kasetsart University's Andaman Coastal Research Station for Development that was also hit hard by this tragic incident. The recovery process of these two small villages can be used as proxies for many small local communities in the southern Thailand about how they have adapted themselves to restore their communities back to their normal stages and eventually to have a sustainable immunity to this natural hazard. The tsunami impacts and detailed restoration and reconstruction processes of these two villages are discussed from the day the disaster occurred until recently. It can be concluded that for small local communities, the external supports, either from central government or the private sectors, are as important as the wills of the residents to support themselves. Without the external help, it is extremely difficult for such small local communities in Thailand to get back on their feet within a short time. In addition, the large amount of the funding support must be distributed to the affected communities within a

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short time in order to provide effective recovery processes. It can be seen for this specific case study that the continuation of the long term support to the affected communities and the participation of the victims in the restoration and reconstruction processes are also very important in order to help the victims restore their lives and to avoid any social problems that may occur in the affected communities in the future.

Keywords Tsunami • Restoration process • Coastal communities • Ranong • Thailand

6.1 Introduction

The tsunami occurred from the M_w 9.15 Sumatra earthquake (Chlieh et al. 2007) on December 26th, 2004 caused widespread damages along the coastlines of Thailand at different degrees, from minor damages to completely devastation with estimated casualties of over 5,000 s and the economic loss between 50,000 s and 60,000 s million baht (i.e. DDPM 2005; Kittiampon 2005 and The Center for Economic and Business Forecasting of the University of the Thai Chamber of Commerce 2005). Since then, most communities have been gradually recovered from this disaster through various restoration processes. In Ranong province, the tsunami affected 45 local villages (a community that is considered the official smallest administrative division of Thailand) in four districts and killed 161 people that included both residents and tourists (Navachinda 2005 and MCOT 2013).

After the tsunami, various studies have been done in many aspects regarding the effects of the tsunami and some restoration processes and tsunami hazard managements in Thailand. Unfortunately most of these studies concentrated on the landmark areas or famous tourist locations that were easy to gain access and were internationally well known to the world (i.e. Choowong et al. 2009; Larsen et al. 2011; Malain et al. 2012). In fact these studies may not reflect the real situations for the majority of the affected communities in Thailand of which most of them were just small communities such as relatively small local villages that were less known to the world. Therefore the aim of this study is to present the impacts of the tsunami and various post-disaster recoveries in two adjacent small local villages: the Nua village and the Hat Sai Khao village in Ranong province in the southern Thailand for a case study that can reflect the post-disaster situation of typical small local villages in the southern Thailand that were affected by the tsunami. The damage assessment and the post-disaster recovery of these villages are compared with those of the Kasetsart University's Andaman Coastal Research Station for Development, one of the government academic institutes, that is located nearby and received the same degree of violence from the tsunami waves, as an example for a comparison of the effects and the restoration processes between local communities and the governmental supported institution. In addition, the current situations of these communities are discussed in term of both physical and social aspects.

6.2 Study Sites

The Kasetsart University's Andaman Coastal Research Station for Development (ACRSD), previously known as the Ranong Coastal Resources Research Station, the Nua village (previously known as Thap Nua village) and the adjacent Hat Sai Khao village are all located within the Kamphuan municipal district's jurisdiction. Kamphuan sub-district is in the Suk Samran district, Ranong province in the southern Thailand along the Andaman coastline. The ACRSD and the Nua village is located along the Praphat beach, one of the local favorite tourist sites while the Hat Sai Khao village is located further landwards to the east along the Kamphuan canal (Fig. 6.1). The role of the ACRSD is to be an international

Fig. 6.1 Current locations of the Nua village (indicated by a *yellow box*), Hat Sai Khao village (indicated by a *blue box*) and the Kasetsart University's Andaman Coastal Research Station for Development (indicated by a *green box*) (Source: Google Maps and Google Earth)

research center to support the university's students and staffs in conducting researches in various fields such as environment, marine sciences, fishery, biodiversity and ecology long the Andaman coastline. It is also a hub of the university in the southern Thailand to conduct a knowledge transfer and educational outreach to the locals.

At the time of the disaster, the ACRSD hosted one two-stories research and training building, 3 single-story office and research buildings, 5 two-stories residences and 3 single-story residences (Recovery and Development Committee 2005). There were 15 employees stationed at the research center during the time of the incident. Due to the increase in the research center's activities, the number of employees is currently increased to 21. According to the census in 2008, the Nua village had a population of 1,397 (422 families) and the Hat Sai Khao village had a population of 561 (234 families). The major occupations of the residents in these villages are fisheries and small groceries venders. The others are small poultry and livestock raising and self-employed.

6.3 Methods

Since the purpose of the is work is to compare the impacts and the recovery processes of the affected sites, the effects from the disaster such as physical, economic, social and health damage assessments, and typical disaster recovery processes (i.e. Natural Hazards Center 2006) such as removal and disposal of debris, temporary shelters, infrastructure and utility restoration, livelihood restoration, reconstruction and hazard mitigation were compiled from various sources such as research papers, technical reports, museum displays, other articles and interviews recorded during the field surveys. As the it has been 9 years since the incident, many documents were missing. In addition, as the affected sites, especially these local villages in this work, were relatively small (although they reflect the situations of the small affected communities in Thailand very well.), there were very little specific information regarding the tsunami impacts and the restoration processes of these selected villages documented in the official report. Therefore a large portion of the data is acquired by interviewing the witnesses in the affected communities.

Interviews were conducted with 12 residents, both victims and witnesses, from all three study sites during the 5 days site visit in August 2013 to gain insight of the impacts of the disaster and restoration processed that were not documented, especially for the social aspect. The qualitative data gathered here is used to understand the human experiences at the affected location and specific situation (Winchester and Rofe 2000). The conclusions drawn from the interviews, however, do not necessary reflect the experiences of the remaining population. Nevertheless, this procedure provides deeper understanding of the individual's experiences that were never been documented elsewhere.

6.4 Impacts of the Tsunami

The Nua village and the Andaman Coastal Research Station for Development is located along the Praphat beach, less than 200 m from the shoreline with low elevation (1–5 m). Therefore the damage was considerably much more than those of the Hat Sai Khao village which was located further inland along the distributary channel, the Kamphuan canal, about 900 m away from the beach with low elevation as well (Fig. 6.2). The tsunami wave height was reported to be about 6 m at the Praphat beach, which destroyed a large portion of the ACRSD and most of the Nua village.

Part of the Hat Sai Khao village was damaged by the tsunami coming from both the beach through the low land and along the Kamphuan canal. According to the witness (August, 2013) at Hat Sai Khao village, the maximum wave height at this location was about 4 m. In addition to the inundation of the low area along the distributary channel, the western part of the mangrove flat land along the Kamphuan canal and the further inland part of the Hat Sai Khao village were also partly flooded

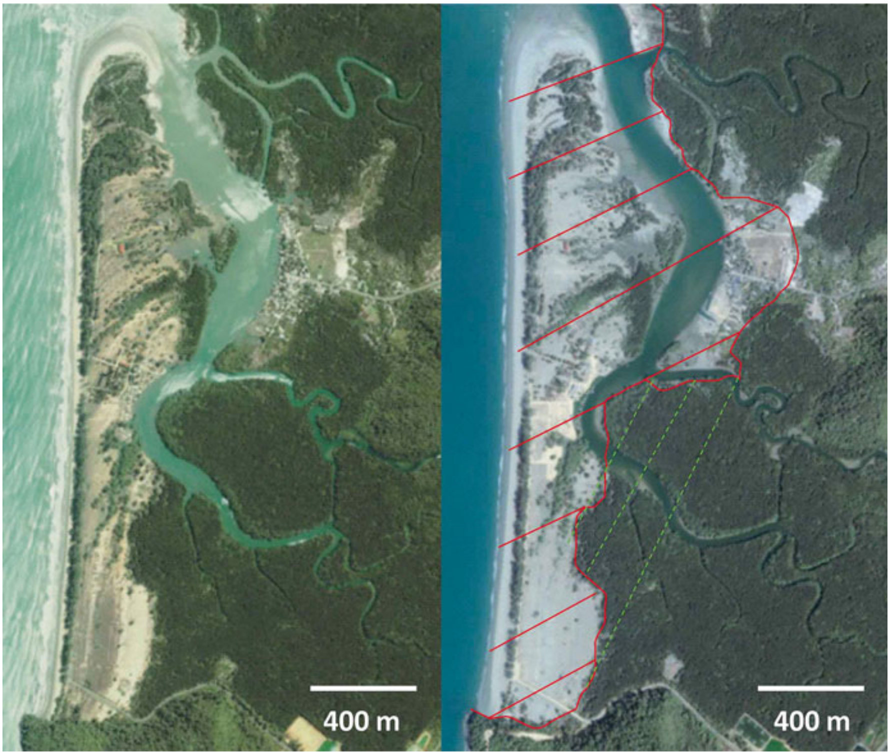

Fig. 6.2 The study area before (*left*: photo taken on 6/5/2003) and after the tsunami (*right*: photo taken on 2/6/2005). The *red shaded area* indicates the approximate inundation zone in the residential areas and the *green shade* indicates the approximate flooding zone in the mangrove forest (Source: Google Earth)

Fig. 6.3 Directions of the tsunami wave hitting the Andaman Coastal Research Station for Development, the Nua and the Hat Sai Khao villages. Note that the tsunami wave travelled both across the Praphat beach (indicated by the *red arrows*) and along the distributary channel, the Kamphuan canal (indicated by the *yellow arrows*) (Source: Google Earth (2/6/2005))

(Fig. 6.3). The witness reported (August, 2013) that the flooding stayed for about 15 min before the water retreated.

The tsunami wave caused considerable damages to the affected areas (Fig. 6.4). Many one-story research buildings at the ACRSD were either completely destroyed or heavily damaged. Many parts of the walls also collapsed. Most of scientific instruments stored on the first floors and vehicles were either heavily damaged or lost. Four employees of the research center were killed on duty (RCRRS 2005). In Nua village, 51 houses were completely destroyed (Recovery and Development Committee 2005). Forty-nine residents and additional 16 tourists visiting the Praphat beach at the time the tsunami arrived were killed (RCRRS 2005). According to the witnesses (August 2013), 10 people were killed in the Hat Sai Khao village.

Fig. 6.4 Damages in the Kasetsart University's Andaman Coastal Research Station for Development (*top left*), the Nua village to the east of the center (*top right*), the Hat Sai Khao village (*lower left*) and the mangrove forest that were filled with debris (*lower right*) (Source: Images by ACRSD and Tambon Kamphuan Community Learning Center (between late December 2004 – early January 2005))

Sixty houses located along the Kamphuan canal riverbank were damaged and many houses located further inland were momentarily inundated. In addition, most of the fishing boats and the fishing equipment in both Nua and Hat Sai Khao villages were completely destroyed which caused the people in both villages unable to go fishing and lost their jobs at least temporarily.

The tsunami also caused variable damages to the electrical power systems by destroying many electrical poles in all three communities. Most of the shallow water system pipelines were either unearthed or destroyed. The roads were temporarily flooded, but most of them sustained only minor damages or not damaged.

As both villages did not have any schools in the area, the educational system in the communities was not affected by the tsunami. Schools in the adjacent area reopened not long after the incident. Unfortunately, many students from both affected villages still could not go to school due to the lost of their family members and their properties. In addition, although the Praphat beach is the local tourist spot, most of the tourists visited the beach only during the daytime for swimming or having a picnic on the beach, therefore there were no tourism facilities such as hotels in the area. Most of the small food shops in the affected sites were located at the higher elevation and were not affected by the tsunami.

6.5 Immediate Relief and Recovery

After the incident, Kasetsart University repaired parts of the buildings that have been partially damaged and converted them to temporary offices. For the affected people in both villages, the residents either lived with their relatives that were not affected by the tsunami or stayed in the refuge center that was adapted from the child development center. The others stayed temporarily in the Ban Kamphuan School nearby while waiting for the temporary shelters being built, which took about 2 months. In addition, the World Vision Foundation of Thailand built additional temporary shelters in the previous sport field in the Hat Sai Khao village. The Royal Thai Air Force also built temporary shelters in the empty land nearby. Many supplies such as food, drinking water and clothes were provided to the victims during the recovery period.

For the clean up process (Fig. 6.5), the debris at the Andaman Coastal Research Station for Development were cleaned up by the employees who took about 2 months to complete the tasks. In Nua village, the affected residents were paid daily (about $6 per day, a typical daily wage in Ranong province during that time) by the World Vision Foundation of Thailand to help clean up debris in the village.

Fig. 6.5 The clean up process in the affected areas. *Top left*: a large television was picked up in the mangrove forest. *Top right*: the backhoe lifted the flooded van at the Kamphuan canal. *Lower left*: a pile of cleaned up debris were waiting for removal at the back of the Andaman Coastal Research Station for Development along the Kamphuan canal. *Lower right*: temporary shelters provided by the Royal Thai Air Force (Source: Images by ACRSD, the Recovery and Development Committee and Tambon Kamphuan Community Learning Center (between December 2004 to January 2005))

In Hat Sai Khao village, the large wreckages were removed by the backhoes supported by the Ranong Provincial Administration Organization. Most of the rest of the small rubbles were cleaned up by residents, which also took about 2 months.

The government allocated the emergency recovery fund to compensate the victims due to their losses. For the case of losing lives, the relatives of the victims received 20,000 baht for each casualty (The average exchange rate in 2005 varies from approximately 38.4 to 41.7 baht/dollar; x-rates.com 2014.). The injured received between 2,000 and 5,000 baht. The people who lost their job received a compensation of 2,000 baht (Nitcharat 2005).

6.6 Restoration Processes

6.6.1 Reconstruction of the Residences and Buildings

Many buildings and residences in the Andaman Coastal Research Station for Development were either partially or completely damaged. Some partial damaged buildings were repaired and used as temporary offices. In 2005, the university received the special recovery fund from the government for about 171 million baht to build a new research and development center and to acquire a replacement of scientific equipment that were damaged by the tsunami (RCRRS and ACRSD 2005). The construction of the new buildings in the research center area started in 2006 and completed in 2008. The new complex building was designed to be a tsunami resistant building and could be used as an emergency tsunami shelter for both ACRSD's employees and the residents nearby (Fig. 6.6).

Fig. 6.6 The satellite images of Kasetsart University's Andaman Coastal Research Station for Development before (*left*: image taken on 6/5/2003) and after the tsunami (*right*: photo taken on 2/3/2007). Note the new research building in the center that was designed for additional purpose as an emergency tsunami evacuation shelter (Source: Google Earth)

Fig. 6.7 Kasetsart University's Andaman Coastal Research Station for Development preserved part of the damaged area as a tsunami monument for both remembrance and educational purposes. *Top left*: the signpost indicating the height of the tsunami wave of 6 m (*red arrow*). *Top right*: the newly built monument's entrance. *Bottom*: the monument area that preserves the damages in the research center

The university conserved the buildings, vehicles and some scientific instruments that were considerably damaged by the tsunami. A piece of land in the research center was preserved as a tsunami monument for both educational and tourism purposes (Fig. 6.7). The partially damaged buildings were restored and have been in use until now.

At Nua village, the residents used to live in the land properties that overlapped with those of the ACRSD where both pieces of land belonged to the government. The overlapping land use caused some conflicts between these communities in the past. After the tsunami, the ACRSD built fences surrounding the center area, separating the land of the center from the land of the Nua village (Fig. 6.8).

The relocated Nua village was moved to the government land nearby the old area to the south of the ACRSD. The Royal Thai Air Force built 52 new houses with funds provided from various sources. It took about 1 year to complete the construction of the new village. The newly built houses were two-story houses of which the first floor was intended to be a kitchen and the toilet while the second floor contained one bedroom, like a typical Thai government residences (Fig. 6.9). Along with the houses, necessary supplies such as clothes, cooking utensils and

Fig. 6.8 The satellite images of the Nua village before (*left*: image taken on 6/5/2003, after the tsunami (*middle*: photo taken on 2/6/2005) and after restoration (*right*: photo taken on 2/3/2007). Note that the village (yellow boxes in the left and the right photos) was relocated from the overlapping land with the Andaman Coastal Research Station for Development to the separated area to the south of the center. Note the temporary shelters built after the tsunami (the red box in the middle photo). (Source: Google Earth)

some electric appliances were donated altogether. The budget for constructing one house was around 120,000 baht. The residents who lived here had to pay 140 baht to the government annually for the land usage fee. People who did not take the houses received about 40,000–50,000 baht for the compensation of their property's damages. As most of the residents were fishermen, the new port was also built for fishing boats nearby the new village.

At Hat Sai Khao village, about 60 houses along the Kamphuan canal were heavily damaged by the tsunami wave that both came from the beach and travelled through the canal. Since the incident, the houses along the Kamphuan canal were relocated further inland away from the canal (Fig. 6.10). The newly built houses were divided into three groups. The first group consists of 50 houses, which were located in a new land bought and built by the Royal Thai Air Force with the donated money. Other necessary supplies for living were also donated along with the houses as those of Nua village. People who did not want to take the new house received 30,000 baht for a compensation of their losses. As there were only 50 houses in this group, residents who wanted this new house had to make a draw and could not choose which house to live in. The second group of the houses was built by using the fund from foreign organizations in a condition that the new owner had to find their own piece of land. Then these organizations would provide the necessary equipment and materials for constructing the new house, which was built by the local residents. This group consisted of ten one-story, moderate size houses locating in the same area. The third group of the reconstructed houses (14 units) was supported by the Nurses Association of Thailand who bought the land from the locals and built the houses at the location nearby the second group. As most of the land in the Hat Sai Khao village was in the National Park boundary, the residents of the new houses were only allowed to live there, but did not own the right of land.

Fig. 6.9 The (then) newly built tsunami resilient houses at Nua village: at the beginning after the construction completed (*top left*: photo taken late 2005-early 2006, image by the Tambon Kamphuan Community Learning Center), house waiting to be renovated (*top right*, photo taken in August 2013) and the renovated houses (*bottom*: photos taken in August 2013)

Fig. 6.10 The satellite images of the Hat Sai Khao village before (*left*: image taken on 6/5/2003), after the tsunami (*middle*: photo taken on 2/6/2005) and after restoration (*right*: photo taken on 2/3/2007). Note that the village (*yellow boxes* in the *left* and the *right* photos) was relocated from along the Kamphuan canal to further inland with slightly higher elevation. Note the temporary shelters built at the soccer field after the tsunami (the *red box* in the *middle* photo) (Source: Google Earth)

Although the new villages have been relocated from the previous location that was flooded by the tsunami, the location of the new site for the Nua village was unfortunately still in the low elevation that could still be affected by the tsunami in the future. Therefore it is important to provide a tsunami early warning message to the locals with adequate time so that the residents can escape to the safer place.

6.6.2 Restoration of Infrastructures

Several electrical poles in the affected sites were destroyed by the tsunami that disrupted the electrical power systems in all three communities. After the incident, the Kamphuan Sub district Administrative Organization contacted the Provincial Electricity Authority who was responsible for maintaining the electrical power system in the area to repair all the damages to the power lines.

For local water supply, the ACRSD had its own water storage tank that was not damaged by the tsunami. The research station just replaced the damaged water pipeline system with the new one. The situation was different for the Nua village that previously shared the water supply with the research center as they lived in the same area before the incident. After the tsunami, as the Nua village was relocated away from the ACRSD and the population in the village increased, the residents in the Nua village had to find new water sources. The water storage tank was built at higher elevation nearby in the National Park property and water was released to the village occasionally, depending on the amount of the stored fresh water in the tank (Fig. 6.11). During the days that the village did not received water, the residents had to use the surface water from the shallow wells. At many times, there were water shortage problems in the village, especially during the dry season.

For the Hat Sai Kao village, the situation was better than that of the Nua village as the village owned a water storage tank that was not damaged by the tsunami. All they had to do was to install the new water pipeline system to the new relocated village nearby. In addition, the municipal district sent the water truck into the villages occasionally, especially during the dry season.

For the drinking water, at the beginning of the aftermath, there was plenty of donated bottled drinking water. After that the residents originally drank directly from the refurbished tap water system. As the tab water system had high level of sanitization in order to maintain the drinking water quality standard, sometimes the water had unpleasant smells from the chemical used in the water treatment. Although the smell was not harmful, it made the residents dislike and refrained them from drinking the tap water directly. Eventually most of the residents had to buy the water gallons that cost about 10 baht (approximately 3 US dollars) per one 20-l gallons and have continued until now. To provide the economic perspective of the recent time, the current minimum wage in Thailand is 300 baht per day.

Fig. 6.11 A shallow water wells at the Nua village (*top left* photo). Many wells are abandoned due to intrusion of the brackish water, especially during the dry season (*lower left* photo). The new water storage tank was constructed at the higher elevation nearby (*top right* photo) which released the water to the village occasionally. The released water was then kept in a storage tank at the individual house (*lower right* photo)

Most of the roads presented slight damages mostly due to the temporarily flooding of the seawater by the tsunami (Fig. 6.12). Therefore the main restoration process was to clean up the debris on the roads with some minor repairs that were responsible by the Department of Rural Roads. Some new roads were built into the newly relocated communities in both Nua and Hat Sai Khao villages. The riverbank along the Kamphuan canal was heavily damaged due to the erosion by the tsunami wave. In 2005 the ACRSD build new embankments along the Khamphuan canal behind of the research center to prevent further erosion of the riverbank.

6.6.3 Livelihood Restoration

The majority of the residents in both Nua and Hat Sai Khao villages were fishermen. The tsunami caused nearly total damage to both their fishing boats and fishing equipment and made them lose their jobs. Many organizations came in to help by

Fig. 6.12 Typical road damages (*top left*; early 2005) and erosion damage due to the tsunami wave along the Kamphuan canal (*top right*; December 2004); rebuilt of the Kamphuan canal's banks (*bottom*; mid 2005) behind the ACRSD (Source: ACRSD)

giving the new boats to them. The residents in the Nua village received the new boats and fishing tools donated by several sectors such as the Coca Cola Thailand Ltd., the World Vision Foundation of Thailand and Kasetsart University (Fig. 6.13). It took about 3–4 months for the villagers at the Nua village to reestablish themselves and continued to live on their lives. At the Hat Sai Kao village, the residents who lost their boats got compensations between 40,000 and 60,000 baht, depending on the size of the boat that was registered. Some residents received a new boat with the fishing gears provided by the American Refugee Committee (ARC) who donated about 150 fishing boats for the entire Suk Samran district.

For the land use, before the tsunami large areas in the ACRSD and in the Nua village used to be grass fields where the locals feed their livestock. Since the tsunami, most of the livestock were killed without being replaced. The field then became abandoned lands with tall grasses and brushes. In the Hat Sai Khao village, the areas along the Kamphuan canal riverbank that most of the houses were destroyed became abandoned lands as well. In addition, various vegetation such as pine and coconut trees were grown and some small temporary shelters were built in this empty land to accommodate the hired boat guards.

The communities in the area affected by the tsunami did not encounter any special new diseases except for the depression of some victims due to their losses of family members and properties. Volunteers were sent into the affected villages to comfort the people for their grieves.

Fig. 6.13 Typical fishing boats donated to the victims by various organizations (*left*). Images by the Recovery and Development Committee and the Tambon Kamphuan Community Learning Center. This figure also shows the example of donated boats that are still in use (*top right*) and the boats that are kept unused (*lower right*) (Source: Recovery and Development Committee and the Tambon Kamphuan Community Learning Center)

6.7 Tourism

The Praphat beach is one of the famous tourist locations for the locals, especially during the weekend. Many tourists were killed during the incident. After the tsunami, the tourists disappeared due to the bad memories and the ongoing rebuilding of the affected area. The tourists have gradually come back to the beach eventually. The tsunami caused moderate erosion along the shoreline and caused many fallen trees. The eroded beach caused by the tsunami gradually restored (Fig. 6.14). Currently, the Praphat beach still encounters the erosion problem as those of many beaches along the Andaman coastlines.

6.8 Hazard Awareness and Disaster Mitigation

After the tsunami, several organizations came into the affected areas to educate people about the hazard of this natural disaster and taught about how to prepare themselves for it. The evacuation procedures were planned. The evacuation routes and signs were designed and built (Fig. 6.15). At the beginning, the ACRSD built a manual system tsunami-warning tower that the commanding officer had to turn on

Fig. 6.14 The condition of the Praphat beach after tsunami (*left*: photos taken in December 2004) and the current condition of the beach (*right*: photos taken in August 2013). Note the moderate shoreline erosion problem along the beach

Fig. 6.15 A hand-drawing draft of the tsunami evacuation route map made by the local authority for the Nua village (*left*), the tsunami evacuation sign near the Praphat beach (*middle*) and the tsunami warning tower at the Hat Sai Khao village (*right*) (Source: Tambon Kamphuan Community Learning Center)

the warning signal manually. Then two additional warning towers were built in the Nua village near the Praphat beach and at the soccer field in the Hat Sai Khao village. The tsunami warning system installed in these new warning towers, were connected directly to the national tsunami warning system and will be alarmed automatically from the central command office in Bangkok. There has been a

Fig. 6.16 The construction site of the standard emergency tsunami shelter (inset) at the Nua village, Kamphuan subdistrict, Suk Samran district, Ranong province that is funded by the government

tsunami evacuation drill held annually by the Department of Disaster Prevention and Mitigation (DDPM), the Ministry of Interior of Thailand and the Kamphuan municipal district, receiving good cooperation from the locals.

MCOT (2013) reported that the government provided 20 million baht to fund the construction of two tsunami emergency shelters in Ranong province. One shelter is being constructed (as of August 2013) in the Nua village (Fig. 6.16). Therefore people in nearby areas can escape to this shelter if the tsunami occurs. The shelter is scheduled to be finished by 2014.

6.9 Discussion

6.9.1 Recovery Progress

It has been 9 years since the devastation for these local communities; Table 6.1 compiles the present damages, restoration and deficiencies in the affected. Most of the affected areas have gone back to their feet.

The Kasetsart University's Andaman Coastal Research Station for Development has a full capacity to conduct their routine research work as they were capable of before the incident. The people in the Nua village still have an ongoing problem

Table 6.1 Comparisons of various damages and restoration aspects among the affected communities

Aspects	Kasetsart University's ACRSD	Nua village	Hat Sai Khao village
1. Degree of overall damages	Moderate-high	Severe	Moderate-high
2. Physical damages	Many one-story research buildings and scientific equipments	Most houses (45), – most fishing boats and gears	Most houses along the Kamphuan canal (60)
	Shoreline erosion along the Kamphuan canal	Shoreline erosion along the Kamphuan canal	Most fishing boats and gears
	Minor road damages, and water pipeline system	Water pipeline system	Shoreline erosion along the Kamphuan canal
			Water pipeline system
3. Psychological and social damages	Depression due to loss of the family members and interrupting in normal routine work	Depression due to loss of the family members, properties and occupations	
4. Loss of lives	4 employees	49 residents and 16 tourists	10 residents
5. Major supports	Government funding	Government and private sectors	Government and private sectors
6. Major restoration processes	Restoration of damaged buildings and construction of new ones	Relocation of the village	Building of new houses
	Construction of the embankment along the Kamphuan canal	Building of new houses	Provision of fishing boats and gears
	Scientific equipment reacquisition	Provision of fishing boats and gears	Compensations
	Restored water pipeline system	Compensations	
	Preserved area for tsunami monument and education		
7. Hazard mitigation	Building of tsunami warning sign and tower and tsunami shelter. Tsunami evacuation drill held annually		
8. Existing problems	–	Water shortage, – decreases of marine resources	Decrease of marine resources
		Unemployment	Unemployment
		Changes in livelihood	Changes in livelihood

regarding the water shortage, especially in the dry season as most of shallow wells become brackish due to the seawater intrusion to the groundwater system. Eventually, the residents have to buy water for their consumption.

The interview of the residents recently (August 2013) revealed that the amount of the marine resources for the fishery has decreased greatly since the tsunami. It has decreased so much that it has not been profitable to become fishermen any-more. Many people then quit their fishermen career and turned to find new career paths such as construction workers or self-employed. In the Nua village, during the monsoon season, nearly 60 % of the people do not live in the donated house. Instead, they move away to get new jobs such as agricultural related employees. They return to their home after the monsoon season was over. The situation in the Hat Sai Khao village is not much different. As most residents do not have other careers besides fishery, when doing fishery was not profitable, most of them quit their job, sold their boats and houses they received from the donation and moved away. Currently, ten out of fifty families do not live in the donated houses anymore. According to the witness in the village, among 50 boats that were donated by the ARC, only 10 boats are still in working condition. To relieve the unemployment problems in these villages, several organizations sent the volunteers to the villages to train the residents to start alternative careers occasionally. Unfortunately, due to the lack of the continuation of the activities and due to the fact that the new trained careers did not fit the job market for the locals, the result was disappointed. The residents have not been able to switch to the new careers and many of them are still unemployed.

The social situation in the affected communities has changed since the tsunami as well. We were told by the residents in the villages recently (August 2013) that in the past people living in the villages tended to rely on each other and had good relationship among the families in the villages. Unfortunately, the relationship among the residents has deteriorated to be very socially distant and more self orientated. Most of the younger generation moved away to find the new jobs and left the elderly at home unattended.

6.9.2 Challenges

Although the affected communities in this study received relatively quick assistances from various organizations, there are still several issues that can be improved.

Due to limited funding and short restoration time frame, most of the houses in the affected area that were reconstructed with supports from the government were typical standard two-stories government residence styles. The styles of these houses were the same at both the Nua and the Hat Sai Khao villages; unfortunately these houses were somewhat too small for the whole family to live in. Another problem was that the two-story house was not suitable for the families that have the senior member who has a difficult time going upstairs. In addition, as Ranong province has rainy season for about 8 months yearly, the stair that was located outside the house's shade deteriorated very quickly due to the rain and the moisture. As the residents in the affected areas did not have chances to select the housing style that would fit their need most, they had to accept whatever was donated to. Due to this limitation, most people who lived in these houses had to renovate the house using either their own money or by supports from private foundations who came to help in renovation.

At Nua village, although the village was relocated away from the previous site to resolve the land use conflict between the village and the ACRSD, another problem has arrived instead: the water shortage, especially during the dry season. Moreover, the location of the new site for the Nua village was unfortunately still in the low elevation that could still be affected by the tsunami in the future. Therefore the planning of a land use and the natural resources sharing need to be considered very seriously in order to sustain a long term wellbeing of the residents.

As most of the housings and living supplies including fishing boats were donated to the affected people without much participations from the victims for what they really needed, the values of these donated items were much less appreciated by the recipients than what they were supposed to. Many houses were deserted; many fishing boats were left unattained and eventually deteriorated with times. A large portion of the donated funds used for these purposes were unfortunately wasted in vein.

Another challenge in the recovery processes in the affected small communities is how we can help these communities to finally have sustainable, resilient communities that have immunities to the tsunami disaster in the future. As these villages in this work and other large number of the small communities along the Andaman coastline are relatively small, there have been very little scientific studies on the tsunami hazard for these communities. Most of the tsunami hazard mitigations in such small villages are almost purely based on the commonsense of the residents and the planners, limited resources and only the data from the last tsunami (such as the run up heights and inundation zones). There is a real need for the scientific studies for supporting the hazard mitigation and emergency planning (such as tsunami inundation modeling) to make it work very effectively if the disaster really occurs. In addition, most of the residents in small communities such as these two villages in our study rely their lives almost purely on the warning signal from the warning towers, which is very risky. There are many “what if” questions that we need to consider such as “what if the earthquake occurs at 3 am in the morning and what if the warning system breaks down during the incident?” Residents in the potential hazard areas need to have self-awareness about the disaster such as they need to be realized that if the ground shakes violently at 3 am in the morning, they should move to the safe higher ground without having to wait for the warning signal. This awareness can be obtained only with a routine education outreach distributed throughout the affected communities.

6.10 Concluding Remarks

This chapter compares the effects and the restoration processes of the communities that were devastated by the 2004 tsunami between one of the government institutes: the Kasetsart University’s Andaman Coastal Research Station for Development and two small local communities: the Nua and the Hat Sai Khao villages, in Ranong province, southern Thailand. Although all affected areas could be recovered back to normal stages as those before the tragedy, the discrepancy still remains. For the

Andaman Coastal Research Station for Development, the recovery process went very quickly and effectively due to the additional large funding support from both university and the government. However, the story was totally different for such small local communities such as the two villages in this study. Although the communities received various supports from many organizations at the beginning, the residents appeared to get back to their normal lives slowly, partly due to the lack of wills caused by irreplaceable losses of lives in the family leaders who might be the main taskforces for making a living in the families or the lost of their properties that would take a long time for them to recover. In addition, after the tragedy, their lives appear to change forever due to the changes in both environmental and social aspects that surround them. The case studies of the restoration processes from these two such small local communities are a good example for other typical small local communities in Thailand that are not considered a high priority for the government to put all the efforts in the recovery process such as those cases in the famous tourist communities where full forces of support were provided by both government and tourism industries (i.e. MFC 2014; Guidescenter 2005).

In order to help these communities recover from the losses due to a devastating natural disaster in a short time, the government needs to:

– Provide enough emergency financial support and personnel to the affected communities at the earliest time to supply sufficient immediate relief at the beginning stage and to help in reconstruction of the communities at the later time.
– Need to let the victim participate in the restoration processes in order to correspond to their needs as much as possible and to raise the appreciation of the proved supports.
– Maintain the continuation of the support for physical, psychological and social aspects until the affected residents in the communities can get back on their lives as before the tragedy.
– Need to support the scientific studies of the Tsunami hazard that can be used for disaster mitigation and planning, especially in the small, local communities.
– Maintain the awareness of the people for the danger of the natural disaster through educational outreaches and drills. It is also very important to maintain the critical facilities for the disaster monitoring and warning network such as a tsunami warning system, tsunami shelters, and tsunami evacuation route maps.

In addition, for this specific case, the affected residents need additional supports from many organizations to renew their careers. The supports include the ecological and environmental studies in order to restore the environment especially for rehabilitating damaged coastal ecosystems to enhance fisheries to the original condition. The alternative support can be introducing the new career paths in the marine related occupation such as aquaculture as long as it still preserves the environment especially for the mangrove forest and coastline. These kinds of supports can help the affected residents to return to the villages and continue to live their normal lives.

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Chapter 7
Reconstruction Process and Social Issues After the 1746 Earthquake and Tsunami in Peru: Past and Present Challenges After Tsunami Events

Erick Mas, Bruno Adriano, Julio Kuroiwa Horiuchi, and Shunichi Koshimura

Abstract Tsunamis, oceanic wave events that are most often triggered by earthquakes at interplate subduction areas, result in damaged infrastructure, ecological disruption and a substantial number of deaths among coastal communities. In recent years, a key concept in the assessment of tsunami events has been *resilience*, which can be understood as the ability of a group to anticipate risk, limit negative impacts and recover rapidly from a catastrophic event through processes of survival, adaptability, evolution and growth. The term *resilience* incorporates a dynamic and durable connotation of constant preparedness, not only for the next tsunami event but also for the ensuing process of reconstruction. The reconstruction of a community devastated by a tsunami poses a multiplicity of challenges, including environmental, social, political, scientific, engineering and architectural challenges. In this paper, we first examine a 1746 tsunami event (Mw9.0) that occurred on the coast of Viceroyalty-era Peru and consider the challenges reported during the subsequent reconstruction of a devastated city and port. We contrast those challenges, reported nearly 250 years ago, with analogous challenges observed in more recent tsunami events. The paper concludes with comments on the lessons learned and suggests areas of future research.

Keywords Reconstruction • Tsunami • Peru

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7.1 Introduction

Tsunami events result from the displacement of a large volume of water in a short time due to earthquakes, volcanic eruptions, submarine landslides or meteorite impacts. Tsunamis, although rare, have been widely portrayed in the worldwide media since the beginning of the twenty-first century due to a recurrence of megathrust earthquakes. Historical evidence of tsunamis dates to more than 2,000 years ago in China (Cartwright and Nakamura 2008; Qinghai and Adams 1986). Tsunamis are therefore not a new type of disaster for human societies. The conditions of human society, however—such as the degree of urbanization, technological capabilities and dominant economic systems—have changed with time; thus, it would seem likely that the post-disaster activities of an earlier era would no longer be relevant to authorities responding to a contemporary tsunami event.

Peru's capital city, Lima, and the nearby coastal province of Callao suffered one of the greatest earthquakes in their history on October 28, 1746. With an estimated magnitude of between Mw8.6 (Dorbath et al. 1990) and Mw9.0 (Jimenez et al. 2013), the 1746 Lima-Callao earthquake was comparable to the region's previous great earthquake—which struck on October 20, 1687, with a magnitude of Mw8.4-8.7 (Perez-Mallaina 2005)—and is classified as a uniquely destructive event in local history.

Although there are no extant details regarding housing damage to verify the historical testimonials, the number of casualties was estimated at 5,000 in 1687 and at 5,941[1] in 1746. Reports claim that during the 1746 event, 1,141 people were killed in Lima alone. In the Port of Callao, where only 221 out of the 5,000 inhabitants survived, it was easier to count survivors than victims (Kuroiwa Horiuchi 2004; Perez-Mallaina 2005).

It is important to revisit these events, not only from a geophysical perspective but also in consideration of their societal impact, and to understand the subsequent reconstruction efforts undertaken by a devastated city. Such a historical analysis helps us understand how communities struggle to live in harmony with nature and how the people of different eras have coped with disasters.

Our objective in this paper is to present the historical accounts of this historical disaster and to discuss the similarities and differences between this important historical event and particular modern experiences of disasters. It is crucial that we bring the historical record to bear upon the present and contrast the societies of the past with contemporary at-risk communities to apply the lessons of our forebears to enhance the resilience of present-day communities.

[1]Other documents report a total of 11,000 people killed in Lima and Callao (Lozano 1748; Odriozola 1863).

7.2 Lima and Callao Before the Earthquake

7.2.1 The City of Lima

The Spanish conquistador Francisco Pizarro founded Lima in 1535. In 1746, Peru had been under Spanish colonial control for more than 200 years and had experienced several earthquakes during that time (1555, 1586, 1609, 1630, 1655, 1678 and 1687), the largest of which, according to the manuscripts of Fray Antonio Vasquez de Espinosa,[2] occurred on July 9, 1586. Despite these catastrophic events, in the New World of the eighteenth century, Lima was described as a city that had achieved perfection (Lozano 1748; Odriozola 1863).

Before the 1746 earthquake, Lima was a fortified city with a small suburb outside the city walls. The city was located approximately 8 km from the coast. The city plan shown in Fig. 7.1 displays a grid of narrow streets, 24 churches identified

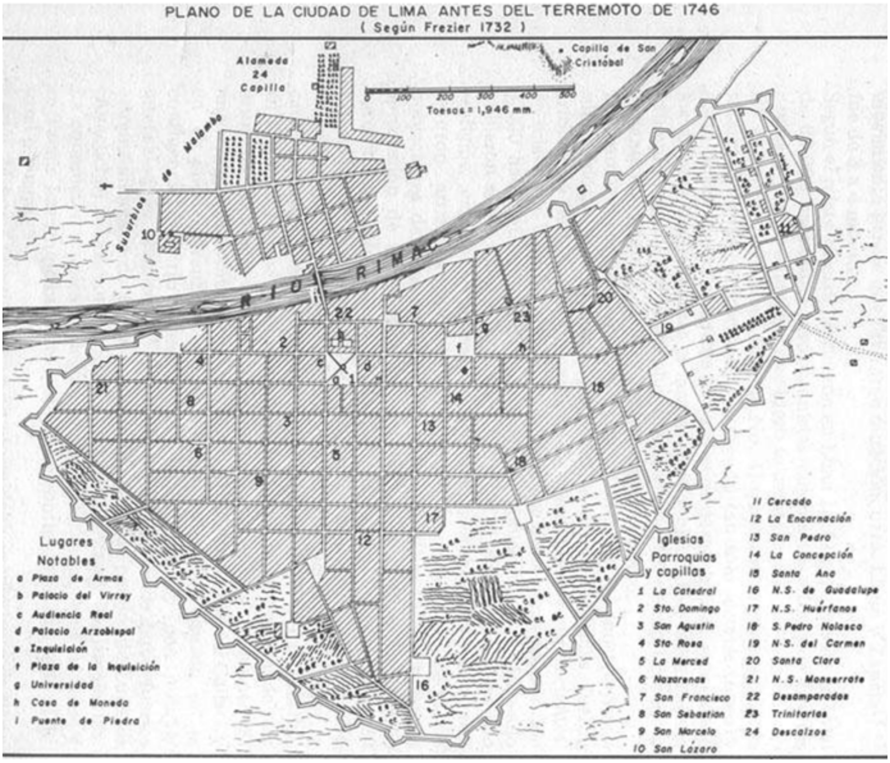

Fig. 7.1 Lima city prior to the earthquake and tsunami of 1746 (Source: Silgado 1978, INGEMMET/CERESIS. http://www.ceresis.org/intensidades/hist/776.html)

[2] N/A-1630, Spanish monk of the Discalced Carmelites who describes his journeys through Mexico and Peru in manuscripts discovered at the Vatican Library in 1929.

by numbers on the map and some important landmarks such as the Main Square, The Viceroy Palace, the National University of San Marcos (the oldest in the Americas) and the Stone Bridge of Lima, which is still standing and which connected Lima with the suburb of Malambo (now known as Rimac).

Catholicism was an important component of Lima's society at the time, and Church representatives powerfully influenced politics and social behavior (Perez-Mallaina 2001). For the residents of Lima, the most important building was the Cathedral, a three-nave edifice with great towers. Except for the few homes closest to the Main Square, most houses in Lima at the time were built with only one story due to the belief that earthquake damage would affect larger homes much more than smaller ones. Perhaps paradoxically, the construction of large churches was still very much encouraged.

Construction materials consisted largely of stone, timber, cane (quincha), adobe or brick, the latter of which was baked for use in large structures and unbaked for the construction of small houses (Command of Viceroy 1748). Because it rarely rained in the city, the majority of houses lacked roofs—to help prevent a dangerous collapse during an earthquake—and were instead shaded with a single mat.

It is important to note how the houses were built, especially the walls: two outward-facing layers of bricks were placed approximately 1.5 m apart, and the interior space was filled with soil. This resulted in a width of nearly 2 m, creating a massive structure that could ultimately be deadly in the event of an earthquake.

7.2.2 The Town and Port of Callao

The port of Callao is located south of the mouth of the Rimac River and north of the peninsula today known as La Punta, approximately 8 km southwest of Lima. The port faces two islands, San Lorenzo and Callao (also known then as Isla del Muerto and today known as Isla Fronton). The port was one of the most important points of connection to Mexico, Guatemala, Panama, Chile, Spain, France and all the coastal regions of Peru and was therefore of particular interest to the Spanish Crown (Garcia Acosta 1997). Callao was also a strategic location for commerce and the military protection of Lima from pirates or other threats. Due to its close proximity to the sea, Callao was sometimes flooded (notably in 1713) by strong ocean surges (Command of Viceroy 1748).

At the time of the 1746 earthquake, Callao was characterized by wide streets and mostly one-story homes. The streets were not perfectly aligned at their corners but for the most part were straight. In contrast to the streets of Lima, the dusty paths of Callao would not have allowed for a pleasant walk. The port and town were surrounded by protective walls, as shown in Fig. 7.2, and two small suburbs—*Old PitiPiti* and *New PitiPiti*—sat outside the southern and northern edges of the enclosure, respectively. Among the important buildings in town were the Governor's residence and the Royal Palace, where the Viceroy lodged when visiting from Lima.

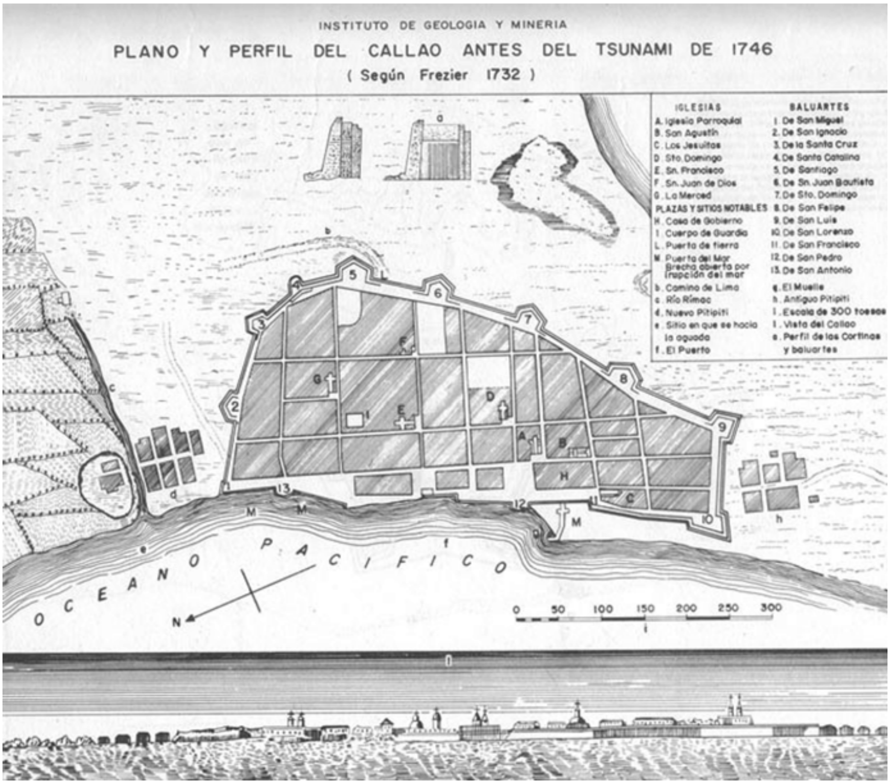

Fig. 7.2 Callao and its fortress prior to the earthquake and tsunami of 1746 (Source: Silgado 1978, INGEMMET/CERESIS. http://www.ceresis.org/intensidades/hist/776.html)

The population of Callao was approximately 5,000, and the majority of the inhabitants were fishermen who lacked formal education and did not receive any payment for their work. Other demographic groups included the inhabitants of the inner city, the traders and the workmen (e.g., carpenters, caulkers, etc.).

Several orchards—in which a variety of olives, oranges and citron trees were cultivated—could be found on the route from Lima to Callao. The walls surrounding the town were fortified by 10 bastions on the inland side and cannons on the side facing the sea.

7.3 The 1746 Earthquake in Peru

On the night of October 28, 1746, a strong ground motion struck the city of Lima and the port of Callao, beginning at 10:30 and continuing for approximately 3–4 min. As described above, the city's massive walls and narrow streets crushed inhabitants both outdoors and in their homes. Many buildings collapsed, especially the large structures and tall towers of the city's churches.

7.3.1 Damage and Effects in Lima

Out of the 60,000 inhabitants of Lima, it is estimated that 1,141 were killed by the earthquake, and many more died in the aftermath due to epidemics and sickness. Whereas the unfortunate people were killed by heavy walls or wooden roofs, some survivors found safety during the tremor by running out into their gardens or orchards. Of Lima's 3,000 houses, divided among 150 blocks inside the city walls, only 25 survived the strong ground motion. Even the Viceroy palace collapsed and was unable to continue serving its function. Lima, the capital of Peru, was in a regrettable state (Godoy 2007; Vargas Ugarte 1956). Several church towers had collapsed, and the Santa Ana Hospital reported 60 people buried by their roofs. It is interesting to note that despite the number of religious buildings damaged, few nuns or priests were killed or injured (Lozano 1748). The nuns had known that, because of their vows, they would not be able to escape to the outside in the case of an earthquake and thus had designated clear escape routes into their gardens and orchards in advance. This planning can be considered an early manifestation of disaster-response behavior (Contreras Badajos 2011). The Viceroy himself organized the search and rescue missions, as there were no organizations or institutions established to take charge of this activity. In the following days, the city began to stink with the remains of the many residents and horses still trapped under the debris. According to Jose Eusebio de Llano Zapata (cited in Odriozola 1863), between the time of the earthquake and February of the following year, at least 2,000 people died due to epidemics of diseases such as cholera and typhus.

Lima's economy relied on warehouses near Callao, but news of the event arriving from Callao the next day informed the survivors of Lima that a massive tsunami had destroyed the port and town as well as nearly all of its population. For at least 3 days, Lima had no food supply. The Viceroy designated as top priorities the repair of ovens and the importation of wheat from other areas, and by the fourth and fifth days after the earthquake, bread had begun to be made and distributed. Unfortunately, some people began to sell food at four times its usual price. Looting activity and treasure hunting amid the debris were also reported in the aftermath. People could not remain in their homes, which had been reduced to debris, and thus, the city's squares and its gardens and orchards became places of provisional shelter, fortified with material recycled from the ruins of former houses. The wealthy abandoned the city in favor of ranches in the countryside; others migrated to Arequipa to the south. By January of the following year, the people had largely rebuilt their houses using material recycled from the debris. Then, on February 21, 1747, with the passing of King Felipe V and the coronation of King Fernando VI, it became necessary to honor and celebrate both the previous and incoming kings. To this end, despite the broken economy of the city and the slow process of rebuilding, the Viceroy ordered the construction of a temporary wooden church to replace the main Cathedral, as the massive damage sustained by the latter would require a protracted reconstruction. At the same time, 23 streets and four squares were cleaned up for the special event honoring the two kings. On September 23, 1747, with many of its wealthy inhabitants back in the city, Lima began to close a terrible chapter in its history.

7.3.2 Damage and Effects in the Port of Callao

The situation in Callao was even worse than in Lima. At 11:00, only 30 min after the earthquake and just as the 5,000 inhabitants were emerging into the chaos of the damaged town, the first wave of a mega-tsunami struck the coast. Conservative estimates reported the sea to have been between 4 and 7 m higher than its normal level; others reported a rise of 10–15 m. In any case, it is clear that the waves topped the town walls, inundated an inland area of over 4 km and sank 19 out of the 23 offshore ships. The other four ships were carried as far as 2 km inland. One of these latter ships, the San Fermin, was of particular importance to the Viceroy due to the treasures and food it contained (Vidal Gomez 1901), and he sent his officials to find it and to report back to him on its condition. Today, the figurehead of the San Fermin is placed at the entrance of the Callao market at a near location where the boat was found stranded (Fig. 7.3). The combined disaster of the earthquake and the tsunami

Fig. 7.3 Figurehead of the San Fermin placed at the entrance of the Callao market at a near location where the boat was found stranded (Source: http://callao-querido.blogspot.jp/2012/10/callao-historia-cocteleria-chalaca-el.html)

claimed the lives of 90 % of the population. Only 221 people survived, some by clinging to walls or timber and some thrown as far as nearby islands and other shores; one couple was found alive 3 days after the tsunami on a beach south of Callao (Arrus 1904). Rescue efforts here were even more difficult than in Lima due to the flooding and the debris. Reaching people who survived by clinging to floating trunks was often impossible. The coast of Callao was full of dead bodies, and authorities lamented that they did not have the capacity to attend to all of the victims. It was said that many bodies ultimately became food for birds. It was not until August 1, 1747, that the construction of the new city wall for Callao began, and even the first stage of this new construction was not finished until 1761.

7.4 Reconstruction After the 1746 Earthquake

The Viceroy Manso de Velasco (Fig. 7.4) had acquired experience dealing with earthquakes and managing reconstruction while he had been in Chile during the 1737 Valdivia earthquake (magnitude Ms7.7). In the first month after the tragedy of October 28, 1746, he spearheaded several tasks (Odriozola 1863):

- Rescuing survivors from the debris. Many survivors who had drifted by sea to the nearby islands of San Lorenzo or Callao were retrieved and brought back to the mainland. People trapped under the debris were rescued one by one, though many of them perished nevertheless.

Fig. 7.4 After overseeing years of reconstruction, the Viceroy Jose Antonio Manso de Velasco was awarded the title of First Count of Superunda (Superunda means "over the waves") for his efforts in the reconstruction of Lima and Callao after the earthquake and tsunami of 1746 (Source: http://historiadordelperu.blogspot.jp/)

- Burying the dead. Dead bodies were buried in mass graves and in the areas surrounding churches; however, there were not enough resources to accomplish this task as quickly as desired. According to Llano Zapata (cited in Odriozola 1863), the injured were gathered in city squares without any medical aid, and some of them perished where they lay. Even more difficult was the removal of the nearly 2,000 dead horses and mules trapped under the debris, which resulted in a disgusting odor that lingered in the city for days.
- Feeding the people. Obtaining bread, meat and water was of the highest priority. The Viceroy ordered that all ovens be repaired and that bakers be brought from nearby cities. He mandated that the quantity of meat being sold remain at normal levels. Water fountains and sewage channels were to be restored immediately.
- Protecting the Crown's treasures. Because the port of Callao was continuously threatened by pirates (and now by local looters as well), the Viceroy appointed a military guard to protect the warehouses containing the money and treasures of the King.
- Reconstructing the Main Palace, where essential functions such as the judiciary and tax offices were housed (Walker and Ramirez Castaneda 2002).

The future of the city of Lima became a subject of debate. The first proposal involved the outright relocation of the city, although due to the complex socioeconomic problems involved and the potential loss of strategic value for the Royal Crown, this plan was not adopted. Luis Godin of San Marcos University was subsequently charged with developing a plan for the reconstruction of the city. The first draft of his proposal was presented on November 10, sparking a debate over the proposed architectural and structural designs of Lima's houses. Some residents were in favor of limiting houses to a single story, in which case the remaining houses of two or more stories would be destroyed as part of the reconstruction process. The walls of houses at the time were built to a substantial width, which presented potential danger in the case of their collapse; one aspect of the proposal, therefore, included a plan for thinner walls and roofs supported by wooden beams. The use of alternative building materials such as "quincha" was also encouraged. In Godin's proposal, churches with wooden roofs could be constructed with walls higher than those of houses but would no longer be built with towers. Godin also proposed the destruction of what remained of the city wall and the construction of wider streets; unfortunately, these particular suggestions were ultimately not adopted. In contrast, landlords—many of whom belonged to the Church or to wealthy families—wanted to build multi-story rental homes that would bring in more profit, and ultimately, this powerful demographic convinced the Viceroy to withdraw Godin's plans for reconstruction.

In the reconstruction of the port of Callao, the construction of housing was prohibited, and it was decided that with rebuilt walls, the port would henceforth serve only commercial and military purposes (Saenz Mori 2009) (Fig. 7.5). A new town was built outside the limits of the flood zone. Located roughly one league (5 km) from the peninsula, this town was called Bellavista and was intended as the new destination for the warehouses and workers previously located in the port of Callao.

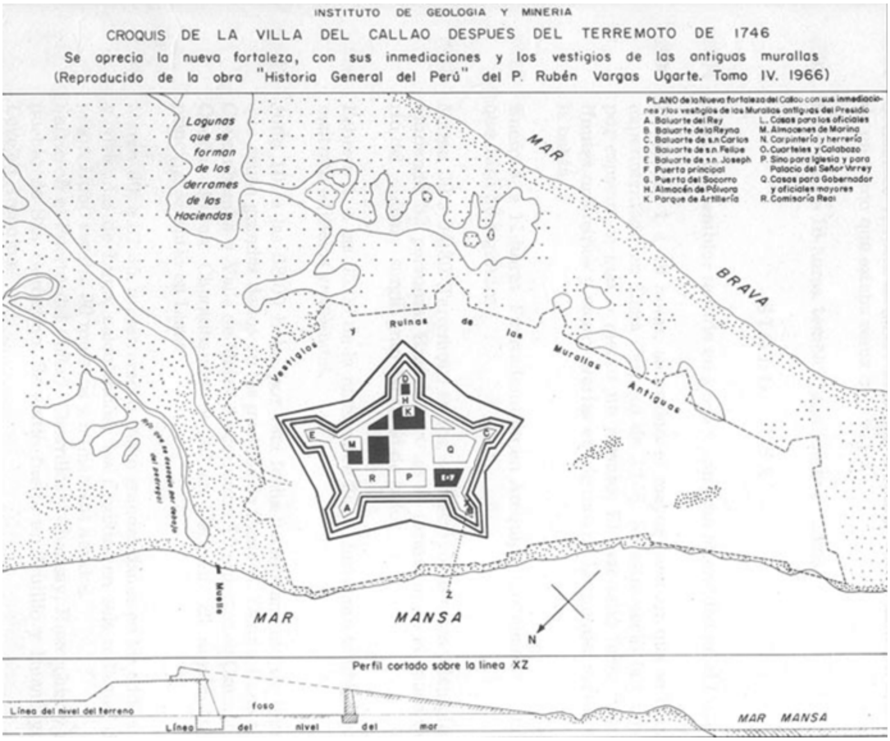

Fig. 7.5 Callao and the new Real Felipe fortress after the earthquake and tsunami of 1746. Note the *dashed line* indicating the previous location of the town walls (Source: Silgado 1978, INGEMMET/CERESIS. http://www.ceresis.org/intensidades/hist/776.html)

7.5 Past and Present Challenges for Post-earthquake and -Tsunami Reconstruction

The French philosopher Jean-Jacques Rousseau wrote in 1756 that society is responsible for its own calamities: in his opinion, it was the architecture and urban layout of crowded cities—with high-rise buildings that collapse easily—that were ultimately responsible for the numerous deaths registered after earthquakes (Perez-Mallaina 2005). The 1746 disaster in Peru proves this argument to be correct. Today, this argument is understood in an even broader context in which cities have become megalopolises and in which urban architecture has become more complex and increasingly dependent on advanced technologies. Today, Rousseau's notion of social responsibility can be conceptualized in terms of *resilience* and *disaster-prevention culture*.

Clearly, the particular facts described above belong to a different time, one in which post-disaster priorities for aid and reconstruction differed from those of today. If we look closely, however, at the experience of the Peruvian population and the government of the time, we can discern that the challenges of responding to modern disasters—though they occur in more complex environments and though we have access to more advanced tools and technologies for shaping our response—are quite similar. In 1746, the Viceroy was most immediately concerned with the rescue of survivors, the protection of Royal assets, feeding the hungry, the preservation of sanitation services and city health; post-disaster management in the twenty-first century, by comparison, similarly requires the mobilization of search and rescue teams, medical services, measures to prevent epidemics and to discourage looting and other concerns. In 1746, the Viceroy possessed total authority to make decisions and impose all emergency laws and response activity, and because there were no other organizations or authorities above him, there was no need for regulations. By contrast, in the twenty-first century, where in addition to the authorities, the involved parties include local and international organizations, first responders and others; it is necessary to establish parameters regarding each group's role and how certain actions are to be coordinated. Humanitarian and international laws must also be taken into account to ensure an adequate response to an emergency.

In 1746, the great majority of Lima's population considered the disaster to be a punishment for their sins by a higher deity, in this case, the God of Catholicism. This attitude could also be found years earlier, after the 1687 earthquake in Lima or even the 1650 earthquake in Cuzco. Interestingly, a similar attitude has been described in the Muslim communities of Indonesia after the 2004 tsunami in the Indian Ocean (Kurita et al. 2007). We might think that because neither Wegener's theory of continental drift nor the theory of tectonic plates was articulated until the early twentieth century, the lack of a scientific explanation for the earthquakes in the eighteenth century makes a turn to the supernatural as a more plausible. Even at that time, however, scientific communities had developed theories to explain the natural causes for earthquakes, including the postulation of a relationship between seismic movements and the gases trapped under the Earth's crust and attempts to predict seismic activity using astronomical clocks (Odriozola 1863). Nonetheless, even scholars of geography and the related sciences could not refrain from attributing the generation of earthquakes at least in part to God's will. More important than the knowledge of modern tectonic theories, however, are the socio-cultural influences that religion exercises in our communities. The importance of studying the particular case of Lima-Callao lies in the way that historical analysis allows us to predict possible scenarios for the future (Adriano et al. 2013) and to more effectively use available technologies to assess risks and reduce future losses (Mas et al. 2014).

7.6 Final Comments

In this paper, we have summarized the historical accounts of the tragic 1746 earthquake and tsunami, and the subsequent reconstruction, in Lima and Callao, Peru. The condition of the cities before the earthquake and the resulting damage after the event were both presented to give a sense of the challenges faced by these historical communities in their response to these adversities. Instead of findings, the results of this research, presented below, can be understood as a series of reminders regarding what we can learn from the past, what we can be proud of in the present and what we can work toward in the future to ensure the resilience of our communities.

1. A society is responsible for its own calamities. It is we who decide to build our cities in safe or risky areas. It is our construction standards and methods that can protect or condemn us in the case of an earthquake. It is our attitude that will leave us either prepared or panicked in an emergency. It is we who should care about living in harmony with nature.
2. Today, societies and environments are both more extended and more populous and therefore depend upon complex systems and technology, the disruption of which can result in a feedback loop of multiple disasters. Whereas in the past, an earthquake might have triggered urban fires at most, it is now possible for chemical accidents, industrial fires, nuclear accidents, oil spills, water contamination and other secondary disasters to materialize all at once. The 2011 Great East Japan Earthquake provided a recent example on this effect. We should prepare for such complex scenarios using appropriate technology.
3. Despite the possibility of multiple disasters, it is interesting to note that the urgent post-disaster needs of historical communities remain the basis of present-day rapid responses. Our contemporary contingency and operational plans mirror many of the actions taken by the Viceroy and the population at large in 1746 Peru: search and rescue; the disposal of dead bodies; the restoration of basic services; and measures to prevent epidemics, food panics (Gomez 2013) and looting (American Red Cross Multidisciplinary Team 2011).
4. A lesson from both the past and the present is that science and faith must both be brought to bear in acknowledging the source of disasters in the disharmony between human communities and nature and therefore to encourage a more proactive social attitude toward nature.

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Chapter 8
The Tsunami Warning System in Thailand: A Part of the Reconstruction Process After the 2004 Indian Ocean Tsunami

Natt Leelawat, Anawat Suppasri, and Fumihiko Imamura

Abstract A disaster early warning system is an important tool to prevent a large number of human casualties from natural disasters such as earthquakes and tsunamis. In Thailand, an early disaster warning system has been established as a part of the reconstruction process after the 2004 Indian Ocean earthquake and tsunami. This chapter focuses on the establishment, development and management process of this early warning system, with particular emphasis on tsunami hazards. This study considers face-to-face interviews with executive officers from the National Disaster Warning Center (NDWC) and the Seismological Bureau of the Thai Meteorological Department (TMD). Moreover, observations of a warning drill conducted in September 2013 in Bangkok, Thailand are also considered. Relevant issues and findings are discussed while providing suggestions for the potential development of early warning systems of a similar nature in other developing countries.

Keywords 2004 Indian Ocean earthquake and tsunami • Disaster reconstruction • Early warning system • Thailand • Tsunami

8.1 Introduction

A M9.3 earthquake was recorded at 00:59 UTC on December 26, 2004 on the seafloor off the western coast of northern Sumatra in Indonesia. It affected many countries in the Indian Ocean, such as Bangladesh, India, Indonesia, Kenya, Mauritius,

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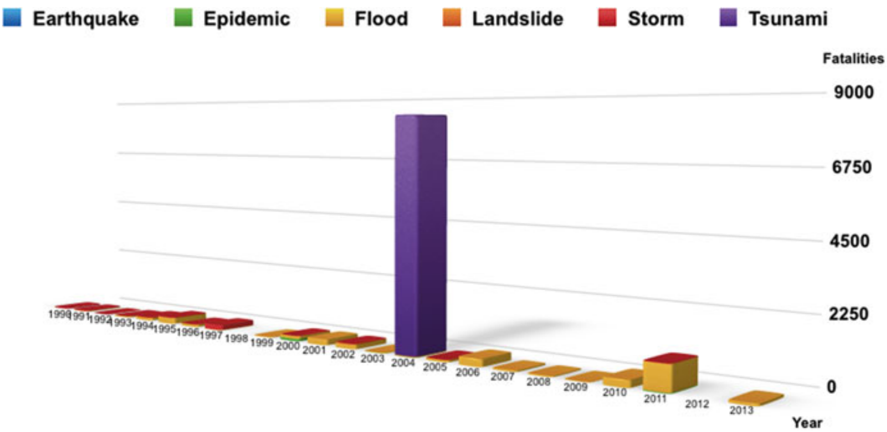

Fig. 8.1 Fatality numbers caused by natural disasters in Thailand for 1990–2013 (Source: CRED 2014; http://www.emdat.be)

Malaysia, the Maldives, Myanmar, Seychelles, Somalia, Sri Lanka, and Thailand (Polngam et al. 2005). For Thailand, the gigantic wave hit the Andaman coast at 09:30 a.m. local time (02:30 UTC) on that day, including the provinces of Phuket, Phang Nga, Krabi, Ranong, Trang, and Satun (Thanawood et al. 2004). Although flooding is the most costly natural disaster for Thailand (i.e., the 2011 Thailand flood caused total damage of more than USD 40 billion), the 2004 Indian Ocean tsunami is considered the largest natural disaster in terms of fatalities after generations of no major natural disasters in the country. According to the Centre for Research on the Epidemiology of Disasters (CRED) (2014), the greatest number of deaths by a natural disaster in Thailand was due to the 2004 tsunami totaling 8,345 deaths (Fig. 8.1). Therefore, it is the most destructive natural disaster in this country's history.

"Identify, assess and monitor disaster risks and enhance early warning" has been established as one of the five priority areas of action in the Hyogo Framework for Action 2005–2015 (United Nations International Strategy for Disaster Reduction (UNISDR) 2005), as well as the recognition of the "early warning as an effective tool to reduce vulnerabilities, save lives and help protect livelihoods and national development gains, and to improve preparedness and response to natural hazards" (Thomalla and Larsen 2010 p. 250). In light of this, the present chapter examines the disaster early warning system of Thailand to better understand its establishment, development and management process with particular emphasis on tsunami hazards and future improvements.

8.2 Research Design

The present qualitative study has been designed to understand the organizational management concept and processes of the existing early warning system through a narrative design using interviews. The analysis is based on enterprise engineering methodology (Dietz 2006; Perinforma 2012).

Data collection was undertaken in August – December 2013. The primary data came from face-to-face interviews with the Acting Director of National Disaster Warning Center (NDWC), Ministry of Information and Communication Technology (MICT); and the Director of the Seismological Bureau, Thai Meteorological Department (TMD-MICT) in September 2013. The interviews were all undertaken following a semi-structured style complemented with observation from a warning drill by the NDWC.

8.3 The Tsunami Warning System in Thailand

8.3.1 Organizational Development

The 2004 Indian Ocean earthquake and tsunami disaster was a trigger for the development of early warning systems in many countries in the Indian Ocean region, especially Indonesia, Sri Lanka, the Philippines, and Thailand (Thomalla and Larsen 2010).

As part of the broader support from the United States government (USA) for the Indian Ocean Tsunami Warning System (IOTW), the NDWC in Thailand received a grant from the U.S. Trade and Development Agency (USTDA). This grant was used primarily for technical assistance from the Pacific Disaster Center (PDC) and partners in disaster management and the warning capabilities of the system. Vulnerability reduction programs have been implemented in Thailand including mitigation plans such as "Risk Assessment and Vulnerability Analysis", "Land Use Planning", and "Enrichment of Beach Forests and Rehabilitation of Coral Reefs and Sea Grass Beds", and preparedness plans including "Installation of Warning System", "Development of Education Programmes", "Raising Awareness", "Organizing Evacuation Drills", "Construction of Tsunami Memorial", and "Disaster-related Research" (Thanawood et al. 2004).

8.3.2 Information Sources

The information and experiences used for the establishment of the disaster warning system in Thailand consisted of domestic as well as foreign/international sources as shown in Table 8.1. In addition three Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys have been deployed (N9 E89, N9.30 E95.42, and N7.30 E96.10) complementing the data. The first of these buoys was deployed in 2006 while the others in 2010. The performance of the first DART buoy was observed throughout the recordings of the tsunami in 2007 (Lorito et al. 2008).

Table 8.1 Thailand Early Warning Information sources

Domestic sources
Thai Meteorological Department (TMD), Ministry of Information and Communication Technology
Department of Disaster Prevention and Mitigation of the Ministry of Interior
Department of Mineral Resources of the Ministry of Natural Resources and Environment
Hydrographic Department of the Royal Thai Navy (HRDTN)
Department of Water Resources of the Ministry of Natural Resources and Environment
Royal Irrigation Department (RID) of the Ministry of Agriculture and Cooperatives
Pollution Control Department of the Ministry of Natural Resources and Environment
Electricity Generating Authority of Thailand (EGAT) of the Ministry of Energy
Royal Forest Department of the Ministry of Natural Resources and Environment
Department of National Parks, Wildlife and Plant Conservation of the Ministry of Natural Resources and Environment
Foreign/International sources
Pacific Tsunami Warning Center (PTWC)
Japan Meteorological Agency (JMA)
United States Geological Survey (USGS)
National Oceanic and Atmospheric Administration (NOAA)
European-Mediterranean and Seismological Center (EMSC)
Malaysian Meteorological Service (MMS)
Intergovernmental Oceanographic Commission of UNESCO (IOC)
German Research Centre for Geosciences (GFZ)
Global Disaster Alert and Coordination System (GDACS)

Source: Ekmahachai 2013; Thailand National Disaster Warning Center. NDWC

8.3.3 Organizational Management Process

Through our present analysis and that of Leelawat et al. (2014), the overall process of the establishment and work of the Early Warning System in Thailand can be better understood. According to the interview data, there are two key actor roles in the process i.e. the *warning announcer* i.e., the NDWC, and the *seismic information provider*. The National Disaster Warning Center (NDWC) is a centralized official unit that receives, monitors, processes, and relays critical natural disaster information (Thanawood et al. 2004) and was established in May 2005 by the Royal Thai Government.

Four key Natural Disaster Groups of various organizations responsible for monitoring and data analyses are directly in contact with the National Disaster Warning Center (NDWC). The existence of these four Groups are due to the fact that natural disasters in Thailand are classified into four main types: Geological Disaster, Hydrological Disaster, Meteorological Disaster, and Forest Fire (Table 8.2).

As shown in Table 8.2, tsunamis are also included as a part of the Hydrological Disaster Group. However, it is also associated with earthquakes, as it has been shown in the case of the 2004 earthquake-induced tsunami. Thus, monitoring of tsunamis is often accompanied by the monitoring of earthquakes.

Table 8.2 Natural disaster classifications in Thailand

No.	Natural disaster group	Natural disaster
1	Geological disaster	Earthquake, volcanic eruption, land/mudslide, sinkhole, crack
2	Hydrological disaster	Flood, tsunami, storm surge, limnic eruption
3	Meteorological disaster	Cyclone, onshore cyclone, hailstorm, heat wave, drought, cold
4	Forest fire	Forest fire

Source: Ekmahachai 2013; Thailand National Disaster Warning Center. NDWC

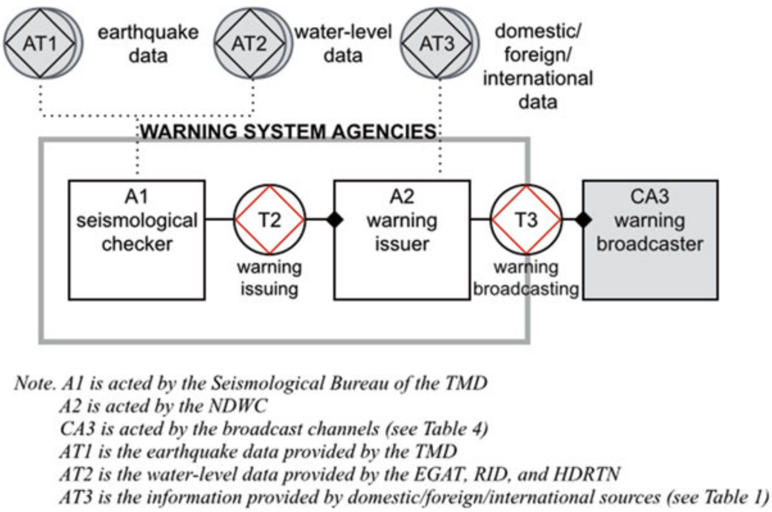

Fig. 8.2 Organization construction diagram of tsunami early warning system in Thailand

According to our analysis, the Organization Construction Diagram of tsunami early warning system in Thailand is shown in Fig. 8.2. A tsunami warning classification process follows that of earthquakes i.e. 'advisory', 'watch', and 'warning' with the final state of 'terminate'. The criteria for these warning classification process is further described in Table 8.3.

The organizational process of tsunami early warning system in the country first considers each organization in the above mentioned four main groups, which monitor the information and makes it available to the organizations related to the warning system (AT3 in Fig. 8.2). Thereafter, when the seismic stations detect anomalies they immediately transfer the earthquake magnitude, water level values, field observation data, and/or tsunami warning classification through the TMD, EGAT, RID, and HDRTN.

While the Seismological Bureau of the TMD (A1) is responsible for operating a seismic network and transferring the earthquake information (AT1) to the NDWC, the other three (EGAT, RID, and HDRTN) are responsible for the water-level information (AT2). Moreover, the NDWC also retrieves the information from the other named sources (AT3) (Table 8.1).

Table 8.3 Criteria of tsunami warning based on earthquake-related parameters

Area of surveillance in Thailand	Magnitude of the event (Richter scale)	Hypocenter Less than 100 km	Hypocenter More than 100 km
(1) Latitudes of N3-N23 & Longitudes of E88-E103	5.0–6.5	Advisory	Advisory
	6.6–7.7	Watch	Watch
	7.8 and higher	Warning	Watch
(2) Latitudes of S7.5-N25 & Longitudes of E75-E125	5.7–7.0	Advisory	Advisory
	7.1 and higher	Watch	Watch
Other than (1) and (2)	7.0 and higher	Advisory	Advisory

Source: Ekmahachai 2013; Thailand National Disaster Warning Center. NDWC

Table 8.4 Broadcast channels as of September 2013

Channel	Number	Channel	Number
Short message service (SMS)	More than 20 million users	Warning box at City halls and the National Broadcasting Services of Thailand	166 boxes
Fax server	16 equipments	Village alarm tower	654 towers
Hot lines	8	Village leader radio devices	1,590 devices
Email	–	News center	70 terminals
Television program (via the Television Pool of Thailand)	6 public channels	Government Information Network	All government agencies
Website	–	Smartphone server	600,000 licenses
Warning tower	328 towers	Web EOC	–

Source: Ekmahachai 2013; Thailand National Disaster Warning Center. NDWC

Finally, the NDWC (A2) is responsible for retrieving the seismic information to analyze the severity of the situation and potential hazard issuing the warning as appropriate. Once the disaster is over, the NDWC terminates the warning process. This agency has two offices being the operational one primarily run by the Bangna Office which is located in the same area as the TMD and works 24 h a day, 7 days a week to ensure that highest possible level of efficiency. In the case of an electrical black out, the NDWC is able to continue operating using their emergency power supply for at least 12 h.

Figure 8.2 Organization Construction Diagram of Tsunami Early Warning System in Thailand Currently, there are many communication channels used by the NDWC to broadcast the warnings (Fig. 8.2-CA3) as seen in Table 8.4. As it happens, although the warning broadcast towers have been installed in all areas of the country, especially on the coastlines, the exception is the capital city (Bangkok) because of the problem of land availability. However, the other available channels are believed to reach the metropolitan area, particularly through television channels. All the broadcasted messages given through the warning broadcast towers include English, German, Chinese, and Japanese for foreign tourists as well as Thai language for the locals; the messages also give instructions to the citizens regarding how to respond to the specific warning.

In order to ensure that the warning broadcast keep the awareness of people high through the channels and the system is appraised, the NDWC tests the towers, warning boxes, village alarm towers, and village leader radio devices by opening with the Thai national anthem twice a month (on the 1st and the 15th of each month at 8:00 a.m.). In case there is a problem and the community cannot hear the national anthem they can in turn contact the NDWC to address the problem for the agency to make the necessary repairs.

The performance or timing for issuing the early warning alarm to the people in the country seems to be a point of concern, not only since its the most important factor for an effective early warning and evacuation action during a disaster, but also because its decision making and issuing process seems to be long and complicated with a variety of organizations involved at each step. It is important to highlight though that despite of this arrangement the time required from detecting until issuing the warning message does not take long.

In September 2010, after the tsunami stroke, according to the Committee on National Disaster Warning Administration (CONDWA 2010), there was a tsunami warning and evacuation drill for the six provinces of the Andaman Coast (i.e., Ranong, Phang Nga, Phuket, Krabi, Trang, and Satun). During that time, after the TMD reported an earthquake, 2 min were required for making the seismological decision; six broadcast stations received the running caption warning information via fax within 4 min; and finally, the warning towers in the six provinces were activated in the next 4 min. In total, 8 min passed after the NDWC received the message from the TMD or 10 min after the TMD reported the earthquake (CONDWA 2010). In the drill undertaken by the NDWC in 2013, we found that the 8-min period was reduced to only 5 min showing a big improvement.

When a real hazard situation occurred on April 11th, 2012, we found through the conducted interviews that Thailand's early warning system has announced the warning messages in a timely manner showing the effectiveness of the established early warning system.

8.4 Discussion and Conclusions

Although Sorensen (2000) mentioned, "… a 100 % reliable warning system does not exist for any hazards", an effective early warning system is still expected to save many citizens. Of the four crucial elements for an effective warning system of Simonvic (2011), "risk knowledge phase", "monitoring phase", "dissemination and communication phase", and "response capability development phase", the early warning system in Thailand includes them all.

As the NDWC is the only organization officially assigned to be the warning announcer for the entire country, this prevents the confusion that may occur from many announcing sources, therefore it is a good practice of role assignment in the early warning system of the country. Nevertheless, and despite of the drill results, the chain of processes, from monitoring to broadcasting can be further improved in terms of accuracy as also there are many steps requiring human decision making which in turn also requires some amount of time. With the specialized expertise of the officials and more supporting information, the current timing for the tsunami warning drill process could become shortened. Its important to note also that according to Suppasri et al. (2012) due to the location of the possible earthquake epicenters and the geography of the country it seems to allow for a certain period of time (approximately 90 min) for announcing the warning and conducting the evacuation.

As stated by Joseph (2011), “A timely, 100 % accurate and precise warning is of no use as far as protecting citizens unless the information reaches them in time and unless they know how to respond to the emergency”. Moreover, as the Hyogo Framework highlighted the importance of “integrated, multi-hazard approaches” (UNISDR 2005) and de León et al. (2006) suggested “Effective early warning systems require strong technical foundations and good knowledge of the risks”, we conclude also that as part of the current developed and further improvement of the early warning system procedures as well as the evacuation drills in Thailand, there is a need to increase the evacuation efficiency itself. For the purpose there is a need for the responsible agency to develop a computerized user-friendly tsunami evacuation maps to optimize the evacuation process especially the traffic management during the evacuation. Likewise, we suggest that there is a need to include the wave height into the criteria of tsunami warning since the tsunami wave heights may also differ depending on other conditions (e.g., geographical conditions, coastal depth).

Further refinement of the existing early tsunami (and overall) warning system is possible by also considering recent knowledge and experiences as well as research studies from abroad, as well as from Thailand. This is of particular importance not only for the country but also as the existing early warning system could be transferred to other developing countries.

Like in Thailand, countries in the Indian Ocean Region have developed tsunami early warning systems i.e. India, Indonesia, Malaysia, Singapore (Joseph 2011; PTWC 2009). As of March 2013, the PTWC has stopped taking on additional areas of responsibility in the Indian Ocean, most likely due to the development of early warning systems being developed by Regional Tsunami Service Providers in Australia, India, and Indonesia (PTWC 2009) posing a challenge and opportunity for the early warning Thai system to prove and improve its efficiency, while encouraging the development of networks in the Region.

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Chapter 9
Effects of the Offshore Barrier Against the 2011 Off the Pacific Coast of Tohoku Earthquake Tsunami and Lessons Learned

Nobuhito Mori, Nozomu Yoneyama, and William Pringle

Abstract In this study, the effectiveness of an offshore breakwater for the 2011 off the Pacific Coast of Tohoku Earthquake Tsunami was examined by two-dimensional (2D), quasi three-dimensional (quasi-3D) and three-dimensional (3D) numerical models. First, both 3D numerical models were applied to the behavior of tsunami inundation for Kamaishi Bay in Iwate Prefecture where an offshore deep-water breakwater was installed against an assumed tsunami before 2011. The numerical results indicate 20 % error of maximum inundation height compared with the post-event tsunami survey on the land. It is found that the offshore breakwater significantly reduced the tsunami height on the land. The reduction of tsunami height on the land gave about 30 % tax revenue in comparison with similar locations with or without breakwater. Based on the results the construction and or rebuilding of damaged offshore breakwaters can be considered as a viable option against tsunami particularly in vulnerable areas.

Keywords Tsunami height • Offshore breakwater • Numerical modeling • Economic recovery

9.1 Introduction

The 2011 off the Pacific coast of Tohoku Earthquake Tsunami (denoted 2011 Tohoku Earthquake Tsunami hereafter for simplicity) was a tremendous and tragic earthquake-tsunami disaster for Japan. An earthquake of magnitude 9.0 occurred off the Pacific coast of Tohoku, Japan, on March 11, 2011, at 14:46:23 Japan Standard Time (+9 UTC) and the rupture area, assumed to be approximately

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450 × 200 km, generated a tsunami that struck Japan from Hokkaido to Kyushu as well as various locations around the Pacific Ocean.

The tsunami first reached the Japanese mainland about 20 min after the earthquake and ultimately affected a 2,000 km stretch of Japan's Pacific coast (The 2011 Tohoku Earthquake Tsunami Joint Survey Group 2011). The Tohoku region consists of several prefectures ranging from north to south, Aomori Prefecture, Iwate Prefecture, Miyagi Prefecture, and Fukushima Prefecture, which border the Pacific Ocean. Sendai is the largest city in the region. The southern part of Tohoku is relatively flat, especially the Sendai plain. The coastal geomorphology of northern Tohoku features ria coasts, which are steep, narrow bays. The northeastern part of Pacific side of Tohoku is known by the name of Sanriku region starting from North Miyagi Prefecture to South Aomori Prefecture. As of August 8 in 2012, official fatalities were 15,867 with an additional 2,903 missing (National Police Agency of Japan). The major cause of death was the tsunami, and most fatalities occurred in Tohoku, 58 % in Miyagi Prefecture, 33 % in Iwate Prefecture and 9 % in Fukushima Prefecture. There were 126,631 totally damaged and 272,653 partially damaged buildings, along with 116 bridges (National Police Agency 2014).

Before this event, the risk of earthquakes and tsunamis off the Tohoku coast was believed to be high. The Japanese government reported that magnitude 7.5 and 7.7 earthquakes along a 200 km fault offshore of Sendai in southern Sanriku-Oki were expected to occur with 99 % probability and 70–80 % probability within 30 years, respectively (The Headquarters for Earthquake Research Promotion 2005). The 1896 Meiji Sanriku earthquake (Mw 8.2–8.5) and tsunami caused 21,915 deaths, the 1933 Showa Sanriku earthquake (Mw 8.1) and tsunami caused 3,064 deaths, and smaller tsunamis have occurred roughly every 10–50 years. Thus, earthquake and tsunami disaster countermeasures, such as seawalls, gates and offshore tsunami breakwaters, planted trees as a natural tsunami barrier, vertical evacuation buildings, and periodic evacuation training were implemented and practiced in these areas. Therefore, we emphasize that Tohoku was an area highly prepared for tsunamis. Nevertheless, the tsunami disaster countermeasures were insufficient against the 2011 event. Tsunami barriers (onshore and offshore breakwaters, and natural tsunami barriers) were severely damaged, some reinforced concrete buildings were totally destroyed, and the extent of inundation was underestimated in several areas.

This event is important for future tsunami preparation to classify various modern counter measures against mega-tsunami. Therefore, understanding the effectiveness of countermeasures and estimation of error of impact assessments are critical. First, this paper re-analyzed the tsunami inundation heights and run-up heights by the three different numerical models at Kamaishi bay where offshore breakwater was installed before the event. The effectiveness of offshore breakwater and error of numerical model is discussed in comparison with the survey data. The relation between damage and tax revenue is discussed to understand long-term impact on the catastrophic event and its protection.

9.2 Numerical Modeling

9.2.1 Outline of Numerical Models

A series of numerical simulations were performed to estimate the influence of offshore breakwaters on the tsunami inundation heights and to check the uncertainty of numerical modeling for inundation of mega-tsunami. The calculations were conducted by three different methods.

The first numerical model is a conventional nonlinear shallow water equation that assumes irrotational, inviscid and hydrostatic pressure distribution vertically (denoted 2D hereafter). The 2D model uses a standard staggered grid system horizontally and the leapfrog method for time discretization so that the linear terms in the scheme are 2nd-order accurate everywhere. The 2D method was developed in house but it follows standard methodology of tsunami wave modeling. We use the 2D model as a reference to the standard way of impact assessment of tsunami inundation modeling (e.g. Pringle and Yoneyama 2013; Goto et al. 1997).

The second numerical model is the quasi-3D model based on the Euler equation that assumes hydrostatic pressure distribution vertically but allows arbitrary distribution of vertical velocity without irrotational and inviscid assumptions (Yoneyama et al. 2012 and Mori et al. 2013; denoted Q3D hereafter). Turbulence mixing is considered using the *k-e* model vertically and the parameterized Smagorinsky scheme based on the eddy viscosity model horizontally. The Q3D model uses the Euler equation with curvilinear-sigma coordinates vertically. Therefore, the Q3D model can resolve both tsunami wave motion and bathymetry effects independent from the discretization. These characteristics of Q3D model are expected to improve the inundation modeling compared with the 2D model.

The third numerical model is the full 3D model based on the Navier-Stokes equation that contains no approximation for fluid motion except for turbulence modeling (denoted 3D hereafter). The 3D model uses a standard staggered grid system. The free surface motion is simulated by volume of fluid (VOF) method and bottom bathymetry is approximated by an improved FAVOR method. Turbulence mixing is considered using the *k-e* model. The tsunami modeling by the 3D model with staggered grid system may encounter difficulties when resolving surface motion due to the vertical scale difference from offshore to near shore. For example, 20 vertical layers at a depth of 100 m describe 5 m resolution but this corresponds to only a few grids near shore. Therefore, the 3D model introduces a non-uniform vertical grid system and two-way coupling between the 2D and 3D model (see detail in Pringle and Yoneyama 2013). Due to the non-uniform grid system, the vertical resolution near the mean water level becomes double near the bottom. The two-way coupling solves the offshore region by the 2D model and the 3D model simulates the near shore region. The hybrid system is not only enhanced due to the reduction in computational time but the vertical resolution of the 3D model is increased near shore.

9.2.2 Numerical Conditions

The horizontal mesh size was set as 50×50 m for all models. The vertical discretization of the 3D model were set to 2 m near the free surface and down to 5 m below the water column, while 10 vertical layers were used in the Q3D model. The wet-dry condition and offshore radiation boundary condition were applied in the three models.

The target area for computation is Kamaishi Bay area. Bathymetry for both Kamaishi Bay (southern part) and Ryoishi Bay (northern part) are provided at a resolution of 50 m by the Cabinet Office, Government of Japan. Due to the coarse bathymetry information, land areas are described with a uniform height. The computation was carried out with Dt = 0.1 s time intervals from the time of the earthquake until 2 h later. The astronomical tide was not included in all of the 3D, Q3D and 2D computations. The landside structures and land use are regarded as roughness in terms of Manning's n coefficients based on the Cabinet Office dataset. The time series of measured tsunami by the Kamaishi GPS buoy (Kawai et al. 2011) was used as a lateral boundary condition for the offshore side. The local inundation heights were validated with the measured inundation and run-up heights (TTJS 2011; Mori et al. 2011, 2012).

9.3 Results and Discussion

9.3.1 Numerical Results

A series of numerical computations was performed for Kamaishi Bay and Ryoishi Bay at Iwate Prefecture together because two bays are surrounded by the two long peninsula at the south and north borders, although they are separated by the short peninsula at the middle (see Fig. 9.1). Kamaishi City in Iwate Prefecture is located in the Sanriku ria coast area. An offshore breakwater for tsunami protection is installed at the mouth of Kamaishi Bay. The construction of offshore tsunami breakwater began in 1978. A pair of offshore breakwaters with lengths of 990 and 670 m was finally completed in 2006 in a water depth of 63 m, making it the deepest caisson breakwater in the world (Tanimoto and Goda 1991).

It is important to examine the effectiveness of offshore breakwater for 2011 event and estimate numerical errors dependent on the scheme. We have to note that the water depth of Kamaishi Bay and Ryoishi Bay are 50 and 100 m, approximately, therefore direct comparison of the two bays are physically incorrect.

Figure 9.1 shows the maximum water surface elevation for computations with the offshore breakwater for three different methods. The amplification of the tsunami can be seen for several steep valleys in both bays. The influence of the offshore tsunami breakwater can be seen clearly around the breakwater in Fig. 9.1. Within the bay, the maximum surface elevation is reduced from about 12–15 m to 9–11 m depending on the location. This corresponds to a 20–40 % reduction of

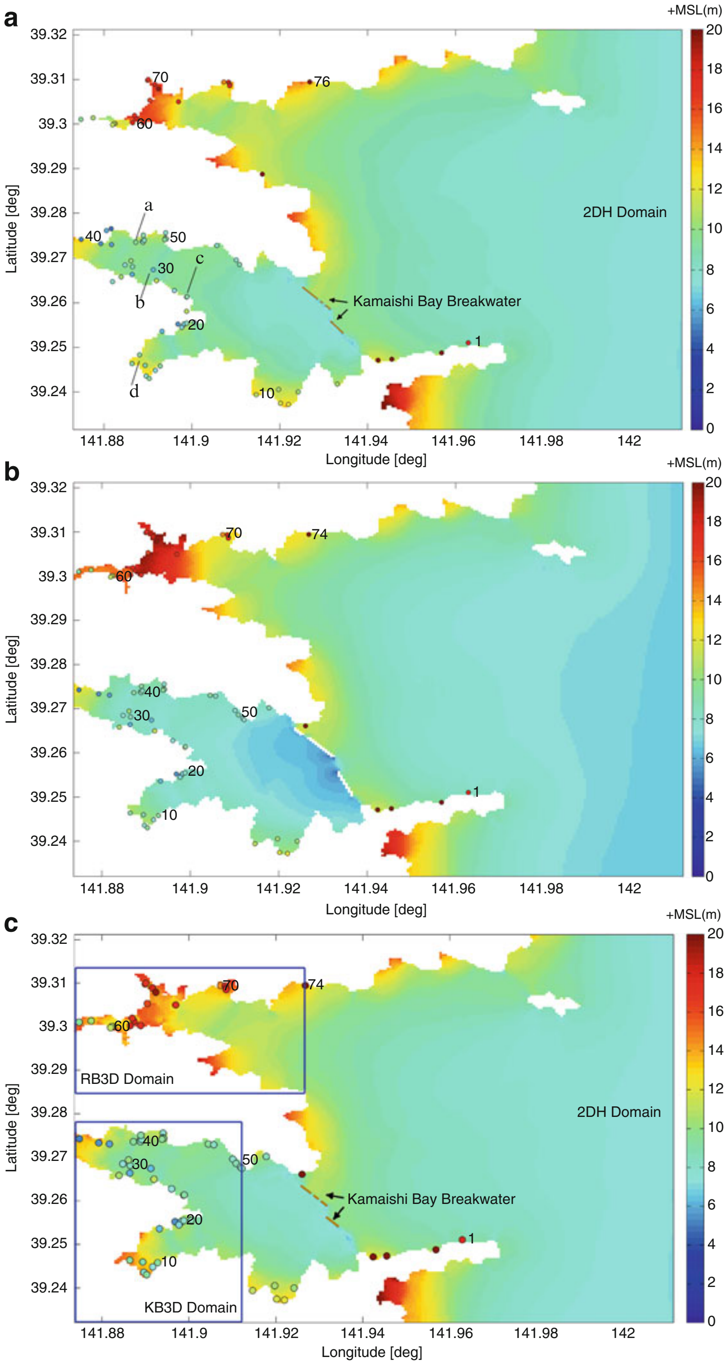

Fig. 9.1 Maximum water level simulated by three different models (contour: model, *circle*: survey data). 2D model (**a**), (**b**) Q3D model and (**c**) 3D/2D hybrid model (*blue boxes* indicate computational region for 3D model)

inundation height along the shores of Kamaishi Bay (Mori et al. 2013). The reduced tsunami energy in Kamaishi Bay gives different damage characteristics and post event impact compared to Otsuchi Bay that will be described in the next section. Regarding the differences between three models, the results outside of Kamaishi bay are quite similar between the 2D, Q3D and 3D models, respectively. The maximum run-up is reached at 30 m maximally at the Ryoishi area. The run-up height is reduced significantly in Kamaishi bay for three models, although they are different at the onshore side. The run-up height of Kamaishi Bay is initially 22 m at the bay mouth, drops to 10 m near the offshore breakwater, and remains roughly constant at 10 m to the shoreline. The 2D or 3D results are higher than the Q3D results at the deep region inside of Kamaishi bay. This is due to reduction of tsunami height near the offshore breakwater. In addition, the 3D model gives slightly higher run-up/inundation height than the 2D model on the landside. This difference is due to the difference in the governing equations and modeling of bottom roughness. Overall, the Q3D model gives the best results with respect to the survey data. The relative computational costs of 3D and Q3D are 20 and 5 times longer respectively, than those of the 2D simulation under an OpenMP environment.

The effects of the offshore breakwater can be verified by the difference between simulations with or without the breakwater. Figure 9.2 shows comparisons of surface elevation on the land between numerical results by the Q3D model with or without the offshore breakwater and survey data (the locations are denoted in Fig. 9.1a). The maximum values of inundation height by the Q3D show relatively good agreement with the survey data except far from coastal line. These locations are strongly influenced by on-land structures that are not considered in the models. Through the comparison of two different runs, it is found that the offshore breakwater reduced the tsunami height by about 25–40 % and significantly lessened the damage at Kamaishi area. The arrival time of the maximum height was delayed 1.8–2.5 min due to the offshore breakwater.

Figure 9.3 and Table 9.1 indicate the direct comparison of maximum inundation height between three models and survey data along the coast (location numbering is indicated in Fig. 9.1). The location numbers from 1 to 53 are located at Kamaishi Bay and the others are located at Ryoishi Bay. The amplification of the tsunami can be seen for several steep valleys in both bays. Both the 2D model and Q3D model are overestimated in Kamaishi Bay but three models are slightly underestimated in Ryoishi Bay. The root-mean-square error (RMSE), maximum absolute error (MAE) and standard deviation (STD) indicate 2.4–3.9 m errors. These numerical results agree with the observed survey observations within 20 % accuracy and the Q3D model are 15 % better than the other methods. The Q3D model uses terrain following coordinate considering vertical velocity profile which has an advantage over the structured grid system used in the 2D and 3D models. The validation of the numerical model is required for velocity because the damage of structure depends on the momentum of fluids that is proportional to water depth times the square of the velocity. The relative differences in computed peak velocities are approximately 50–250 % onshore. The velocities of the 2D model are smaller than the 3D and Q3D

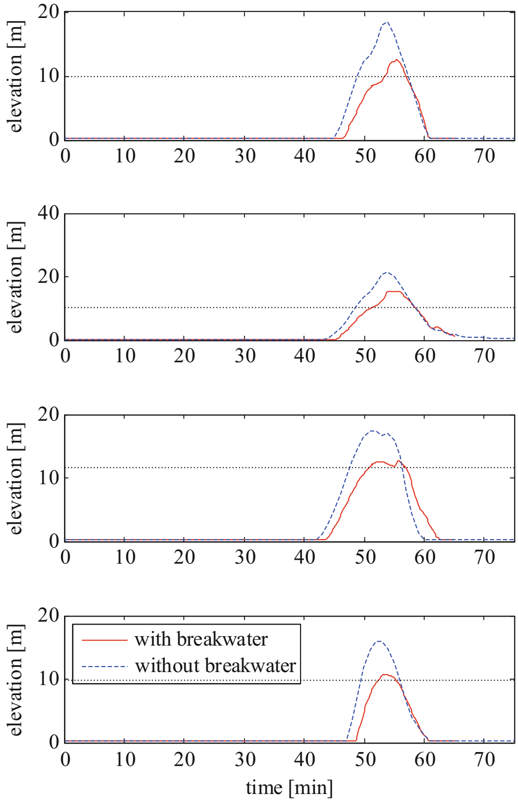

Fig. 9.2 Comparison of surface elevation on the land between numerical results by Q3D model with/without offshore breakwater and survey data (locations: **a**–**d** from *top* to *bottom* denoted in Fig. 9.1a, *solid line*: with breakwater, *dashed line*: without breakwater, *dashed horizontal line*: survey data by TTJS 2011 and Mori et al. 2011)

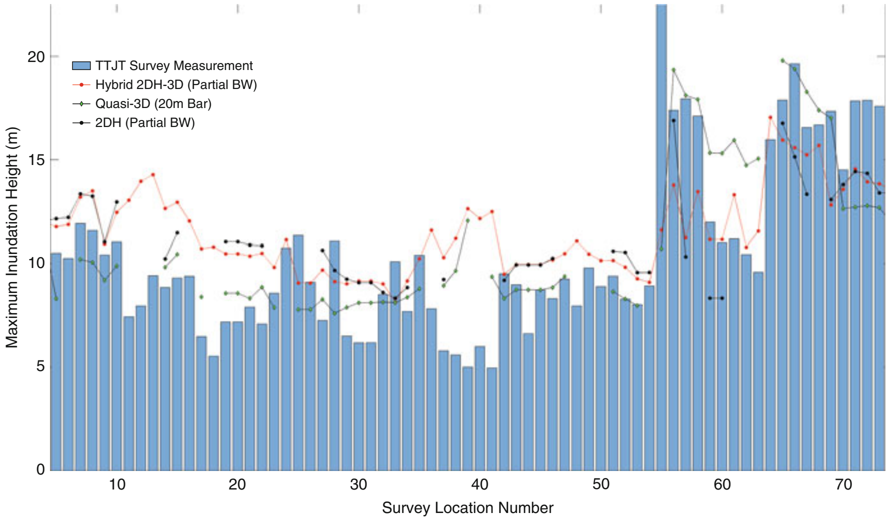

Fig. 9.3 Comparison of maximum inundation height along the coast between three models and survey data (*bar*: survey data (TTJS 2011; Mori et al. 2011), *red line*: 3D model, *green line*: Q3D model, *black line with circle*: 2D model, position of location number is denoted in Fig. 9.1)

Table 9.1 The accuracy of maximum inundation height hindcast (unit: m)

	2D			Q3D			HYBRID 3D/2D		
	RMSE	MAE	STD	RMSE	MAE	STD	RMSE	MAE	STD
Kamaishi	3.1	2.5	1.9	2.4	1.7	1.9	3.5	2.6	2.2
Ryoishi	2.9	2.4	3.3	3.3	2.6	3.9	2.8	2.6	3.0
Heita	3.7	3.6	1.2	1.3	1.2	1.3	3.7	3.7	1.6
Mean	3.3	2.6	4.7	2.9	2.0	5.5	3.5	2.7	4.8

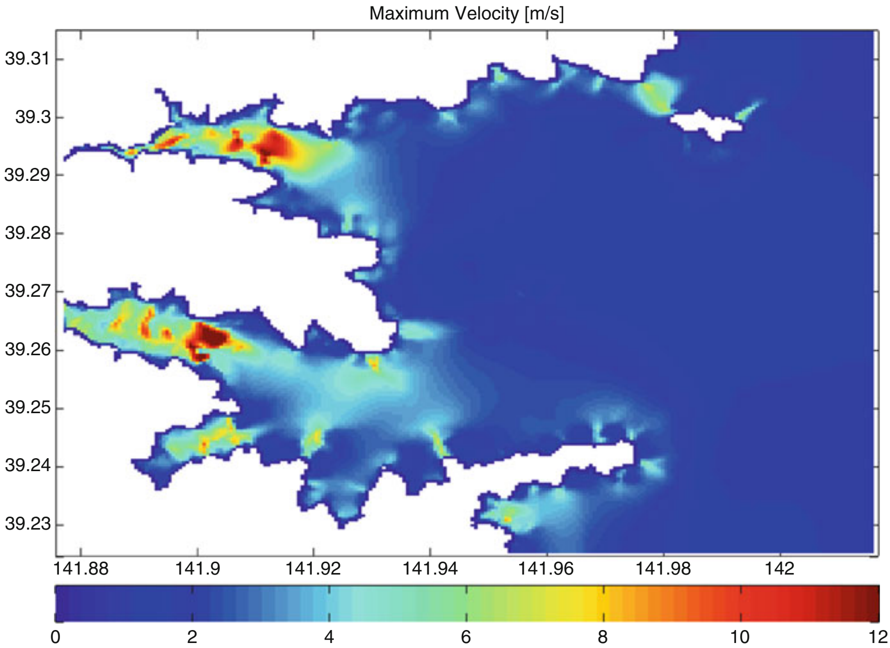

Fig. 9.4 Maximum depth integrated horizontal velocity by the Q3D model

models overall. As a result, the depth-averaged momentum can vary quite significantly depending on the numerical model. Due to page limitation, there is no space to discuss the accuracy of velocity but Fig. 9.4 shows the maximum velocity distribution by the Q3D model. The maximum velocity is reached at 12 m/s and the high velocity regions are located near shore and landside. The numerical modelings of these regions are sensitive to local acceleration of fluids and are highly dependent on the numerical scheme.

Concluding the above discussion, the tsunami wave reduction by offshore breakwater can be estimated in the range of 20 % error and it can be improved by further development of the numerical scheme. The reduced tsunami energy in Kamaishi Bay gives different damage characteristics compared to Otsuchi Bay, which will be discussed in the next section.

9.3.2 Damage and Recovery Relations Based on Tax Revenue

Otsuchi village in Iwate Prefecture is located just north of Kamaishi city in the Sanriku ria coast area. The water depth in the middle of Otsuchi Bay is similar to that of Kamaishi, so that the previous Showa Sanriku tsunami in 1933 and expected tsunami heights were similar for the two locations. For example, the measured inundation heights from the Showa Sanriku tsunami at Otsuchi Bay and Kamaishi Bay were 5.4 m and 6.0 m, respectively. However, the offshore tsunami breakwater was constructed at Kamaishi Bay after that thus the difference of damage can be mainly regarded offshore breakwater effects. A 6.4 m high onshore breakwater protected Otsuchi village. An offshore breakwater protected Kamaishi city.

These two locations show large differences as shown in Fig. 9.5. Two pictures of Kamaishi port and Otsuchi port were taken at April 2011. The damage of Kamaishi port is significantly smaller than Otsuchi port, qualitatively. Collapse of small structures can be seen but larger buildings were relatively undamaged on the Kamaishi waterfront. On the other hand, the most of structures and onshore breakwaters near the port in Otsuchi were totally destroyed as shown in Fig. 9.5b. The fatality ratios of Otsuchi area and Kamaishi area are 8.12 and 2.63 %, respectively. Although the damage to Kamaishi port was severe, it was not at the level of destruction observed at Otsuchi, reinforcing the conclusion that the offshore breakwater significantly reduced the extent of damage in this area.

Based on analysis of numerical calculations, it can be seen that the influence of offshore tsunami breakwaters significantly reduced the tsunami impact on onshore damage, in comparison with other similar areas such as Otsuchi. Not considering the cost of construction, effectiveness of tsunami mitigation through the use of breakwaters was verified for the first time by the experience of the Tohoku Earthquake tsunami. The degree of damage to the residential area strongly influence on the recovery of the devastated area. Table 9.2 and Fig. 9.6 show the time history of local tax at Kamaishi city and Otsuchi village based on public release, respectively. Kamaishi city includes the southern part of Otsuchi bay, Ryoishi Bay and

Fig. 9.5 Difference of damage at two different bays (April, 2011); Kamaishi port (*left*; **a**) and Otsuchi port (*right*, **b**)

Table 9.2 Changes of local tax revenue at Otsuchi and Kamaishi from 2008 to 2013

	Kamaishi		Otsuchi	
	Total revenue (million Yen)	Ratio to 2008	Total revenue (million Yen)	Ratio to 2008
2008	48.878	1.000	11.747	1.000
2009	41.515	0.849	11.436	0.974
2010	41.266	0.844	10.606	0.903
2011	33.174	0.679	5.084	0.433
2012	35.394	0.724	4.813	0.410
2013[a]	35.203	0.720	5.693	0.485

[a]2013 is estimated value

Source: White Papers issued by Otsuchi and Kamaishi cities; financial data available in http://www.town.otsuchi.iwate.jp/bunya/zaisei_jyoho/ and http://www.city.kamaishi.iwate.jp/index.cfm/10,0,79,html respectively

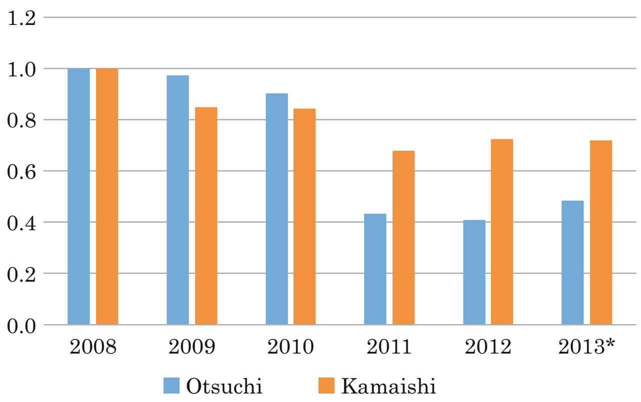

Fig. 9.6 Local tax revenue at Otsuchi and Kamaishi normalized at 2008 (Source: White Papers issued by Otsuchi and Kamaishi cities; financial data available in http://www.town.otsuchi.iwate.jp/bunya/zaisei_jyoho/ and http://www.city.kamaishi.iwate.jp/index.cfm/10,0,79,html respectively)

Kamaishi Bay. Therefore, some part of the damage in the Otsuchi Bay is included in Kamaishi city. The local tax revenue is the sum of city tax, property tax, light vehicle tax and tobacco tax and is one of representative values of local activity. The local tax revenue dropped 28 % from 2008 to 2012 in Kamaishi city but such reduction was more severe in Otsuchi village. The local tax revenue decreased 59 % from 2008 to 2012. The loss of local tax revenue mainly caused by reduction to city tax and property tax (80 %). Once residence disappears and the tax revenue is decreased, it is difficult for the local economy to recover. The minimum protection of the area is necessary even for severe hazards.

9.4 Conclusion

The 2011 Tohoku Earthquake Tsunami was the first case where modern, well-developed tsunami countermeasures were put to the test for such an extreme event. One of the most important issues in natural science, engineering, and social science is to understand the relationships among tsunami forces, local damage, and the community resilience. For future improvement of tsunami disaster countermeasures much can be learned from this catastrophic event.

The damage to coastal structures, ports, houses, buildings, bridges and other infrastructure was strongly dependent on location and protection methods. Here we selected one typical area in the ria coastal region of Sanriku for study, Kamaishi, where an offshore tsunami breakwater was installed as an expensive hardware protection. The offshore tsunami breakwaters, which were partially destroyed, were still effective in mitigating the level of destruction in the Kamaishi port area. We quantitatively discussed the estimated error of the effectiveness of offshore breakwater protection by three different numerical methods, 2D, Q3D and 3D models. The validation results of maximum inundation height on the landside against survey results gave 20 % error of impact assessment of offshore breakwater depends on the numerical method. It indicates that further investigation of numerical modeling on the landside behavior of tsunami is necessary for understanding tsunami dissipation onshore. Furthermore, our analyses of numerical results indicate that such structural protection may have resulted in lower overall inundation heights and could avoid catastrophic destruction of the city. The local tax revenue indicates more than 30 % difference of economic impact due to offshore breakwater and its effect continues a few years after disaster.

From important lessons learned from the 2011 Tohoku tsunami, we have the opportunity to further vital preparation against tsunamis in future.

Acknowledgements We gratefully acknowledge efforts on the survey results of the 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) group. This study is dedicated to all who have been affected by the earthquake in Japan on March 11, 2011.

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Chapter 10
A Method to Determine the Level 1 and Level 2 Tsunami Inundation Areas for Reconstruction in Eastern Japan and Possible Application in Pre-disaster Areas

Abdul Muhari, Kentaro Imai, Daisuke Sugawara, and Fumihiko Imamura

Abstract After the 2011 tsunami, a new approach to land use planning was introduced and is starting to be applied in some areas of Japan. Depending on the characteristics of the tsunami hazard, an area that is likely to be affected by high-frequency but low-impact tsunamis is identified as a 'Level 1' tsunami inundation area. An area that is likely to be affected by low-frequency but high-impact tsunamis is identified as a 'Level 2' tsunami inundation area. The countermeasures adopted in the two areas are different. The improved design of physical structures will be used to minimize the medium-to-low impact of tsunamis on people and properties in tsunami inundation Level 1 areas. Because the coverage of the flooded area is much wider in tsunami inundation Level 2 areas, improvements to the evacuation facilities and better education are the major efforts to save lives because man-made structures may not be able to significantly reduce the potential risks. This paper proposes a method to distinguish the boundaries between tsunami inundation Level 1 and 2 areas. We first use numerical simulations to establish a framework that classifies areas as Level 1 or Level 2 in a post-disaster area. Next, we examine the possibility of applying similar techniques to a pre-disaster area. We demonstrate that distinguishing areas of tsunami inundation Level 1 and Level 2 is not only important for the reconstruction of the post-disaster areas but also necessary to mitigate future tsunamis in pre-disaster areas.

Keywords Tsunami area Level 1 • Tsunami area Level 2 • Numerical simulation • GIS modeling

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10.1 Introduction

Because the basic guidelines for reconstruction have stated that 'multiple defense' should be used to shape a disaster-resilient community (Reconstruction Agency of Japan 2011), a new act in Japan (Act No. 123/2011) that mandates tsunami-safe cities requires local governments to simulate the impacts of massive tsunamis in the development of zoning policy (Cyranosky 2012). Because of the implementation of this concept, two levels for potential tsunami-affected areas have been proposed as follows (e.g., Shibayama et al. 2013).

Tsunami area Level 1 (the Tsunami Protection level): These tsunami events represent events with a return period of several decades to slightly over 100 years. The Japanese expression that has been used in coastal engineering discussions would literally translate as a return period from 50–60 to 150–160 years. These tsunamis would generate relatively shallow inundation depths, typically less than 7–10 m.

Tsunami area Level 2 (the Tsunami Evacuation level): These events, in contrast, would be far rarer events, typically taking place at intervals between every few hundred and a few thousand years. The tsunami inundation depths would be much larger, typically over 10 m, but would include inundations of up to 20–30 m. Both the 2004 Indian Ocean tsunami and the 2011 Great Eastern Japan Earthquake and Tsunami would fall within this category.

In the post-disaster areas, the application of this concept is taking place by simply relocating people to higher ground if there are natural hills available nearby. In these locations, lowland areas will be elevated to the same height as the maximum tsunami flow depth generated by earthquakes with a return period less than 150 years. The high ground, where the new settlement will be located, should be higher than the maximum possible tsunami with a return period longer than centuries (e.g., Bureau of Reconstruction and Minami-Sanriku town 2012).

In the plains, however, tsunamis can penetrate farther inland. The determination of Level 1 and Level 2 areas, therefore, should be conducted in a more careful manner. The absence of natural hills implies the need to construct more artificial barriers along the shore, which attempt to reduce the damage to property and the loss of lives (e.g., Sendai Reconstruction Bureau 2012). The determination of tsunami Level 1 and Level 2 areas in this context plays a fundamental role as the basis for the land use planning.

This article proposes a method to determine tsunami Level 1 and Level 2 areas. In the first part, we demonstrate the use of numerical simulations to provide input for GIS modeling to classify post-disaster areas. We model tsunamis from historical and future possible earthquakes that have affected or may affect the Sendai plain. We will show the different impacts of the tsunamis in the existing and in the future topographic conditions by following the reconstruction plan of Sendai City. We developed an improved GIS framework to estimate the affected ratio and the statistical description of variable tsunami flow depths that impact a particular location inside the tsunami inundation area.

Based on the exercises in the post-disaster area, we apply a similar technique in a pre-disaster area. Because the act mandating simulation-based zoning will be applied in all coastal cities in Japan, the determination of the tsunami Level 1 and Level 2 areas is also crucial in pre-disaster areas. The future improvement of structural and non-structural countermeasures should rely on such information because relocating the existing residents of coastal areas might be difficult. The results presented in this paper are expected to be applied not only in Japan but also in the other tsunami-prone areas worldwide.

10.2 Data and Modeling Framework

10.2.1 Input Data for Numerical Model

We conducted numerical simulations in two locations to represent post- and pre-disaster areas. Sendai City was chosen as an example of a post-disaster area. The city is now applying the concept explained in the previous section to the reconstruction process following the 2011 tsunami event. The numerical simulation on the Sendai plain was performed using a set of nested grid systems (Fig. 10.1). The data we used in regions 1–4 were obtained from the Disaster Management Council (Cabinet Office of Japan) and have accuracies of 1,350 m, 450 m, 150 m and 50 m. We resampled these data into 1,215 m, 405 m, 135 m and 45 m cell sizes for use in regions 1, 2, 3 and 4, respectively. In the smallest region, we used the surveyed ground elevation data of the Geospatial Information Authority in Japan prior to the 2011 Japan tsunami. These digital elevation data have an original accuracy of 5 m, but they were gridded into 15 m cells to ensure the stability of the numerical model.

For the pre-disaster situation, Owase City in Mie Prefecture, Japan, located in the south of Honshu Island, was selected as a case study. Presently, this city and all areas in the south of Japan in general are facing the potential of a large earthquake that could generate a huge tsunami from the Tokai, Nankai and Tonankai troughs (Earthquake Research Committee 2005). The selection of this area as a case study is therefore highly relevant. To construct the numerical domain, we used the topographic data obtained from the local government of Owase City. A high-resolution Digital Terrain Model (DTM) and a Digital Surface Model (DSM) are available, with 10 m grid accuracy. In addition, the other input data used to establish a nested grid system with five sub-domains are also available with grid sizes of 810 m, 270 m, 90 m and 30 m (Fig. 10.2).

The numerical simulation utilized the linear and nonlinear shallow water equations, which were discretized in the leapfrog scheme (Imamura 1996). For both areas, the tsunami was modeled for 3 hours of simulation time. The effect of the bottom roughness of the Sendai plain was considered by assigning a homogeneous value of 0.025 for the bottom friction coefficient. This value represents the condition of smooth sand or natural channels in good condition (Linsley and Franzini

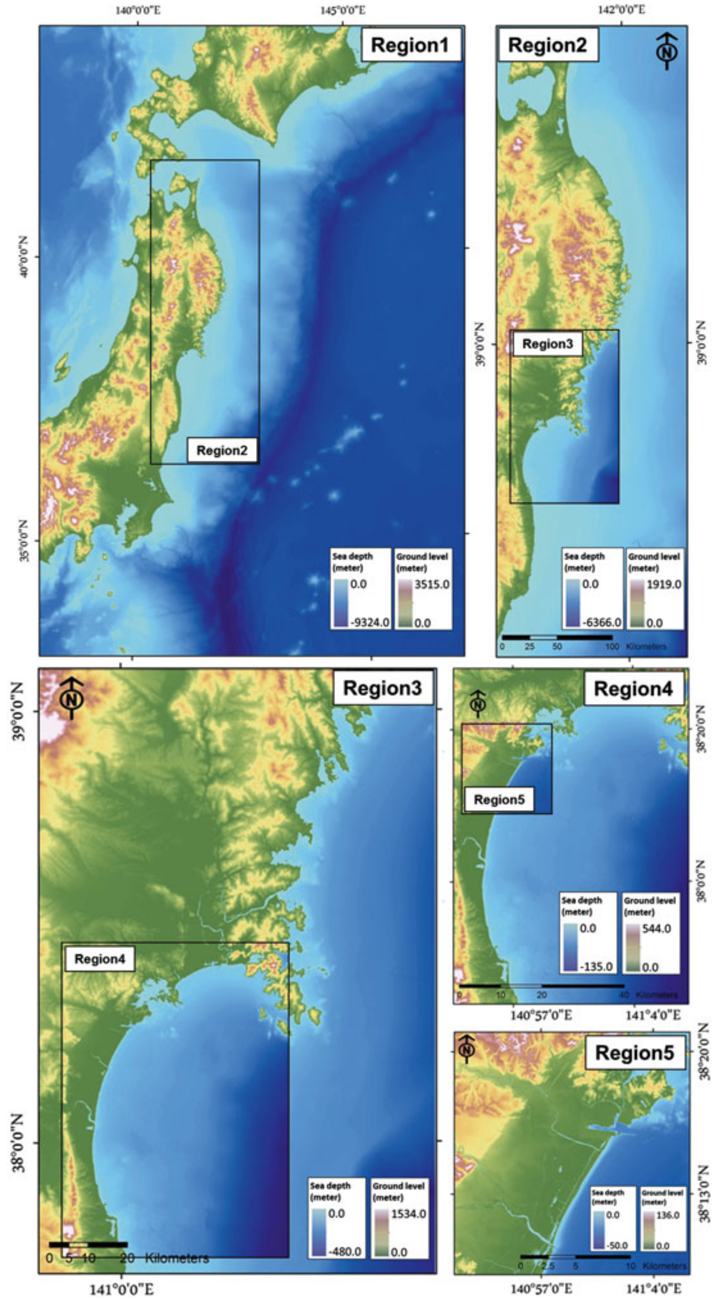

Fig. 10.1 The designed nested grid system as the input for tsunami modeling for the Sendai plain

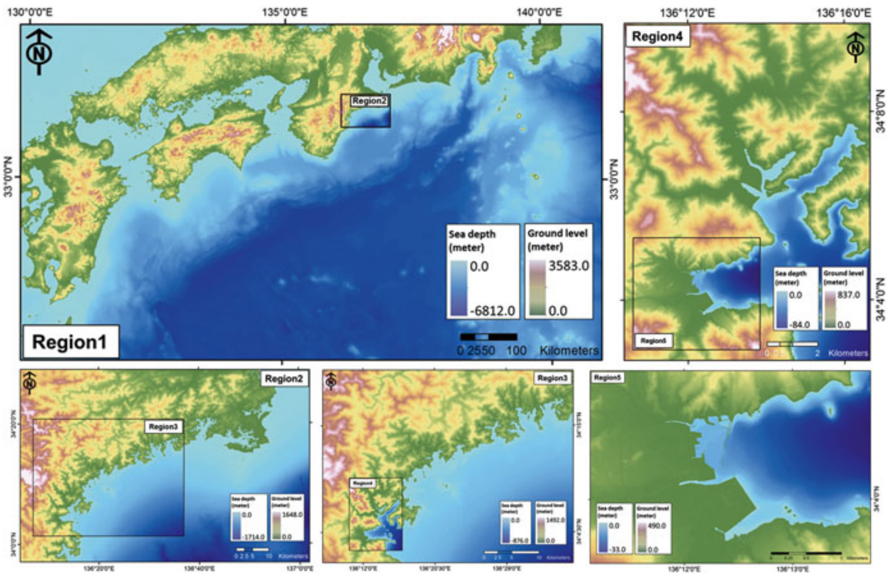

Fig. 10.2 The designed nested grid system as the input for tsunami modeling in Owase City

1979). This assumption was based on the present condition of the Sendai plain, where there are almost no houses or the other structures remaining after the 2011 tsunami. In Owase City, conversely, houses, buildings and the other man-made structures are plentiful. Therefore, the effect of those structures should be taken into account in the numerical model. We decided to integrate the macro-roughness features, such as houses, sea wall and others, into the digital elevation model. This is a practical way to represent the actual city condition in a pre-disaster situation (Muhari et al. 2011).

10.2.2 Tsunami Source Model

The tsunami source models in both locations were determined by using a deterministic method based on the available historical data in each area. For the Sendai plain, tsunamis coming from the northern part of the Japan Trench (northeast region of Honshu Island) have lower impacts compared those occurring in the central and southern parts of the Japan Trench, as indicated by the tsunami run-up database (Iwabuchi et al. 2008). However, only limited historical data were available for earthquakes in the central and southern parts of the Japan Trench. Recently, paleo-tsunami research has shown evidence of past tsunami inundations of the Sendai plain (e.g., Minoura et al. 2001; Sugawara et al. 2013), but the reliability of the estimated magnitudes is still being discussed (e.g., Namegaya and Satake 2014).

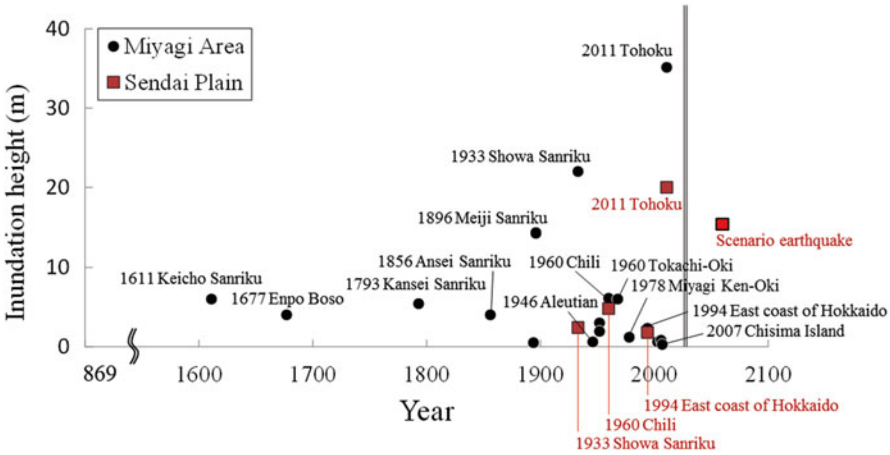

Fig. 10.3 The historical records of maximum tsunami inundation heights on the Sendai plain (*red rectangles* and names) and in all areas of the Miyagi Prefecture (*black circles* and names)

To start the numerical model, we used the earthquake events available in the historical records for the Sendai plain (Fig. 10.3). The Miyagi-Ken Oki earthquake was considered to be representative of M 7 class earthquakes. This earthquake was modeled with variable fault parameters, following the Technical Reports of the National Seismic Hazard Maps for Japan (NIED 2009), and it is the most likely class of earthquake, with a 99 % probability of occurring off the Miyagi coast every 30 years on average (Earthquake Research Committee 2005). Next, the AD 869 Jogan earthquake tsunami (Minoura et al. 2001; Sugawara et al. 2013; Namegaya and Satake 2014) was modeled to represent M8 class earthquakes in the region. Finally, the 2011 East Japan earthquake tsunami (Sugino et al. 2013) was modeled to represent M 9 class earthquakes, where the rupture area occupied almost all sections of the Japan Trench in front of the Tohoku and Fukushima coasts. These events were then expanded by changing the tensor parameter for the single fault model (up to 8.4 Mw) and up to 9.2 Mw for the multiple fault models, as shown in Table 10.1. The scenarios that used the single fault model were located mostly off the Miyagi and Fukushima coast, while the scenarios with multiple fault models included areas from northern Tohoku southward to Ibaraki Prefecture.

In total, 38 earthquake scenarios were modeled for the Sendai plain. Among these, 26 cases were M 7 class earthquakes, which considered 21 scenarios based on the probability analysis provided by NIED (2009). Nine cases were M 8 class earthquakes, and three cases represented M9 class earthquakes, including the 2011 event. We modeled the seabed displacements using the formula provided by Okada (1985), the results of which are given in Fig. 10.4 for earthquakes larger than 8 Mw.

Similarly, the historical earthquakes in the Tokai and Tonankai regions were modeled as the basis for further scenarios in Owase City. The 1498 Meio earthquake (M 8.6; Aida 1981a), the 1605 Keicho earthquake (M 7.9; Aida 1981a), the 1707

Table 10.1 Parameters of the extended earthquake scenario along the Tonankai

No	Magnitude (Mw)	Latitude	Longitude	Length (m)	Width (m)	Slip (m)	Strike (°)	Dip (°)	Rake (°)	Depth
1	8.2	39.34	143.84	208,929.61	81,658.24	2.94	194.18	13.13	90	15,000
2	8.4	39.60	143.93	269,153.48	94,188.96	3.94	194.18	13.13	90	15,000
3	8.1	36.95	143.19	184,077.20	76,032.63	2.54	219.07	13.11	90	15,000
4	8.4	37.25	143.50	269,153.48	94,188.96	3.94	219.07	13.11	90	15,000
5	8.0	39.35	142.45	162,181.01	70,794.58	2.20	193.75	18.88	90	25,000
6	8.2	39.56	142.52	208,929.61	81,658.24	2.94	193.75	18.88	90	25,000
7	8.0	39.35	142.45	162,181.01	70,794.58	2.20	193.75	18.88	90	45,000
8	8.2	39.56	142.52	208,929.61	81,658.24	2.94	193.75	18.88	90	45,000
9	8.9	40.10	143.08	241,228.87	134,586.04	8.24	189.45	18.00	90	27,500
		38.44	142.72	265,760.01	134,586.04	8.24	201.30	20.00	90	27,500
10	9.1	40.10	143.08	241,228.87	155,238.70	11.06	189.45	18.00	90	27,500
		38.44	142.72	405,665.86	155,238.70	11.06	201.30	20.00	90	27,500
		35.73	141.40	6,235.00	155,238.70	11.06	199.43	20.00	90	27,500
11	9.2	41.04	143.40	142,295.00	166,724.72	12.82	194.40	22.00	90	27,500
		40.10	143.08	241,230.00	166,724.72	12.82	189.45	18.00	90	27,500
		38.44	142.72	357,785.00	166,724.72	12.82	201.30	20.00	90	27,500
12	2011 earthquake	Sugino et al. (2013)								

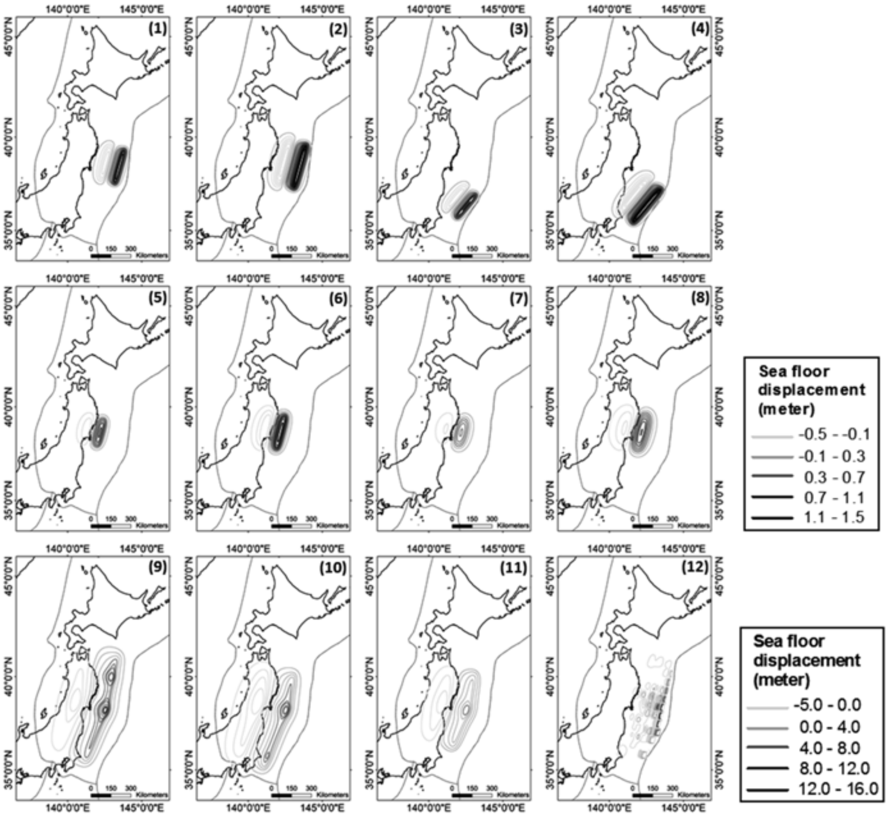

Fig. 10.4 The results of the seabed displacement model for earthquakes with magnitudes larger than 8 Mw in the Tohoku region. The *upper* legend is used for (1) to (8) and the *lower* legend is used for (9) to (12)

Hoei earthquake (M 8.4; Ando 1975; Aida 1981a, b; Furumura et al. 2011), the 1854 Ansei Tokai earthquake (M8.4; Ando 1975; Aida 1981a) and the 1944 Showa Tonankai earthquake (M7.9; Kanamori 1972; Ando 1975; Inouchi and Sato 1975; Ishibashi 1981; Aida 1979) were modeled, and the results of the their seabed displacement models are given in Fig. 10.5.

Those historical events were then enhanced by extending the tensor parameters to larger magnitudes, up to M 9.0. In addition, we simulated the scenario recently developed by the Center of Disaster Management, Cabinet Office of Japan. This scenario accommodates slip variability in the shallow sediment along the Tokai, Tonankai and Nankai trenches (Cabinet Office of Japan 2013). In contrast to the Sendai plain, more historical data are available for the southern part of Japan. Thus, the earthquake scenario could be extended to 137 cases. Half of these cases were M 7 class earthquakes, 30 % were M 8 class earthquakes, and the other 20 % were M 9 class earthquakes. Among the total number of modeled scenarios, only 64 scenarios generated tsunami inundation of Owase City, and these were used for further analysis (the earthquake parameters are given in Table 10.2 at the end of this chapter).

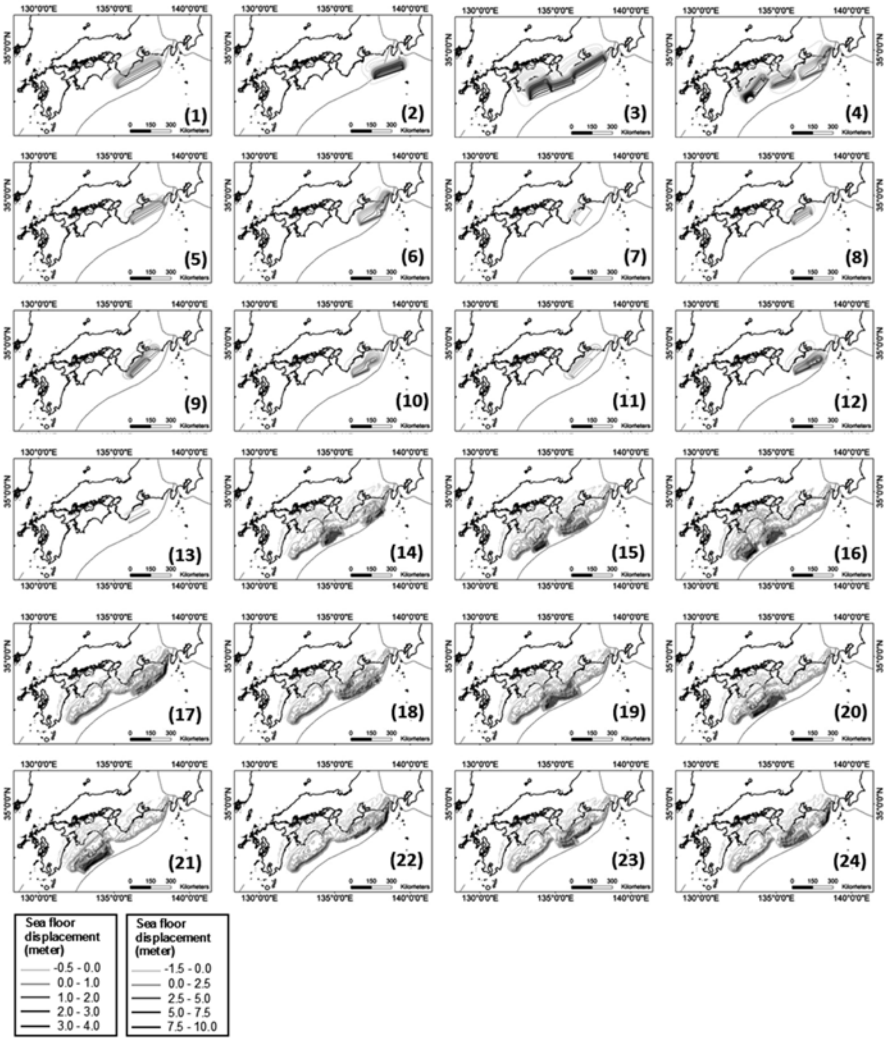

Fig. 10.5 The results of the seabed displacement models for earthquakes with magnitudes larger than 8 Mw in the Tokai and Tonankai regions, including the new scenario provided by the Cabinet Office of Japan (2013). Legend on the right hand side is used for (1) to (13) and the legend on the left hand side is used for (14) to (24)

10.2.3 Framework of the Geographical Information System

The determination of the areas of Level 1 and 2 tsunami inundation was conducted in the GIS platform (Fig. 10.6). This concept was developed by following Strunz et al. (2011) and Wegscheider et al. (2011), who estimated the risk of being affected by tsunamis as the ratio the number of tsunami scenarios that affect an area to the total number of simulated cases. We improved their GIS model not only to estimate

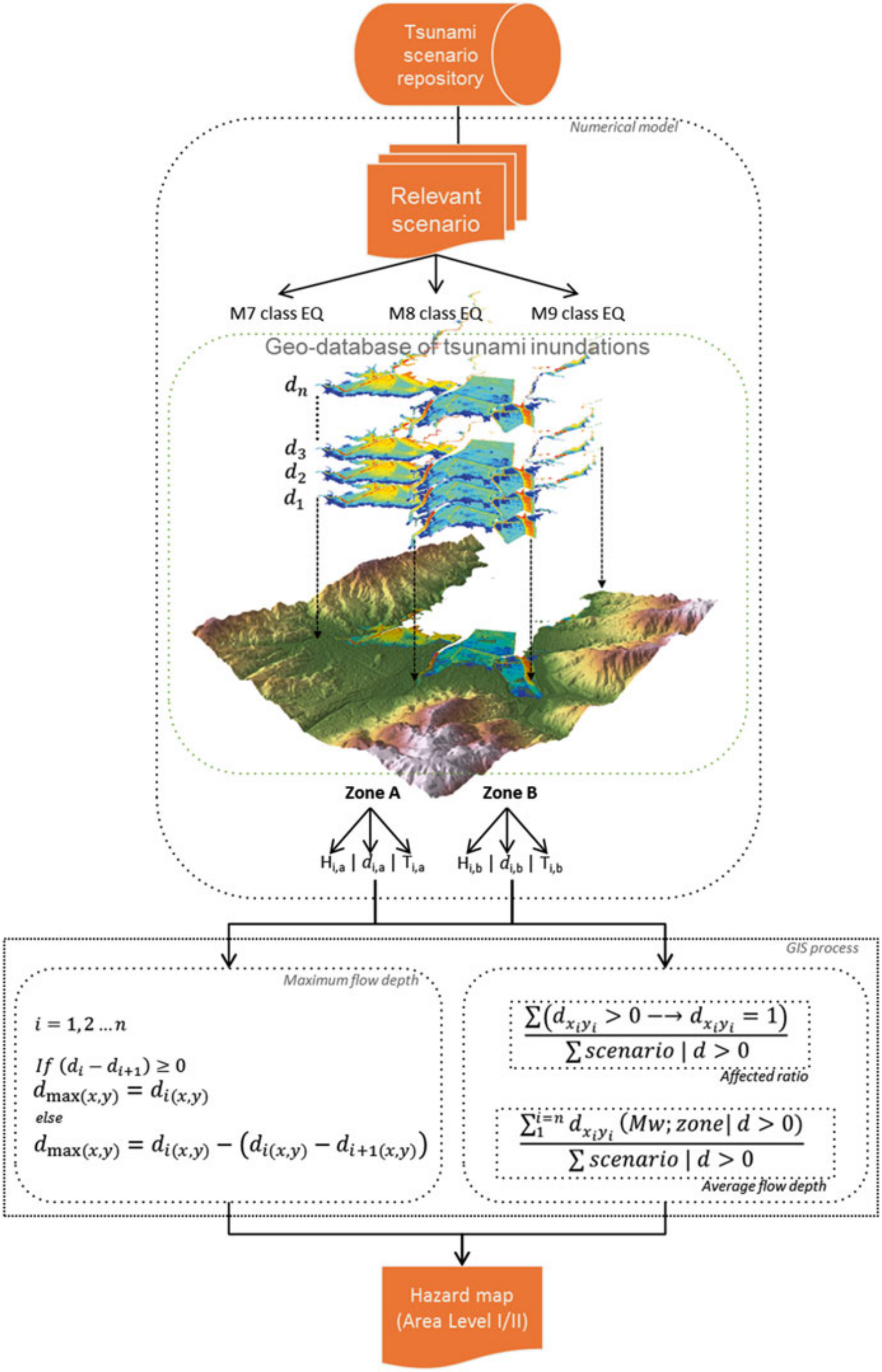

Fig. 10.6 The GIS framework of the tsunami modeling results to determine the areas of Level 1 and Level 2

the affected ratio but also to statistically analyze the tsunami height that affected a particular place in a given simulated scenario. By doing so, we could estimate how many times a location was potentially affected by a pool of tsunami scenarios with a range of earthquake magnitudes and a range of flow depths.

There are two major outputs of the GIS process, which are as follows. (1) The tsunami affected ratio: this map indicates how many times (accumulation) each pixel inside the tsunami area is affected by a tsunami relative to the total number of simulated scenarios. (2) The maximum tsunami inundation depth: this map illustrates the maximum tsunami height of the total simulated scenarios. The maximum tsunami inundation depth at a particular point might be different than the result obtained in the other places inside the same tsunami inundation area because the energy radiation of the modeled tsunami is highly dependent on various aspects in the earthquake parameters, such as strike and slip distribution, which will be discussed further in the next sub-chapter.

The maps were developed by first entering all of the simulation results into a geo-database. This database consists of all the simulated tsunami parameters, such as the maximum tsunami heights, maximum tsunami flow depths and arrival times of each scenario at the coast. Next, the map showing the affected ratio was developed by using the combine resample and raster calculator tools in ArcGIS software. The tools were compiled in an iterative scheme in a model builder frame to automatically obtain the affected ratio in each study area.

Similarly, the maps of the maximum tsunami flow depth were developed by using raster calculator in an iterative scheme in the model builder frame. The iterative process checked the value of the tsunami flow depth at a particular location against a given raster file to determine whether the value was higher than the values at the same location from the other files. By iterating this selection process for all the files, the software could find the maximum tsunami flow depth at all locations inside the tsunami inundation area from all simulated scenarios.

In the figure above, *d* denotes the inundation depth in meters; suffix *i* (1, 2, 3…n) represents the number of the modeled scenario. H denotes the maximum tsunami height at the coast. T represents the tsunami arrival time in seconds. Zone A is the Tohoku region and Zone B is the Tonankai region.

10.3 Discussion

10.3.1 Tsunami Sources

We analyzed the maximum simulated tsunami height and maximum tsunami flow depth produced by different fault models from both areas. The results were compared to each other by plotting the maximum simulated tsunami height and flow depth relative to the earthquake parameters, i.e., magnitude, the maximum co-seismic slip, and the fault width. These three parameters were chosen because they significantly influence the resulting simulated tsunami parameters. For instance, the

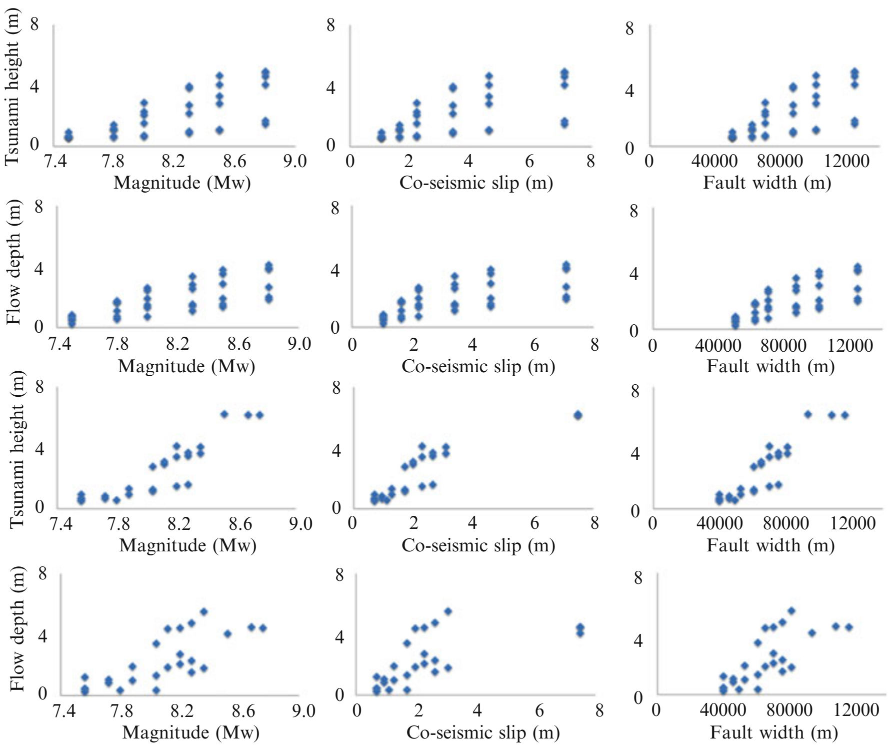

Fig. 10.7 The comparisons between the simulated tsunami heights and flow depths correlated with the earthquake magnitudes, the maximum co-seismic slips and fault widths

earthquake magnitude affects the tensor parameters. The maximum co-seismic slips and the fault widths act to increase the maximum height (and subsidence) of the sea floor displacement and the tsunami period, respectively.

Based on Fig. 10.7, the tsunami heights and flow depths resulting from scenarios that used single rectangular faults increased linearly with magnitude, maximum co-seismic slip and fault width. In these cases, less uncertainty was found in terms of the resulting maximum tsunami heights at the coast and the flow depths relative to the earthquake source parameters.

Conversely, in the case of earthquakes with multiple rectangular faults, we obtained discrepancies in the maximum simulated flow depths, which were not always linearly correlated with the earthquake source parameters (Fig. 10.7). This means there is still a similar trend between the earthquake source parameters (magnitude, the maximum co-seismic slip and fault width) and the resulting maximum tsunami height at the coast, but the tsunami flow depth may be variable, depending on the built environment of the city. This observation suggests that the maximum tsunami height at the coast does not always indicate the maximum flow depth or inland run-out.

Another consideration in the case of the simulations using the multiple-fault model is the spatial distribution of the slips. The scattered slip rate may cause the maximum energy radiation to not directly face the area of interest. Thus, increases in the earthquake magnitude and maximum co-seismic slip may not cause linear increases in the resulting tsunami height and flow depth.

10.3.2 Model Application in the Post-disaster Area

On the Sendai plain, all M 7 class earthquakes generated insignificant inundations. This result is consistent with the official hazard maps prior to the 2011 East Japan earthquake, which predicted the tsunami hazard zone to be less than 1 km from the shore. The impacts of the minor tsunamis generated by the M 7 class earthquakes coming from the offshore Miyagi and Fukushima prefectures should be diminished by 3-m-high coastal dikes and a 250-m-wide pine forest along coastal areas. However, the M 8 and the M 9 class earthquakes, excluding the 2011 event, generated large tsunamis that flooded areas comparable to the one caused by the 2011 East Japan tsunami (Fig. 10.8).

The simulation results indicated that the existing topographic condition allowed the penetration of tsunami inundations up to 6 km inland because the average ground height up to the inundation limit of the 2011 tsunami was less than 2 m. Thus, the tsunamis generated by M 8 to M 9 class earthquakes can reach far inland once they overtop the coastal dike and pass through the coastal forest.

Because of the huge exposed area, the Sendai City office for reconstruction has decided to localize the impact of future tsunamis to only the area near the coast. In a post-disaster situation, fortunately, the modification of land use is possible because

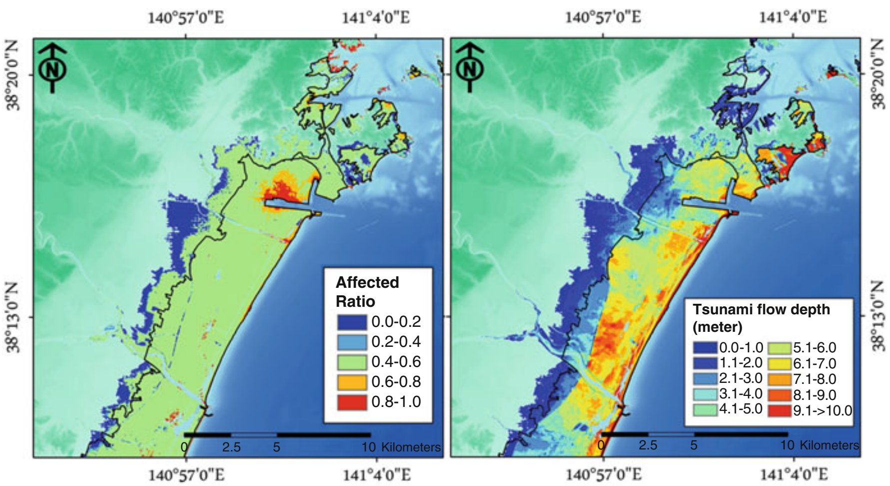

Fig. 10.8 The affected ratio (*left*) and the maximum tsunami flow depth (*right*) of the area up to 6 km from the coastline of the Sendai plain, based on the simulated tsunami inundations. The *solid black line* is the observed maximum inundation from the 2011 East Japan tsunami

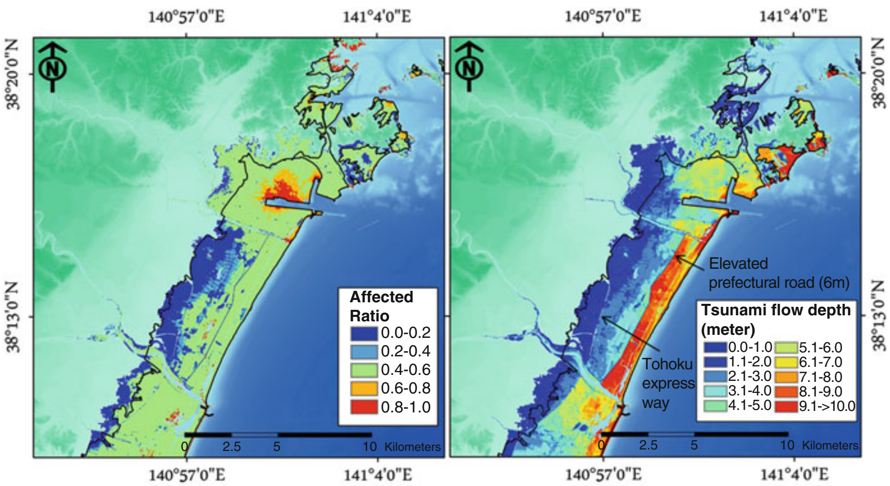

Fig. 10.9 The affected ratio (*left*) and the maximum simulated tsunami flow depth (*right*) of the Sendai plain by considering the new land use

there is almost no settlement remaining in the tsunami-affected area. The new land use will apply multi-layer tsunami protection, which consists of 7.2 m high coastal dikes and 6 m high elevated roads for areas located 1 km from the shore and the existing Tohoku expressway (Fig. 10.9). The configuration and design height of these structural protections are determined based on the simulation of the 2011 Japan tsunami, using the earthquake scenario from Imamura et al. (2012). The numerical simulations for both the existing and future topographic conditions conducted by Koshimura et al. (2013) show that the multiple barriers reduce the tsunami energy significantly. Thus, the remaining waves are expected to be less than 2 m high if the tsunami overtops the elevated prefectural road (Sendai Reconstruction Bureau 2011).

By taking into account the existence of the multiple barriers in the topographic input for numerical model, we obtained a pattern consistent with the research mentioned previously. With the assumption that the barriers withstand the tsunami, the simulated tsunami inundations from scenarios of M 8 and M 9 class earthquakes, excluding the 2011 event, were localized to the area between the coastline and the elevated prefectural road. However, in contrast with the previous research (Koshimura et al. 2013), our simulated tsunami inundations (other than the 2011 event) indicated that tsunamis from M 9 class earthquakes could still penetrate up to the maximum inundation distance of the 2011 East Japan event, even if the multiple barriers functioned properly (Fig. 10.9). In this case, it should be noted that there are always uncertainties in simulated tsunami heights and flow depths. The recent study of MacInnes et al. (2013) argued that variable results could be obtained if modelers use different slip distributions to model a tsunami. Additionally, the probability of the barriers being damaged by the tsunami is not included in the numerical model, as indicated in Koshimura et al. (2013). In this sense, estimating the error margin can be useful for adjusting the design height or determining the range of acceptable risk to address limitations of the technology in reducing the impacts of future disasters.

Based on the above numerical results, the area from the coast to the elevated prefectural road should not be resettled. Although the multiple barriers reduce the effects of the M 7 class earthquakes, which are likely to occur more frequently off the Miyagi (Sendai) coast, the inundations generated by the M 8 and M 9 class earthquakes can be amplified by the existence of barriers and thus increase the risks.

For the area between the prefectural road and the Tohoku expressway, our numerical simulations indicated that 40 % of the 14 total scenarios of M 8 and M 9 class earthquakes could still affect this area with maximum and average simulated tsunami flow depths of 4.3 m and 2 m, respectively. As highlighted through the developed fragility curves for Miyagi Prefecture by Koshimura et al. (2013), this area may still be used for non-residential activities, including factories with reinforced concrete buildings.

The above observations are consistent with the decisions made by the Sendai City Government. The area between the coastline and the elevated prefectural road has been declared a tsunami Level 1 area, where no resettlement is allowed. The area between the prefectural road and the maximum tsunami inundation from the 2011 event has been declared a tsunami Level 2 area. This new zoning policy has now been applied to the reconstruction and in the official tsunami evacuation plan in Sendai City (Fig. 10.10).

10.3.3 Model Application in the Pre-disaster Area

In Owase City, only 64 of the total 137 simulated tsunamis generated inundations. Among those, the 13 cases that reached the maximum inundation distance originated from earthquakes with magnitudes larger than 9.0 Mw. Similar to Sendai, earthquakes with magnitude 9.0 Mw have never been recorded in the past. The historical flow-depth data in Owase City indicate a maximum value of 4 m, which has been correlated with M 8 class earthquakes in the past. Our modeling results from M 8 class earthquakes were consistent with these historical data. By taking the median of the simulated flow depths, the modeling results can fairly accurately reproduce the historical tsunami flow depths in Owase City (Fig. 10.11).

We include the results of the M 9 class earthquakes for comparison in Fig. 10.11. Here, we can see a significant discrepancy between the historical records and the potential maximum tsunami flow depths that may occur in the future. This condition is similar to the situation in Sendai prior to the 2011 tsunami event. There were no records above 5 m available in the historical data when the old hazard map of the Sendai plain was developed. Based on the 2011 tsunami, therefore, the results of the present study are fundamental to updating the existing hazard maps and the evacuation plan in Owase City.

Fig. 10.10 The new tsunami evacuation map (upper figure) and land use that includes the multiple barriers (Lower figure) in Sendai City (Source: Sendai Reconstruction bureau, 2011)

We overlaid the simulated inundations from all classes analyzed in the developed GIS framework. The maximum simulated tsunami flow depths and the affected ratios are given in Fig. 10.12.

The maximum tsunami flow depth in Fig. 10.12 highlights the vulnerability of the northern part of Owase City. This area could potentially be inundated by an average 5 m tsunami. Although there is a breakwater present, it would not significantly reduce the tsunami impact on the area behind. In contrast, the southern part of Owase City would experience lower tsunami flow depths, although the inundation distance appears to be wider. This is due to the different ground level heights between the reclamation area in the north and the southern part of Owase City. The average ground level height in the area near the coast in the northern part of Owase city is 2 m, whereas in the southern part, the average ground level is 3.5 m. However,

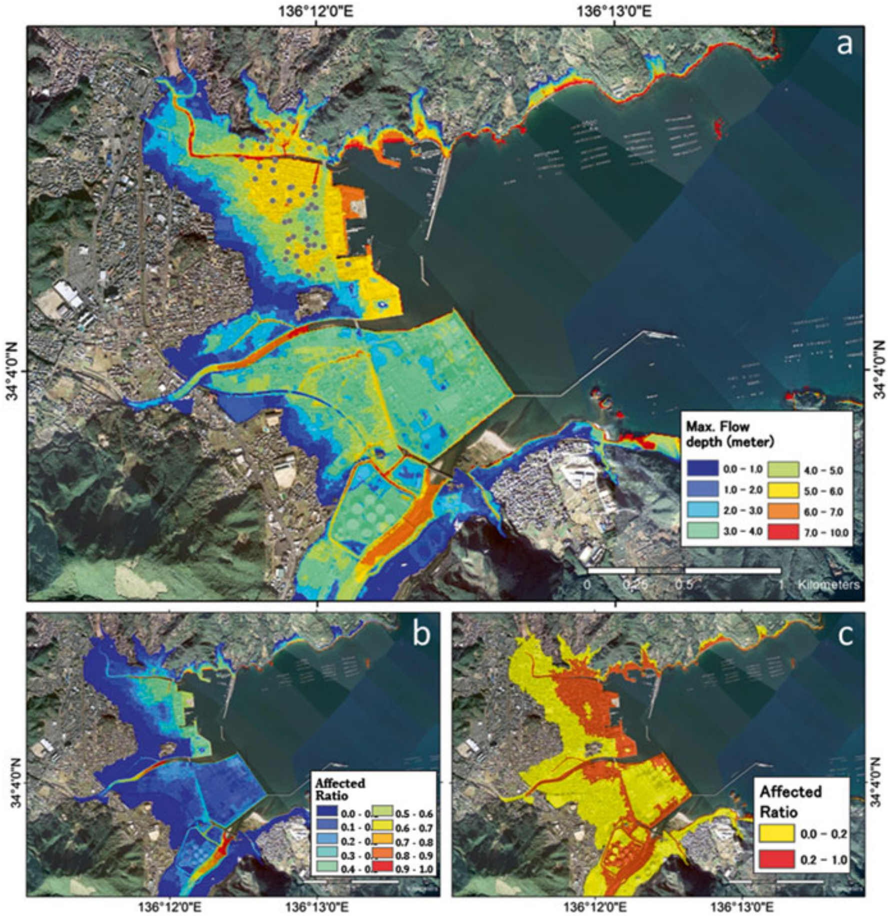

Fig. 10.11 The comparison between the historical data with the mean, median and the maximum simulated flow depths

the existence of large rivers, particularly the one in the southernmost part of Owase City, enables tsunamis to penetrate further inland by overstepping the riverbanks.

The affected ratio of each pixel is presented in Fig. 10.12b The results indicate that the northern part of the city is impacted by almost 80 % of the 64 scenarios. These simulated scenarios involved earthquakes with magnitudes greater than 7.7 Mw, which are highly likely to occur in the near future. We then separated the areas that were affected by M 9 class earthquakes (20 % of the affected ratio) from the areas that were impacted by almost all scenarios involving M 7 and M 8 class earthquakes (80 % of the affected ratio). We attempt to distinguish between the areas affected by the high-frequency tsunamis and areas that are likely to be flooded only

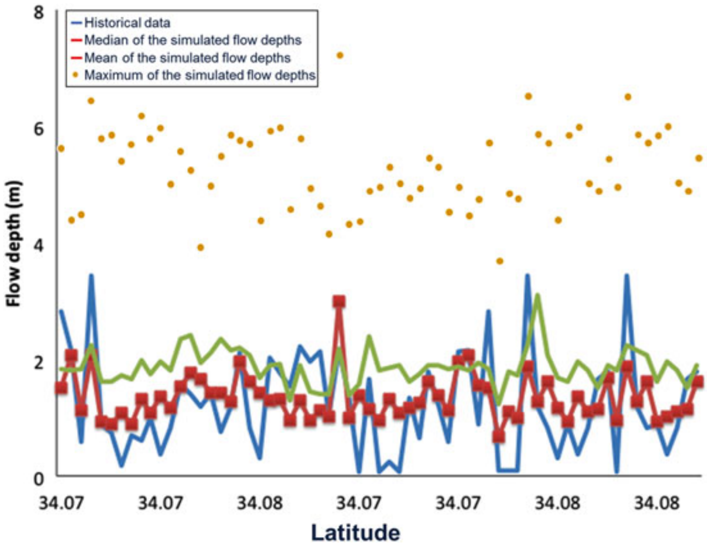

Fig. 10.12 The results of the maximum tsunami flow depths and affected ratios in Owase City. *Gray dots* in (**a**) indicate locations of the observed flow depths from historical data

by the M 9 class earthquakes (which are less likely to occur). M 8 class earthquakes in the southern part of Japan have an 88 % occurrence probability in Tokai (in the next 30 years) and a 72 % in the Tonankai region (Earthquake Research Committee 2005). In this context, by referring to the definition of the tsunami inundation area Level 1, the zone indicated by the red color in Fig. 10.12c should be considered a Level 1 area and the area indicated by the yellow color Level 2. However, it should be noted that the Level 1 area still has a 20 % ratio of being impacted by tsunamis generated by M 9 class earthquakes, which amplifies the risk in this area. Given the existing conditions, therefore, the red-colored area should only be considered as the tsunami inundation area Level 1 in terms of the affected ratio variable. In terms of the hazard intensity, a range of tsunami flow depths generated by M 7 to M 9 class earthquakes should be considered. In this context, the improvement of the structural quality of buildings and other built environments in the Level 1 tsunami area may be urgently needed. Nevertheless, public education and exercises, which are already conducted in this city (e.g., Katada et al. 2006), should be continuously improved to obtain a more effective and efficient evacuation plan.

Although land use modifications and the construction of physical inland countermeasures may be difficult in a populated city in a pre-disaster situation, the results highlighted in this study may change if there are new countermeasures applied in Owase City.

Table 10.2 Details of the extended modeled earthquake scenario for Tohoku region

No	Magnitude (Mw)	Latitude	Longitude	Length (m)	Width (m)	Slip (m)	Strike (°)	Dip (°)	Rake (°)	Depth
1	7.5	138.10	34.00	86,000.00	50,000.00	1.04	242.00	30.00	90	1,000
2	7.5	141.75	34.18	86,000.00	50,000.00	1.04	287.00	30.00	90	1,000
3	7.5	134.74	32.68	86,000.00	50,000.00	1.04	250.00	20.00	90	100
4	7.5	138.39	34.39	86,000.00	50,000.00	1.04	240.00	25.00	90	100
5	7.5	137.35	33.88	86,000.00	50,000.00	1.04	242.00	7.00	90	2,300
6	7.5	136.40	33.17	86,000.00	50,000.00	1.04	250.00	25.00	90	100
7	7.7	139.41	35.02	62,690.00	57,147.86	1.40	147.10	33.76	90	15,000
8	7.7	138.41	34.47	68,500.00	57,147.86	1.40	205.80	30.00	90	40,000
9	7.7	135.52	33.85	110,917.48	57,147.86	1.40	256.63	28.64	90	40,000
10	7.7	137.29	34.63	110,917.48	57,147.86	1.40	219.91	27.80	90	15,000
11	7.8	138.10	34.00	126,000.00	62,000.00	1.63	242.00	30.00	90	1,000
12	7.8	141.75	34.18	126,000.00	62,000.00	1.63	287.00	30.00	90	1,000
13	7.8	134.74	32.68	126,000.00	62,000.00	1.63	250.00	20.00	90	100
14	7.8	138.39	34.39	126,000.00	62,000.00	1.63	240.00	25.00	90	100
15	7.8	137.35	33.88	126,000.00	62,000.00	1.63	242.00	7.00	90	2,300
16	7.8	136.40	33.17	126,000.00	62,000.00	1.63	250.00	25.00	90	100
17	7.9	139.41	35.02	62,690.00	65,917.39	1.88	147.10	33.76	90	15,000
18	7.9	138.41	34.47	68,500.00	65,917.39	1.88	205.80	30.00	90	15,000
19	8.0	135.82	33.90	162,181.01	70,794.58	2.20	256.63	28.64	90	15,000
20	8.0	138.10	34.00	162,000.00	70,000.00	2.20	242.00	30.00	90	1,000
21	8.0	141.75	34.18	162,000.00	70,000.00	2.20	287.00	30.00	90	1,000
22	8.0	134.74	32.68	162,000.00	70,000.00	2.20	250.00	20.00	90	100
23	8.0	138.39	34.39	162,000.00	70,000.00	2.20	240.00	25.00	90	100
24	8.0	137.35	33.88	162,000.00	70,000.00	2.20	242.00	7.00	90	2,300

(continued)

Table 10.2 (continued)

No	Magnitude (Mw)	Latitude	Longitude	Length (m)	Width (m)	Slip (m)	Strike (°)	Dip (°)	Rake (°)	Depth
25	8.0	136.40	33.17	162,000.00	70,000.00	2.20	250.00	25.00	90	100
26	8.1	139.41	35.02	62,690.00	76,032.63	2.54	147.10	33.76	90	15,000
27	8.1	138.41	34.47	68,500.00	76,032.63	2.54	205.80	30.00	90	15,000
28	8.3	139.41	35.02	62,690.00	87,700.08	3.40	147.10	33.76	90	15,000
29	8.3	138.41	34.47	68,500.00	87,700.08	3.40	205.80	30.00	90	15,000
30	8.3	136.25	33.98	237,137.37	87,700.08	3.40	256.63	28.64	90	15,000
31	8.3	138.10	34.00	237,000.00	87,000.00	3.40	242.00	30.00	90	1,000
32	8.3	141.75	34.18	237,000.00	87,000.00	3.40	287.00	30.00	90	1,000
33	8.3	134.74	32.68	237,000.00	87,000.00	3.40	250.00	20.00	90	100
34	8.3	138.39	34.39	237,000.00	87,000.00	3.40	240.00	25.00	90	100
35	8.3	137.35	33.88	237,000.00	87,000.00	3.40	242.00	7.00	90	2,300
36	8.3	136.40	33.17	237,000.00	87,000.00	3.40	250.00	25.00	90	100
37	8.4	138.41	34.47	68,500.00	94,188.96	3.94	205.80	30.00	90	15,000
38	8.4	136.43	34.02	269,153.48	94,188.96	3.94	256.63	28.64	90	15,000
39	8.5	139.41	35.02	62,690.00	101,000.00	4.57	147.10	34.00	90	15,000
40	8.5	138.41	34.47	68,500.00	101,157.95	4.57	205.80	30.00	90	15,000
41	8.5	136.64	34.05	305,492.11	101,157.95	4.57	256.63	28.64	90	15,000
42	8.5	138.10	34.00	305,000.00	101,000.00	4.60	242.00	30.00	90	1,000
43	8.5	141.75	34.18	305,000.00	101,000.00	4.60	287.00	30.00	90	1,000
44	8.5	134.74	32.68	305,000.00	101,000.00	4.60	250.00	20.00	90	100
45	8.5	138.39	34.39	305,000.00	101,000.00	4.60	240.00	25.00	90	100
46	8.5	137.35	33.88	305,000.00	101,000.00	4.60	242.00	7.00	90	2,300
47	8.5	136.40	33.17	305,000.00	101,000.00	4.60	250.00	25.00	90	100

48	8.6	139.41	35.02	62,690.00	109,000.00	5.30	147.10	34.00	90	15,000
49	8.6	138.41	34.47	68,500.00	108,642.56	5.30	205.80	10.00	90	15,000
50	8.6	136.87	34.10	346,736.85	108,642.56	5.30	256.63	28.64	90	15,000
51	8.7	138.41	34.47	68,500.00	116,680.96	6.14	205.80	30.00	90	15,000
52	8.7	137.14	34.14	393,550.08	116,680.96	6.14	256.63	28.64	90	15,000
53	8.8	138.10	34.00	446,000.00	125,000.00	7.10	242.00	30.00	90	1,000
54	8.8	141.75	34.18	446,000.00	125,000.00	7.10	287.00	30.00	90	1,000
55	8.8	134.74	32.68	446,000.00	125,000.00	7.10	250.00	20.00	90	100
56	8.8	138.39	34.39	446,000.00	125,000.00	7.10	240.00	25.00	90	100
57	8.8	137.35	33.88	446,000.00	125,000.00	7.10	242.00	7.00	90	2,300
58	8.8	136.40	33.17	446,000.00	125,000.00	7.10	250.00	25.00	90	100
59	8.9	136.08	33.34	141,846.65	134,586.04	15.00	257.70	30.00	90	15,000
60	8.9	138.47	34.78	329,288.15	134,586.04	15.00	233.86	30.00	90	15,000
		136.08	33.34	141,846.65	134,586.04	15.00	257.70	20.00	90	15,000
		134.83	33.11	35,855.00	134,586.04	15.00	243.08	12.00	90	15,000
61	9.1	138.47	34.78	329,288.15	155,238.70	15.00	233.86	30.00	90	15,000
		136.08	33.34	141,846.65	155,238.70	15.00	257.70	20.00	90	15,000
		134.83	33.11	165,046.05	155,238.70	15.00	243.08	12.00	90	15,000
		133.51	32.55	16,950.00	155,238.70	15.00	228.45	10.00	90	15,000
62	9.1	136.08	33.34	141,846.65	155,238.70	15.00	257.70	30.00	90	15,000
63	9.2	138.47	34.78	329,288.15	166,724.72	15.00	233.86	30.00	90	15,000
		136.08	33.34	141,846.65	166,724.72	15.00	257.70	20.00	90	15,000
		134.83	33.11	165,046.05	166,724.72	15.00	243.08	12.00	90	15,000
		133.51	32.55	105,129.00	166,724.72	15.00	228.45	10.00	90	15,000
64	9.2	136.08	33.34	141,846.65	166,724.72	15.00	257.70	30.00	90	15,000

10.4 Conclusions

We have presented a framework for determining the areas of Level 1 and Level 2 tsunamis. The proposed method can be used to adjust land use planning by clarifying the potential tsunamis risks of an area based on a specific range of flow depths at a particular area in the post-disaster situation. In the same manner, this method can also provide important information on how frequently a particular place is likely to be affected by tsunamis, based on a given scenario with a specific level of risk in the pre-disaster area. This information may be necessary for risk reduction strategies in pre-disaster situations if the relocation of settlements and/or economic activities away from the potential tsunami inundation is difficult. It should be acknowledged that the present study includes only a limited number of modeled tsunami scenarios. Future improvements, such as using probabilistic tsunami hazards and inundation assessments, will provide more complete information on the potential affected ratio of a particular place over a specific return period with a specific range of tsunami flow depths.

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Chapter 11
Effectiveness of Real-Time Near-Field Tsunami Inundation Forecasts for Tsunami Evacuation in Kushiro City, Hokkaido, Japan

Aditya Riadi Gusman and Yuichiro Tanioka

Abstract An algorithm called NearTIF, designed to produce tsunami inundation maps of near-field sites before the actual tsunami hits the shore, was previously developed by the authors. This algorithm relies on a database of precomputed tsunami waveforms at several near-shore locations and tsunami inundation maps from various earthquake fault models. In the event of a great earthquake, tsunami waveforms at the above mentioned near-shore locations are computed on the basis of real-time observation data by use of linear long-wave equations. Simulating these tsunami waveforms takes only 1–3 min on a common personal computer, so the realistic offshore tsunami waveforms can be forecasted. The offshore real-time simulated tsunami waveforms are then compared with precomputed tsunami waveforms in a database to select the site-specific best fault model and the corresponding tsunami inundation map. The best tsunami inundation map is then used as the tsunami inundation forecast. We evaluated the effectiveness of this algorithm in the real world by carrying out a tsunami evacuation drill in Kushiro City, Hokkaido, Japan, involving the city residents. The drill started with the announcement of a tsunami warning, to evacuate the residents to the nearest evacuation building. Approximately 10 min after the announcement, the tsunami inundation forecast map was given to the participants in the drill. The participants found that the use of the tsunami inundation forecast map produced by NearTIF was effective in helping them make better decisions with high confidence during the tsunami evacuation drill. The NearTIF algorithm is recommended for use as part of the reconstruction policy by local authorities to improve the evacuation efficiency, particularly in tsunami-prone areas.

Keywords Tsunami inundation forecast • Tsunami evacuation drill • Tsunami early warning • Precomputed tsunami database

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11.1 Introduction

Most great earthquakes that occur along subduction zones generate large tsunamis. Within less than an hour, a tsunami can reach and destroy coastal communities near its source region. Japan has an advanced tsunami early warning system that takes advantage of the velocity difference between the much faster seismic wave and the slower tsunami wave (Kamigaichi 2011). The Japan Meteorological Agency (JMA) operates this tsunami early warning system and categorizes tsunami forecasts as "Tsunami Advisory," "Tsunami Warning," and "Major Tsunami Warning." During the 2011 Tohoku earthquake, JMA issued tsunami early warning messages and forecasts of tsunami heights along the coast of Japan as soon as 3 min after the earthquake was triggered (Ozaki 2011).

The 2011 Tohoku tsunami inundated up to 3 km inland in Rikuzentakata, Japan, and residents living 2–3 km away from the coastline were killed by the tsunami. The forecasts of tsunami height along the coast were therefore not enough to allow people living that far away from the coastline to escape from such a huge tsunami (Tanioka et al. 2014). We argue that tsunami inundation forecasts on high-resolution topography can help people to make better decisions during a tsunami evacuation.

One way to acquire tsunami inundation forecasts is by simulating tsunami inundation in real-time by use of a numerical forward model. This approach is adopted by the Short-term Inundation Forecast for Tsunamis (SIFT) (Titov et al. 2005; Tang et al. 2009; Titov 2009), which was developed at the National Oceanic and Atmospheric Administration (NOAA). The method was implemented and tested for far-field sites in the Hawaiian Islands. However, numerical forward modeling of tsunami inundation on high-resolution topography is numerically expensive. The approach may work even for near-field sites in Japan, but the real-time simulations should be run on a very powerful supercomputer to obtain simulated tsunami inundations before the actual tsunami hits the shores.

We have developed a methodology for near-field tsunami inundation forecasting (NearTIF) that is designed to provide tsunami inundation forecasts for near-field sites (Gusman et al. 2014; Tanioka et al. 2014). The NearTIF algorithm is equipped with a database that contains pairs of precomputed tsunami inundation and precomputed tsunami waveforms at specific sites from hypothetical earthquake fault models. After information about a tsunami source is obtained, tsunami waveforms at near-shore points can be simulated in real time. One of the fault models in the database can be selected as the site-specific best fault model by minimizing the root mean square (rms) misfit between the simulated tsunami waveforms and those in the database. Then, the corresponding precomputed tsunami inundation of the best fault model is selected as the tsunami inundation forecast (Gusman et al. 2014). We found that the forecasting algorithm is capable of providing a tsunami inundation forecast similar to that obtained by numerical forward modeling, but with remarkably less runtime (Gusman et al. 2014; Tanioka et al. 2014). We tested the NearTIF algorithm in a retrospective forecast experiment on the 2011 Tohoku tsunami. We found that the tsunami inundation forecasts produced by the NearTIF algorithm are reliable for tsunami early warning purposes and considerably similar to the observations. The algorithm required only 3 min to produce tsunami inundation forecast maps of 15 sites, whereas a tsunami inundation model, running on a common laptop computer, required approximately 40 h to produce the maps (Gusman et al. 2014).

We previously built a precomputed tsunami database for Kushiro City from hypothetical earthquake fault models off the Pacific coast of Hokkaido (Tanioka et al. 2014). The precomputed tsunami database was used with the NearTIF algorithm to produce a tsunami inundation map in Kushiro City from an assumed future earthquake event with an earthquake source mechanism that is the same as that estimated for the seventeenth century great Hokkaido earthquake. In this paper, we report the use of tsunami inundation forecast maps produced by the NearTIF algorithm in a tsunami evacuation drill in Kushiro City, Hokkaido. The tsunami evacuation drill was set up with the assistance of the NHK Television Network (2013) and involved the residents of Kushiro City as participants. In this paper, we show how the NearTIF algorithm works and report the effectiveness of using a tsunami inundation forecast map in a tsunami evacuation drill.

Section 11.2 describes every component in the NearTIF algorithm. Section 11.3 shows inversion methods that directly or indirectly estimate a tsunami source model from seismic wave data, GPS time series data, or tsunami waveforms. Section 11.4 describes the identification of Kushiro City as a tsunami-prone area. Section 11.5 describes the assumed earthquake for the tsunami evacuation drill in Kushiro. Section 11.6 reports how the participants in the tsunami evacuation drill learned the effectiveness of using a tsunami inundation forecast map during the simulated evacuation.

11.2 Method of Near-Field Tsunami Inundation Forecasting (NearTIF)

If different earthquakes produced the same tsunami waveforms at near-shore locations, the tsunami inundations in the coastal areas from those tsunamis would be the same. Based on this reasonable assumption, we developed a methodology for near-field tsunami inundation forecasting (Gusman et al. 2014). The Near-field Tsunami Inundation Forecasting (NearTIF) algorithm has three main components: a precomputed tsunami database, a tsunami numerical model, and a tsunami database search engine. These three components are explained in the following subsections.

11.2.1 Precomputed Tsunami Database

The first component of the algorithm is a tsunami database that contains pairs of precomputed tsunami waveforms and tsunami inundations from hypothetical tsunami source models. The hypothetical tsunami source models can be made from simple earthquake fault model scenarios with variable earthquake source parameters (i.e., strike, dip, rake, slip amount, and depth), or tsunami source models.

We have built a precomputed tsunami database for Kushiro City from thrust earthquake scenarios of a simple rectangular fault model with moment magnitude ranging from Mw 8.0 to 9.0 and an interval of 0.1 (Tanioka et al. 2014).

As explained in Tanioka et al. (2014), for the database, we arranged 32 reference points along the subduction zone off the Pacific coast of Hokkaido as the center top of the fault planes. Depth and dip angle for each fault model are based on the SLAB1.0 slab model for subduction zones (Hayes et al. 2012). Points are grouped into four depth categories, which are the shallowest, upper intermediate, lower intermediate, and deepest plate interface. Earthquake fault models for each depth category have moment magnitudes of Mw 8.0 to 9.0, Mw 8.0 to 8.9, Mw 8.0 to 8.8, and Mw 8.0 to 8.7, from the shallowest to the deepest plate interface, making a total of 304 fault models (Fig. 11.1).

Tsunami waveforms at near-shore points (45 points) shown in Fig. 11.2 are computed beforehand by solving the linear shallow water equations from each fault model. The numerical method to compute tsunami propagation on the spherical coordinate system is described in Johnson (1998). For the simulation, the GEBCO 30 arc-second bathymetric grid and 1 s of computational time step are used. The precomputed tsunami waveforms with 15 s of time step and that are 3 h long are stored in the database. Figure 11.3 illustrates the database of tsunami waveforms at the near-shore points.

We simulated 3 h of tsunami inundations in Kushiro from the fault models by solving the non-linear shallow water equations (Imamura 1996; Johnson 1998;

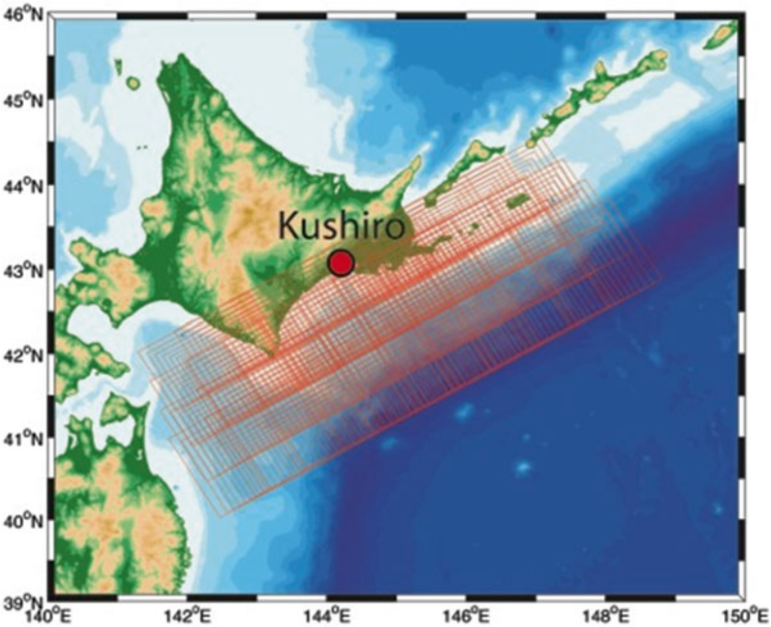

Fig. 11.1 Location of Kushiro City and the hypothetical fault models (*red rectangles*)

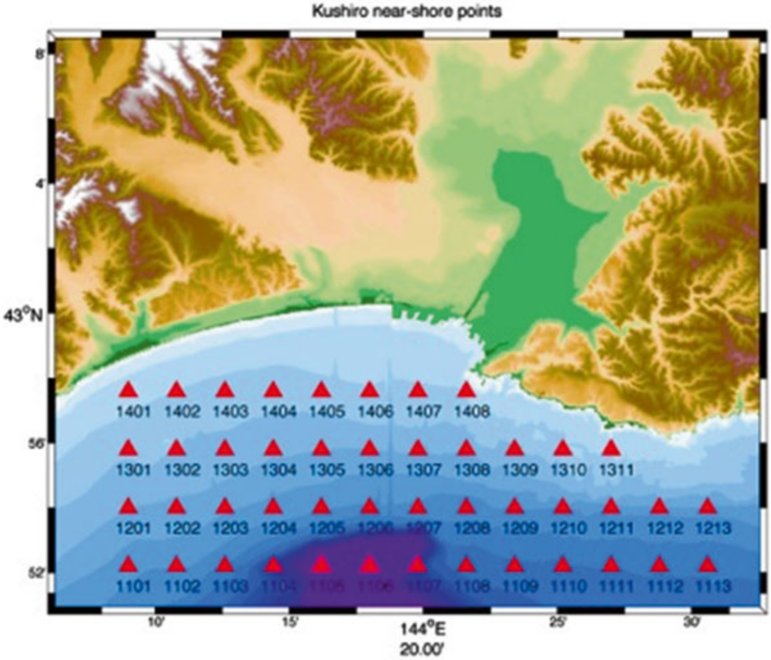

Fig. 11.2 Map of near-shore points for Kushiro (*red triangles*) at which tsunami waveforms are simulated

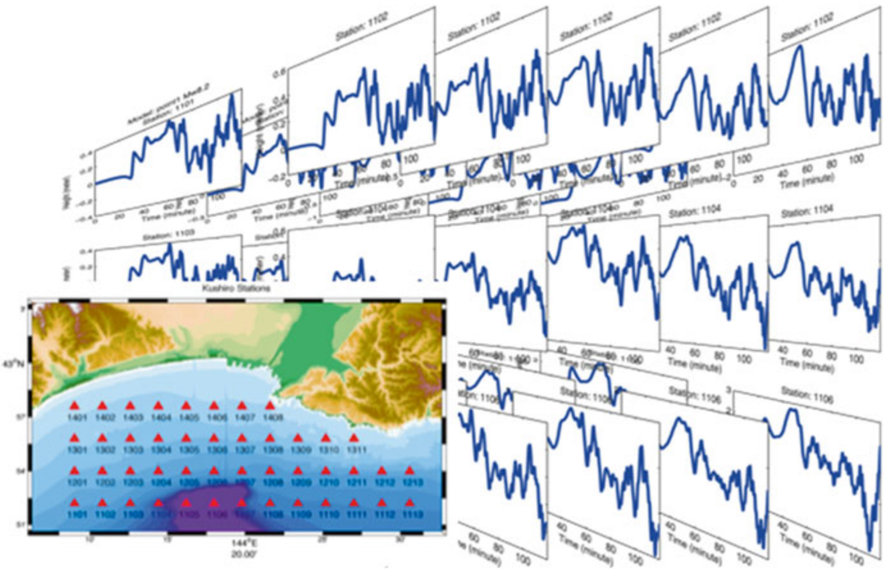

Fig. 11.3 Illustration of the precomputed tsunami waveform database

Goto et al. 1997) on the spherical coordinate system. A nested grid system with resolutions of 30, 10, 3.33, and 1.11 arc-sec is used.

A homogeneous Manning's roughness coefficient of 0.025 is assumed on the grid system, a value widely used in tsunami inundation modeling (Imamura 2009). The maximum tsunami inundations over 3 h of simulation are stored in the database (Fig. 11.4).

11.2.2 Tsunami Numerical Model

During a real tsunami event, the first step for NearTIF is to simulate tsunami propagation by use of a tsunami numerical model in real time. After information about the tsunami source is obtained, we can use it as an input for the tsunami numerical model. The input can be earthquake source parameters (i.e., moment magnitude, epicenter, strike, dip, rake, and depth), an earthquake fault model, such as slip distribution, or initial sea surface deformation. The tsunami numerical model solves the linear shallow water equations to simulate the tsunami waveforms at the near-shore points. The model parameters and the bathymetry data used should be the same as those used for the tsunami waveforms database. To simulate 3 h of tsunami propagation and obtain simulated tsunami waveforms at points near shore to Kushiro takes approximately 2 min.

11.2.3 Tsunami Database Search Engine

The tsunami database search engine is designed to search for a fault model in the database that gives the precomputed tsunami waveforms most similar to those obtained by the tsunami numerical model. The search engine is programmed to rank the fault models based on the similarity between precomputed tsunami waveforms in the database and the tsunami waveforms from the tsunami numerical model. To evaluate the similarity, we used root mean square (rms) misfit between the precomputed tsunami waveforms and simulated tsunami waveforms. For a specific event and a specific site, a fault model with the highest rank will be selected as the site-specific best fault model. The steps for obtaining the site-specific best fault model are listed below:

- The simulated tsunami waveforms within a time window are selected for the rms analysis. The time window is based on wave cycles of the tsunami waveforms that are automatically detected by the zero up/down crossing method.
- The NearTIF algorithm analyzed only the sets of tsunami waveforms with the mean of maximum heights that is within a threshold of 30 % from the tsunami waveforms from the tsunami numerical model.
- The tsunami waveforms are shifted by an optimal time shift (τo) that minimizes the rms misfit of the waveforms. Every scenario will have a root mean square

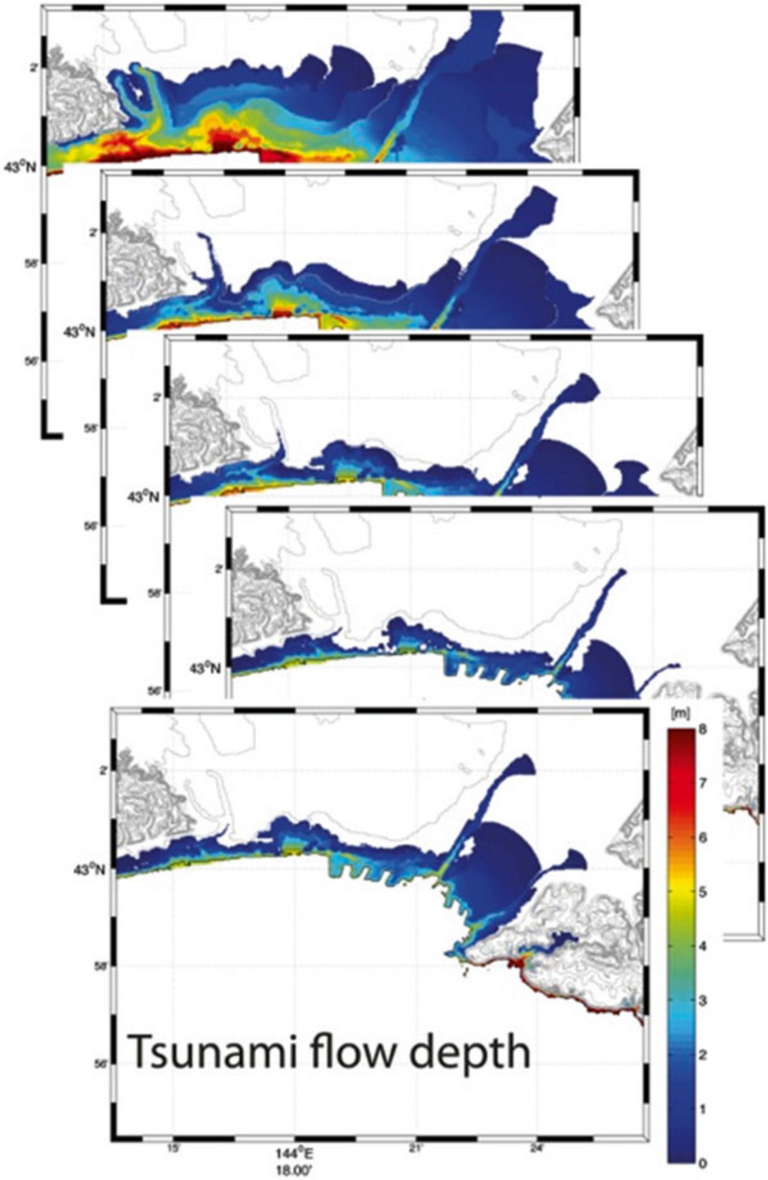

Fig. 11.4 Some examples of precomputed tsunami inundation in Kushiro

error (rmse) value based on the similarity of tsunami waveforms. A scenario that gives the smallest rmse value is selected as the site-specific best scenario.

- The last process is straightforward, which is selecting the precomputed tsunami inundation of the site-specific best scenario as the tsunami inundation forecast.

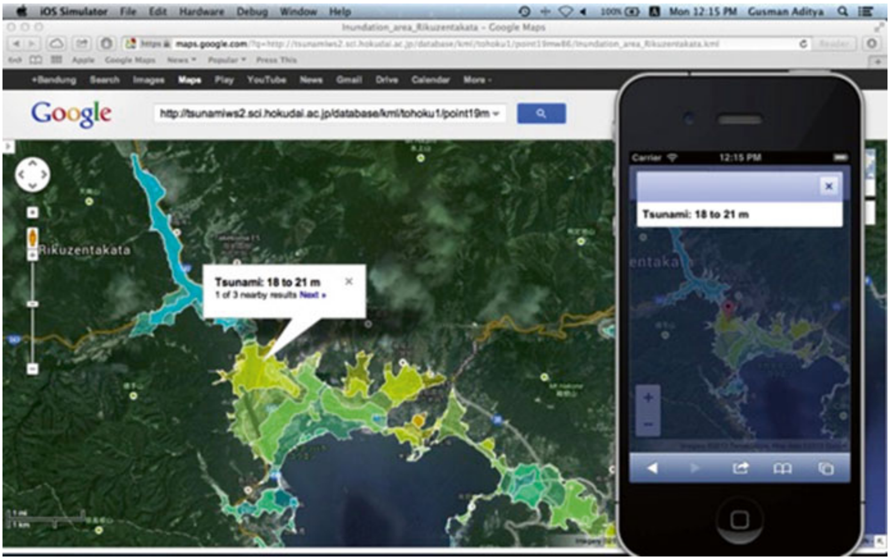

Fig. 11.5 Tsunami inundation forecast map visualized by Google Maps (Source: Google Maps)

11.2.4 Dissemination of the Tsunami Inundation Forecast Map

The precomputed maximum tsunami inundation maps from all fault models are exported as Keyhole Markup Language (KML) files and stored in the database. KML is an Extensible Markup Language (XML) notation for expressing geographic annotation and visualization within Internet-based, two-dimensional maps and three-dimensional Earth browsers. Google Maps is a desktop and mobile service application provided by Google Inc. that can visualize the KML file. During a tsunami event, the KML file for the tsunami inundation forecast map would be uploaded to a web server so it can be visualized over the Internet by use of the Google Maps application on a desktop computer or mobile device (Fig. 11.5).

11.3 Tsunami Source Estimations Based on Real-Time Observations in Japan

A tsunami can be generated by several types of events, such as earthquakes, volcanic eruptions, submarine landslides, or meteor impacts. Earthquakes generated most of the tsunamis in the world. The input of NearTIF can be an initial sea-surface deformation by a tsunami caused by any of the events mentioned above. However, in this paper we discuss only tsunamigenic earthquakes (earthquakes that can generate tsunamis). In the event of a tsunamigenic earthquake, the earthquake source parameters, earthquake fault model, or tsunami source model can be estimated from real-time observations of seismic waves, crustal deformation, or sea level.

A tsunami source model inferred from tsunami waveforms directly estimates the tsunami source, whereas earthquake fault or source models from seismic wave data or GPS data indirectly estimates the tsunami source. The sea-floor deformation caused by fault motion can be calculated by the elastic theory (Okada 1985), using the earthquake fault parameters of longitude, latitude, depth, strike, dip, rake, slip amount, fault length, and fault width. We may assume that the sea-floor deformation is the same as the sea-surface deformation because, in most cases, the wavelength is much greater than the water depth. The velocity of rupture propagation is much faster than the propagation of a tsunami wave; therefore, the sea-surface deformation can be assumed to occur instantaneously.

11.3.1 Scaling Relations

A scaling relation is needed to estimate rupture area from the earthquake's moment magnitude. The moment magnitude (Mw) to fault area (A) relation of Wells and Coppersmith (1994) is widely used in seismic hazard analysis. The scaling relation was derived from a database that includes all slip types of continental interplate or intraplate earthquakes, with the exception of subduction zone earthquakes, both those at the interface and those within the oceanic slab. Other recently developed scaling relations focus on continental events (Hanks and Bakun 2002) and on subduction zone events (Blaser et al. 2010; Murotani et al. 2013). Table 11.1 shows the scaling relations of Hanks and Bakun (2002), Blaser et al. (2010), and Murotani et al. (2013) and those used by the JMA. From the scaling relations of Hanks and Bakun (2002) and Murotani et al. (2013), we may obtain area from moment magnitude, and then to obtain fault length (L) and width (W), we may assume L = 2 W. In the NearTIF algorithm, we used the scaling relation of Hanks and Bakun (2002) because it gives a rupture area that is consistent with the major slip region of the 2011 Tohoku earthquake (Gusman and Tanioka 2013).

Table 11.1 Scaling relations for first-order approximation of rupture area from earthquake moment magnitude

Authors	Scaling relation
Hanks and Bakun (2002)	$Mw = 4/3 \times \log A + 3.03$
Blaser et al. (2010)	$\log L = 0.57 \times Mw - 2.37$
	$\log W = 0.46 \times Mw - 1.86$
Murotani et al. (2013)	$A = 1.34 \times 10^{-10} \times Mo^{2/3}$
	$D = 1.66 \times 10^{-7} \times Mo^{1/3}$
JMA (Kamigaichi 2011)	$\log L = 0.5 \times M - 1.8$
	$\log W = 0.5 \times M - 2.1$
	$\log D = 0.5 \times M - 3.3$

Area (A) is in km^2, length (L) and width (W) are in km, and slip amount (D) is in m

11.3.2 Earthquake Source Parameters of the JMA Earthquake Early Warning (EEW) System

The JMA uses a real-time seismic data processing system to determine an earthquake's hypocenter and magnitude. The calculated hypocenter parameters of longitude, latitude, depth, and magnitude are used as input for the JMA tsunami forecasting system. Although earthquake source parameters can be obtained by the EEW system within a short time period (3 min), the system might underestimate the magnitude of great earthquakes, Mw more than 8.5, as was revealed during the 2011 Tohoku earthquake event. The JMA's initial magnitude estimate for the earthquake was M 7.9, and the final estimate from the system was M 8.1 (Ohta et al. 2012), which are much smaller than the Mw 9.0 estimated by many studies (e.g., Ide et al. 2011; Yoshida et al. 2011; Ozawa et al. 2011; Fujii et al. 2011; Gusman et al. 2012; Satake et al. 2013). Therefore, during an earthquake event, we prefer to wait for more data to become available to obtain more reliable earthquake source parameters.

11.3.3 Earthquake Source Parameters from W Phase Inversion

Previous studies show that W phase data can give a reliable earthquake magnitude estimate (Kanamori and Rivera 2008; Duputel et al. 2011; Gusman and Tanioka 2013; Benavente and Cummins 2013). Our previous study showed that reliable centroid moment tensor solutions of the 2011 Tohoku earthquake can be estimated by use of 5 or 10 min of W phase data recorded at Japanese F-net stations (Gusman and Tanioka 2013; Gusman et al. 2014). The centroid moment tensor solution from the W phase inversion, with a scaling relation of moment magnitude and rupture area, can be used to estimate a simple fault model. Benavente and Cummins (2013) explored the ability of W phase waveform inversions to recover first-order coseismic slip distribution for great earthquakes.

11.3.4 Earthquake Fault Model from GPS Time Series Inversion

To estimate a fault model in real-time from Real Time Kinematic (RTK) GPS time series data, Ohta et al. (2012) developed the Real-time Automatic detection method for Permanent Displacement (RAPiD) algorithm. The coseismic displacement fields caused by the 2011 Tohoku earthquake were estimated by the RAPiD algorithm using 1-Hz GPS time series data recorded at 527 GEONET stations. The final fault model (Mw 8.7) and coseismic displacement field due to the earthquake was estimated within 4 min and 35 s after the earthquake occurred (Ohta et al. 2012).

The tsunami inundation forecast produced by the NearTIF algorithm from this simple fault model slightly underestimates the observations but is considered reliable for tsunami early warning purposes (Gusman et al. 2014).

11.3.5 Tsunami Source Model from Tsunami Waveform Inversion

At least two methods that use offshore tsunami data have been developed for real-time tsunami forecasting. The Center for Tsunami Research (NOAA) has developed the Short-term Inundation Forecast for Tsunamis (SIFT), a real-time tsunami inundation forecasting scheme (Titov et al. 2005; Tang et al. 2009; Titov 2009), which is now fully operational in NOAA's Tsunami Warning Center. Another method is the tsunami Forecasting based on Inversion for initial sea-Surface Height (tFISH), for near-field tsunami forecasting (Tsushima et al. 2009). The algorithm is currently being integrated into the JMA tsunami forecasting system. Both algorithms determine an initial sea-surface deformation in a possible tsunami source area and then synthesize tsunami waveforms at some points of interest by utilizing precomputed tsunami Green's functions (Titov et al. 2005; Tang et al. 2009; Titov 2009; Tsushima et al. 2009, 2011; Wei et al. 2013).

11.4 Tsunami Hazard Map for Kushiro City

According to historical records, great earthquakes have frequently occurred in the Tokachi-oki and Nemuro-oki segments off the Pacific coast of Hokkaido. These earthquakes are the 1843 Tokachi-oki earthquake, the 1952 Tokachi-oki earthquake (Mw 8.2), the 2003 Tokachi-oki earthquake, the 1894 Nemuro-oki earthquake (Mw 8.2), and the 1973 Nemuro-oki earthquake (Hatori 1984; Hirata et al. 2003; Tanioka et al. 2004, 2007). A great earthquake that possibly occurred in the early of seventeenth century has been discovered from tsunami sediment data (Nanayama et al. 2003). The earthquake fault model for the seventeenth century great Hokkaido earthquake has been estimated by use of tsunami sediment data in previous studies (Satake et al. 2005; Ioki 2013). From these historical and prehistorical tsunamigenic earthquakes, Kushiro City has been identified as a tsunami-prone area.

Tsunami hazard maps can increase the effectiveness of evacuation plans for communities at risk. The Kushiro City Office has provided a tsunami hazard map for Kushiro City to the public (http://www.city.kushiro.lg.jp/common/000049875.pdf) (Fig. 11.6). The tsunami inundation limit and tsunami flow depth shown on the map represent the worst-case scenario. The locations and elevation above mean sea level of evacuation buildings and areas are also shown on the map (Fig. 11.6). Once the areas of tsunami inundation hazard have been identified, a community-wide effort

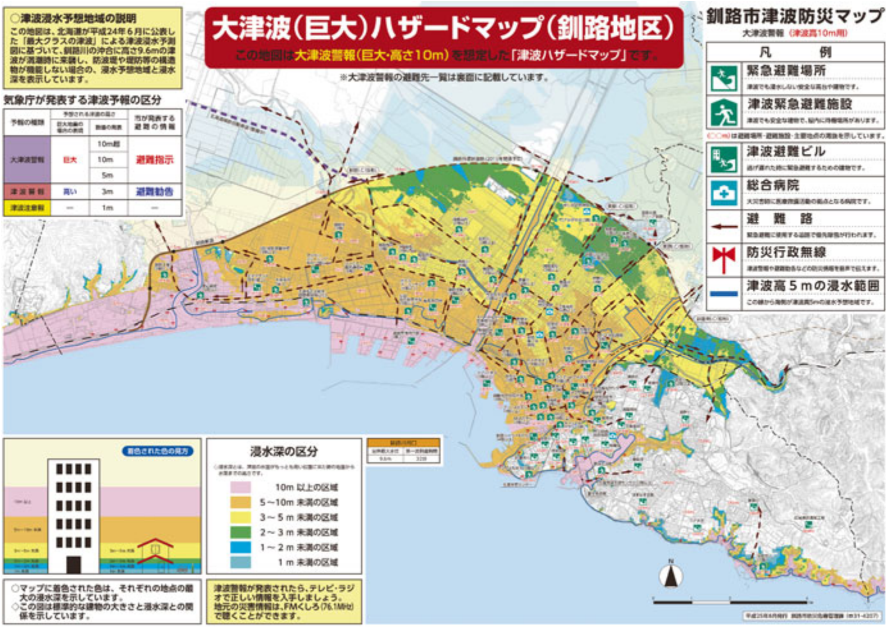

Fig. 11.6 Tsunami hazard map for Kushiro City. Color areas indicate tsunami flow depth from the worst-case tsunami scenario for Kushiro City. Locations of tsunami evacuation buildings and areas are shown on the map

of tsunami hazard awareness is essential to educate the residents to take the appropriate actions in the event of a tsunami (Imamura 2009). One way to increase or maintain the awareness of a tsunami hazard is by periodically conducting tsunami drills in tsunami-prone areas (Imamura 2009).

11.5 Hypothetical Earthquake (Mw 8.7) Off the Pacific Coast of Hokkaido

For the purpose of a tsunami evacuation drill in Kushiro City, we used a hypothetical great earthquake (Mw 8.7) in the subduction zone off the pacific coast of Hokkaido. The earthquake fault parameters are strike = 250°, dip = 10°, rake = 90°, depth = 10 km, fault length = 200 km, and fault width = 100 km. The initial sea surface deformation of this hypothetical earthquake is shown in Fig. 11.7.

The fault model of the hypothetical earthquake fault model (Mw 8.7) is used to simulate tsunami waveforms at the near-shore locations (Fig. 11.8). Then, the tsunami waveforms are used to find the site-specific best scenario that can give the most similar precomputed tsunami waveforms. The comparison between tsunami waveforms from the hypothetical scenario and those from the site-specific best fault

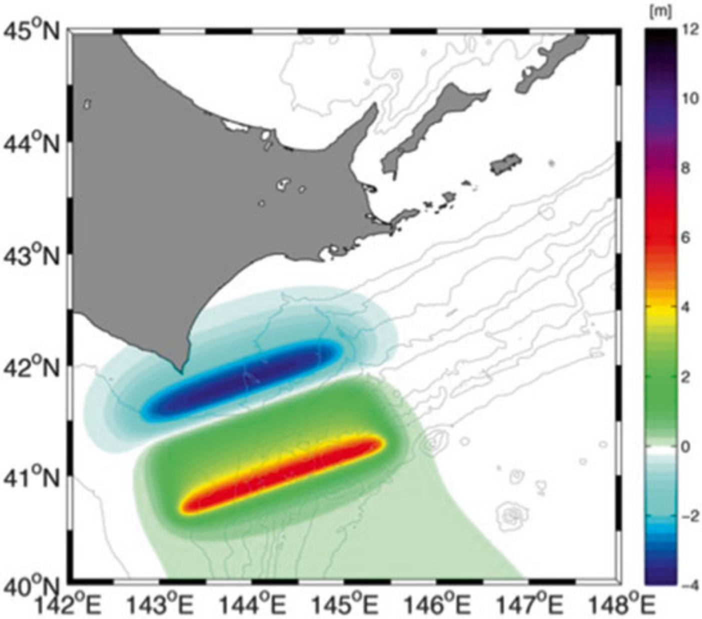

Fig. 11.7 Sea-surface deformation of the hypothetical earthquake (Mw 8.7) off the Pacific coast of Hokkaido used for the tsunami evacuation drill in Kushiro City

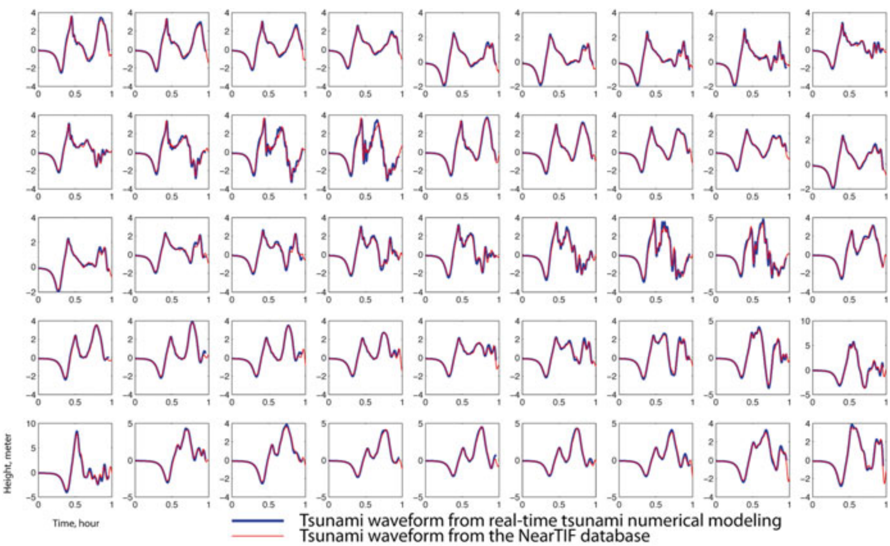

Fig. 11.8 Comparison of tsunami waveforms from numerical forward modeling (*blue lines*) and precomputed tsunami waveforms of the site-specific best fault model from the database (*red lines*)

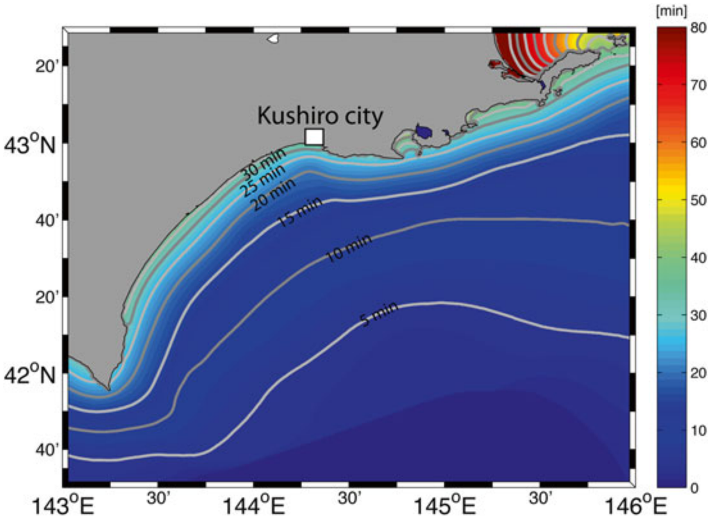

Fig. 11.9 Tsunami travel time map for the hypothetical earthquake simulated by the tsunami numerical model

model are shown in Fig. 11.8. From the tsunami simulation, the hypothetical tsunami would hit the shore of Kushiro City approximately 35 min after the earthquake was generated (Fig. 11.9).

The tsunami inundation forecast for the hypothetical fault model that is produced by the NearTIF algorithm is shown in Fig. 11.10. The tsunami inundation that is simulated by numerical forward modeling directly from the hypothetical fault model is shown in Fig. 11.11. These two tsunami inundation results are very similar. The NearTIF algorithm can give tsunami inundation forecast within 2 min after the earthquake source parameters are obtained, whereas the forward numerical modeling required approximately 70 min to obtain a result. This rapid result is the main advantage of using the NearTIF algorithm rather than a forward numerical model to produce tsunami inundation forecast maps. The use of the NearTIF algorithm can significantly reduce the time required to produce a tsunami inundation forecast map without compromising the accuracy very much.

11.6 Tsunami Evacuation Drill in Kushiro City, Hokkaido

A tsunami evacuation drill in Kushiro City involving the city residents was set up with the assistance of the NHK Television Network (2013) (Fig. 11.12). One of the purposes of this drill was to see how a tsunami inundation forecast influences the decision making for evacuation by the participants.

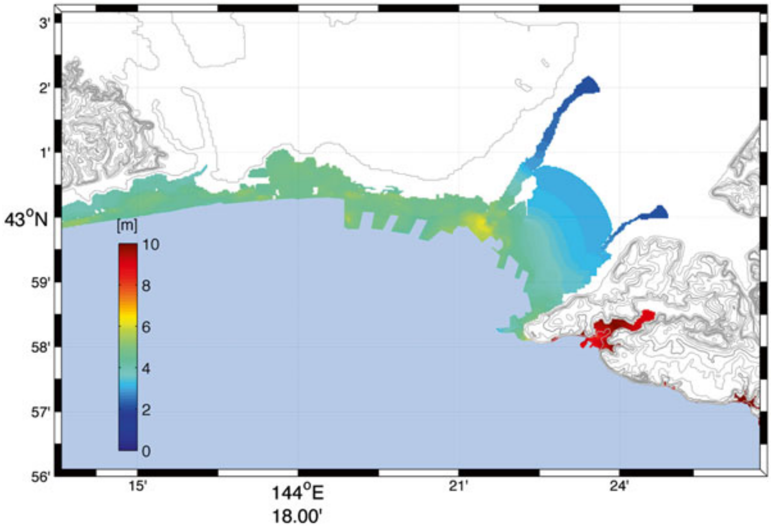

Fig. 11.10 Precomputed tsunami inundation forecast map of the site-specific best fault model for the hypothetical earthquake (Mw 8.7)

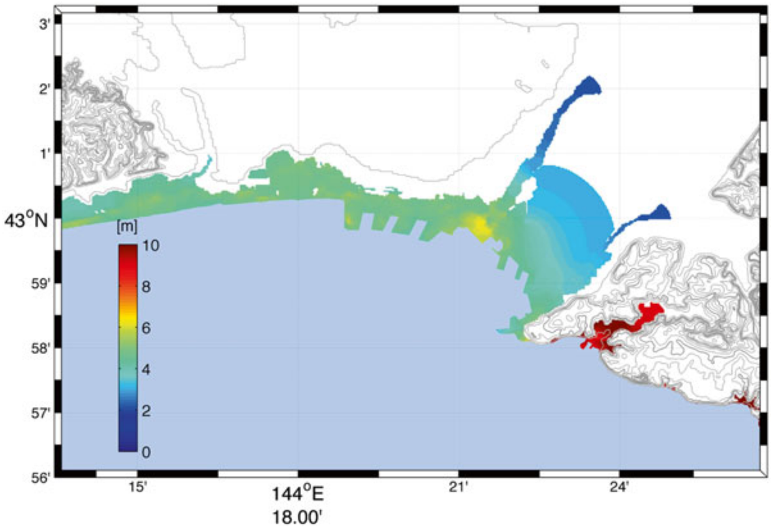

Fig. 11.11 Tsunami inundation forecast map directly simulated from the hypothetical fault model (Mw 8.7) by the numerical forward model

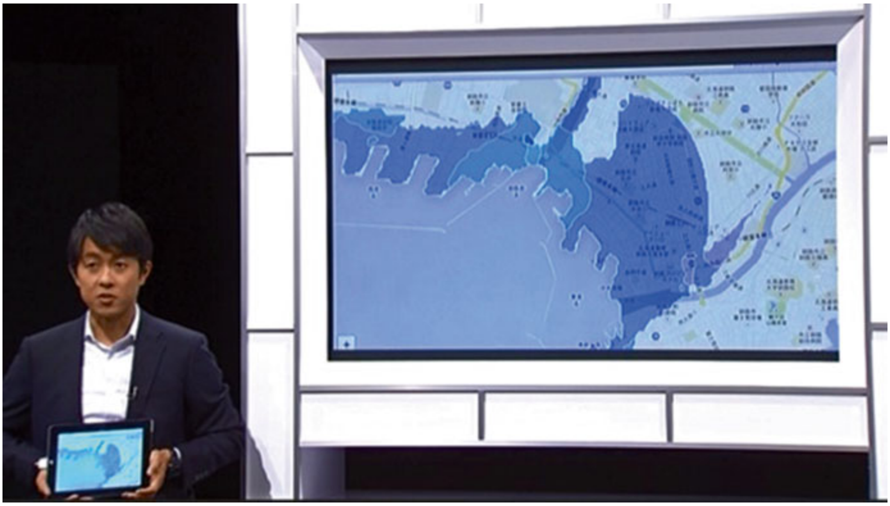

Fig. 11.12 NHK presenter showing an example of the tsunami inundation forecast (Source: NHK Television Network 2013)

Fig. 11.13 Residents of Kushiro City making an evacuation plan using the tsunami hazard map provided by the Kushiro City Office (Source: NHK Television Network 2013)

The participants were split into different groups that started the evacuation process from two separate locations. The participants studied the tsunami hazard map for Kushiro City to locate the closest tsunami evacuation building relative to their positions (Fig. 11.13). The nearest evacuation building for both groups was a three-stories-tall high school building with a rooftop located approximately 2.5 km from the shoreline and 2.8 m above the mean sea level. Another nearby evacuation

Fig. 11.14 Tsunami inundation area (*blue area*) forecasted by the NearTIF algorithm. Locations of the participants of the tsunami evacuation drill in Kushiro City; the high and elementary school buildings designated as tsunami evacuation buildings by the Kushiro City Office (Source: NHK Television Network 2013)

building was an elementary school building located farther inland, approximately 3.7 km from the shoreline, and 3.5 m above the mean sea level (Fig. 11.14).

In the tsunami evacuation drill, we assumed that the JMA works as it should and delivers the tsunami messages to the residents of Kushiro within 3 min after the earthquake. Upon receiving the announcement of the tsunami warning, the participants immediately evacuated to the nearest evacuation building. At this point in time, they did not know the tsunami flow depth at their exact position or the limit of the tsunami inundation. That information was not given because we preferred to wait until we had more data so we could obtain more reliable earthquake source parameters, and we needed more time to obtain the tsunami inundation forecast map from the NearTIF algorithm. At 10 min after the initial warning, both groups receive new information for the tsunami inundation forecast map. They viewed the map via Google Maps over the Internet on a tablet computer (Fig. 11.15). The two groups made different decisions based on their own situations.

The first group was just in front of the high school building when they received the newly available tsunami inundation forecast. According to the tsunami inundation forecast, the building they were about to use as an evacuation building could be inundated by the incoming tsunami, and the tsunami at that building could be 3 to 4 m high. They considered the position of the evacuation building that is 2.8 m above mean sea level, the height of the building, and the tsunami inundation forecast (Fig. 11.14). They also considered evacuating to another evacuation building that would not be inundated by the tsunami, according to the tsunami inundation forecast. However, their final decision was to go to the initial evacuation building

Fig. 11.15 The residents viewing the tsunami inundation forecast map that is available at 10 min after the initial announcement of the tsunami evacuation (Source: NHK Television Network 2013)

located approximately 10 m away from their position, but this time, they decided to evacuate to the rooftop of the building instead of evacuating to the second floor of the building (their initial evacuation plan).

The second group was on their way to the initial evacuation building (high school building) when they received the tsunami inundation forecast. They were between two evacuation buildings (the high school building and the elementary school building). According to the tsunami inundation forecast, the evacuation building to which they were headed would be inundated by the tsunami, but the other building would not be inundated by the tsunami (Fig. 11.14). They decided to evacuate to the elementary school building that would not be inundated by the tsunami because the distances to the two buildings from their position were more or less the same.

After the evacuation drill, we asked the participants about the importance of the tsunami inundation forecast. They told us that they were able to carry out their tsunami evacuation with much more confidence after they received the inundation forecast than before they received it.

11.7 Conclusions

The ground shaking from a great earthquake can be a natural warning of a possible tsunami danger for people living in the near-field region. Tsunami early warning messages from tsunami warning centers are confirmations of whether an earthquake generated a tsunami. The tsunami early warning system in Japan can give quantitative forecasts along the Japanese coastline and forecasts of coastal tsunami heights. This information might not be enough for people living more than 1 km inland. Unfortunately, providing near-field tsunami inundation forecasts is beyond the capability of any existing tsunami early warning system. The Near-field Tsunami

Inundation Forecasting (NearTIF) algorithm is developed to produce a reliable tsunami inundation forecast map on high-resolution topography. The algorithm relies on a precomputed tsunami database to ensure the promptness of the forecast.

The accuracy of a tsunami inundation forecast is directly related to the accuracy of the tsunami source information. We may need to wait more than 5 min after an earthquake occurs to obtain more data for a reliable tsunami source estimate. Once a reliable tsunami source model is estimated, tsunami inundation can be simulated accurately by solving the nonlinear shallow water wave equations. However, high-resolution tsunami numerical forward modeling is numerically expensive. If we conduct high-resolution tsunami inundation modeling in real time during an event, we might not be able to obtain results before the actual tsunami hits the shore. The NearTIF algorithm can give a tsunami inundation forecast map that is similar to that obtained from numerical forward modeling, but in remarkably less run time.

We evaluated the effectiveness of using tsunami inundation forecast maps in the real world by carrying out a tsunami evacuation drill in Kushiro City, Hokkaido, Japan, involving the city residents. The drill was started by the announcement of a tsunami warning to evacuate the residents to the nearest evacuation building. Approximately 10 min after the announcement, a tsunami inundation forecast map produced by the NearTIF algorithm was given to the participants in the drill. The participants found that the use of the tsunami inundation forecast map was effective in helping them make better decisions with high confidence during the tsunami evacuation process.

The NearTIF algorithm is recommended for use as part of the reconstruction policy by local authorities to improve the evacuation efficiency, particularly in tsunami-prone areas. We also recommend the use of the NearTIF method for developing future tsunami forecasting systems with a capability of providing tsunami inundation forecast maps for locations near the tsunami source area.

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Chapter 12
Advanced Real Time Monitoring System and Simulation Researches for Earthquakes and Tsunamis in Japan

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Abstract Mega thrust earthquakes generated large tsunamis quite often. Based on lessons learned from the 2004 Sumatra and the 2011 East Japan Earthquakes/Tsunamis, we recognized the importance of real time monitoring on the natural hazards. Monitoring systems using multi kinds of sensors such as the accelerometer, broadband seismometer, pressure gauge, difference pressure gauge, hydrophone and thermometer is indispensable not only for mitigation of damage from earthquakes and tsunamis, but also for understanding of broadband crustal activities around mega thrust earthquake seismogenic zones. Therefore, we have developed the Dense Ocean floor Network for Earthquakes and Tsunamis (DONET) to acquire the seafloor data in real time around the Nankai trough seismogenic zone, southwestern Japan. The first phase of deployment (DONET1) was completed and the second phase (DONET2) is being developed at the time of writing of the manuscript. At the 2011 East Japan Earthquake, DONET1 observatories detected offshore tsunamis 15 min earlier than onshore stations. Furthermore, DONET1 and DONET2 will be expected to monitor silent phenomena such as low frequency tremors and slow earthquakes for the estimation of seismic stage which would occur in the inter-seismic or pre-seismic stage. The recurrence cycle of mega thrust earthquakes, modeling of tsunami inundation and seismic response on buildings and cities are also

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important in the disaster mitigation programs and related measures. Real-time monitoring data should be integrated with the advanced simulations for precise earthquake and/or tsunami early warnings and rapid estimation of the damages.

Keywords DONET • Real time monitoring • Simulation • Nankai trough

12.1 Introduction

The one of lessons learned from the 2011 East Japan Earthquake is the importance of real time monitoring for earthquakes and tsunamis. Especially, offshore monitoring is indispensable for the earthquake and tsunami early warnings. Actually, two cabled pressure gauges at offshore detected the 2011 large tsunami offshore in advance. From these observations, tsunami heights were estimated over 5 m. Consequently, these tsunami detections in advance were successfully used to upgrade tsunami warning level from 3 m to 6 m immediately. The ocean-bottom data are also needed in estimation for the recurrence cycle of mega thrust earthquakes and tsunamis. In the previous simulation researches, the result of recurrence cycle simulation indicated the difference patterns and intervals of mega-thrust earthquake recurrences in each cycle (e.g. Kodaira et al. 2006; Ohtani et al. 2014). These results were consistent with the recent historical earthquakes in 1854, 1944/1946 and 1707 around the Nankai trough. In the past two historical events, first ruptures were starting from the Tonankai seismogenic zone. Therefore, real-time monitoring of the Tonankai seismogenic zone is expected to improve accuracy of the recurrence cycle simulation to understand the system of mega thrust earthquakes around the Nankai trough. We accordingly deployed DONET1 as a real-time monitoring system focusing on the Tonankai seismogenic zone (Kawaguchi et al. 2012; Kaneda 2013), and deploying DONET2 focusing on the Nankai seismozenic zone. Also, in order to utilize these real time data for prediction researches and disaster mitigation, we investigate the advanced simulation using high performance computers.

12.2 Previous Studies of the Nankai Trough Seismogenic Zone

12.2.1 Nankai Trough Seismogenic Zone

The Nankai trough seismogenic zone is one of the most important seismogenic zones for disaster mitigation in Japan. In the Nankai trough, M8 class earthquakes have occurred with the intervals of 100–200 years. At the latest

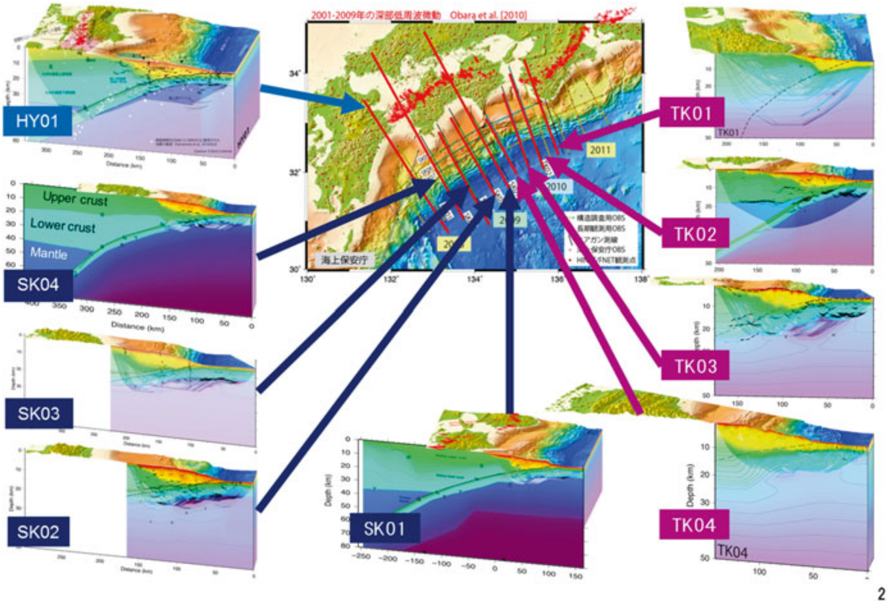

Fig. 12.1 Imaged various structures of the subducting plate and surrounding area along the Nankai trough

events, the 1944 Tonankai and the 1946 Nankai earthquakes, each hypocenter was located off the Kii peninsula. We have carried out many seismic surveys to understand structural elements (e.g., Yamamoto et al. 2013) concerned in the recurrence cycle system of mega thrust earthquakes around the Nankai trough. From the crustal structural researches, we found splay faults in the Tonankai seismogenic zone (Park et al. 2002), the irregular structure off Cape Shiono located at the boundary between the Tonankai and Nankai seismogenic zones (Kodaira et al. 2004). The imaged irregular structures at the segment boundary between the Tonankai and Nankai earthquake rupture zone, seem to be controllers of the Nankai Trough mega-thrust seismogenic zone system (Fig. 12.1).

Furthermore, the results of recent simulation study of mega-thrust earthquakes recurrence cycles indicated that these irregular structures seem to act as a controller of recurrence cycle and pattern of mega-thrust earthquakes in the Nankai trough (Fig. 12.2, Kodaira et al. 2006). And in these simulations, the first ruptures were starting from the Tonankai seismogenic zone ahead of the Nankai seismogenic zone. These results were consistent with the past two earthquakes in 1854, 1944/1946 (Fig. 12.3). These results are very important and significant for the Nankai trough mega thrust earthquake researches.

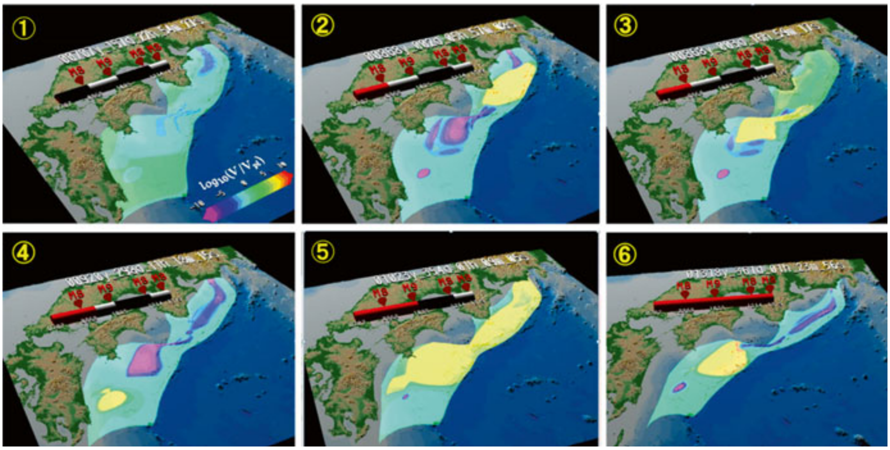

Fig. 12.2 The result of recurrence cycle simulation. The *red/yellow* colors indicate earthquake slips. (*1*) interseismic stage, (*2*) rupture of the eastern (Tokai) segment, (*3*) rupture of the western (Nankai) segment, (*4*) the rupture of the M7 class earthquake, (*5*) the rupture of M9 class earthquake, (*6*) the rupture of the western segment

12.2.2 The Dense Ocean Floor Network for Earthquakes and Tsunamis (DONET)

According to the previous researches, the Tonankai seismogenic zone is important to understand the system of Nankai trough mega-thrust earthquake occurrences. Therefore, we proposed and have been starting to deploy the dense ocean floor observatory network system equipped with multi kinds of sensors such as seismometers, pressure gauges etc. around the Tonankai seismogenic zone (Kawaguchi et al. 2012; Kaneda 2013). High-precision multi pressure gauges will be most useful sensor to monitor ocean floor deformation with long term observation. This ocean floor network was equipped with 20 observatories with seismometers and precise pressure gauges.

This ocean floor deformation data will be applied to the data assimilation to improve recurrence cycle simulation. This observatory system will be one of the most advanced scientific tools to understand the mega thrust earthquakes around the Nankai trough. This DONET system has useful functions and purposes as follows:

1. Redundancy, extension and advanced maintenance system using the looped cable system, junction boxes and the ROV (remotely operated vehicle)/ AUV(autonomous underwater vehicle) etc. (Fig. 12.4).
2. Multi kinds of sensors to observe wide range phenomena such as long period tremors, low frequency earthquakes and strong motion of mega thrust earthquakes over M8 (Fig. 12.4).
3. Speedy evaluation and notification for earthquakes and tsunamis. This function is the most important for disaster reduction /mitigation.

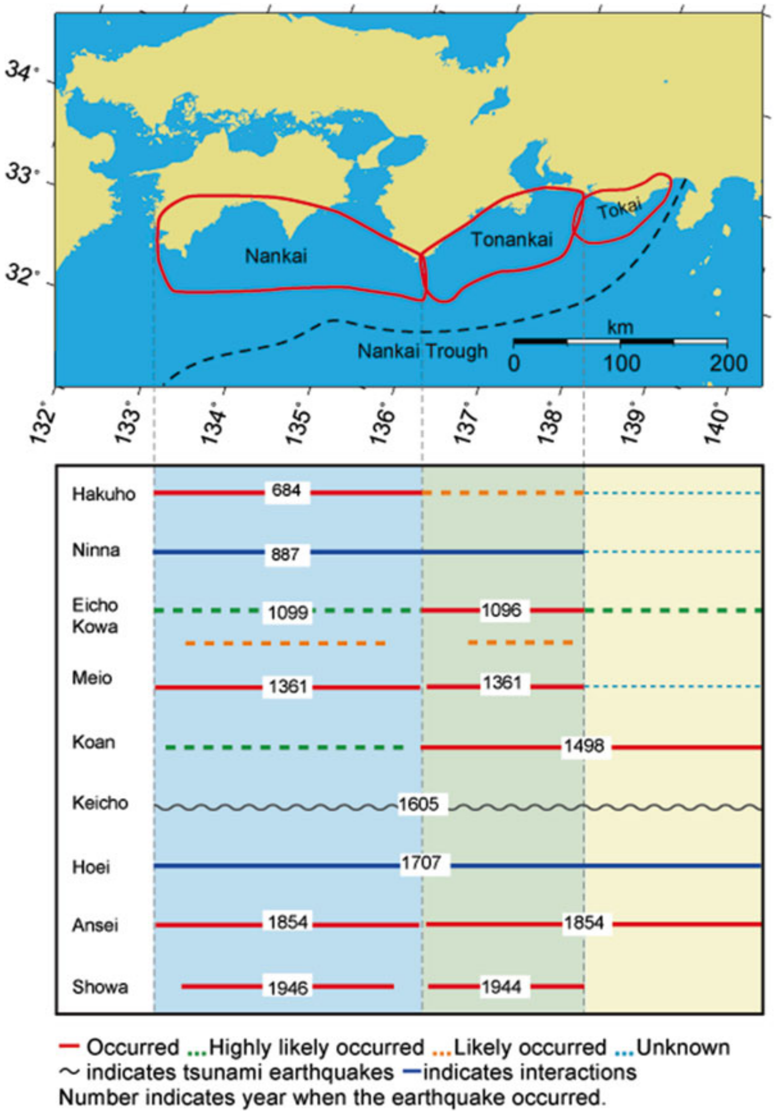

Fig. 12.3 Historical Earthquakes around the Nankai trough (modified from Ishibashi, 2004)

4. Development of new ocean observing technologies such as cable systems, advanced ROV/AUV etc. (Fig. 12.5).
5. Provide observed data such as ocean floor deformation derived from pressure gauges to improve the simulation and modeling researches about the mega thrust earthquakes (Fig. 12.6). These ocean floor deformation data are quite necessary for the data assimilation to improve simulation models.
6. Understanding of the interaction between the crust and upper mantle around subduction zone.

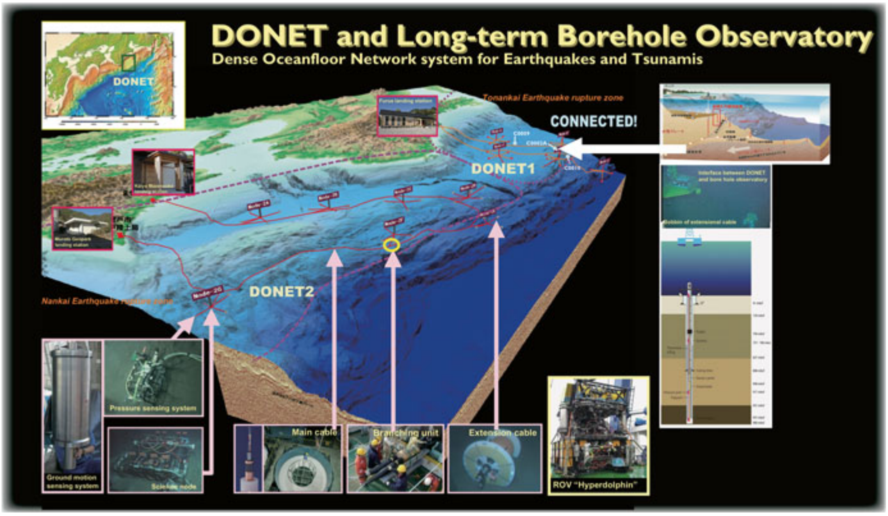

Fig. 12.4 The outline of advanced ocean floor network around the Nankai Trough. This ocean floor network is equipped with 51 observatories with seismometer and precise pressure gauge

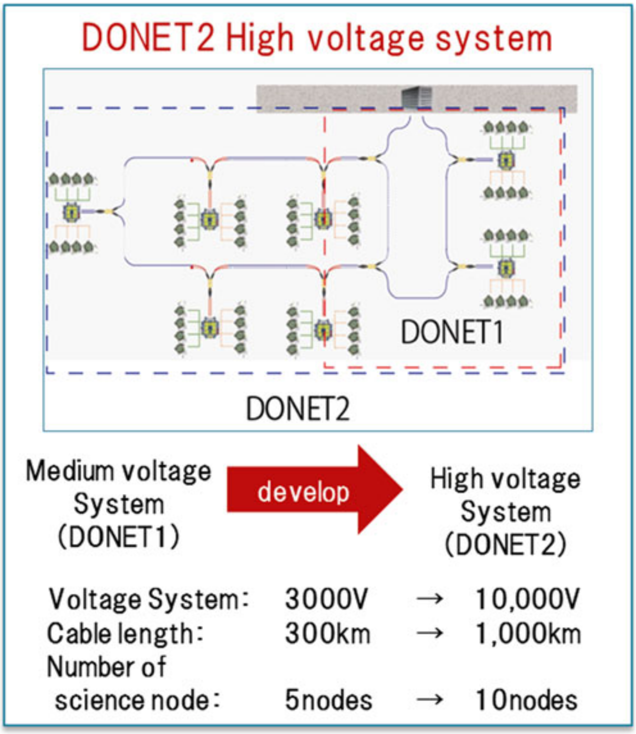

Fig. 12.5 The concept of advanced ocean floor network system

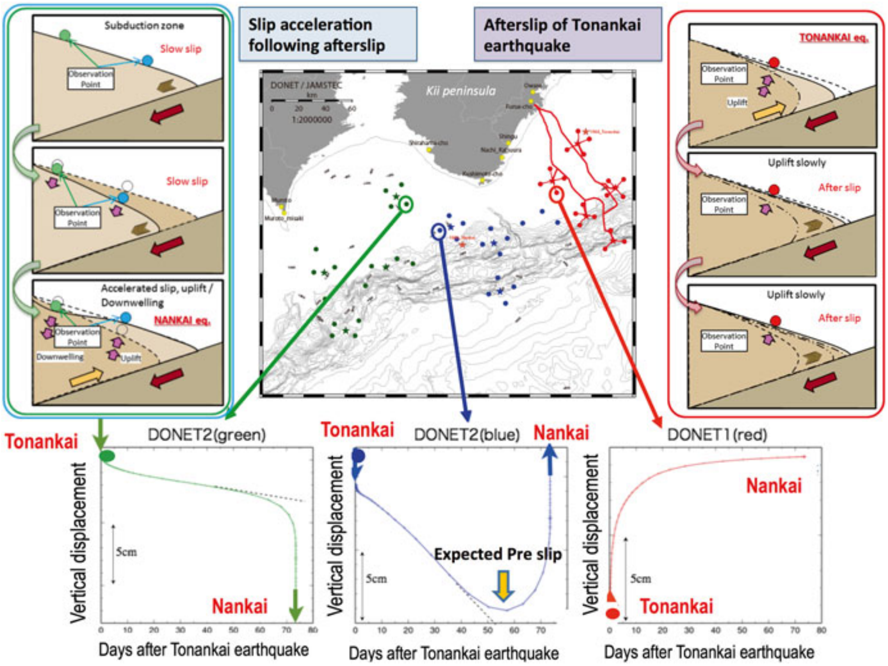

Fig. 12.6 Estimated phenomena for improvement of prediction researches. At the stations of DONET2 (*green* and *blue* colored), subsidence is expected first because the afterslip occurs away from the stations. Then, the afterslip propagates below the blue stations and uplift is observed there. On the other hand, the slip does not reach below the *green* stations, subsidence continues there. Finally, slip is accelerated to become Nankai earthquake

12.3 Off East Japan Seismogenic Zone

12.3.1 Mechanism of the East Japan Earthquake in 2011

A M9 great earthquake occurred around East Japan in March 11 2011. This earthquake generated the large tsunami and damaged many coastal cities along the Pacific. According to the observations around the east Japan seismogenic zone, average seismic coupling is less than 30 % (e.g. Peterson and Seno 1984). The stable slip was expected for the remaining 70 % of the relative plate motion. It generally defined that the stable slip zone doesn't accumulate the stress around the plate boundary. Therefore, we speculated that the Off East Japan seismogenic zone was composed of small and medium size asperities (Yamanaka and Kikuchi 2004). The severe stress accumulation that causes the great earthquake was not expected in the region before the 2011 Great East Japan earthquake. However, the estimated slip zone of the 2011 East Japan Earthquake was overlapped with the assumed stable slip zones. Figure 12.7 shows the difference of bathymetry around off Miyagi near the epicenter of 2011 East Japan Earthquake (Fujiwara et al. 2011; Kodaira et al. 2012).

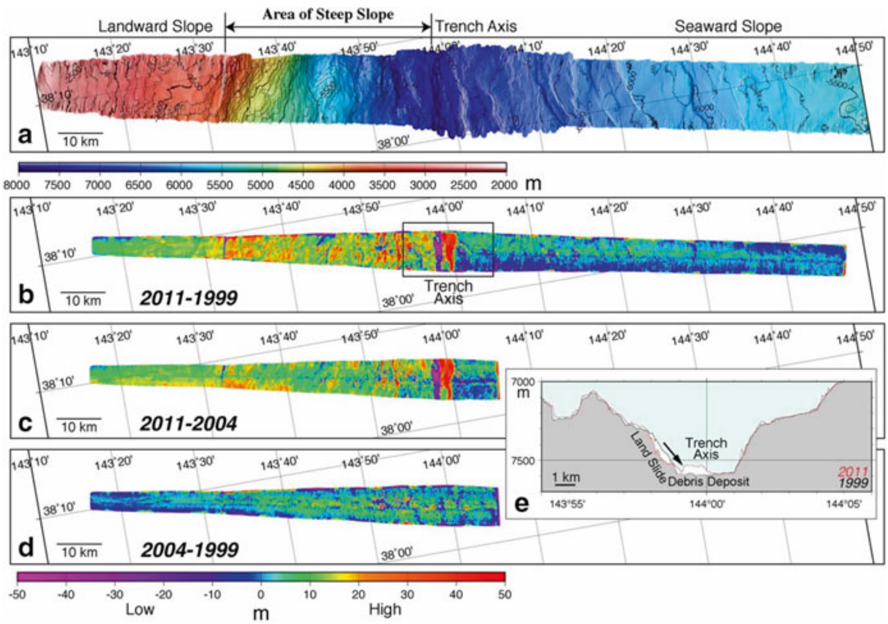

Fig. 12.7 Ocean floor displacement at the 2011 East Japan earthquake (Source: Fujiwara et al. 2011 (modified))

It is clear that the large movement of ocean floor around off Miyagi generated the large tsunami. The maximum ocean floor displacement was estimated over 50 m to cause the large tsunamis at the 2011 East Japan Earthquake (Fig. 12.7). This means that seismic energy has been accumulated in the assumed stable sliding zone. Finally, several seismogenic segments simultaneously ruptured as the one great earthquake in 2011.

12.3.2 Observation Records of the 2011 East Japan Earthquake

The offshore tsunami waveforms were obtained by the pressure gauges with cabled off Kamaishi (Maeda et al. 2011). Two types of tsunami were seen in the record. The one was typical tsunami waveform with the long period, and the other one was rapid increase like a pulse on the typical tsunami. Probably, the tsunami pulse was generated by the large movement of ocean floor off Miyagi (e.g. Satake et al. 2013). These tsunamis further increased their amplitudes according as the approaching to coastal areas around East Japan due to shoaling and bathymetric effects, and coastal cities were inundated and damaged severely. The real-time offshore records of pressure gauges have the great importance to improve the earthquake and tsunami early warning systems for the mega thrust earthquakes and tsunamis.

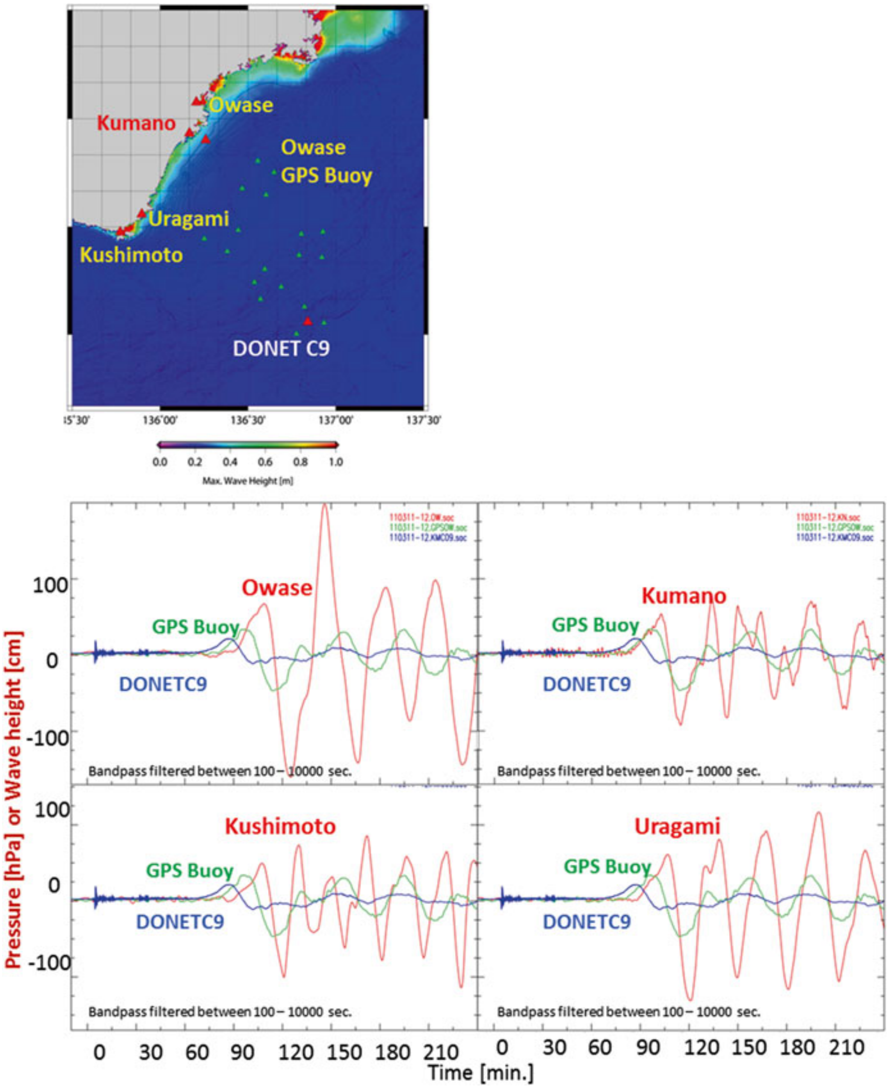

Fig. 12.8 Records of pressure gauges of DONET1 during the 2011 East Japan earthquake

DONET1 observatories recorded the seismic waves and tsunamis of the 2011 East Japan Earthquake. Figure 12.8 shows the DONET1 tsunami records at this earthquake (Baba et al. 2013), and indicates the importance and significance of off-shore observation for the advanced earthquake and tsunami early warning. We could estimate the ratio of tsunami amplification from offshore site to onshore site. In this case, the ratio was estimated to be about 6–10 times. By using ocean floor network as DONET, we can detect earthquakes and tsunamis earlier than the land stations and estimate approximately tsunami amplitude at the onshore areas. These advantages

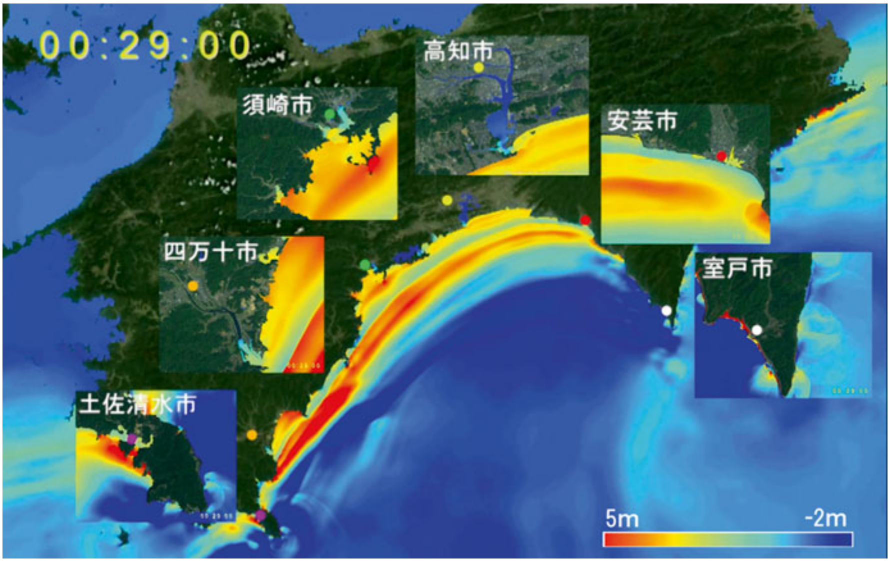

Fig. 12.9 Tsunami simulation focused on Kochi prefecture. Total grid numbers are 680 million with about 5 m-grid-spacing for the coast along the whole Kochi prefecture. About 7 h took for the 5 h calculation using 5,184 nodes of K-computer, which is the fastest supercomputer in Japan

are indispensable for disaster reduction of earthquakes and tsunamis. And, if the tsunami source is accurately acquired in real time from the offshore observation, we can execute a high-speed tsunami simulation such as shown in Fig. 12.9 using high-performance computers that provide us accurate prediction of tsunami (Baba et al. 2014). Such information will contribute to the speedy preparations for rescues. In Japan, not only DONET1, DONET2, but also, another cabled network project has started to monitor the East Japan seismogenic zones.

12.4 Future

We deployed the advanced ocean floor network off Kii peninsula not only in the Tonankai seismogenic zone, but also for the Nankai seismogenic zone. We have started to apply the data from network for disaster mitigation and seismological research with the advanced simulations. In the near future, the necessities for monitoring southwestern Japan seismogenic zone that includes Kyushu Island and Okinawa Islands by the ocean floor networks will be increasing and indispensable. We will continue to develop advanced ocean floor network cable technologies and data analyses researches for realizations of the future ocean floor network plans. It is also needed to integrate the ocean and land network data, and further to collaborate with international network systems making a global network for progresses in geosciences and mitigations of the earthquake and tsunami disasters.

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Chapter 13
Seawall Performance Along Southern Coast of East Japan Impacted by the 2011 Tohoku Tsunami; A Note for the Reconstruction Process

Shinji Sato

Abstract This article describes the performance of seawalls in the 2011 Tohoku Tsunami on the basis of tsunami surveys along the southern coastline of East Japan. In Chiba and Ibaraki Prefectures where incident tsunami was slightly higher than the height of seawalls but lower than the backshore dune height, the tsunami was blocked by the presence of the dune as well as the seawalls. Significant flooding damage was developed only in the harbour area as well as in the area around the river mouth. The presence of the water gate at the river mouth appeared to be effective to minimize the flooding. In the south of the Fukushima Prefecture where incident tsunami was 1–3 m higher than the height of seawalls, a clear contrast was observed in the damage of seawalls as well as in the inland damage behind collapsed and survived seawalls, which provided valuable hints for tenacious seawall structure that enhances durability against tsunami overflow. These observations helped to establish a new strategy for tsunami disaster mitigation and thus to promote the reconstruction process on the basis of proper understanding of the limitation and effectiveness of seawalls.

Keywords Tsunami inundation • Seawall performance • Tsunami disaster mitigation

13.1 Introduction

Catastrophic tsunami disaster was developed by the 2011 Tohoku Tsunami, which was generated by a $M_w = 9.0$ earthquake with 300 km by 500 km large source zone. Characteristics of the mega-tsunami and resultant coastal damage were investigated by many survey teams under the coordination of the Tohoku Tsunami Joint Survey

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Group (hereafter referred to TTSG 2011) (e.g., Mori et al. 2011; Mori and Takahashi 2012). Coastal damage was found to depend on various geophysical properties, such as the incident tsunami height, marine bathymetry, nearshore and coastal topography, and conditions of shore protection structures (e.g., Shimozono et al. 2012).

Many seawalls were collapsed especially on the Sanriku Coast which had experienced a series of historical Sanriku Tsunamis such as 1611 Keicho Tsunami, 1896 Meiji Tsunami and 1933 Showa Tsunami. Trans-Pacific 1960 Chilean Tsunami also affected the district. The height of the 2011 Tohoku Tsunami was much larger than the height of seawalls designed on the basis of these historical tsunamis, and therefore destroyed seawalls resulting in catastrophic flooding in the coastal area. Maximum tsunami runup reached 40 m above sea level in Iwate Prefecture. It was sometimes difficult there to estimate the mechanism of seawall destruction since the seawalls were completely broken by the tsunami much larger than the design level. On the other hand, in the area south to the Fukushima Prefecture, the tsunami height was of the same order with the height of seawalls. Figure 13.1 illustrates the tsunami watermark heights in the TTSG database compared with the height of seawalls in

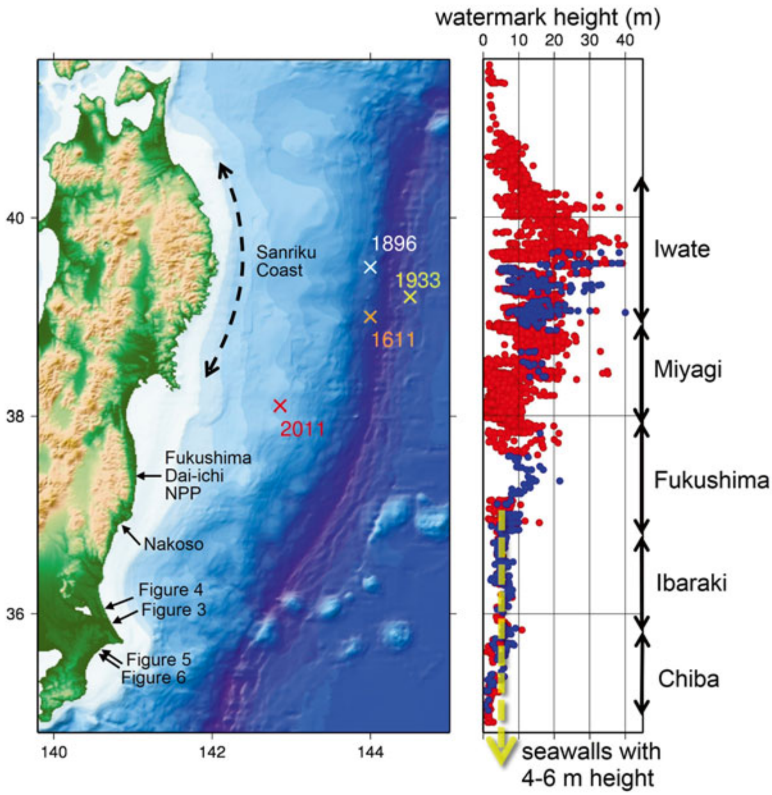

Fig. 13.1 Tsunami watermark heights along the east coast of the Honshu Island compiled in the TTSG database

the southern part of East Japan, that is, Fukushima, Ibaraki and Chiba Prefectures. In these areas, many measurements were conducted by survey teams organized by researchers in the University of Tokyo. The survey teams observed clear contrasts in damage behind collapsed seawalls and survived seawalls, which appeared to provide valuable hints for tenacious seawall structure that enhances durability against tsunami overflow. This article describes tsunami surveys in the areas south to the Fukushima Prefecture focusing on the limitation and effectiveness of seawalls.

13.2 The Survey

13.2.1 Kujuukuri and Kashima Beaches

Field surveys in Chiba and Ibaraki Prefectures were conducted on March 12, 15 and 18–19, 2011 (Shimozono et al. 2011). Tsunami watermark heights were measured by a VRS-mode Real-Time Kinematic Global Positioning System (RTK-GPS) in Ibaraki Prefecture and by an auto-level in Chiba Prefecture. The RTK-GPS presents the local elevation data with an accuracy of a few centimeters in terms of Tokyo Peil standard (T.P., T.P. zero corresponds to the mean water level at the Tokyo Bay, which is the standard datum level for land topography in Japan).

Hereafter, all the measured elevation data are referred to the T.P. standard. The measurements by the auto-level were based on local sea level, which were converted to the standard datum T.P., by using tide charts at nearby tide gauges. The watermark heights measured at the landward boundary of the flood area are specified as 'run-up heights' while those inside the flood area are called as 'inundation heights.'

Figure 13.2 shows topography in the study area, location of measurements and measured height of tsunami watermarks. The topography in Chiba is characterized by a 40 km stretch concave beach, Kujuukuri Beach, isolated by headlands at both ends and backed on the land side by a flat coastal plain with many small rivers. On the other hand, the topography in Ibaraki is characterized by a relatively narrow sandy beach like Kashima Beach, which is backed by high hills with 20–30 m elevation with fewer rivers flowing to the sea. Sand dunes are formed on both beaches which develop backshore dune in parallel to the shoreline with height 7–9 m T.P.

The backshore dune is discontinuous at the mouth of a number of small rivers on the Kujuukuri Beach while the dune develops continuously on the Kashima Beach because of fewer rivers. Measured tsunami heights shown in Fig. 13.2 varied in a range from 4 to 8 m T. P. with gradually decreasing trend from north to south. The tsunami height is large at Oarai and Choshi, located at the end of concave sandy beach.

The large tsunami heights near Oarai and Choshi are due to marine bathymetry characterized by contour lines convex to the sea that converge tsunami rays due to refraction. In contrasts, tsunami height becomes small near the central part of the concave beach owing to energy divergence due to concave bathymetry. Such convergence/divergence of tsunami energy due to convex/concave bathymetry is also observed on the Sendai Coast (Sato et al. 2014) and on the Fukushima Coast (Sato et al. 2013).

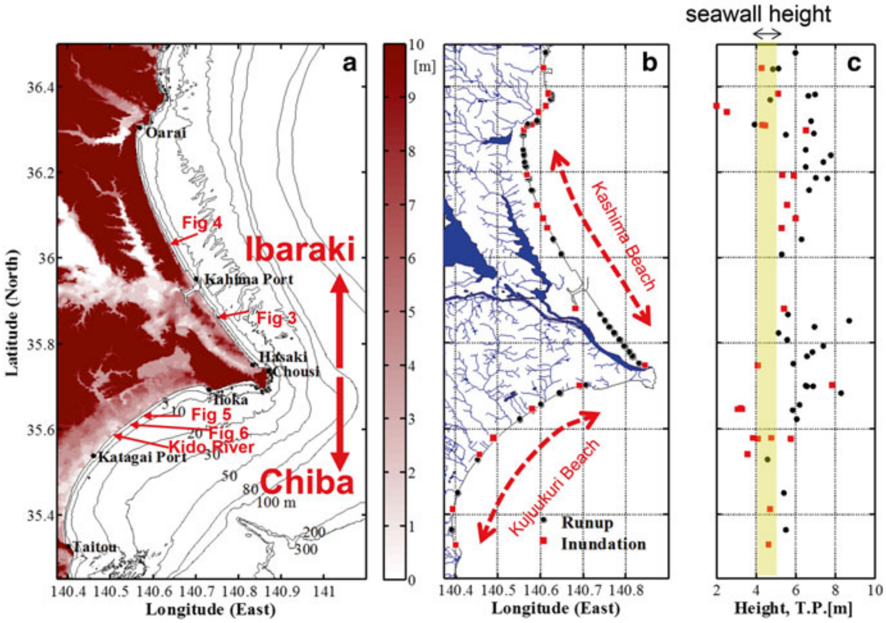

Fig. 13.2 Topography and bathymetry of the survey area (**a**), location of measurements (**b**) and measured watermark heights (**c**) in Chiba and Ibaraki Prefectures. The coast is partly protected by piecewise seawalls with height 4–5 m T.P.

13.2.1.1 Tsunami Protection by Seawalls and Sand Dunes

Some coastal stretches in the study area were intermittently protected by piecewise height calculation of design storm waves because the height of the historical tsunami was smaller than the runup of storm waves. Since the height of the 2011 Tohoku Tsunami was mostly larger than the height of seawalls, tsunami overflowed the seawalls. However, no large-scale inundation was developed except in the area near river mouth because the top of the backshore dune was higher than the tsunami. Figure 13.3 shows a typical example of tsunami runup line traced on the seaside slope of backshore dune. Distribution of debris and clear boundary between dry and wet sand surface presents tsunami runup line observed on March 12, 2011, one day after the tsunami. It is noted that the measurement at this location is registered as UTMS-0174 in the TTSG database. All the photographs taken in the survey are archived and available on the Internet in Tsunami Joint Survey Group Photo Archive 2013. In the study area in Ibaraki Prefecture, large-scale inundation was developed only around the harbour area at Oarai.

Significant damage concentrated near harbours was also observed in Chiba Prefecture, in which Choshi and Iioka were among severely damaged communities. In other areas, tsunami damage was limited to the narrow coastal zone close to the shore. Even in the narrow affected area, the damage appeared to be minimized

Fig. 13.3 Tsunami runup observed on backshore dune, Kashima Beach, Ibaraki Prefecture (March 12, 2011); watermark measured at 7.0 m T. P., 150 m from the shoreline (UTMS-0174 in the TTSG database, location marked in Fig. 13.2)

owing to the presence of seawalls. Figure 13.4 shows a typical example in Hokota, where a wooden house located behind the seawall was inundated to the level of 6.0 m T.P. but remained unbroken. Seawalls appeared to decrease the volume and the flow intensity of overflowed tsunami in case the overflow depth of tsunami was of the order of 1–2 m above the top of the seawall.

The tsunami flooding reduction by sand dune was also observed on Kujuukuri Beach in Chiba Prefecture. Figure 13.5 shows a typical example of watermark measured on the top of an artificial sand dune with top height 6.2 m T.P., constructed in parallel to the shore on the sea side of coastal pine trees. Wood fences around the pine trees were partially destroyed by the tsunami. The tsunami overflowed the 4.0 m T.P. seawall on the shore as well as some sections of the artificial sand dune. Since the erosion of natural/artificial sand dunes was found insignificant, alongshore sand dunes appeared to be effective in protecting the areas on the landside. Significant damage was observed however near the river mouth where sand dune was discontinuous due to the river flow. The most significant inundation was observed near the Kido River mouth (location marked in Fig. 13.2), where tsunami overflow from the sea was prevented by high sand dunes but tsunami intruded into the river and destroyed river banks, resulting in flooding over a large area. The largest inundation depth around the Kido River mouth was measured at 1.2 m (UTMS-0155 in the TTSG database).

The tsunami flooding through the river was minimized in case a water gate was installed at the river mouth. Figure 13.6 shows a water gate at the Shimbori River

Fig. 13.4 Tsunami watermark measured in Hokota, Ibaraki Prefecture (March 19, 2011); watermark measured at 6.0 m T. P., 55 m from the shoreline (UTMS-0181 in the TTSG database, location marked in Fig. 13.2)

Fig. 13.5 Tsunami watermark measured on Kujuukuri Beach, Chiba Prefecture (March 18, 2011); a watermark was measured on the top of an artificial dune, 6.2 m T. P. and 17 m from the shoreline protected by a seawall with height 4 m T.P. (UTMS-0209 in the TTSG database, location marked in Fig. 13.2)

Fig. 13.6 Water gate at the Shimbori River mouth, Chiba Prefecture (March 19, 2011); measured watermark height was 6.6 m T. P. and 1.0 m higher than the top of the gate (UTMS-0163 in the TTSG database, location marked in Fig. 13.2)

mouth, located 10 km north to the Kido River mouth (location marked in Fig. 13.2). In the residential area behind the water gate, only small flooding was observed by the tsunami overflowed the gate by 1 m. In contrasts to the large flooding damage in the Kido River, the tsunami damage through the Shimbori River appeared to be reduced by the water gate. The effectiveness of water gate is also observed in Ootsuchi, Iwate Prefecture, where tsunami intrusion to the Koduchi River was minimized by the river mouth water gate while tsunami flooding was significant for the gate-less Ootsuchi River. Tsunami intrusion into rivers and flooding via rivers are also observed in many rivers such as the Samegawa River and the Kido River in Fukushima Prefecture, the Kitakami River in Miyagi Prefecture and the Kesen River in Iwate Prefecture (e.g. Tanaka and Nguyen 2012; Sanuki et al. 2013; Liu et al. 2013).

13.2.2 Nakoso Coast

Nakoso Coast is a sandy pocket beach in Fukushima Prefecture facing to the Pacific Ocean. Figure 13.7 presents the general layout of the area. It is an arc-shaped concave beach with an approximate length 7 km and isolated by two headlands, Cape Ryuugu on the north end and Cape Unoko on the south end. The Samegawa River, as

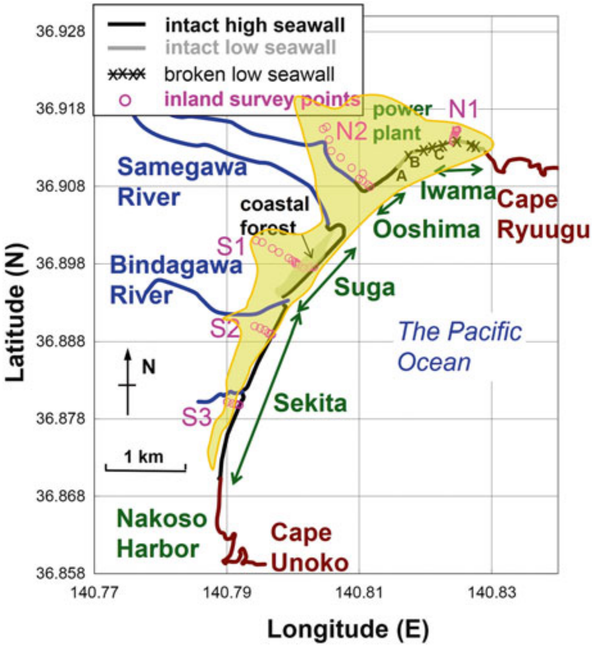

Fig. 13.7 Tsunami survey at the Nakoso Coast, Fukushima Prefecture; Yellow zone represents inundation. The coastal area is divided into five districts, Iwama, Power Plant, Ooshima, Suga and Sekita Districts. The symbol 'A', 'B' and 'C' refers to Fig. 13.9

the most predominant river in this area flows into the northern part of the Nakoso Coast. About 1.5 km south of the Samegawa River, a small river, the Bindagawa River, is located. A coal thermal power plant is located to the north of the Samegawa River mouth. The yellow area in Fig. 13.7 represents the area inundated by the tsunami, which covers a wide area in Iwama and Ooshima Districts located to the north of the Samegawa River, Suga District between the Samegawa River and the Bindagawa River and the Sekita District located to the south of the Bindagawa River.

13.2.2.1 Seawalls Performance

Field surveys were conducted twice on March 24–25 and April 1–2, 2011, 2–3 weeks after the tsunami attack (Sato et al. 2012). On March 24–25, the survey was focused on the general information of the tsunami damage, e.g., tsunami inundation height and run-up height, which were identified from the mud-line watermark on the wall or window of surviving buildings and the diffused debris on the slope ground, respectively. On April 1–2, attention was focused on the performance of seawalls and the relationship between the inundation area and the inland topography. According to the inundated stopped clock found in the Iwama District, the tsunami inundation time is 15:38 JST, approximately 1 h after the earthquake. A video clip was taken from the top of a building of the power plant located to the north of the Samegawa River. The clip recorded the arrival of the first tsunami at 15:33 which overflowed the seawall at 15:35 JST. The inundation level appeared to reach maximum by the second or the third tsunami which arrived at 15:40 JST, which is consistent with the time indicated by the stopped clock.

The instruments used in the field survey mainly include the RTK-GPS system, a handy GPS, a laser ranger and a measuring staff. The coast is protected by seawalls with top height 5.5–6 m in Sekita, Suga and Ooshima Districts and 4.2 m in Iwama District. The heights of seawalls had been determined on the basis of storm waves since the largest historical tsunami record was lower than the runup height of storm waves. Five survey lines behind the seawall, i.e., N1, N2, S1, S2 and S3 in Fig. 13.7, were also considered to estimate the tsunami profiles along the cross-shore direction. Figure 13.8 illustrates the height of watermarks compared with the top height of seawalls. The blue bar indicates inundation height and the white bar denotes run-up height. Tsunami heights near the shoreline are found to be 6–7 m T.P. except for smaller tsunami observed in the southernmost region. Since the tsunami height on the shore was larger than the seawall height by 1–3 m, inundation was developed

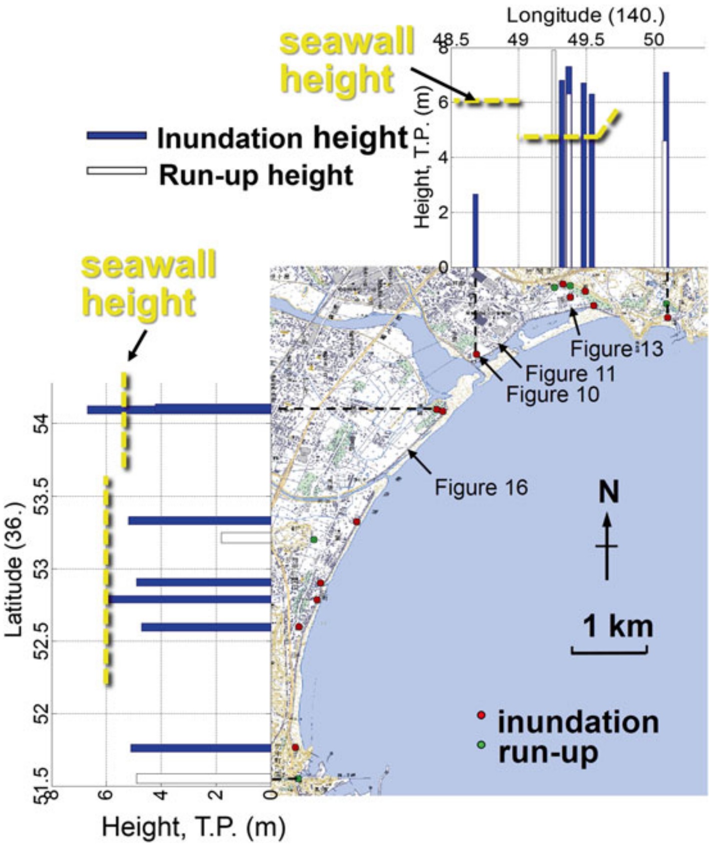

Fig. 13.8 Distribution of tsunami watermark heights in the Nakoso Coast compared with the hight of seawalls; The inundation height is 6–7 m except in the south region (All the measurements are registered as IBRK-0004 ~ IBRK-0016 in the TTSG database)

behind the seawall as shown in Fig. 13.7. In the area close to the Samegawa River and the Bindagawa River, flooding over the river banks was superimposed. The smaller tsunami height in the south region is considered to be due to the sheltering effect due to the Cape Unoko and breakwaters of two nearby fishery harbours.

Iwama District located north of the Samegawa River was the most damaged region. A number of the seawalls were broken, which appeared to increase the inundation tsunami volume. To demonstrate the relationship between the seawall height and tsunami damage, we conducted detailed measurements on the top height of post-tsunami seawalls, which is presented in Fig. 13.9 Before tsunami, the seawall in Iwama District had a total length of 2 km with two different designed heights, i.e., 6.0 m on the south near the Samegawa River mouth with a length of 950 m, and about 4.2 m for the remaining northern part. In the high seawall section, all seawalls were intact after the tsunami attack; whereas, around 750 m long seawall was broken within the original low seawall section, i.e., 71 % of the low seawall was collapsed.

Figure 13.10 shows the seawall in the Ooshima District. Although the tsunami overflowed the 6 m seawall constructed on the ground level as low as 2 m T.P., the damage was found to be insignificant. In this region, the seawall height had been raised to the present 6 m after the overtopping of the storm waves in 1950s. Figure 13.11 shows a typical damage behind the seawall. Although the parapet of the seawall remained intact, the concrete apron on the landside was partially broken with basement land scoured by the overflowed tsunami.

At the location "A" in Fig. 13.9, the seawall height suddenly decreases from 6.0 to 4.2 m. This is considered to be due to the presence of a wide barrier sand bar in the Iwama District formed in front of the seawall, which decays the height of storm waves. Figure 13.12a shows a panorama image taken at this location. Careful

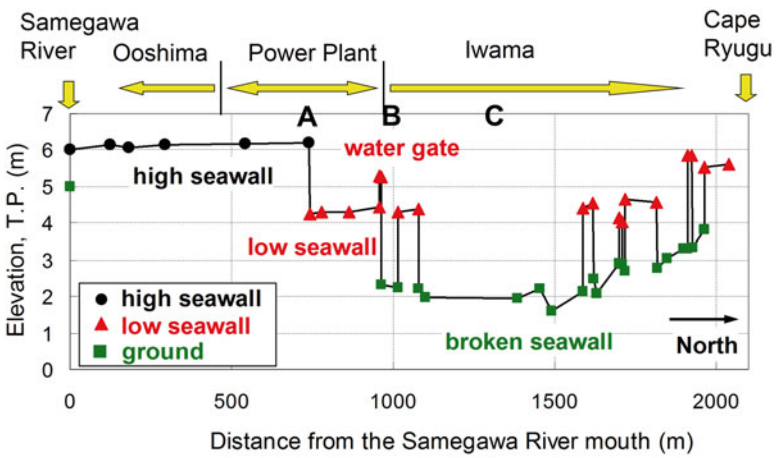

Fig. 13.9 Alongshore distribution of the post-tsunami seawall heights and ground elevations on the north of the Nakoso Coast; The seawall height was discontinuous at Point 'A'. Most of the lower seawall was broken. The symbols 'A', 'B' and 'C' refer to Fig. 13.7

Fig. 13.10 Insignificant damage behind a high seawall in Ooshima District. (March 25, 2011). The location is marked in Figs. 13.8 and 13.14

Fig. 13.11 Intact parapet and broken apron concrete with land scoured by overflowed tsunami in Power Plant District (March 25, 2011). The location is marked in Figs. 13.8 and 13.14

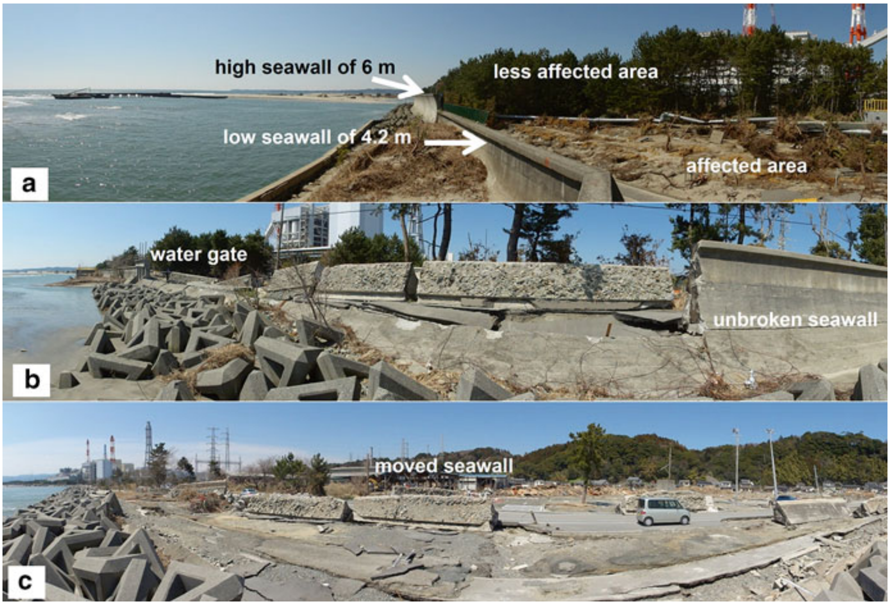

Fig. 13.12 Panorama images taken at three specified locations (March 25, 2011). The locations A, B and C are indicated in Figs. 13.9 and 13.14

observations on the status of pine trees, steel fence and pipeline on the land side demonstrated the different performance of seawalls: behind the 6 m seawall, most local properties were conserved; on the contrary, significant damage developed behind the 4.2 m seawall with pine trees, fence and pipeline being ruined away. Further north beyond the water gate, many seawall blocks were broken and moved landward by the tsunami. The panorama photo Fig. 13.12b taken at location "B" in Fig. 13.9 presents the destruction of seawalls. Since the highest water level due to the tsunami at the seawall is more or less 7 m as confirmed in Fig. 13.8, it is considered that the criterion of the seawall collapse is in between 1 and 2.8 m by the overflow depth. In this area, the relative seawall height was around 2 m with the ground elevation being around 2 m T.P. At location between 1,100 and 1,600 m (in the vicinity of point "C" in Fig. 13.9), all seawall blocks were broken as revealed from Figs. 13.9 and 13.12c.

Some seawall blocks were even pushed across the road, and found far away inland as shown in Fig. 13.13. During the field survey, the survey team found one broken seawall block transported 35 m landward from its original location. This concrete block had a dimension of 0.5 (upper boundary) × 1.7 (lower boundary) × 2 (height) × 10 m (length) with an estimated mass of approximate 53 ton, which demonstrated the massive power of the tsunami as described by Liu et al. (2014). At location 1,500 m north from the river mouth, it is found the ground elevation increases to 4 m at the north end as it approaches to the Cape Ryuugu. Correspondingly, the seawall height increases to 5.6 m T.P. finally. Nevertheless, the

Fig. 13.13 Displaced and Broken seawall block in Iwama District (March 25, 2011). The location is marked in Figs. 13.8 and 13.14

relative seawall height decreases to 1.6 m at the end. Collapse of seawall is intermittent in this section which induced different damages to the backside community.

Figure 13.14 describes tsunami damage to houses and seawalls in the Iwama District. Damages were identified by the comparison of two aerial photos taken by Geographical Information Authority of Japan, on March 12, 2011 and in 2009. Lost houses were marked as 'washed away' when the roof disappeared after tsunami at the original location found in the 2009 photo. The concrete blocks of the seawall are denoted by white rectangles where they are found broken. The change in the shape of barrier sand bar located seaside of the seawall was also illustrated in the figure. The large shoreline retreat is due to the erosion by tsunami flow as well as by the co-seismic land subsidence of the order of 0.5 m. Such large change in nearshore morphology is also reported in the Sendai Plain, Miyagi Prefecture, by Tappin et al. (2012), Udo et al. (2012) and Tanaka et al. (2012). The large deformation of the nearshore bathymetry on Nakoso Coast is also described by Uda et al. (2012) and Tanaka et al. (2013). The shape of the barrier sand bar after the tsunami indicates that the deformation was significant in the region where seawalls were completely broken. The barrier sand bar in front of the Ooshima District remained un-deformed. This is considered to be due to the difference in flow intensity on the seaside of the seawall. Collapse of seawalls makes the incoming tsunami more progressive rather than reflective, which tends to increase the flow velocity due to tsunami and thus erode the barrier sand bar. The concentration of the receding tsunami flow to the collapsed section is considered to contribute to further erosion. The monitoring of the

Fig. 13.14 Tsunami damage in Iwama District, presenting lost houses, collapsed seawall and deformed barrier sand bar; Most of the houses were washed away in the Iwama District as compared with a photograph taken October, 2009. Broken seawall blocks were transported inland

recovery of the barrier sand bar is important since the presence of the barrier sand bar is essential to the damping of storm waves and the safety of the community.

Figure 13.15a presents the cross-shore profile of the ground elevation and tsunami inundation height along survey lines N1 and N2. Along the line N1 in the Iwama District, the seawall has a height of 4.5 m and the nearby ground elevation is 2.5 m.

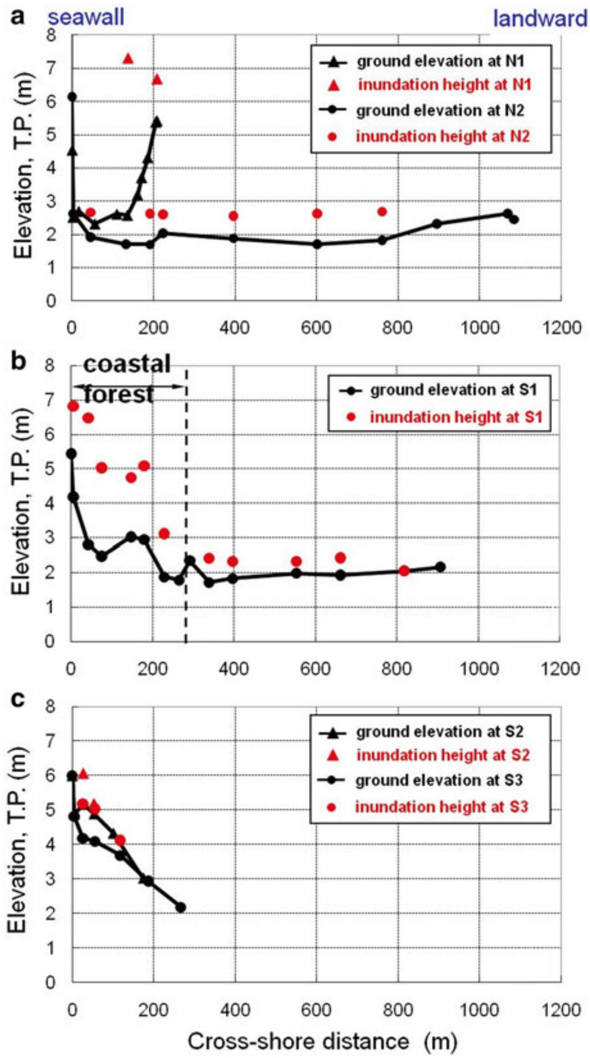

Fig. 13.15 Cross-shore distribution of ground elevation and tsunami inundation height along survey lines N1 & N2 (**a**), S1 (**b**) and S2 & S3 (**c**). The lines N1 to S3 are shown in Fig. 13.7

The inland ground elevation gradually increases to 5.4 m at location 210 m, about 3 m higher than the ground level at the seawall. The measured inundation height is 7.3 m (4.7 m above the local ground level) at location 137 m. In the vicinity of broken seawall, the inundation height is only 6.3 m as is confirmed in Fig. 13.2. At the same time, tsunami inundation height is 6.7 m at location 210 m. Therefore, the following mechanism can be inferred from Fig. 13.15a with respect to line N1: After tsunami overflowed the seawall, the tsunami height increased by 1 m within a cross-shore distance of 150 m owing to the formation of standing waves on the narrow plain bounded by steep hill. Subsequently, inundation height decreased by 0.6 m from 150 to 210 m, which is ascribed to the significant flow resistance by the presence of dense houses.

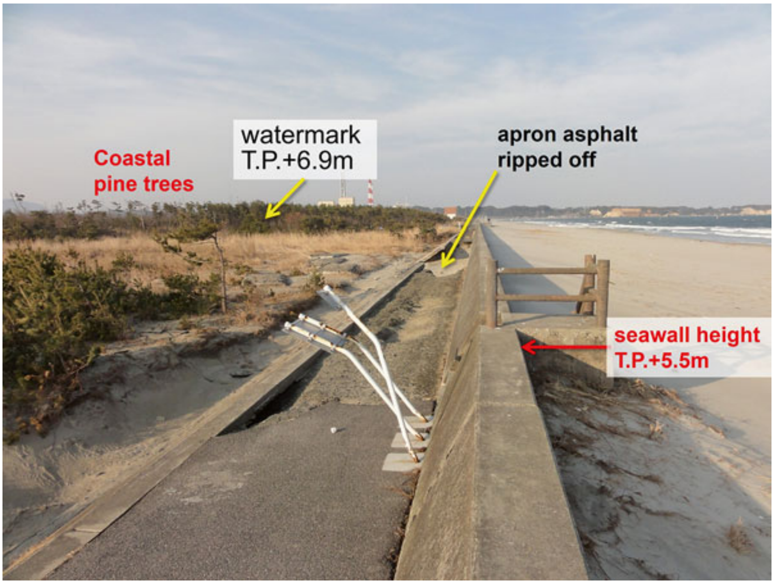

Fig. 13.16 Partially broken seawall and coastal pine trees in Suga District. The photograph was taken at the seawall on the line 'S1' marked in Fig. 13.8 (April 1, 2011). The watermark in the pine trees is the most seaward measurement plotted in Fig. 13.15b

Along the line N2 in Ooshima District, the local seawall has a height of 6.2 m and the nearby ground elevation is 2.6 m. Moving to the landward, there is no significant change on the ground elevation with a certain decrease by 1 m just after the seawall. The inundation height is around 2.6 m for all measured points (the inundation depth is approximately 0.6 m). According to the interview to the local residents, although the overflowed tsunami inundated the residential area, the tsunami intensity/velocity was significantly mitigated/reduced because of the protection of the high seawall. Therefore, the damage to the local houses is fairly mild. Increase of the water level in this district is assumed to be inch by inch and spatially uniform. However, the inundated area in Ooshima District is relatively large, which covers more than 1 km landward of the seawall. This is due to the low land elevation and due to the additional flood water overflowed from the river bank. The inundation and the resultant damage in Iwama and Ooshima Districts demonstrates a sharp contrast owing to the difference in seawall height and inland topography.

Figure 13.15b illustrates the cross-shore distribution of the ground elevation and tsunami inundation height at the survey line S1 in Suga District, which crosses the coastal pine trees as displayed in Fig. 13.16. The local seawall has a height of 5.5 m whereas the nearby ground elevation is 4.2 m (the relative seawall height is 1.3 m). The inland ground elevation decreases to 1.8 m at 260 m from the seawall. The tsunami inundation height also drops significantly in the pine trees, i.e., from 6.8 m near the seawall to 3 m at the 230 m location. The function of coastal forest as a buffer zone against the tsunami attack, which increases the flow resistance, is obviously demonstrated in this figure. Further beyond, the ground level keeps around 2 m and the corresponding inundation depth is only 0.5 m, leading to insignificant damage in this area. The most inland run-up location was found at location 820 m from the seawall.

Figure 13.15c demonstrates the cross-shore distribution of ground elevation and tsunami inundation height at survey lines S2 and S3 in Sekita District. It is clear that the local seawall height is 6 m at these two locations with a relative seawall height being 1.2 m. The inland ground elevation is maximum at the seawall and gradually decreases to 2.0 m with an approximate slope of 1/100. The inundation depth near the seawall is about 1 m, which decreases to 0.4 m, 120 m landward along the line S2, and to 0.3 m, 50 m landward along the line S3. Compared with the region north of the Samegawa River, the damage in Sekita District was minor, which appeared to be due to slightly smaller tsunami height in the southern region and due to the high and intact seawalls. Relatively high elevation of land topography as confirmed in Fig. 13.15c is considered to be another reason of the minor damage.

The efficiency of seawalls in decreasing tsunami overflow volume is also observed in Minami-Soma, Fukushima Prefecture, where tsunami height is about 4–6 m larger than that of Nakoso. The inland inundation level in a coastal section with surviving seawalls was significantly smaller than that in the area where more than 30 % of the seawalls were completely broken (Sato et al. 2014). This suggests that unless they were completely destroyed, the seawalls must have reduced somewhat the inland inundation level by decreasing the tsunami overflow volume.

13.3 Reconstruction Plan Based on Two Tsunami Hazard Levels

Based on the lessons learned in the Tohoku Tsunami, the Japanese Government decided to introduce two-level tsunami hazards to deal with tsunami disaster mitigation. The first-level tsunami hazard (Level-1 tsunami) is defined as a frequent tsunami with the return period of a hundred years. Seawalls are designed for a Level-1 tsunami, which dictates crown elevations along with other design criteria. On the other hand, the second-level tsunami hazard (Level-2 tsunami) represents the probable maximum tsunami and is used to establish evacuation strategies and plans. The return period of the Level-2 tsunami is considered at a thousand years.

Figure 13.17 illustrates the reconstruction plan of the Iwama District compiled by Iwaki City, Fukushima Prefecture, in February 2013 (Iwaki City 2013). It is composed of the construction of a 7.2 m T.P. seawall, alongshore green belt and relocation of a part of communities to higher ground. The height of the new seawall was determined by the runup height of the design storm waves, considering the significant erosion in nearshore bathymetry as well as the co-seismic land subsidence

Fig. 13.17 Reconstruction Plan of the Iwama District, Iwaki City, as compared with a post-tsunami aerial photograph

which increased the runup height. The seawall height required for the Level-1 tsunami was computed by a numerical tsunami propagation model, which was found lower than the runup height of the storm wave. The shore parallel green belt will be constructed by a landfill with the same height of the seawall, with a purpose of reducing tsunami overflow and thus helping secure evacuation for the infrequent tsunami larger than the design level of the seawall.

Partially damaged seawalls remain capable of reducing tsunami effects for tsunamis exceeding their design level (Level-1) as revealed in many tsunami surveys including the survey described in this article. Hence the shore protection structures should remain even effective for an event larger than the design level, unless the structures were totally destroyed. Therefore, it is important to construct such structures with the consideration of tsunamis beyond the design level (Level-1). Seawalls should be designed to maintain partial effectiveness even for "beyond-the-design-basis" conditions. This design concept is called "Nebari" in Japanese, which implies tenacity, toughness and resilience or never giving up. Careful field observations on damaged seawalls as described in this article should lead to valuable insights for how to design seawalls using the 'Nebari' concept.

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Chapter 14
A Consideration Aimed at Improving the Resiliency of Protective Structures Against Tsunami

Taro Arikawa and Takayuki Oie

Abstract In this paper the effectiveness of breakwaters to provide protection against huge tsunami was considered using numerical simulations. Kamaishi Bay, where large breakwaters had been installed, was selected as the target area, because about half the breakwaters were washed away by the tsunami produced by the Tohoku Earthquake in 2011. Therefore, the effect of breakwater protection against the 2011 tsunami is verified by comparing the different states of damage to breakwaters with numerical simulations. The results show that the protective effect provided by breakwaters against tsunami depends on the rate of opening gap, and suggest that this is an efficient way to improve the resiliency of deeper-region breakwater structures.

Keywords Resiliency • Breakwaters • Tsunami • Overflow • Numerical simulations

14.1 Introduction

Coastal areas around Japan historically have been protected against storm surge and tsunami by seawalls and breakwaters. Kamaishi was one such area. Huge breakwaters with caissons more than 30 m high were installed at the mouth of Kamaishi Bay. While these caissons ranked among the largest in the world, roughly half of the breakwaters were washed away by the tsunamis subsequent to the 2011 Tohoku Earthquake, causing severe damage to the hinterland.

The Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunami, in response to *Lessons Learned from the "Great East Japan Earthquake" (2011)* produced by the Central Disaster Management Council proposed that basically two levels of tsunami must be hypothesized to build future

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tsunami countermeasures. One level is a tsunami hypothesized to build comprehensive disaster prevention countermeasures centered on evacuation of residents. This level is set based on a survey of tsunami deposits formed over long-term observations of crustal movement, and is a maximum class tsunami which, although rare, causes devastating damage when it does occur. The other level is a tsunami hypothesized to build coastal protection facilities such as breakwaters and seawalls that prevent tsunami from inundating inland regions. This level of tsunami occurs most frequently and although the class is low, the damage it causes is severe. To prepare for such times, technological development capable of improving the resiliency of protective structures under tsunami forces higher than the design loads must continue for coastal protection to be effective.

In this paper, ‘effectiveness’ is clarified for resiliency of protective structures against tsunami forces. First, the damage to breakwaters at Kamaishi port is summarized. Next, numerical simulations are conducted under deferent states of breakwaters to clarify the effectiveness of protection. Finally, the decreasing effect of the disaster against varying tsunami heights is considered.

14.2 State of Damage of Breakwaters at Kamaishi Bay

14.2.1 Outline

The summary of damage of breakwaters in ports was described by Tomita et al. (2013). Breakwaters at the mouth of Kamaishi Bay consist of three parts as shown in Fig. 14.1, the 990 m North Breakwater, the 670 m South Breakwater, and the 300 m submerged breakwater at the mouth of the bay.

The North and South parts of the breakwaters consist of a deep region breakwater and a shallow region breakwater. The breakwater at the deep region is formed by trapezoidal caissons or rectangular caissons. The crest height of all caissons is D.L. + 6.0 m (T.P. +5.12 m). Figure 14.2 (1) shows the typical cross section of the trapezoidal caissons in the deep region, which have a rubble foundation that extends from a depth of −60 m to −27 m. In the shallow region, the caissons are rectangular, as shown in Fig. 14.2 (2). A submerged breakwater is installed at the central opening of the baymouth breakwater to close the baymouth as much as possible; the height is from 10 to 15 m and the depth at the mouth is D.L. −19 m.

14.2.2 Damage Due to the 2011 Tsunami

Figure 14.3 shows caissons which slid or inclined according to the results of a survey by the Tohoku Regional Development Bureau. At the north side breakwater, 7 of the 22 caissons in the deep region were washed away, 14 were inclined, and 1 was undamaged. Of the 22 caissons in the shallow region 11 were washed away, 5 were

Fig. 14.1 View of the Breakwaters at the Mouth of Kamaishi Port after the 2011 Tsunami (Source: Tohoku Regional Development Bureau; Japan)

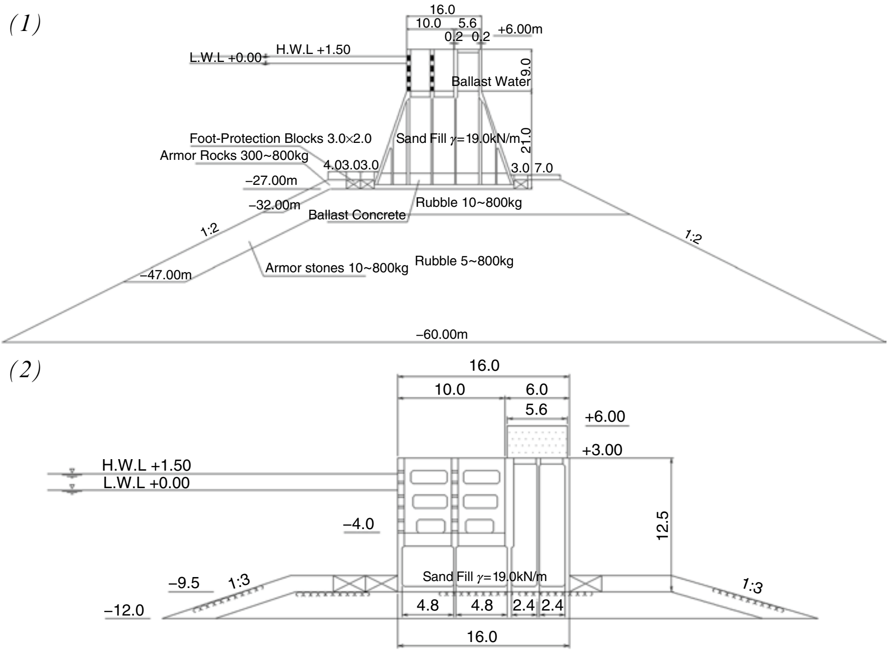


Fig. 14.2 Standard cross sections at Kamaishi port. (*1*) Typical cross section of trapezoidal caisson in the deep region (above), and typical cross section of caisson in the shallow region (*2*) (Source: Tohoku Regional Development Bureau; Japan)

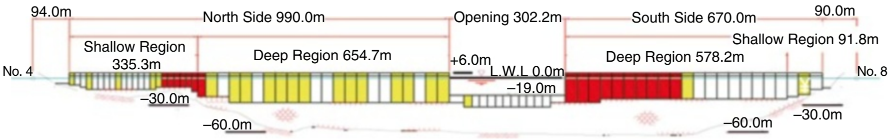


Fig. 14.3 State of damage to caissons (*Red*: undamaged, *Yellow*: inclined, *White*: fallen) (Source: Tohoku Regional Development Bureau; Japan)

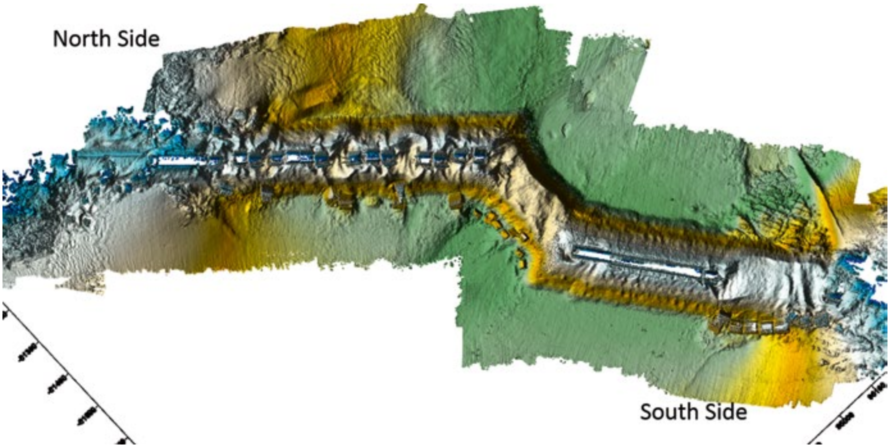


Fig. 14.4 State of damage (Narrow multi-beam measurement results) (Source: Tohoku Regional Development Bureau; Japan)

Fig. 14.5 State of breakwater damage in the deep region (Source: Tohoku Regional Development Bureau; Japan)

inclined, and 6 were undamaged. Of the 6 undamaged caissons, friction increasing mats were placed on 5. At the baymouth, of the 13 submerged breakwaters, only 1 of the 13 remained; the rest fell. At the south side, of the 19 deep caissons, 8 were washed away, 1 was inclined, and 10 were undamaged, and in the shallow region, 2 were washed away and 1 was inclined. The state of damage of the overall breakwater structure is shown in Fig. 14.4. At the north side breakwater many sections slid, then fell without overturning, while of the South side Breakwaters, sections closer to the surviving caissons overturned after sliding. Overall, at parts of the shallow section where friction was not increased, sections of the breakwater either fell or were inclined, while in the deep section, roughly half of the breakwater fell, and at the north side breakwater, sections that remained were also inclined. Figure 14.5 shows the difference between the sections before and after the damage. It shows that at the north side breakwater, the mound was scoured between 5 and 10 m. At both the south side breakwater and north side breakwater, the shoulder of the slope of the mound on the inside port side was severely deformed, and the caisson slid down the mound.

14.3 Protection Effectiveness of Breakwaters

14.3.1 Conditions of Numerical Simulation

At Kamaishi Bay, various parts of the breakwaters were damaged. Because the influence of the protective effectiveness of breakwaters was unclear, numerical simulations were conducted to study the efficiency of the protective effect. A STOC-ML (Tomita et al. 2006) simulator was used to approximate wave pressures as hydrostatic pressures and to calculate free water surface positions with a continuity equation. Nested grids are used as shown in Fig. 14.6.

The grid size of the final calculation domain is 5 m. Calculations are conducted under 7 conditions on the state of breakwaters. No breakwaters is set as Case 1, which is the basic data to which the results of other cases are compared. In Case 2, the breakwater is assumed to have no damage, retaining the shape it had before struck by the 2011 tsunami. Case 3 is the ideal case, that is, the whole baymouth is closed by the D.L. +6.0 m high wall. In Case 4, the simulation is conducted using the shape after the 2011 tsunami. Because the safety factor of the submerged breakwaters is the lower than that of the other breakwaters, the effect of the submerged breakwaters is negligible in Case 5. The results of the safety factor indicated that there was a high possibility that the north side breakwater was the last to be washed

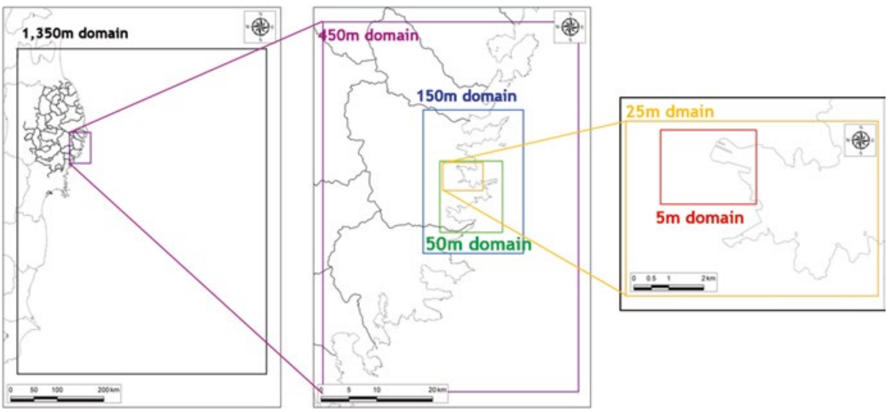


Fig. 14.6 Computational domains

Table 14.1 Calculation conditions about breakwaters

Case	Status of breakwaters	Opening ratio at the mouth of bay with still water level (%)
1	Bottom topography (no breakwaters)	100.0
2	Breakwaters of complete shape	6.5
3	Perfectly closed mouth of the bay	0.0
4	Breakwaters with all damage due to the 2011 tsunamis	36.0
5	Breakwaters with damage to submerged breakwaters	11.9
6	Breakwaters with damage in the shallow region and the south part	18.0
7	Breakwaters with damage to submerged breakwaters and to breakwaters in the shallow region and south part	23.3

away. So, in Case 6, the breakwaters in the shallow region and south side are gone. All damage except for the north side breakwater in the deep region is included in Case 7. The summary of the state of breakwaters is shown in Table 14.1, where the number in the right column is the opening rate under each condition when an opening rate without breakwaters is assumed to be 100 %. The cross section is shown in Fig. 14.7. As the tsunami wave source, data of the Central Disaster Prevention Council (2011) were used.

14.3.2 Results of Decreasing Rate

Figure 14.8 shows that the inundation height in each case. Figure 14.9 shows that the relation between the opening ratio and the tsunami decreasing rate, which is calculated by the following equation:

$$1 - H_i / H_1$$

Where, H_1 is the inundated tsunami depth calculated with case 1, which means no breakwaters, and Hi is that of each case. The black dot shows the relation between the decreasing rate calculated using the watermark in the East Japan Great Earthquake tsunami and the opening rate calculated using the remain breakwaters.

This result revealed that the effect of breakwaters would be almost zero if the opening ratio were 40 %. But the decreasing rate in the case of the 2011 tsunami is around 50 %, which is almost the same result as the middle point of cases 5 and 6.

This indicates that the submerged breakwaters were washed away before the maximum tsunami arrived, so the protective effect was almost zero by the submerged

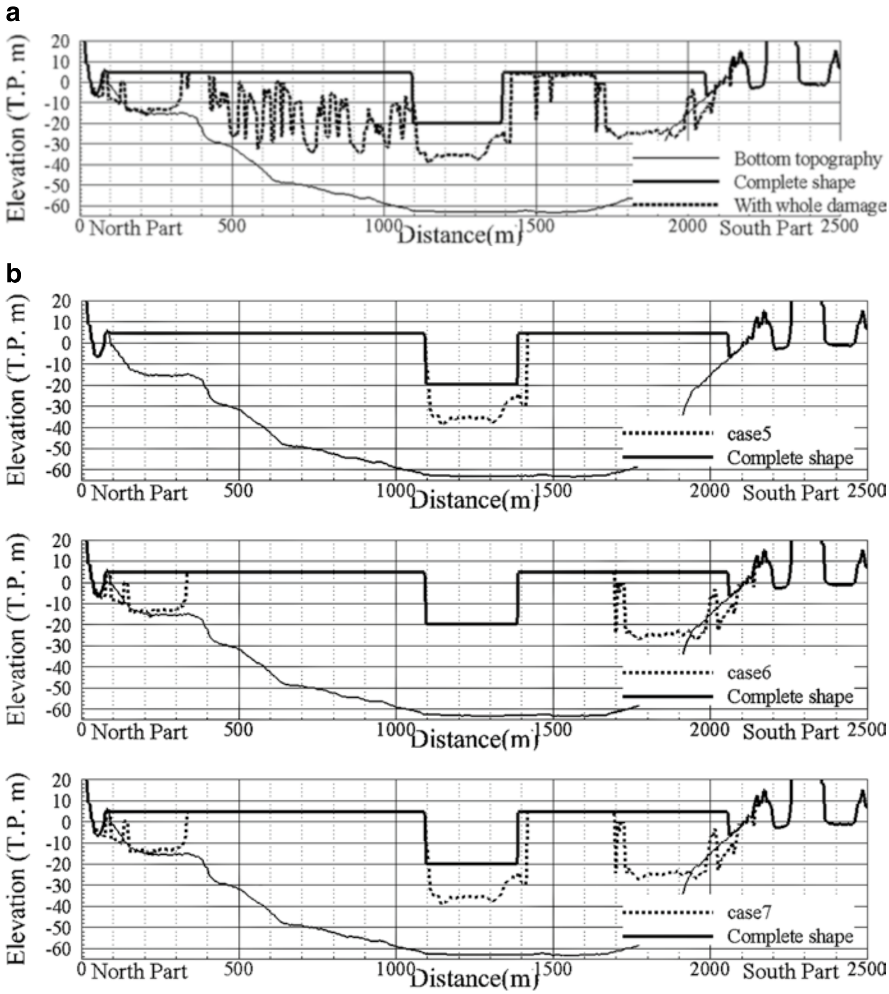


Fig. 14.7 Cross section of the state of breakwaters showing the different Case Scenarios (**a**) *Case 1*: Bottom topography; *Case 2*: Breakwaters of complete shape; *Case 4*: Breakwaters with all damage due to the 2011 tsunamis, and (**b**) *Case 5*: damages of submerged breakwaters; *Case 6*: damages of breakwaters in the shallow region and *Case 7*: damages of both submerged breakwaters and breakwaters in the shallow region

breakwaters. The calculation also considered that the breakwaters in the shallow region and that part of the south side breakwaters may be ineffective against the 2011 tsunami. On the other hand, the breakwaters in the deep region had the protective effect against the tsunami, even if half of the breakwaters were finally washed away or tilted.

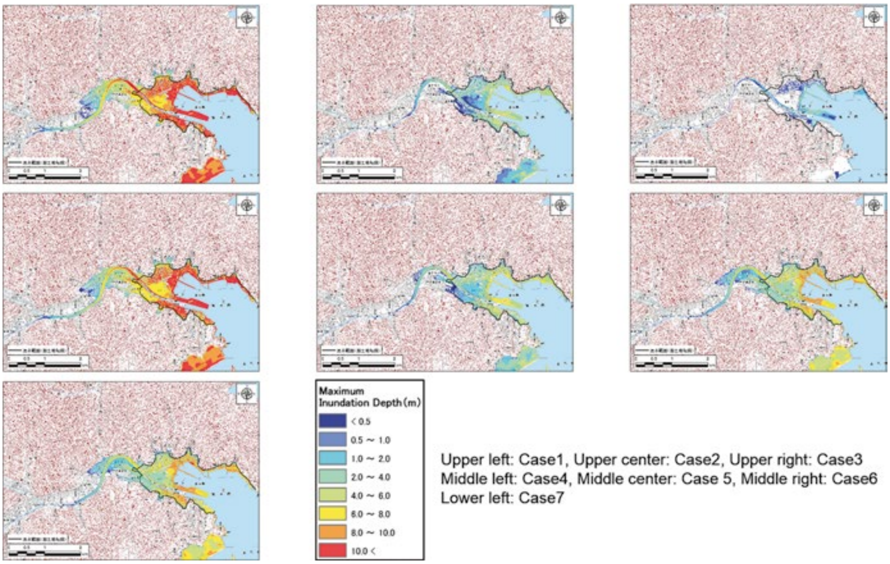
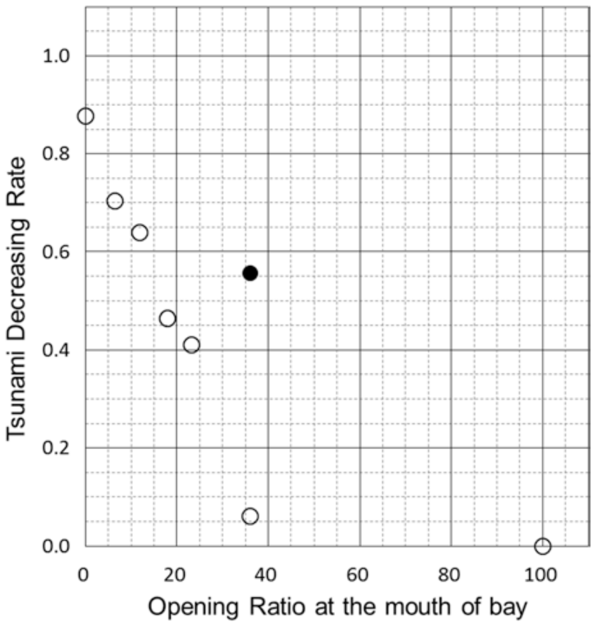


Fig. 14.8 Numerical results of inundation depth in each case

Fig. 14.9 Relation between the opening ratio and the decreasing rate



14.4 Consideration of Resiliency

14.4.1 Decreasing Effect Against Different Tsunami Height

Numerical simulations using different tsunami heights were conducted to consider the tsunami decreasing effect of the breakwaters. Conditions of the tsunami height at the source are 2.0, 1.5 and 0.5 times the height of the 2011 tsunami. The status of breakwaters is set as Table 14.1 as shown before. Figure 14.10 shows the relationship between the rate of change of the inundation depth and the rate of tsunami height at the source. From the results of case 3, as the rate of the tsunami increases, the protective effect decreases due to overflows, even if the mouth of the bay is closed perfectly. From the results of case 4, on the other hand, the protective effect with a 36 % opening should be almost zero at Kamaishi Bay.

The comparison of case 1 and case 7 indicates that the rate of decrease of the tsunami is at least 0.4 under the condition of twice the tsunami height and is the effect of the breakwaters in the deep region. The effect of the submerged breakwaters

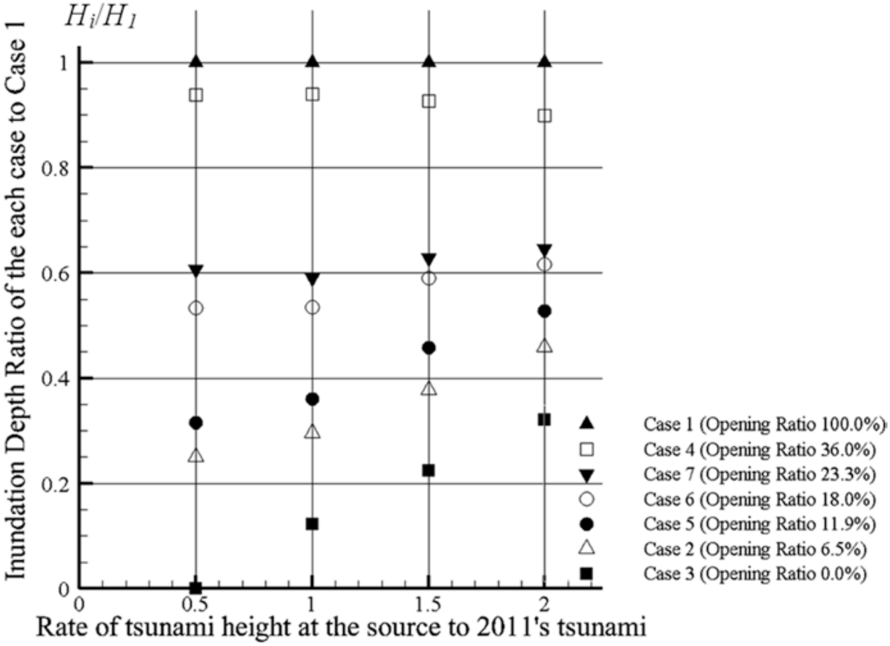


Fig. 14.10 Relation between inundation depth ratio and rate of tsunami height

is estimated to be less than 0.1 under every tsunami condition by comparing cases 5 and 2. The effect of breakwaters in the shallow region also decreases as the tsunami height increases and it estimated to be 0.1–0.2 by comparing cases 6 and 2. Therefore, the influence of both the protective effect of breakwaters in the deep region and the crown height of breakwaters becomes larger as the tsunami height becomes higher.

14.4.2 Effect of Countermeasures

Figure 14.11 shows that the effect of the different countermeasures. The crown height is the same as the original height, but a hard countermeasure against sliding is designed in each case. Countermeasure A in the figure is that all breakwaters including submerged breakwaters can withstand twice the height of the 2011 tsunami. Countermeasure B is that only breakwaters not including submerged breakwaters can withstand 1.5 times the height of the tsunami. Countermeasure C is that breakwaters in the deep region can withstand 1.5 times the height of the tsunami. The protective effect of each countermeasure can be estimated by comparison with the original case. Countermeasure C seems to be better under less than 1.5 times the height of the tsunami. Even so, in the case of twice the height of the tsunami, all countermeasure except Countermeasure A would be useless. From this point on,

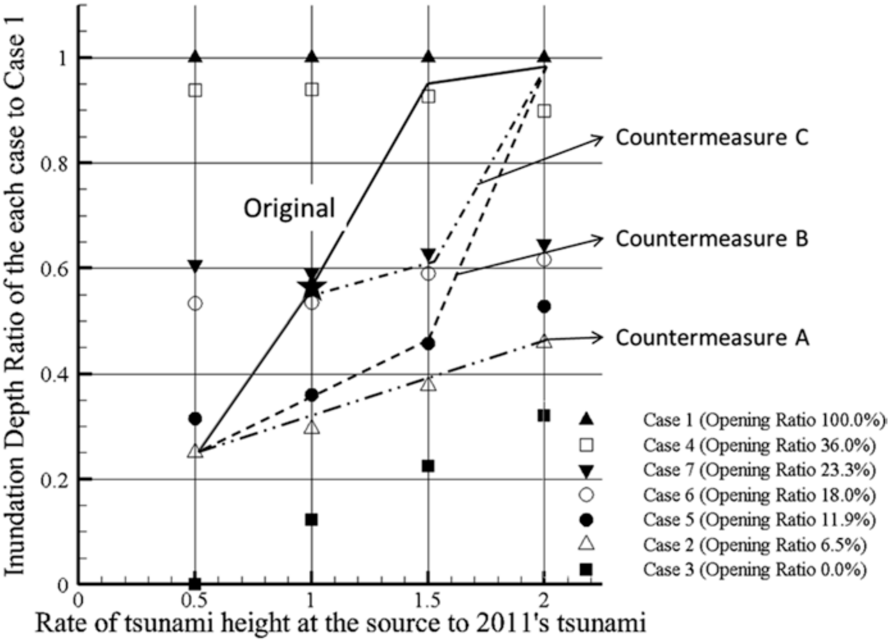


Fig. 14.11 Protective effect of countermeasures

risk analysis should be useful to consider the best countermeasure. At least the protective effect would not be zero even if tsunami overflows occurred when the breakwaters could withstand the overflows. Such an effect should be considered as the effect of resiliency of the protective facility.

14.4.3 Considerations on the Resiliency Structure Against Tsunami Overflow

In the 2011 Tohoku Earthquake Tsunami, some breakwaters collapsed under the action of the tsunami crest. It is suspected that many collapsed as overflow by tsunami. Arikawa et al. (2012, 2013) clarified the mechanism of falling of breakwaters by physical experiments. This report indicated that the main factor causing falling was the lateral force resulting from the difference of the water level on the front and rear sides of caissons. As the size of the tsunami grew, more and more violent overflow fell and reached above the foundation, resulting in scouring of the foundation. Figure 14.12 shows the hydraulic model test in progress. It took only several minutes of on-site conversion from the start of overflow until near-maximum scour depth, at which time the foundation's rubble stones gradually fell into the scour hole. When scouring reached the foundation's rubble stones around the lower parts of the caissons, the caissons started to incline and slid straight down.

Therefore, to protect the basement against scouring behind the breakwater due to overflow is one of the countermeasures against the larger tsunami. The sample of the resiliency structure against tsunami overflow is shown in Fig. 14.13. This type of countermeasure not only strengths the resistance force against lateral force due to

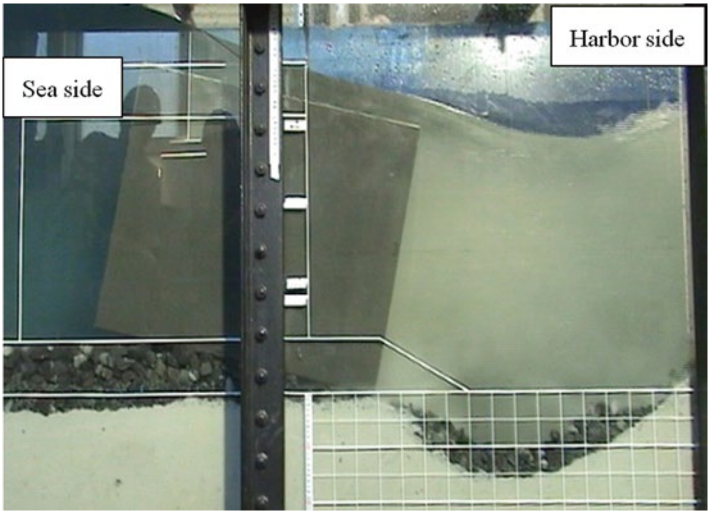


Fig. 14.12 Caisson stability test against overflow scour

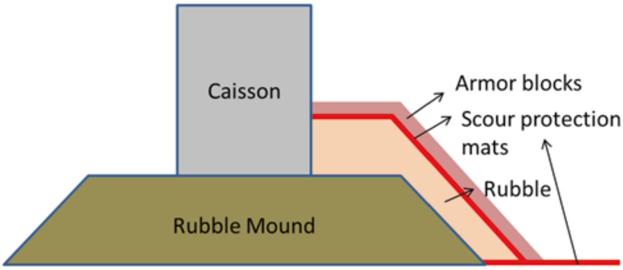


Fig. 14.13 Cross section of the widening work of resiliency structure

Fig. 14.14 State of widening work against overflow (Arikawa et al. 2013)

the tsunami but prevents scouring of the rubble mound foundation or the seabed. The material for the widening work is riprap, which is used to build foundation mounds. It is feared that if only riprap is used, the widening work will be scoured, so armor blocks are installed on the surface of widening work. Still, if the overflow scale increases, the covering work will be washed away and the widening work will be scoured, so as a countermeasure, scouring prevention work is installed.

Arikawa et al. (2013) conducted physical experiments on the effect of widening works against overflow. Widening work at 1/3 of the caisson height was performed, and its effectiveness as a countermeasure against scouring of the foundation mound of the widening work and the seabed ground during tsunami overflow was verified, as shown in Fig. 14.14.

14.5 Conclusions

In this paper, the protective effect of breakwaters at Kamaishi Bay has been considered using numerical simulations. At first, the effect of breakwaters against the 2011 tsunami has been verified by comparing the different states of damage to breakwaters. The result shows that the breakwaters in the deep region had a protective effect against the tsunami, even if half of the breakwaters were ultimately washed away or tilted. Simulations using tsunamis of varying heights were conducted to study the effect of countermeasures. The result indicates that the influence of both the protective effect of breakwaters in the deep region and the crown height of breakwaters becomes larger as the tsunami height becomes higher. The effect of the different types of countermeasures showed that at least the protective effect would not be negligible -or nonexistent- even if tsunami overflow occurred when the breakwaters could not withstand their force.

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Chapter 15
Serious Erosion of the Southern Sendai Coast Due to the 2011 Tohoku Earthquake Tsunami and Its Recovery Process

K. Udo, Y. Takeda, M. Takamura, and A. Mano

Abstract We investigate morphology change of the southern Sendai Coast due to the 2011 Tsunami by analyzing topography and aerial images before and after the tsunami. The results show the characteristics such as erosion in the longshore direction behind seawalls, landward sediment transport during tsunami runup, seaward sediment transport from shore during backwash especially through crevasses of the seawalls, and coastal stabilization by coastal structures such as seawalls, breakwaters and headlands. At the seriously eroded Yamamoto Coast, more than half of the total amount of eroded shore sand above sea level was estimated to be transported seaward due to backwash. After 1 year from the tsunami, the eroded coasts were recovered to form pocket beaches. After another year, the coastal morphology had not changed apparently but seawalls started to be reconstructed. At present, after 3 years from the tsunami, the seawalls with a height of 7.2 m have been reconstructed along the coast. With the reconstruction, the foundation ground of the seawalls has been recovered, but the eroded beaches still remain disappeared. The coast act in Japan was established in 1956 to protect the coast from disasters, and amended in 1999 to also preserve both the coastal environment and its utilization. From the perspective of long-term coastal management, it is strongly required to consider the vision of the future coast.

Keywords Beach morphology • Coastal structure • Ecosystems • Airborne laser scanning data • Bathymetry data

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15.1 Introduction

The 2011 Tohoku Earthquake Tsunami (2011 tsunami) presented its maximum wave height of 6.7 m on a GPS wave gauge installed off the coast of Iwate Prefecture (39°15′31″ N, 142°05′49″E) approximately 25 min after the occurrence of the earthquake (Kawai et al. 2011), and 40 min afterward, the tsunami reached the Sendai Plain. In the Sendai Plain, the tsunami runup reached up to 5 km inland from the coast line (Fig. 15.1), causing tremendous tsunami damage. In addition, crustal movement due to the earthquake induced land subsidence by tens of centimeters along the coast of Sendai Bay (Geospatial Information Authority of Japan 2011).

In relation to morphology change of the southern Sendai Coast in the past several decades until the 2011 tsunami, the enhancement of coastal erosion was relatively being suppressed as a result of erosion prevention measures although the coast had previously been eroded rapidly due to coastal developments and dam constructions during the post-war period (Udo et al. 2012). The 2011 tsunami caused serious beach erosion, especially at the Yamamoto Coast (see Fig. 15.1c, d), around the river mouths, and old river channels. Also, its damage to seawalls was serious especially at the Yamamoto Coast.

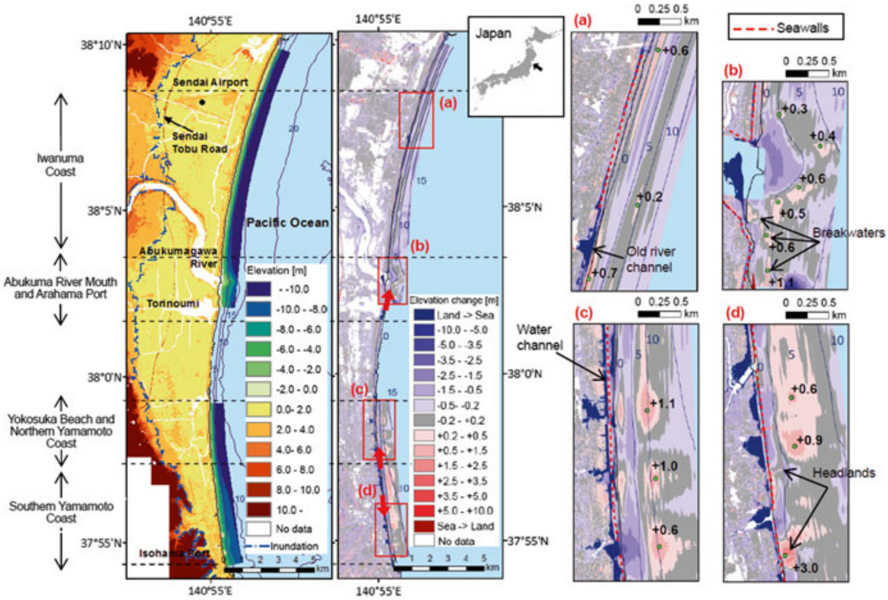

Fig. 15.1 Topography of study area before the 2011 tsunami with inundation area due to the tsunami; elevation change due to sediment transport before and after the tsunami. "Land→Sea" shows changes from land to sea area and "Sea→Land" from sea to land area. *Red arrows* indicate directions of aerial video camera (see Fig. 15.5). *Black numerals* in (**a**) to (**d**) in the figure show changes of elevation (amount of deposition); *Navy-blue* numerals show water depth; and *Red dashed line* shows the location of seawall (Modified from Udo et al. 2013) (Source: Udo et al. 2013 (modified); Japan Society of Civil Engineering)

Morphology changes of the 2010 Chile Earthquake Tsunami (2010 tsunami) and the 2011 tsunami were compared by Tanaka et al. (2011) and Haraguchi et al. (2012). Tanaka et al. (2011) indicated that, in Sendai Bay, the 2010 tsunami ran up rivers without causing any apparent morphology change at the river mouths, whereas the 2011 tsunami caused notable morphology changes at the river mouths and ran up the rivers for extensively long distances. Haraguchi et al. (2012) reported that, in Kesennuma Bay, the 2010 tsunami caused the morphology change by about 50 cm at maximum, whereas the 2011 tsunami induced the elevation change up to 7 m, proving massive impact of the 2011 tsunami.

This study aims to clarify the characteristics of coastal morphology change due to the 2011 tsunami and its recovery process on the southern Sendai Coast by analyzing topography data before and after the 2011 tsunami and aerial images. Also, reconstructions of coastal structures and recovery of ecosystems after the tsunami are shown.

15.2 Study Area and 2011 Tsunami

Figure 15.1 shows the shore morphology of the southern Sendai Coast in 2006 obtained from airborne laser scanning data, and the nearshore morphology in 2009 obtained from bathymetry data provided by Tohoku Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism in Japan (hereinafter referred to as Tohoku Regional Bureau). Along the coast from the shoreline toward land, areas below 1 m in altitude lie broadly. The Sendai Plain had been formed due to sediment supply from the Nanakita, Natori, and Abukuma Rivers at a rate of 0.4–1.2 m year^{-1} for approximately 5,000 years since the period when sea level stabilized (Matsumoto 2001). Seabed slope was 0.01–0.02 in the areas less than 5 m in depth, 0.005–0.01 in the areas between 5 and 15 m in depth, and below 0.002 expanding widely in the areas deeper than 15 m.

On the southern Sendai Coast, the dominant direction of longshore sediment transport by waves is north, and sandbanks at the river mouths extend from south to north. Notable coastal erosion began from the 1970s, particularly on the south side, resulting from measures to prevent the erosion of cliff coast in Fukushima Prefecture which coast was a source of sediment supply, and from the improvement of Soma Port. This led to extensive measures for preventing coastal erosion in the late 1990s (Tohoku Regional Bureau 2009). Total 19 headlands were planned to be constructed, and 7 groins and 2 headlands had been constructed until the tsunami.

In Fig. 15.1, the blue dashed line indicates the boundary of the inundation area (Earth Environmental Engineering Group, Institute of Industrial Science, the University of Tokyo 2011) and a line a few kilometers inland from the coastline with an altitude of approximate 5–10 m shows the Sendai Tobu Road, indicating that inundation at the land side of the road mainly occurred around low altitude areas. The maximum inundation height and runup height in the study area were 13.5 m and 9.6 m respectively at the Yamamoto Coast (The 2011 Tohoku Earthquake Tsunami Joint Survey Group 2012).

15.3 Method

The elevation change of the area landward from the low tide line before and after the tsunami (shore morphology change) was analyzed by using airborne laser scanning data obtained in 2006 and 2011 with a horizontal resolution of 5 m. The changes of the area seaward from the low tide line (nearshore morphology change) between November 2007 and January 2013 were analyzed by using the bathymetry data. The bathymetry was measured along measurement lines in the cross-shore direction (traverse line spacing: 0.2–1 km) and interpolated in the longshore direction. The elevation change due to the tsunami includes the effect of both land subsidence caused by the earthquake and sediment transport caused by the tsunami; therefore, the change only due to sediment transport was obtained by subtracting the land subsidence of 0.2–0.4 m (Geospatial Information Authority of Japan 2011). We ignored the effect of horizontal crustal movement of approximate 3 m shift toward east-southeast because horizontal resolutions of the laser scanning data and bathymetry data were 5 m and 10 m, respectively. Since the data acquisition of land area was infrequent, we analyzed the shore morphology change by using aerial images from September 2006 to June 2013. In addition, we analyzed characteristics of sediment transport during the tsunami event using aerial video taken by Tohoku Regional Bureau's helicopter "Michinoku".

15.4 Results and Discussion

15.4.1 Characteristics of Coastal Morphology Change Due to 2011 Tsunami

From characteristics of morphology changes due to the tsunami, we divided the study area into four areas: Iwanuma Coast (Area A), Abukuma River mouth and Arahama Port (B), Yokosuka Beach and northern Yamamoto Coast (C), and southern Yamamoto Coast (D) (Fig. 15.1). The four areas are (a) slightly eroded coast (Fig. 15.1a), (b) eroded sandbank of river mouth (Fig. 15.1b), (c) seriously eroded but somehow recovered coast (Fig. 15.1c), and (d) seriously eroded coast (Fig. 15.1d). Figures 15.1, 15.2, 15.3, and 15.4 show the elevation changes due to the tsunami, aerial images before and after the tsunami from September 2006 to June 2013, and seabed elevation changes before and after the tsunami from November 2007 to January 2013, respectively. Here, we focus the elevation changes of more than 0.2 m for both land and sea areas considering that the accuracy of land data was approximately 0.2 m (Udo et al. 2012) though that of sea data was unknown. The four areas of (a) to (d) are also picked up in Figs. 15.2 and 15.4.

In relation to shore morphology changes due to the 2011 tsunami, the erosion behind the seawalls lead to the formation of water channels in the longshore direction in Area A (Figs. 15.1a and 15.2a). In Area C, water channels were formed in the

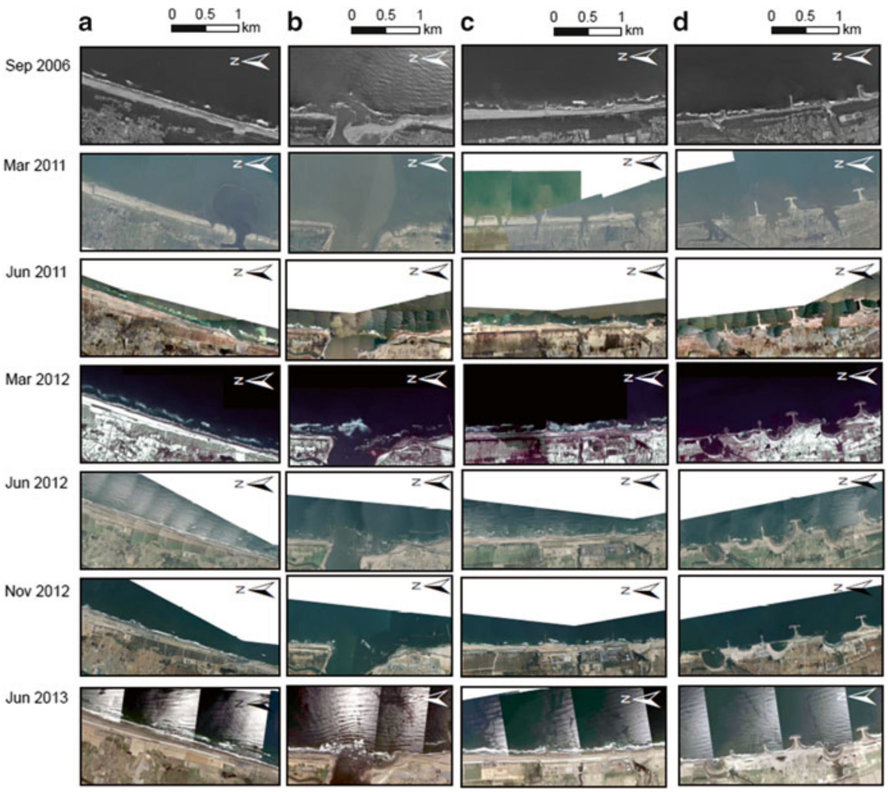

Fig. 15.2 Orthorectified aerial photographs of coastal areas in September 2006, March 2011, June 2011, March 2012, June 2012, November 2012, and June 2013. -see Fig. 15.1 (Source: Tohoku Regional Bureau and GeoEye satellite image (©Digital Globe))

longshore direction behind the seawall and at the same time, sediment deposition was notable just behind the water channels (Figs. 15.1c, 15.2c, and 15.3a). In Area D, the longshore water channels expanded even further compared to Area C and the entire beach disappeared seaward of the seawall crevasse (Figs. 15.1d, 15.2d, and 15.3b). Erosion was severer in the southern coast, especially in Area D where beach erosion was also significant in the past. Further, the old river channel was eroded in Area A (Tanaka et al. 2012; Tappin et al. 2012). In Area B, the sandbanks were eroded (Figs. 15.1b and 15.2b).

Nearshore morphology changes due to the tsunami in the period from September 2010 to April 2011 were greater than other periods and the erosion reached contour lines deeper than 10–15 m in the whole study area (Figs. 15.1 and 15.4). It should be noted that the closure depth due to storm waves is reported to be 8 m or 15 m (Widyaningtias et al. 2013) and the depth due to the tsunami was deeper than that due to storm waves. Deposition with a width of more than 0.5 km expanded in the longshore direction in Area C and D where the water depth was between 5 and

Fig. 15.3 Aerial photographs of coastal areas in September 2010, March 2011, July 2011, September 2012, and November 2013. The locations of (**a**) and (**b**) correspond to those of Fig. 15.2c, d (Source: Tohoku Regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan)

15 m, whereas deposition expands in the narrower and shallower area in Area A. In Area B, the river mouth terrace was eroded and slight deposition was observed on the seaward side. Also, deposition occurred around the breakwaters. In Area D, deposition occurred near the headlands (Fig. 15.1d).

Characteristics of the sediment transport during the tsunami are discussed using the aerial video. In Area A, erosion occurred behind the seawall and water channels were formed. The video image (Fig. 15.5a) of the Fukanuma Beach, located 10 km northeast of the Sendai Airport, where the topography conditions such as beach profile and beach width were the same as those of Area A, shows sediment suspension behind the seawall and succeeding landward sediment transport during the tsunami runup; this must be a major mechanism of erosion behind seawalls (Kato et al. 2013). In the vicinity of the breakwater in Area B where deposition was occurring, eddies were formed and sediment concentration increased (Fig. 15.5b). In Area C and D where beach erosions were apparent and depositions occurred extensively over the sea area (Fig. 15.1c, d), sediment concentration in the sea area increased during backwash, and most significant deposition occurred at the seaward border of the sediment transport zone (Fig. 15.5c, d). This indicates that the deposition was caused by the seaward sediment transport during backwash through the seawall crevasse. These facts demonstrate that coastal morphology change due to tsunami strongly depends on the coastal structures.

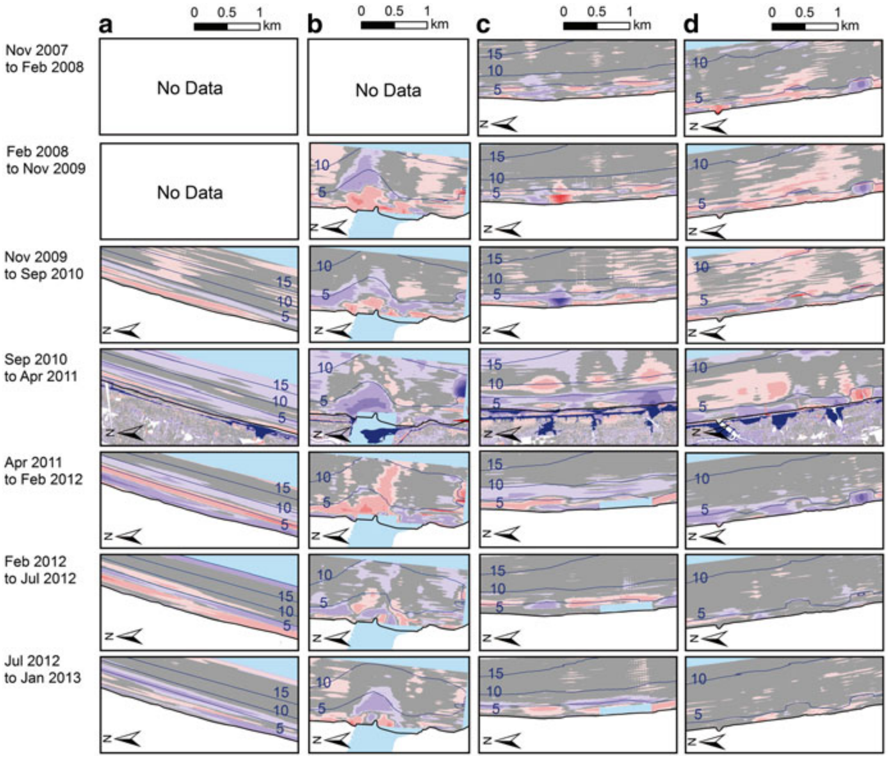

Fig. 15.4 Seabed elevation change from November 2009 to January 2013 (see Fig. 15.1). Land elevation change is also shown only in the figures from September 2010 to April 2011 (Source: Tohoku regional Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan)

Especially in Area C and D where inundation depths were large, deposition area was widely expanded at the sea side of significantly eroded beach (Fig. 15.1c, d), and enormous sediment was transported from land to sea. Sediment deposition volumes over 0.2 m in the sea area were calculated to be 1.6×10^5 m^3 and 7.4×10^5 m^3 in Area C and D, respectively, which corresponds to more than half of the total amount of shore sand above mean sea level.

Considering the characteristics of both the elevation changes and the sediment transport comprehensively, the beach erosion mechanism due to the tsunami is estimated as follows: Surging tsunamis transported sediment landward while causing erosion in the shallow sea area. When the tsunami overtopped the seawall, scouring behind the seawall caused even greater volumes of sediment to be transported landward. Also, return flows concentrated at the points where the seawall was destroyed and at water channels newly formed, eroding the beach and transporting sediment seaward. Erosion was relatively suppressed where seawalls remained existed.

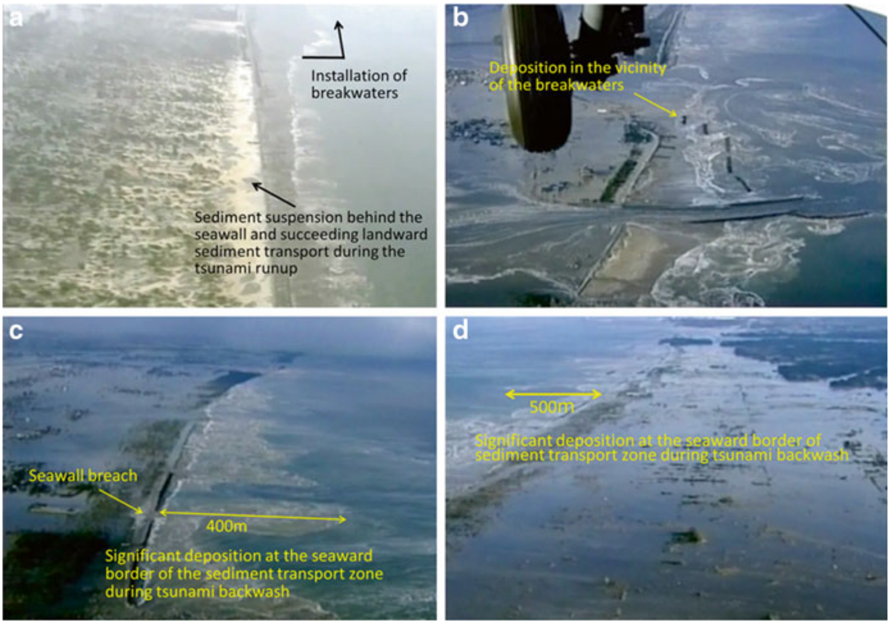

Fig. 15.5 Aerial video images taken by Tohoku Regional Bureau's helicopter "Michinoku" at (**a**) Fukanuma Beach (16:02 JST, March 11; 10 km northeast of the Sendai Airport), (**b**) Abukumagawa River mouth (16:33 JST, March 11; see also Fig. 15.5b), (**c**) Yokosuka Beach and northern Yamamoto Coast (16:37 JST, March 11; see also Fig. 15.5c), and (**d**) southern Yamamoto Coast (16:39 JST, March 11; see also Fig. 15.5d) (Source: Udo et al. 2013 (modified); Japan Society of Civil Engineering)

15.4.2 Characteristics of Coastal Morphology Change Due to Wind Waves After Tsunami

Regarding shore morphology changes (Figs. 15.2 and 15.3), the old river channel in Area A recovered promptly (Hirao et al. 2012). In Area B, the sandbank of the river mouth was newly formed in a slightly upper-stream area compared to that before the tsunami by around March 2012. In Area C and D, the eroded coastline changed to form pocket beaches within a year after the tsunami.

On nearshore morphology changes (Fig. 15.4), in Area A, the movement of an offshore sandbar (shown by deposition and erosion areas in the longshore direction in Fig. 15.4a) was noticed at a depth less than 5 m similarly to that before the tsunami. In Area B, deposition was significant from April 2011 to February 2012; thereafter, deposition at the river mouth and its seaward erosion occurred similarly to those before the tsunami. In Area C, erosion at a depth between 5 and 10 m and deposition at a depth less than 5 m were noticed from April 2011 to February 2012; thereafter, deposition and erosion appeared alternately in the longshore direction similarly to those before the tsunami. In Area D, erosion was noticed at a depth less than 5 m from April 2011 to February 2012; however, after which period changes were insignificant. By comparing morphology changes before and after the tsunami, we found that the change in Area D was likely to decrease after the tsunami even if the effect of nourishment in 2010 is taken into account.

The erosion of shallow sea area in Area C and D just after the tsunami is considered because of landward sediment transport and this contributed to the recovery of shore morphology after the tsunami, based on the facts that shore morphology recovered rapidly just after the tsunami and that the amount of erosion in the shallow sea area was enormous. The reason of the afterward decrease of morphology changes in Area D is unclear and further study is required.

15.4.3 Reconstruction Process of Coastal Structures and Recovery of Ecosystems

Due to the tsunami, seawalls of total 190 km out of 300 km were damaged along the coasts in the three most damaged prefectures (Iwate, Miyagi, and Fukushima; Kato et al. 2013). In the study area, Tohoku Regional Bureau had constructed 17 km temporary seawalls at a height of 3.8–6.2 m relative to Tokyo Peil (T.P.) datum until August 2011 (6 months after the tsunami) in order to prepare for storms in the period from late summer to autumn. Until March 2015, 21 km seawalls at a height of 7.2 m relative to T.P. are planned to be reconstructed. The seawall height was determined by the sum of the mean spring high tide level, the maximum storm surge deviation, 30-year return period wave height, and allowance height, because storm surges are the greatest threat in the study area. Tsunami debris of total 110 thousand m^3 is used as banking material. As of December 2013, 60 % of the seawalls had been constructed and 30 % are being constructed (Fig. 15.3; Tohoku Regional Bureau 2013). With the reconstruction, the foundation ground of the seawalls has been recovered, but the eroded beaches still remain disappeared. On the other hand, the construction plan of headlands and nourishment in progress before the tsunami are revised to continue until the 2070s (Tohoku Regional Bureau 2012a).

Before the seawall constructions, effects of the seawalls on landscape and environment were discussed in committees composed of people of learning and experience, and comments from the committee members on the landscape were considered in seawall design (Tohoku Regional Bureau 2012b). On the environment, monitoring surveys of flora and fauna were conducted in autumn and winter in 2002, autumn and winter in 2011, and summer in 2012, which continue until 2015 in order to investigate the recovery ecosystems (Table 15.1; Tohoku Regional Bureau 2012b). According to that, the number of plant, bird, and land insect species at beaches increased after the tsunami from 67 in 2002 to 248 in 2012, from 37 in 2002 to 55 in 2011 and then 45 in 2012, from 147 in 2002 to 229 in 2012, respectively; however, it remains unclear whether they were caused by the tsunami because the data before the tsunami was obtained in 2002, that is, 9 years before the tsunami. At the

Table 15.1 Number of flora and fauna species before and after the 2011 Tsunami

Place	Survey items	Before 2011 Tsunami	After 2011 Tsunami
Abukumagawa River mouth	Fishes	34 (1) in 2004	30 (0) in 2012
		36 (2) in 2009	
	Benthos	40 (2) in 2004	33 (0) in 2012
		48 (2) in 2010	
	Plants	144 (6) in 2001	228 (8) in 2012
		213 (7) in 2007	
	Birds	48 (4) in 2000	37 (4) in 2012
		39 (1) in 2005	
	Amphibians, reptiles, and mammals	6 (0) in 1998	10 (0) in 2012
		8 (1) in 2003	
	Land insects	224 (26) in 2002	230 (21) in 2012
		331 (31) in 2008	
Beaches from Sendai Port to Isohama Port	Plants	67 (4) in 2002	No data (4) in 2011
			248 (11) in 2012
	Birds	37 (4) in 2002	55 (7) in 2011
			45 (5) in 2012
	Land insects	147 (23) in 2002	229 (25) in 2012

Numbers in parentheses indicate the number of important species (Source: Tohoku Regional Bureau, Ministry of land, Infrastructure, Transport and Tourism of Japan. http://www.thr.mlit.go.jp/sendai/kasen_kaigan/fukkou/image/04data.pdf)

Abukumagawa River mouth, the number of fish, benthos, and land insect species decreased after the tsunami from 34 in 2004 and 36 in 2009 to 30 in 2012, from 40 in 2004 and 48 in 2010 to 33 in 2012, from 224 in 2002 and 331 in 2008 to 230 in 2012, respectively; but those of other species did not show clear changes after the tsunami.

The 2011 tsunami caused great damages in the study area but simultaneously left many datasets such as tsunami runup and inundation heights (Mori et al. 2012), damages of coastal structures (Anawat et al. 2012), coastal morphology change (Tanaka et al. 2012; Udo et al. 2012), and ecosystem change. The monitoring surveys of coastal morphology and ecosystems will continue for at least several years. It is required to continue the surveys on the coastal morphology and ecosystems for decades and evaluate the effects of the tsunami and reconstructions of coastal structures on them.

15.5 Conclusions

This study elucidated the characteristics of coastal morphology changes caused by sediment transport on the southern coast of Sendai Bay by analyzing the topographical measurement data before and after the 2011 tsunami and aerial video taken during the tsunami event. Namely, it was clarified that (i) surging tsunami eroded the land side of the seawalls and transported sediment landward, (ii) land sediment was accreted in the sea area mainly due to return flow during backwash, and (iii) deposition occurred in the vicinity of the breakwaters and headlands and erosion due to backwash was suppressed by seawalls. It was estimated that more than half of the total amount of shore sand above sea level was transported seaward on the Yamamoto Coast where the erosion was especially severe. In addition to the characteristics of coastal morphology changes and the mechanisms, post tsunami reconstruction and restoration in the study area are shown. We hope that this study contributes to further research for disaster reduction, post-disaster restoration, and conservation of coasts.

In Japan, the Coast Act was established in 1956 to protect coasts from disasters, and amended in 1999 to also conserve both the coastal environment and utilization. In the study area, the seawalls are just being reconstructed for disaster prevention. From the perspective of long-term coastal management, it is strongly required to find the vision of the future coast to also conserve the coastal environment and utilization.

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Chapter 16
Resilience and Vulnerability Analysis for Restoration After Tsunamis and Floods: The Case of Dwellings and Industrial Plants

Ahmed Mebarki and Bruno Barroca

Abstract The resilience approach represents a unified and integrated framework for the restoration process following disasters. Under given resilience parameters values, a resilient system is able to recover and be strengthened within a defined recovery period; otherwise, it is a non-resilient system. This chapter considers different structures and focuses on several parameters which govern resilience together with their mechanical vulnerability under various hazards. A new method of theoretically measuring resilience, its link with mechanical vulnerability, and its sensitivity analysis are investigated for dwellings and industrial plants under the effects of flood and tsunami hazards:

– Non-designed (informal) masonry constructions under the effects of a flooding hazard: vulnerability is estimated after a rapid inspection by qualified engineers. Fragility curves are developed and the structural failure risk is calculated and mapped depending on the intensity of the hazard: water height and flow velocity, in a real case.
– Structural and non-structural waste generated by flooding: relevant models are adopted and used for predicting expected quantities of waste. The territory may take several years to recover since generated waste may represent several times annual quantities produced under normal circumstances.
– Coastal industrial plants under the effects of a tsunami hazard: structural failure in tanks results from buoyancy (uplift), overturning, sliding by shear effect, excessive bending, or buckling. Vulnerability and fragility curves are developed for various tanks of small and large sizes.

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Keywords Tsunamis • Floods • Resilience • Vulnerability • Fragility • Hazard • Risk • Masonry • Waste • Buildings • Industrial plants • Metal tanks

16.1 Introduction

The resilience analysis can provide an adequate framework when dealing with the post-disaster restoration process of dwellings, buildings or industrial plants damaged by floods or tsunamis. Resilience concerns the ability of a system to absorb the disturbances and damage caused by an event, and to adapt, recover and return into a viable state in a short time (Barker et al. 2013; Barroca and Serre 2013; Dinh et al. 2012; Cimellaro et al. 2010; Francis and Bekera 2014; Miller-Hooks et al. 2012; Ouedraogo et al. 2013; Ouyang et al. 2012; Pant et al. 2014; Shirali et al. 2012; Steen and Aven 2011; Tisserand 2007). Indeed, the resilience concept is very attractive as it can be applied to any system and can be adequate for economics, social systems, human behavior or structures for instance. However, there is still a need for developing and defining accepted and objective resilience metrics. Therefore, it could be stated that an adequate framework for resilience requires:

– A definition of resilience metrics or values of utility functions,
– An evaluation of the loss of utility functions, which expresses the intensity of damage caused to the system by the hazards,
– A definition of lower and upper limiting values of the utility functions, such as mechanical capacity or waste evacuation capacity, for instance,
– A definition of recovery time or a reference period for post-disaster recovery.

Resilience relies on the preliminary hazard. Vulnerability and risk analysis as a study must be made of the conditions which the system can withstand and under which it can recover, or not, during the expected reference time or life period (Fig. 16.1). In fact, certain governing parameter values will make the system resilient, able to recover and be restored, whereas other groups of values will lead to a non-resilient situation.

The present chapter focuses on several parts of the integrated resilience framework for different mechanical systems:

– Mechanical vulnerability and waste generated for dwelling houses under the effect of floods,
– Mechanical vulnerability of industrial plants under the effect of tsunamis.
– Sensitivity analysis of the resilience indicator, i.e. utility functions depending on the intensity of damage and vulnerability, their threshold values and recovery time.

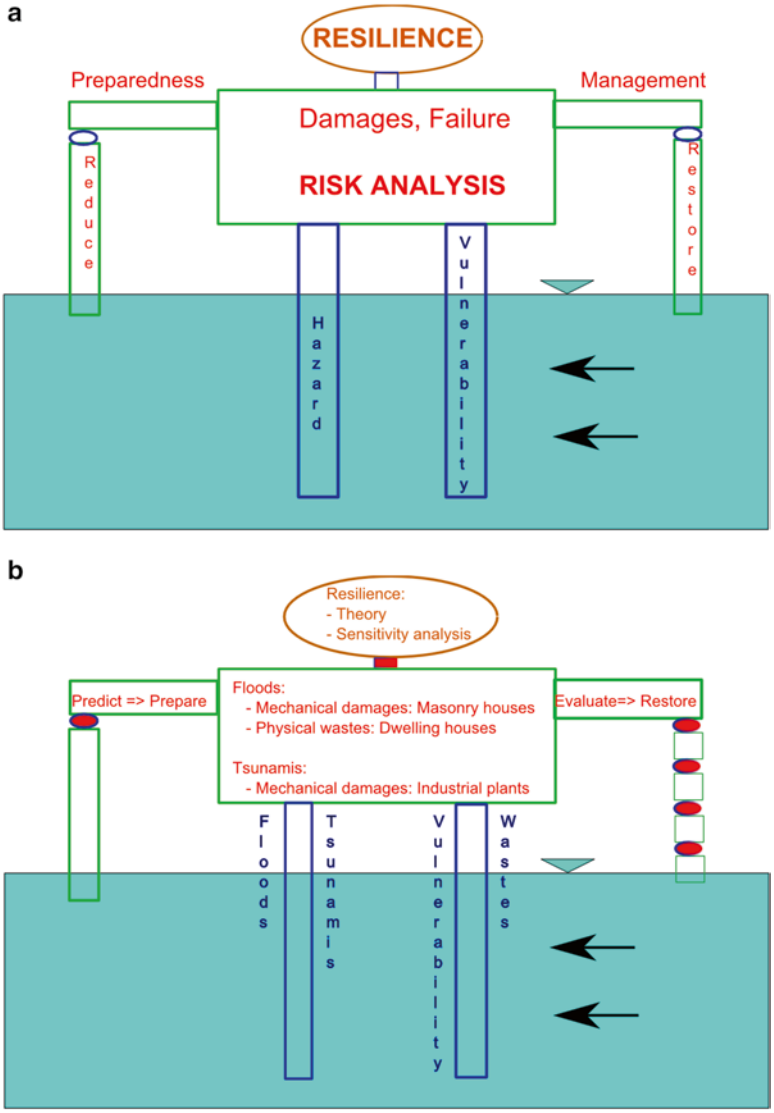

Fig. 16.1 Layout for integrated framework: Hazard – Vulnerability – Risk – Resilience: (**a**) General layout; (**b**) Applications and case studies

16.2 Hazards and Mechanical Effects: Tsunamis and Floods

16.2.1 Resilience Analysis as an Integrated Framework

16.2.1.1 General Framework and Description

The resilience analysis may provide a relevant and objective integrated framework when dealing with disasters and post-disaster restoration (Barker et al. 2013; Barroca and Serre 2013; Cimellaro et al. 2010; Dinh et al. 2012; Manyena 2014; Pant et al. 2014; Schelfaut et al. 2011; Shirali et al. 2012; Wang et al. 2012). However, accurate modeling of hazards, vulnerability, risk, resilience and disaster management is a complex process (Fig. 16.1):

– Hazard modeling for natural or technological events
– Vulnerability and fragility modeling in order to evaluate the capacity of the system to withstand the effects of the hazard
– Risk analysis and failure probabilities
– Resilience analysis and the ability of the system to recover expected utility function values within the defined recovery time.

16.2.1.2 Resilience Analysis and Post-disaster Recovery

Since vulnerability and subsequent damage are of crucial importance, a sensitivity analysis has been developed in order to show their influence on resilience. This type of analysis can be very helpful in reconstruction processes.

Furthermore, for illustrative purposes, various methodologies are presented in order to evaluate the vulnerability of constructions and industrial facilities:

– Masonry constructions: Models already issued by the authors are detailed, (Mebarki et al. 2008, 2012). After a rapid inspection, they evaluate the mechanical vulnerability of non-designed (informal) masonry constructions under the effects of flooding hazards. This evaluation identifies the capacity of the construction on the basis of every governing parameter considered to be influent, for example quality of materials, geometry, number of stories, the slope of the terrain, structural typology and regularity. Corresponding fragility curves estimate the level of structural failure risks. This failure risk *vs.* a given water height and flow velocity can then be mapped. Real cases are used for illustrative purposes.
– Dwelling houses: A new methodology that predicts the volume of waste generated by floods is developed and discussed. Structural, as well as non-structural, vulnerability may give rise to different kinds of waste. Models and fragility curves are adopted in order to predict the waste quantity depending on water height and flow velocity. Depending on this quantity, the territory may take several years to recover.

– Industrial plants: New fragility curves are investigated in order to predict the vulnerability of metal industrial tanks (for oil storage or process) when they are hit by tsunamis. Tank failure may result from buoyancy (uplift), overturning, sliding (shear effect), excessive bending (and stress), or buckling. However, any possible perforation by debris such as containers, ships or cars, structural fragments, or boulders is not investigated in this study. As the recovery process or protection against products escaping after damage depends on the capacity of the plant and its components to resist tsunami effects, vulnerability and fragility curves are developed for small and large size tanks.

16.2.1.3 Resilience Evolution and Disasters

A capacity of a system such as its mechanical capacity, serviceability, sheltering or power supply, can be described by utility functions, F(t), along the time t. Loss of an utility function i.e. damage, D, can result from a hazard which occurs at an instant t_0. The post-disaster capacity equation becomes:

$$F(t) = F(t_0).(1-D), \quad \text{with}: t \geq t_0. \tag{16.1}$$

If there is no evolution, at post-disaster stage, the residual capacity remains constant. In the case of evolutionary conditions, variations of residual capacity depend on resources available (potential energy, plastic capacity, external supply and inward flows, external demand or outward flows). Depending closely on interactions between the different constitutive parts of a system and the exchanges at its frontiers, the system can then evolve towards a worse or a better state, (Fig. 16.2). It is therefore vitally important to develop and identify adequate recovery and evolution functions for each system (Cimellaro et al. 2010; Steen and Aven 2011).

Some parameters governing resilience can be easily evaluated in terms of quantity, whereas others are not easy to measure, for example determination, confidence, past experience and history, education, good, suitable management and adequate, intelligent decision making. For this second group of parameters, probabilistic distributions and statistical analysis may help in constructing and defining adequate forms and measures of their effect on the evolution of the utility function.

16.2.1.4 Resilience as a Governing Indicator for Post-disaster Analysis

Resilience may concern a simple system (one construction) as well as a complex system such as sets of constructions (neighborhoods, industrial plants, urban sets, cities, regions, states, or continents). It can be described by:

$$F_R(t)\Big|_{T_{\text{ref}}} = \iiint_V \left[F(t).(1-D)\right].\left[\left(1+\Phi_r(t).\chi_r(t)\right)\right].dv \tag{16.2}$$

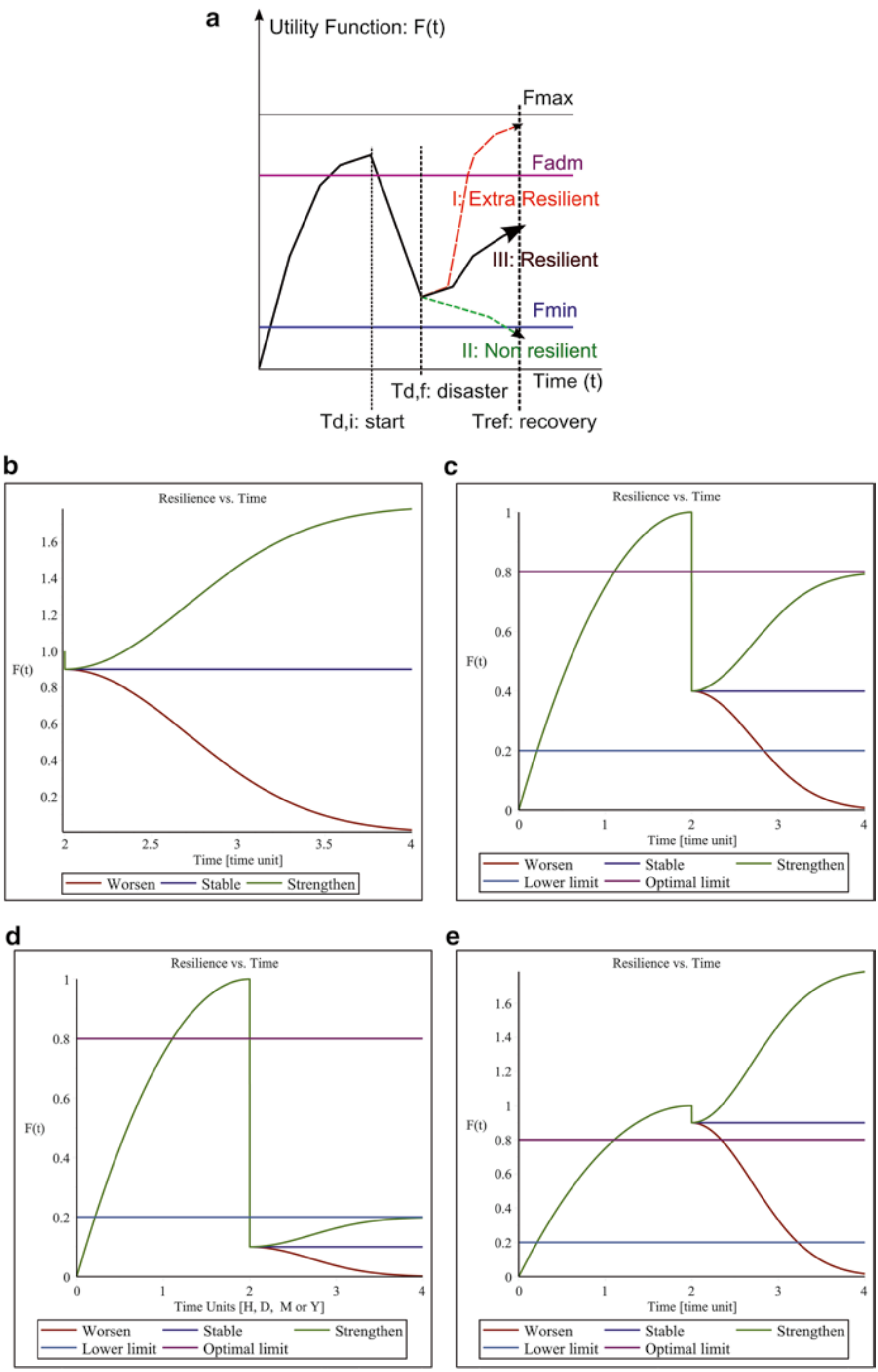

Fig. 16.2 Resilience: (**a**) Global description and evolution; (**b**) Post disaster evolution functions; (**c**) Important damage; (**d**) Very severe damage; (**e**) Very slight damage

where: $F_R(.)$ = Resilience function of the system during the reference period T_{ref}; V = total volume of the system; T_{ref} = duration or reference period for recovery; t = instant ranging between the occurrence of the disaster and T_{ref}; D(.) = damage value (vulnerability) ranging within [0..1]; $\Phi_r(.)$ = recovery evolution function, and $\chi_r(.t)$ = "resilience capability and availability" function which depends on availability of resources (internal or external) and the capacity to react adequately, such as past experience, knowledge and readiness to react.

As resilience depends intimately on the loss of utility functions, the vulnerability and fragility functions (i.e. damage, D) should be accurately modeled for each potential hazard.

16.2.1.5 Resilience: Practice and Illustration

For the purpose of illustration, selected cases are discussed (Fig. 16.2):

- The instant $t_{d,f} = 2$ [time units, *in years for instance*] as an occurrence of the triggering hazard, and $t_{ref} = 4$ [time units, *in years for instance*] as the reference duration time during which the system has to recover its required capacity,
- The minimal threshold below which the system is considered as having *failed* and being out of service is supposed to be $F_{r,min} = 0.2$,
- The optimal value above which the system is considered as being *extra resilient* is supposed to be $F_{r,adm} = 0.8$,
- The system is considered *resilient* and still in service when its resilience function values range within the interval $[F_{r,min}..\ F_{r,adm}]$ during the reference period $[t_{d,f}..t_{ref}]$.

Thus, the final state of the system can be as follows (Fig. 16.2):

- The system is *resilient* in case of non-worsening conditions,
- The system is *not resilient* for any post-disaster evolution conditions since the residual capacity is such that the system can never recover.
- The system is *resilient* and gains in capacity due to the limited amount of damage and adequate strengthening after the reconstruction process.

16.2.1.6 Discussion

Measuring system resilience is a complex process and its objectivity relies on:

- An adequate and accurate choice of relevant values of the threshold $F_{r,min}$, and optimal value $F_{r,adm}$
- Idem for the definition of reference period $[t_{d,f}..t_{ref}]$ for recovering the expected utility functions
- The volume of the system, its internal and external interactions
- Forms of post-disaster recovery or worsening functions

– The value of the damage which depends on both the intensity of the hazard and the vulnerability of the system. This damage amplitude (light, important or severe) expresses the capacity loss or reduction in the function of the utility.

16.2.2 System Fragility and Post-disaster Residual Vulnerability

16.2.2.1 Vulnerability and Resilience

The integrated resilience framework is very complex and accurate vulnerability modeling is required prior to any resilience analysis. Important components of this resilience framework are investigated and detailed in this study. New contributions by authors are provided in certain cases, whereas existing results (Mebarki et al. 2008, 2012) are inter-connected in order to investigate and discuss hazard modeling, fragility functions, capacity loss, post-disaster recovery and effects on resilience. Three illustrative situations have been considered for this purpose:

– Floods hazards and structural vulnerability of informal masonry dwellings for which theoretical fragility curves are reported and discussed (Mebarki et al. 2008, 2012). Resilience results from strengthening constructions and building protective barriers.
– Flood hazards and vulnerability of dwellings for which experimental fragility curves (structural or non-structural debris and waste) have been constructed and discussed. Resilience results from evacuating waste and cleaning as well as installing protective barriers.
– Tsunami hazards and the vulnerability of industrial tanks for which theoretical fragility curves have been developed and discussed. Resilience is related to protecting and cleaning zones after any possible escape of products, as well as building protective barriers.

16.2.2.2 Masonry Dwelling Vulnerability and Flooding Hazard

Systems Under Study and Their Purposes

Non-confined masonry constructions are commonly used worldwide, mainly in developing countries. These dwellings are very often erected in places prone to flooding such as floodplains, riversides or shorelines. The present section focuses on the mechanical effects made by river flooding on masonry constructions and predicts structural damage (Mebarki et al. 2008, 2012). The flooding hazard is defined by the height and velocity of the water flow in the floodplain at the French village of Cheffes-sur-Sarthe, which experienced severe flooding in 1995. Damage has been mapped in order to analyze risk sensitivity to floods (Fig. 16.5).

Hazard Modeling

Hydraulic river discharge is modeled by an extreme distribution whose parameters have been identified on the basis of available historic records. Monte Carlo simulations are made in order to derive the probabilistic distribution of the hydraulic charge at each location in the floodplain (Valencia 2006; Mebarki et al. 2012). Although scouring, erosion, and the presence of debris and mud may have an influence, the simplified hydraulic model does not take their effect into account. However, this theoretical model provides acceptable results (flow height) when compared to the stream height observed in the village during the 1995 historic flooding. Gumbel distribution is well adapted for flow pressure, (Valencia 2006; Mebarki et al. 2012):

$$p_w = \rho_w \cdot \left(H_w + \frac{V_w^2}{2.g} \right) \quad (16.3)$$

Where: p_w [Pa] = Hydraulic pressure generated by flows on the masonry walls; H_w [m] = Height of the flow; V_w [m/s] = Velocity of the flow; g [m/s^2] = universal gravity acceleration; ρ_w [N/m^3] = specific weight of water.

Vulnerability Modeling

Accurate assessment of the vulnerability of constructions requires sophisticated methods. However, a quick visual inspection by qualified and trained engineers can also provide a good estimated approach to vulnerability. Available evaluation forms are developed and calibrated for this purpose. Methodology is summarized as follows for the present study (Mebarki et al. 2008, 2012):

– A set of structural parameters is selected for governing the vulnerability of masonry dwellings under hydro-dynamic pressure: the number of stories, the quality of materials; wall geometry, wall thickness, the state of conservation, the slope of the terrain and foundations, columns and beams, openings (doors and windows), horizontal and vertical regularity, wall orientation, the type of floor slab, location, environment, debris, and the existence of basements. Their influence is such that, depending on their values, the construction will be graded as being "A- Very safe", or "B- Safe", or "C- Dangerous", or "D- Very dangerous", (Fig. 16.3), (Mebarki et al. 2008, 2012). By means of inspection, the construction "vulnerability identity matrix" is identified as:

$$I_v = \begin{bmatrix} & \cdots & \\ \cdots & I_v(i,j) & \cdots \\ & \cdots & \end{bmatrix} \quad (16.4)$$

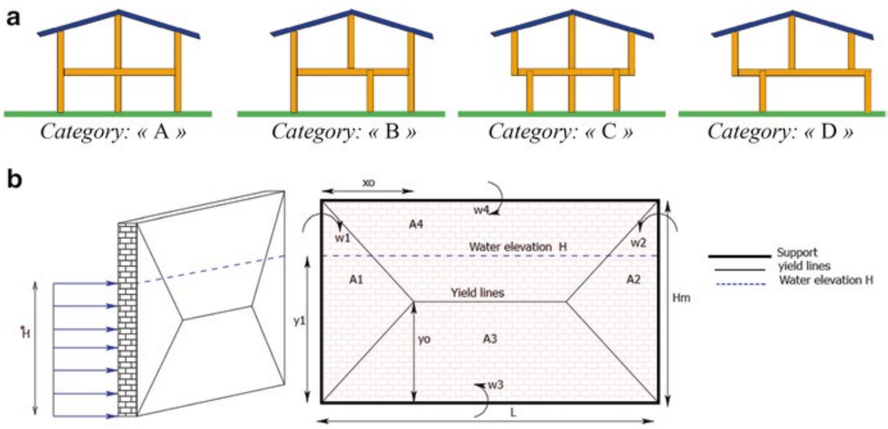

Fig. 16.3 Effect of the vertical regularity of the masonry construction and wall failure: (**a**) Categories of structural vulnerability; (**b**) Crack pattern of masonry panels due to "out of plan" flood effect

Where: $I_v(i,j)=1$ if the i-*th* parameter, i = 1..N (N = 14 governing parameters), is such that the structure has to be classified into the j-*th* category, j = 1..M (M = 4: categories « A », « B », « C » and « D »).

– A vulnerability function is associated with each damage category, which expresses the residual risk of failure, (Fig. 16.4):

$$P_v = \begin{bmatrix} & \cdots & \\ \cdots & P_v(i,j) & \cdots \\ & \cdots & \end{bmatrix} \quad \text{and} \quad \left(\frac{P_{vi}(h)-P_{vi}(h_0)}{P_{vi}(h_{\max})-P_{vi}(h_0)}\right)^2 + \left(\frac{h_{\max}-h}{h_{\max}-h_0}\right)^2 = 1 \qquad (16.5)$$

Where: $P_v(i,j)$ = structural failure due to the i-*th* parameter (i = 1 up to N) when the structure is classified into the j-*th* category (j = 1 up to M); h = water level values taken by the random variable H (water height); h_{max} = maximal or upper limiting value of H; h_0 = the reference value; $P_{vi}(h)$ = value of the probability $P_v(i,j)$ which represents the single damage contribution of the governing i-*th* parameter, in the structural j-*th* category, for the water depth h (Figs. 16.3 and 16.4).

– Global vulnerability derived from the combined influence of individual and supposed independent governing parameters is expressed as:

$$P_f = 1-\prod_{i=1}^{N}\left(1-P_{vi}\right) \quad \text{where} \quad P_{vi} = P_v : I_v \qquad (16.6)$$

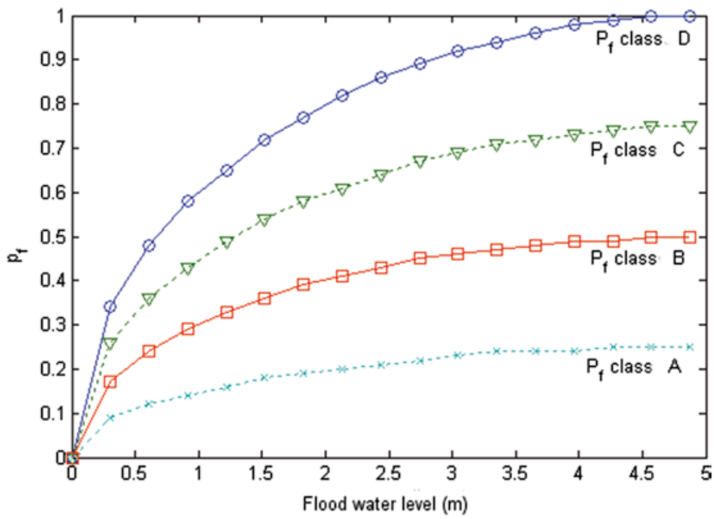

Fig. 16.4 Evolution of damage risk P_f depending on the flood water level

Risks and Decision Making

The Geographic Information System (GIS) maps are adequate tools for mapping risk, hazard and expected socio-economic losses at local or large scales, (Fig. 16.5). They are very helpful when making decisions or analyzing resilience in different flooding scenarios. Adequate solutions can actually be proposed to improve resilience and provide a better capacity to urban systems: building surrounding barriers, dikes, and dams (Mebarki et al. 2012; Schelfaut et al. 2011).

16.2.2.3 Floods, Waste, Structural and Non-structural Debris

In order to anticipate, organize and plan post-flood management, it is vitally important to identify the type and quantity of waste that could be generated by floods. Existing methods specifically concerning flood waste are rare (Chen et al. 2006; Hirayama et al. 2010). Therefore, all the information available on the many different kinds of waste generated by different hazards has been collected from scientific papers and operational or methodological guides (Brown et al. 2011; Chen et al. 2006; FEMA 2014; Hirayama et al. 2010; Office of Emergency Services California 2005; Tansel et al. 1994; Umpierre and Margoles 2005). Existing methods are also intended to be easy-to-use by waste managers and public authorities during post-disaster stages (Hirayama et al. 2010; Office of Emergency Services California 2005; Tansel et al. 1994) or in anticipation of any future disasters (Chen et al. 2006; FEMA 2014; Hirayama et al. 2010; Umpierre and Margoles 2005).

Fig. 16.5 Risk maps: evolution of damage failure in buildings at three different levels of flooding (Source: Mebarki et al. 2012; in Nat. Hazards Earth Syst. Sci)

Systems Under Study and Their Purposes

The efficiency and adaptability of several existing methods has been investigated, (Cochran et al. 2007; FEMA 2014; Hirayama et al. 2010; Hsiao et al. 2002; Office of Emergency Services California 2005; Tansel et al. 1994; Umpierre and Margoles 2005). The selected sources concern construction waste which is sometimes subdivided into sub-categories "building finishes", "structural components" and "foundation materials". For instance, waste production ratios for several waste categories (personal belongings, mobile homes) are addressed by the waste management guide (Office of Emergency Services California 2005). In addition, an existing model also quantifies building and demolition waste, green waste and sediment caused by cyclones and subsequent flooding, (Umpierre and Margoles 2005). However, construction waste is widely considered to be the most important in terms of volume. For instance, building waste represents half the waste produced by hurricane Katrina (Dubey et al. 2007).

The relationships between a territory, flooding and waste production are complex. This section contributes to clarifying this process by presenting indicators in order to quantify the quantity of waste depending on flood parameters: water height and duration.

Hazard Modeling

In general, waste volumes generated during catastrophic situations may be very considerable, as is the case after earthquakes, cyclones, floods, or fires. In fact, these volumes correspond to between 5 and 15 times the normal amounts of waste produced per year on the same territory (Brown et al. 2011).

The quantification method considers two scenarios as a flooding hazard model: flooding lasting less than 48 h or more than 48 h (MECADEPI 2013). Once the building is flooded, all the components such as furniture, equipment and personal belongings, except those concerning health-care, located on the ground floor are expected to be transformed into waste. This notion is valid under the hypothesis that the inhabitants have taken nothing away in the meantime, i.e. all the furniture, items and equipment are still in place.

Vulnerability Modeling

All the waste under study is hazardous or produced in significant quantities. It is supposed to benefit from a waste management/ treatment system, regardless of mixed waste (putrefiable waste such as foodstuffs, textile, books as well as crockery and domestic waste), (Table 16.1). A specific quantification indicator is set up for each of the waste streams, (MECADEPI 2013). Feedback from experts and existing databases collected in France have taken six typical dwellings into consideration (Table 16.2). The fragility curves, i.e. quantity of building waste vs. flooding height, are built for each of the two typical flooding scenarios: under or over 48 h (Fig. 16.6).

The quantity of waste resulting from the flooding of homes is related to the mechanical and physical damage suffered by the home. The simulation model for damage requires a prior classification of the dwellings on the basis of three criteria that significantly influence home damage, (Fig. 16.6): (i) individual or collective housing, (ii) the presence of a cellar or not and (iii) the presence of upper floors or not. These simulations use the “SIMUDOM” model developed in collaboration with a building expert (European Centre for Flood Risk Prevention: CEPRI 2012). Damage is assessed with regard to two flooding parameters, i.e. the water level and the length of time for which the homes are flooded. Although flow velocity, mud presence, salt concentrations and water pollution are also influent, they are not taken into consideration in this study.

16.2.2.4 Risks and Decision Making

A flood causes huge quantities and different types of waste: construction debris, branches, furniture, industrial stocks, agricultural and supermarket products, sludge, gravel and dead animals, all of which are totally waterlogged, mixed up together, and even polluted by hydrocarbons and toxic substances. This waste is defined as being “all the matter, material, objects and sediment that are unfit for consumption,

Table 16.1 Waste streams and MECADEPI method of qualifying flood waste (MECADEPI 2013)

Wastes categories and experts feedback	Purposes of MECADEPI method	Selection criteria					
		Quantification possibilities	Important quantities liable to be generated	Hazard level	Existence of treatment systems	Simple collect-ing and sorting proce-dures	Anticipation and evacuation
Hazardous waste	Hazardous waste	Yes		Yes	Yes		
End-of-life vehicle	ELV	Yes		Yes	Yes	Yes	Yes
Waste electrical and electronic equipment (WEEE)	WEEE	Yes		Yes	Yes	Yes	
Domestic waste	Mixed waste	Yes		Yes			Yes
Soft waste	Furniture waste	Yes		Yes	Yes	Yes	Yes
Furniture							
Bodies of animals				Yes	Yes		Yes
Building waste	Building waste (Fig. 16.6)	Yes	Yes	Yes	Yes	Yes	
Health-care waste	Health-care waste	Yes		Yes	Yes		
Wood					Yes		
Scrap iron					Yes		
Green waste					Yes		

Table 16.2 Types of dwellings considered for fragility curves (MECADEPI 2013)

Type	Code and legend	Flooding duration
Individual: *With Crawlspace, No basement, One floor, 5 rooms (99 m²)*	I1 – Individual > 48 h	>48 h
Individual: *No Crawlspace, No basement, One floor, 4 rooms (89 m²)*	I2 – Individual < 48 h	<48 h
Individual: *With basement, Two floors, 6 rooms (144 m²)*	I3 – Individual > 48 h	>48 h
Individual: No basement, Two floors, 5 rooms (117 m²)	I4 – Individual < 48 h	<48 h
Collective: *With cellar, 3 rooms (77 m²)*	C1 – Collective > 48 h	>48 h
Collective: *No cellar, 2 rooms (38 m²)*	C2 – Collective < 48 h	<48 h

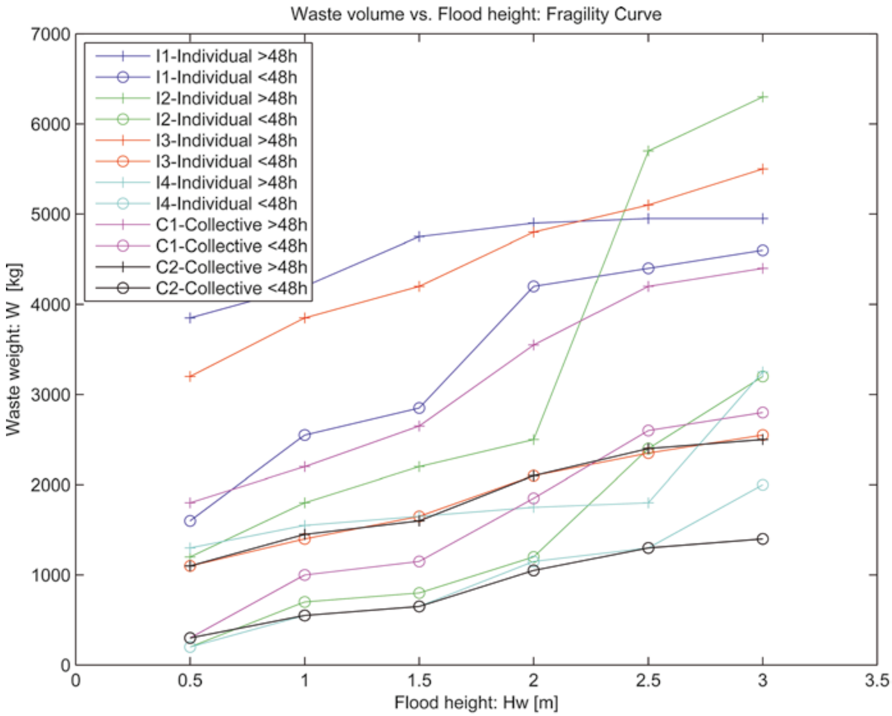

Fig. 16.6 Waste quantities *vs.* flood height (Source: Group MECADEPI 2013; in SAPIENS (http://sapiens.revues.org))

unusable in their present condition and liable to have an impact on the environment and public health or to negatively affect biodiversity, accumulated together as a result of a natural or technological disaster" (Bonnemains 2009). Besides the threat to public health raised by this waste, its evacuation (disposal) is a challenging topic in global crisis management. Regardless of emergency services and movements of populations, putting production resources back into operation, people returning to their homes and work-places or putting public networks back into service, flood waste can have a disruptive impact on a territory's "return to normal" situation. After catastrophic events, it often takes several years to handle all the waste, as has been observed in New Orleans after the Katrina hurricane and the flooding that damaged the levees around Lake Pontchartrain. In 2005, it was estimated that managing post-Katrina waste (over 76 million m^3 of waste generated, or the equivalent of one and a half years' production under normal conditions) would take at least 5 years (Luther 2008; Hassett and Handley 2006) inducing also significant costs. In the Var region in France, managing waste produced by floods in the Draguignan area in June 2010 cost 4.5 millions euros (Liquet 2011). In 2007, the cost of waste management was estimated as being equivalent to more than a quarter of the total costs required for putting the territory concerned back into running order (Brown et al. 2011). Therefore, the impact of waste management on a territory's return to normal conditions is vitally important.

The fragility curves described in this chapter are specific to the types of dwellings collected from the database (MECADEPI 2013). To adapt the methodology to other regions, countries and types of buildings, two different facets should be considered separately: the fixed facet of waste coming from equipment, such as kitchen and lavatories for instance, and a variable facet, which is proportional to the total surface (such as partition walls and constructions debris).

16.2.3 Vulnerability of Coastal Industrial Plants and the Tsunami Hazard

16.2.3.1 Systems Under Study and Their Purposes

This section deals with the case of metal tanks for oil storage and processing that have been erected in coastal industrial plants. The behavior of these tanks is studied under the effect of tsunami waves. They can be damaged and can also release the products in store even when damage is slight or there are just holes due to debris impacts, for instance. The new developments presented in this section concern the fragility curves of the tanks. They study tanks' vulnerability under the external loads generated by tsunami flows.

16.2.3.2 Hazard Modeling

Several sophisticated models can be considered for describing the height of a tsunami and its wave velocity. For the sake of simplicity, a new model for the tsunami run-up, H_{sl}, and velocity, V_{sl}, at the shoreline, is used (Mebarki et al. 2014) (Fig. 16.7):

$$H_{sl} = \left(H_{\text{int}}^2 . \sqrt{(h_{\text{int}} + H_{\text{int}})}\right)^{2/3} . \frac{e^{-\mathbf{b}.D_{\text{int}}}}{1 + D_{\text{int}} . e^{-(M_w - M_o)}} \quad with \quad V_{sl} = \sqrt{g.H_{sl}} \tag{16.7}$$

Where: H_{sl} [*m*] = Shoreline water height (or run-up if the land is flat from shoreline to plant) considered as a random Gamma or Log-Normal random variable; H_{int} [*m*] = Water height at the interface zone; h_{int} [*m*] = Sea depth at the interface zone; D_{int} [*km*] = Horizontal distance from the interface to the shoreline; g [m/s^2] = universal gravity acceleration; V_{sl} [*m/s*] = Velocity of the tsunami flow at the shoreline.

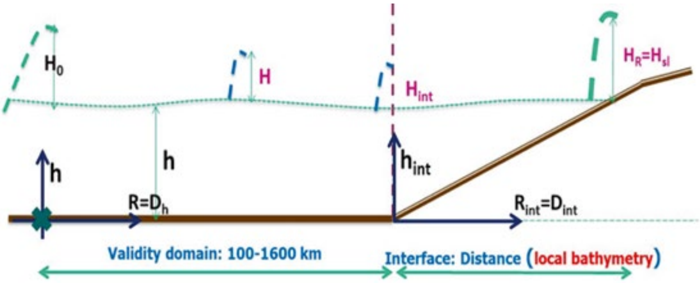

Fig. 16.7 Tsunami path from the epicenter to the shore, inland and run-up (Source: Mebarki et al. 2014 in Springer 2014)

16.2.3.3 Vulnerability Modeling

The structural response of the cylindrical metal tanks to the tsunami hydrodynamic effect concerns the following phenomena, (Fig. 16.8):

- Buoyancy and uplift of the tanks,
- Debris impacts, perforation or collapse of tanks or sections of tank with the ensuing escape of stored products (oil, liquids and gases),
- Excessive bending or shear, as well as sliding and overturning,
- Lateral (circumferential) and longitudinal buckling,
- Rupture of any pipes connected and tank roofs.

Besides the tsunami's height and its velocity, the tank-fullness ratio is also considered as a random variable. Its distribution depends on conditions of service: filling or emptying the tanks. A theoretical Gamma distribution is adopted. However, any experimental feedback could help in defining an adequate distribution for industrial plant use. These parameters influence tank resistance to external flow pressure: the weight of the tank and the liquid that compensates for the uplift effect, the overturning moment, the sliding effect (the friction coefficient is adopted as having a constant value all over the contact of the tank with its concrete support on the ground) as well as circumferential buckling. The numeric values adopted are not provided in detail in this study as its purpose is to discuss relative influences of each potential failure of the tanks depending on the tsunami's height and velocity, in the case of small or large tanks. The failure event, E_f, is defined as a combination of elementary failures:

$$E_f = \bigcup_{i=1}^{N_e} E_{f,i} \quad and \quad P_f = P\left[\bigcup_{i=1}^{N_e} E_{f,i}\right] \tag{16.8}$$

Where: E_f = failure event of the system; P_f = failure probability or vulnerability; $E_{f,i}$ = i-*th* failure event among the total number N_e of failure events: for instance i = 1 for Buoyancy, i = 2 for perforation by debris impacts.

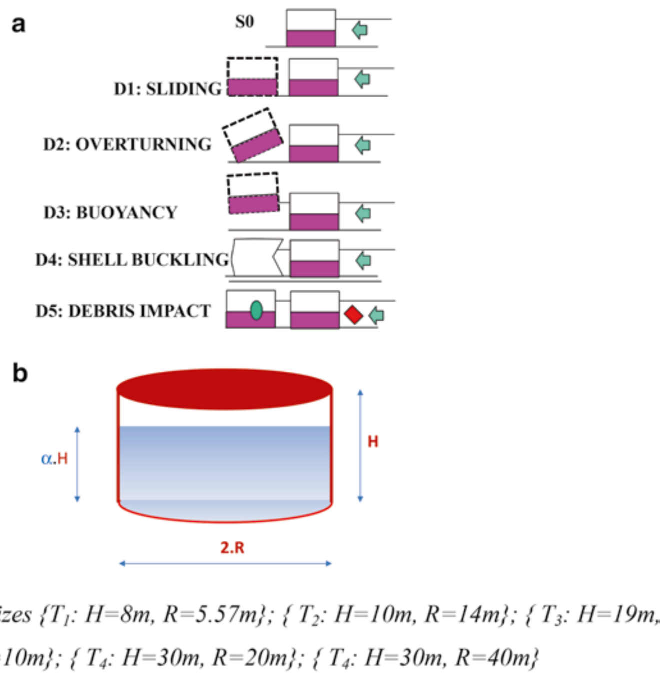

Fig. 16.8 Cylindrical metal tanks for storing oil in industrial plants: (**a**) Failure modes of tanks; (**b**) Various dimensions

16.2.3.4 Risks and Decision Making

The failure probability of a tank can be expressed as, (Mebarki et al. 2014):

$$P_f = \left(R - S \leq 0\right) \tag{16.9}$$

$$p_{hydraulic} = H_w + \frac{V_w^2}{2.g} \quad with \quad H_w = H_{sl} \quad and \quad V_w = V_{sl} \tag{16.10}$$

Where: R = structural capacity of the tank regarding the effect of the tsunami; S = mechanical effect of the tsunami, i.e. the effect of the hydraulic pressure $p_{hydraulic}$; $p_{hydraulic}$ = hydraulic pressure resulting from the height (H_w) and the velocity (V_w) of flow.

Risk of failure can be calculated analytically or numerically by Monte Carlo simulations, (Mebarki et al. 2008). For an industrial plant containing various kinds of metal tanks and erected in a zone prone to tsunamis, the risk concerning the whole plant can be obtained by the use of fragility curves which express the probability of exceeding given damage levels *vs.* tsunami height (H_w) at the tanks' location for each type of tank, (Fig. 16.9).

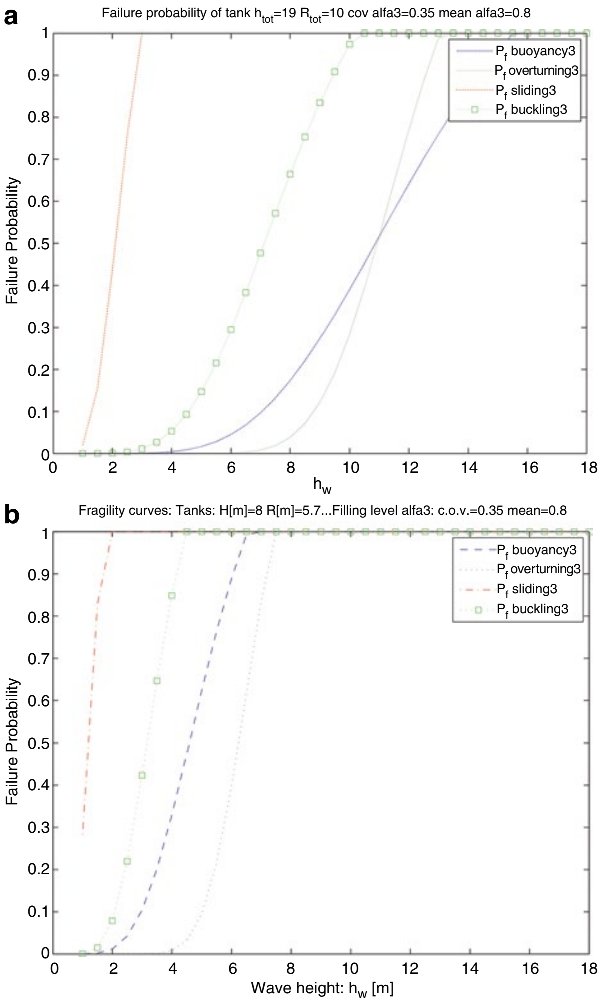

Fig. 16.9 Cylindrical metal tanks for storing oil in industrial plants: (**a**) Multi failure modes = large size tanks; (**b**) Multi failure modes = small size tanks

16.3 General Conclusions and Discussion

Resilience analysis requires prior definition of utility functions, and their upper and lower limiting values, as well as the reference period for a system's recovery, restoration or transformation. Furthermore, recovery as well as disaster mitigation rely on a relevant, accurate analysis of the system's vulnerability to potential hazards, such as flooding and tsunami.

In the case of informal masonry constructions, 14 governing parameters have been selected in order to define the mechanical vulnerability of the constructions under the effect of floods. The theoretical fragility curves that have been developed express the structural damage in masonry constructions *vs.* flood height and velocity;

for a flood height of 4 m, good-quality houses can suffer damage of 0.2 (i.e. 20 % of damage risk) whereas a lower-quality house will reach damage figures almost equal to 1 (complete destruction, since they correspond to 100 % of damage risk). For a flood height of 3 m, the mean damage value is about equal to 0.6, whereas it is about equal to 0.3 for a height of 0.9 m. Flood height and velocity can be derived from numeric simulations depending on the river's discharge and the local topography of the floodplain and river-banks. GIS maps of structural risk of failure are obtained from the fragility curves. They can be drawn up for various flooding scenarios in order to make sensitivity analyses for decision-making, because socio-economic consequences and restoration costs may vary greatly depending on the location of the construction in the floodplain and the hazard scenario.

As a result of flooding, various kinds of waste can be generated in excessive volumes and quantities. This waste may represent more than ten times the yearly volume of waste generated during normal use. Several years' work and important socio-economic costs may then be required to remove, evacuate and process flood waste. In order to predict waste, a database has been created and 6 typical dwelling houses have been studied taking two scenarios into consideration: flooding lasting under 2 days and flooding lasting over 2 days. Fragility curves *vs.* floods height were developed for four individual and two collective typical French houses showing that the volume of waste generated by a flood period lasting over 48 h is almost twice the volume of that created during a shorter period. The volume of waste generated by a flood 3 m high is almost three times the volume of waste generated by a flood 1 m high.

For coastal industrial plants containing metal tanks with various kinds of products, fragility curves were developed on the effects of tsunamis. The height and velocity of the tsunami flow was described by a simplified model valid at the shoreline (at normal sea level) and inland inasmuch as the terrain is flat. Mechanical failure of tanks was investigated, showing that failure may occur from sliding, buoyancy uplift, buckling or overturning. New fragility curves vs. tsunami height were developed for five typical tanks ranging from 8 to 30 m high and from 10 to 80 m in diameter, used for oil storage. Results showed that sliding has more severe effects on tanks than buckling, buoyancy or overturning in the case of small tanks, even if their level of content was not low when the tsunami hit. Large tanks' resistance to sliding is also very weak if no precautions are taken by installing a lateral protective barrier. Without protective barriers, tanks could slide and the pipes connected to it could break even if the tsunami is less than 3 m high; whereas they could withstand tsunamis of almost 10 m before buckling and 15 m before they are damaged by buoyancy or overturning effects.

Sensitivity analysis studies may prove very useful for helping risk managers to prepare themselves in the face of potential hazards such as floods and tsunamis, as well as for designing protective systems i.e. barriers, early warning and alert devices and dikes. Taking these points into consideration is particular important when building new structures during reconstruction processes.

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Chapter 17
Tsunami and Environmental Pollution Hazards: A Note for the Restoration Process

Vicente Santiago-Fandiño and Mi Hyung Kim

Abstract The large destruction of industrial facilities, processing factories and urban areas by the 2011 tsunami along the northeast coast of Tohoku Region (Japan) resulted in extensive contamination in most of the flooded areas and coastal waters; an enormous amount of mixed debris and radiation compounded these problems, creating both potential environmental and human health hazards which should be assessed throughout the reconstruction and the restoration process.

Open-air temporary debris storage sites lacking sufficient insulation have likely contaminated air, soil, marine and freshwater bodies with hazardous chemicals along certain areas in Tohoku. Moreover, construction wooden debris treated with biocides, weathering fixatives and fire retardants accumulated in the sites along the region have likely leached a host of toxic compounds including metals, arsenic and other hazardous substances posing a threat to soil and water sources, including groundwater.

As part of the region's reconstruction process, the potential short, medium and long-term environmental toxicity and damage to key ecosystems, flora and fauna as well as the contamination and impact on commercial resources, soil and water require careful assessment.

This chapter provides a general overview of the potential contamination that may have occurred as a result of the tsunami of March 2011 along the Tohoku Region in Japan. Emphasis is made in the Miyagi prefecture looking at the contamination originated from the storage and management of wooden debris and other sources as well as some of its related environmental consequences.

Keywords Tsunami • Debris • Treated wood • Radiation • Pollution • Miyagi

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17.1 Background

Large tsunamis have hit coastal areas in recent times with serious consequences. Tsunamis affecting Chile (in 1960 and 2010), the Indian Ocean (2004) and northeastern Japan (2011) have destroyed coastlines and settlements, incurring enormous economic losses and hardships to coastal communities, as well as widespread pollution. Massive amounts of debris were left behind as a result of these tsunamis, e.g. the Indian Ocean Tsunami alone generated five million tons in Sri Lanka; 35,000 t in the Ko Phi Phi Islands (Thailand) and 610,000 t in Banda Aceh in Indonesia (UNEP 2005; Notodarmojo 2007).

The Great East Pacific Earthquake and Tsunami in Japan, caused by a large slip of the sea floor (Satake et al. 2013), generated waves over 15 m in height, as well as 40-m run-ups in some areas (Fujii and Satake 2011; Fujii et al. 2011; Fushiwara et al. 2011; Efthymios et al. 2011), resulting in widespread pollution and a massive amount of debris (Santiago-Fandiño 2011a, 2013a).

In Tohoku, debris was widely scattered, covering large areas of land. Initial estimates in low-lying areas ranged between 1,000 and 500,000 m^2, with an average volume of 1,000 to more than 1,000,000 m^3 per site (Andreadakis et al. 2012). Debris also tended to accumulate in certain parts of the coastline according to specific geographical traits, seafloor type and depth, as well as settlement density and type of construction materials. Lighter debris (wood, plastic, etc.) was carried farther inland by the tsunami run-up as well as offshore with backwash, while larger debris (concrete, steel, etc.) tended to remain near their original locations.

About 25 million tons of debris were originally estimated throughout inland areas (MOEJ 2011), but this figure was later revised as a large amount of debris was washed out to sea (Japan Times 2013a). The Ministry of the Environment reported the final figure of debris resulting from the tsunami to be around 18 million tons (MOEJ 2013a), and the Reconstruction Agency of Japan reported over 16 million tons (RAJ 2013). The Prime Minister of Japan (2013) stated that the amount of debris generated in Miyagi, Fukushima and Iwate prefectures (the hardest hit areas) amounted to approximately 20 million tons. Five million tons of debris had washed out to sea, 3.5 million tons (70 %) of which was deposited on the sea bed and 1.5 million tons (30 %), consisting of more than 90 % driftwood and destroyed houses, had floated offshore (Prime Minister of Japan 2013). Timber and wood-plastic, floaters, buoys, fishing nets and shipping containers also constituted a large amount of floating debris which was widely scattered throughout the Pacific Ocean, some of which even washed ashore on Canadian and American coastlines (Inham 2013; NOAA 2013).

In Miyagi Prefecture, the original estimated amount of debris ranged between 15.5 million and 18 million tons, equaling 23 years of waste production by the entire prefecture (Santiago-Fandiño 2013b); more than 10 million tons (67 %) of this debris were treated by the end of 2012 (Taisei Corp. 2013) and the total (18.7 million tons) including tsunami deposits, in March 2014 (MOEJ 2014; Japan Today 2014). To support disposal efforts, 18 prefectures throughout Japan have

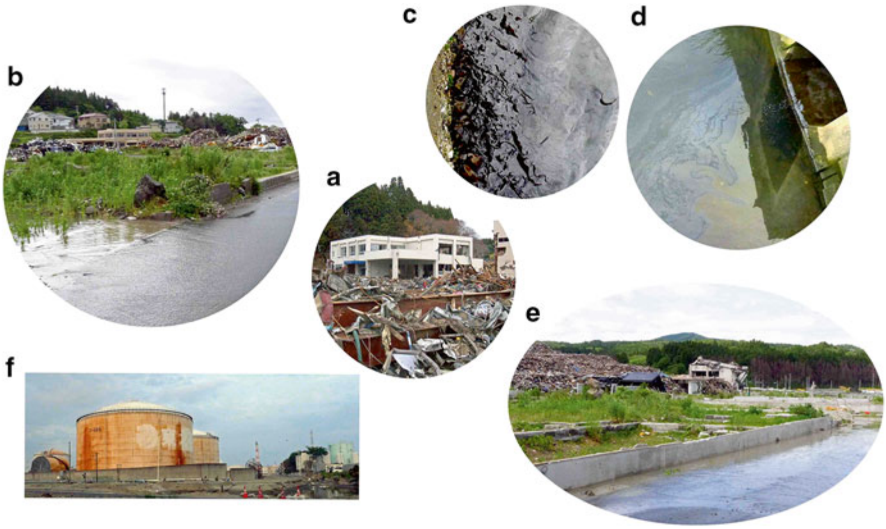

Fig. 17.1 Contamination after tsunami. Scattered, mixed debris in Shizugawa (**a**), Temporary collecting site contaminating soil and water in Minamisanriku (**b**), Oil contaminated macroalgae beds in Shizugawa (**c**); Contaminated water flowing into the river in Minamisanriku (**d**), Sunken ground accumulating polluted water from debris and other sources in Minamisanriku (**e**), and (**f**) Destroyed storage tanks in Ishinomaki

accepted to process 630,000 t of debris from Miyagi and Iwate prefectures. Efforts to process this debris were slowed down, however, due to the many logistical problems posed by safety concerns in dealing with radioactive debris (Japan Today 2013, 2014; Japan Times 2013b).

When a large tsunami hits a coastline area, contamination of water bodies and soil occurs due to seawater's salinity (Villholth and Neupane 2011), destruction of hospitals, houses, food processing plants, ports and fishing facilities, chemical depots, oil, plastic and electronics industries can be washed away, releasing toxic and hazardous substances similar to that of floods (Fig. 17.1) (Young et al. 2003).

A marked rise of infectious bacteria, fungus, as well as breeding grounds for mosquitoes in stagnant water occurs almost immediately following such an event. Cholera, malaria, and tetanus have been found in the aftermath of many instances of tsunami inundation, such as in Banda Aceh in 2004 (Aceh Epidemiology Group 2006). In Miyagi Prefecture, seven cases of tetanus were reported soon after the 2011 tsunami (Morino et al. 2012; Livedoor 2011).[1] Bacteria present in tsunami mud is also capable of producing pneumonia or "Tsunami Lung disease" after people have inhaled or swallowed water while been dragged away by tsunami waters

[1] The Chemical Problem Citizens Group (2012) provided a wealth of links related to health issues relevant to post tsunami conditions i.e. atmospheric pollution, inhalation of dust, etc.

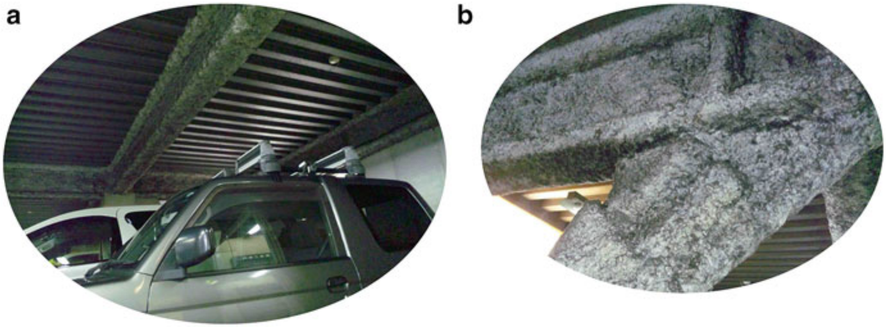

Fig. 17.2 Insulation foam in buildings likely containing asbestos

(Bandyopadhyay and Rudrajit 2012; Allworth 2005; Potera 2005). Last but not least, the presence of asbestos in buildings used in sheeting, fire-proofing and insulation (Fig. 17.2) is commonly found in earthquake and tsunami devastated areas, creating yet more serious health hazards (CBC 2011; Lateline 2013).

Immediately after the 2011 tsunami, the Toxic Watch Network (2011) made a comparison between the Pollutant Release and Transfer Registry (PRTR 2009) companies with flood maps in the Tohoku area. An estimated 1,000 factories and manufacturing companies were likely to have been damaged in Miyagi Prefecture alone, resulting in the release of many toxic and hazardous materials (Bird and Grossman 2011) including ammonia, heavy metals and metalloids (Cd, Cu, Zn, Hg, Ni, As), aldehydes and formaldehydes, dioxins, vinyl, insecticides, petroleum and coal products as well as PCBs, among many other compounds. Moreover, fires resulting from the 145,000-barrel-per-day-capacity oil refinery in Sendai (Eneos Guide Book 2010) and storage tanks released many varieties of dioxins including other hazardous substances (Bird and Grossman 2011).

As rice is grown in Miyagi Prefecture, large amounts of stored fertilizers and pesticides were released by the tsunami, one example being the Miyagi-based Ishinomaki fertilizer facility. Nonetheless, studies based on isotope data from Sendai have shown that the majority of sulphur (S) in the soil originated from seawater. Therefore, sulphur in water-leachable form found in tsunami sediment could not be from fertilizer, which in turn suggests that even if there were some contamination from fertilizer, it would be minimal compared to that of the sea (Chagué-Goff et al. 2012a, b).

Pollution could have also resulted from other sources, such as the seafloor, as sediment is carried inland by tsunami waters. Szczuciński et al. (2005, 2007) showed that the 2004 tsunami in Thailand brought heavy metals ashore. Likewise, Komai et al. (2012) found alarmingly high concentrations of arsenic and lead in sediment found along certain areas of Japan's northeastern coastline (including Miyagi).

Fujikawa et al. (2011) found that the density of sand and mud deposited by the tsunami in Minamisoma City (Fukushima Prefecture) varied from those generally found in farm soil, considering the large particle density of the sandy deposits may be due to the presence of metals or heavy metals.

Pollution from mud and sand containing metals should not always be expected, as other studies have shown this to be the case. Chagué-Goff et al. (2012a) reported that tsunami sediment located in certain areas along the Sendai Plains (Miyagi) presented heavy metal concentrations similar to background uncontaminated soils,, which is probably due to the lack of fine marine sediment entrained by the tsunami and deposited on land. Kawabe et al. (2011) also acknowledged the presence of leached concentrations of lead and arsenic, but stated that their origin needed to be corroborated as it may have resulted from causes other than the tsunami.

Tsunami mud causes a large increase in sea salt concentrations in the soil, which is mainly due to the presence of sea salt-contaminated terrestrial mud (Chagué-Goff et al. 2012a, 2013) in addition to marine mud brought ashore. As a result, such contaminated soil is rendered useless for rice cultivation therefore must be removed (Fig. 17.3).

In addition to the many types of debris caused by the tsunami, there is debris from construction, which presents its own unique set of health hazards as spilled chemicals from destroyed industries, processing facilities and urban areas will have long-term repercussions on the environment. Moreover, wooden debris treated with preservation compounds may potentially be released, presenting yet another source of contamination.

Fig. 17.3 Tsunami mud containing high concentrations of salt removed from damaged paddy fields. Sendai; Miyagi Prefecture

Fig. 17.4 Piled-up wooden debris likely leaching preservatives and other chemicals to the soil

17.2 Wooden Debris and Treatment

Housing planks, line poles, pylons and flooring mats, as well as planks from wooden bridges are commonly found mixed among the debris after the occurrence of tsunamis and large earthquakes. Most, if not all of this debris, has been treated with biocides, fixatives and fire retardants for the purposes of increasing material resilience, weathering and leaching as well as for environmental conditions and management procedures. Depending on the type of compound, these various chemicals could be spread over a vast area, presenting a myriad of potential environmental and health hazards (Fig. 17.4).

Large amounts of treated wooden debris were scattered by the tsunami in coastal areas along the Tohoku region and, depending on when the original material was produced, were subject to treatment with a variety of chemical compounds. Based on the statistics given by the Japan Wood Protection Association (2011), the most common chemical substance used from 1994 to 2005 included Creosote oil, CCA (Chromate copper arsenate), CuAZ (Copper, boron, and azole), ACQ (ammoniacal copper quaternary), BAAC (Quaternary Ammonium Borate) and SAAC (Quat non-ester Pyrethroid), among others.

17.2.1 Creosote Oil

Creosote oil, a dark-brown, oil-based compound, has been widely used as a preservative for protecting wood products since the 1800s, but has now almost completely disappeared from general use in developed countries. From 1994 to 2005, however, about 20,000 cubic meters of wood (mainly rail sleepers) were treated with creosote, although it is still often used in other exterior materials (Japan Wood Protection Association 2011).

The industry has come to recognize the synergistic, toxic effects of creosote oil on termites and other wood-destroying pests (Hale and Aneiro 1997). This coal-tar preservative has over 300 chemicals containing cresols and polycyclic aromatic hydrocarbons or PAH's (85 %), the most toxic being phenolic compounds (10 %) (Kiilerich and Arvin 1996; ATSDR 2002a, b); the low-molecular-mass heterocyclic compounds have been identified as major contributors to the acute toxicity of creosote leachates (Kuehl et al. 1990). In 2013, creosote as a wood-preservative was reviewed and subsequently determined that specific authorization must be received by the USA prior to its use (Health and Safety Executive 2013).

Although some creosote compounds are biodegradable, others are not, hence, creosote-treated wood has been considered to be very strong against weathering, but its eventual loss over time results in substantial pollution of the environment. Studies have shown that creosote's main elements continuously leach from weather-treated wood when washed with rainfall, having the highest loss rate of any chemical wood treatment (Hasan et al. 2010). Considering that some of its compounds are highly mobile in soil, they could threaten resources (Schiøtz Hanse and Ottosen 2002) and a number of its constituents, notably the O- and N-heterocyclics, which exhibit appreciable solubility, may be transported over significant distances via surface runoff or groundwater (Enzminger and Ahlert 1987). Recent studies in Puget Sound (USA) and related waterways have shown toxic creosote compounds released from old treated wood to be very common (Sheets 2011).

Once creosote components reach groundwater they may persist to pose environment and health hazards. Once in the groundwater, breakdown may take years. Most of the components that are not water-soluble will remain in place in a tar-like mass; breakdown in soil can take months for some components of coal-tar creosote, and much longer for others. Small amounts of these chemicals that remain in the soil and water will remain toxic to some animals and possibly to humans (ATSDR 2002b).

17.2.2 CCA (Chromated Copper Arsenate)

CCA is the most common waterborne wood preservative (Townsend et al. 2005), widely used in many countries for lumber treatment due to its low cost, and desirable characteristics of being fast-drying and a relatively leach-resistant compound (Moghaddam and Mulligan 2008). In New Zealand, about 5,000 t of copper, chromium and arsenic (CCA) salt equivalent were used to treat 650,000 m^3 of timber annually (Love 2007). Copper (23–25 %) and arsenic (30–37 %) in CCA act as fungicides and insecticides, while chromium (38–45 %) fixes the chemicals to the wood (APVMA 2003; Greaves 2003); this chemical mixture is injected into the wood under pressure until saturation (Hall and Beder 2005).

Other studies show that the rate at which the CCA elements leach is dependent on the treatment process as well as the environment where the wood is installed

(Hingston et al. 2001), while Zagury et al. (2003), Read (2003) and Cooper and Ung (1997) showed that copper has the highest leaching rate in all environments. The leaching rate of arsenic appears to be related to the amount of chromium, with the minimum occurring at a chromium to arsenic ratio of between 1 and 1.3 (Read 2003). Leaching rates of CCA components have also been shown to decrease over time (Hingston et al. 2001; Read 2003). Certain studies show that the amount of leached compounds also depends on climatic and geological conditions (Hall and Beder 2005).

Ultraviolet exposure increases the leaching rate of arsenic by as much as five times that which is removed through rainfall (Lebow et al. 2003), and weathered wood leaches more of the penta- and toxic trivalent arsenic (Solo-Garbriele et al. 2003a, b; Bernine et al. 2003). Acidity also increases leaching. The CCA chemical itself is acidic, and if not properly applied to the wood, can result in increased levels of chromium present in the surrounding soil. Humic acid in mulch also poses an increased risk of leaching.

It is well known that metal concentrations in humic matter could be a thousand-fold higher than in non-humic conditions, copper being the most conspicuous, as also reported by Enviros Consulting and The BioComposites Centre (2004). Farm soil treated with fertilizer containing calcium, magnesium, potassium and phosphorous also increases the chances of leaching from CCA-treated timber.

Solo-Garbriele et al. (2003a, b) found that the soil below and around CCA-treated timber decks contained an average arsenic concentration of 28.5 mg/kg, well above average background soil arsenic concentrations of 1.5 mg/kg. Runoff collected from the decks contained over 1 mg/L arsenic and chromium. Soil below the CCA-treated timber decks contained an average of 34 mg/kg chromium and 40 mg/kg of copper, in contrast to an average background concentration of 10 mg/kg for both metals (Townsend et al. 2001).

17.2.2.1 Soil and Water Contamination from CCA-Treated Wood

Townsend and Solo-Gabriele (2006) compiled a series of studies on the impacts of CCA-treated wood, and Graham and Scott (2013) and Hall and Beder (2005) showed that CCA-treated timber can leach into both soil and groundwater. It is therefore estimated that there is a possible risk to groundwater quality from treated timber at debris piling sites. CCA soil concentrations were found to reach background levels very close to the source, and as this compound is easily transported by water, it clearly presents a groundwater hazard.

CCA residues from treated wood found in the environment after a natural catastrophe were confirmed in the case of hurricane Katrina in 2005. As in 2003, CCA-treated wood was the most popular wood preservative used in the USA, and large amounts of wooden debris containing arsenic (As) presented dangerous pollution potential (Brajesh et al. 2007).

Japan started using CCA from 1963 until 1996, with an annual production of 300,000 m^3 or almost 75 % of the market, after which use was reduced due to the high cost of wastewater and storm runoff treatment and pollution concerns. Therefore, in 1997, the Japanese government requested companies to voluntarily stop producing this preservative, and by 2003, production of CCA-treated wood had stopped almost completely (Hata et al. 2006; Japan Wood Protection Association 2011). As a result, other wood preservatives such as copper-based (CuAZ and ACQ) and non-copper based chemicals (AAC and BAAC) became popular. By 2005, most treated wooden planks for ground use (sill), exterior use and other materials were treated with these chemical compounds (Japan Wood Protection Association 2011).

Lebkowska et al. (2003) reported that waterborne chemicals could have a negative impact on surface water and groundwater quality. Toxicity tests including luminescent bacteria tests, algae growth inhibition tests and crustacean and fish lethal tests were performed to determine the presence of tebuconazole, propiconazole, 3-iodo-2-propynyl butylcarbamate, cyfluthrin, and alkyd resin. The results showed that wood preservatives leached from wood samples by 10 % within 1 month of exposition when impregnated with chemicals at concentrations of 18,060 mg/L.

A field study done in Canada by Zagury et al. (2003) showed that concentrations of CCA chemicals from treated utility poles are present in soil and groundwater. Copper concentrations in the soil were larger than arsenic and chromium; the highest concentrations were found to be immediately adjacent, i.e. copper 1,460 ± 677 mg kg^{-1}, arsenic 410 ± 150 mg kg^{-1}, and chromium 287 ± 32 mg kg^{-1}. These concentrations decreased with distance reaching almost background levels at 0.1 m for chromium, and 0.5 m for copper and arsenic. On the other hand, the concentrations of copper and chromium in ground water showed to be less than 1.000 mg L^{-1} and less than 0.05 mg L^{-1}, respectively. In the case of chromium Cr(VI), the concentration was less than 0.02 mg L^{-1}. The same authors also concluded that soil contamination is more strongly correlated to soil type rather than the pole age; leaching is higher in low-organic and ion-clay soil types.

Other authors have also shown that concentrations of chemicals in soil from treated poles become reduced as distance from the sources increases (Morrell and Huffman 2004; Cooper and Ung 1997; Hingston et al. 2001; Graham and Scott 2013).

Robinson et al. (2004), found that CCA-treated poles in vineyards located in the Marlborough Region (New Zealand) leached, which in some cases exceeded acceptable levels for chromium and arsenic in agricultural soils set by the Australian National Environment Protection Council's Levels for Soil and Groundwater (NEPC 1999). Up to 25 % of the samples exceeded the guideline levels in the soil for arsenic and 10 % exceeded levels for chromium (100 mg/kg); in urban areas, 20 mg/kg of arsenic or chromium is considered to represent an environmental concern. Moreover, the author highlights the fact that under certain circumstances there may be a risk of arsenic leaching into groundwater, although further research is necessary to ascertain this possibility.

The main impacts of leaching into soil seem to be localized. Townsend et al. (2001) found that the highest concentrations of arsenic, chromium, and copper were found within 5 cm (laterally) of the CCA-treated timber, with the metal-to-soil levels decreasing with distance. The highest median concentrations were found in the upper 20 cm of soil.

Other studies have shown that CCA concentrations in above-ground wood samples are not significantly different from concentrations in new poles, while wood samples from below-ground contain lower CCA concentrations, suggesting that leaching is evidently occurring (Morrell and Huffman 2004). In situations where the groundwater table is close to the surface, concentrations of these elements are expected to be spread further from the poles when compared to unsaturated soil situations (Hingston et al. 2001; Lebow et al. 2003).

Leaching tests showed that arsenic and chromium can be controlled by pH levels (Townsend et al. 2004). Metal leachability from CCA-treated wood is the highest at extreme pH values and lowest around pH-7, and increases with increased contact time. Although copper and chromium leaching from wood reached an equilibrium within 7 days, arsenic continued to increase throughout the test.

Soil type also plays an important role in the mobility of CCA. It has been found that the greatest absorption occurs in soils where organic content is moderate to high, resulting in decreased mobility, while lowest absorption rates are in sandy clays with a low organic content, allowing for greater mobility (Read 2003).

In order to investigate the impact on groundwater from tsunami debris, leaching tests were performed. Research was conducted to examine the possible environmental impacts of using CCA-treated wood for purposes such as landscape mulch. Two pathways, leaching to groundwater and direct human exposure, were examined (Townsend et al. 2004). To examine contamination of groundwater, samples of C&D (construction & demolition) wood debris mulch were tested to determine the presence of CCA-treated wood using the synthetic precipitation leaching procedure (Townsend et al. 2003b). Arsenic presented the biggest problem when results were compared to risk-based target concentrations for groundwater. Since contamination of groundwater depends on many factors, such as underlying soil type, rate of mulch application, extent of application, and depth of groundwater, the results do not directly indicate that groundwater contamination will occur.

Townsend et al. (2003a) reported that copper, rather than arsenic, was most toxic to the aquatic environment. However, when copper was present in the CCA combination, it appears to be have been more toxic than on its own, raising concerns about the synergistic effects of the combination of copper, arsenic and chromium.

Weis and Weis (2004) showed that all the active elements were accumulating in the aquatic environment (particularly in locations with reduced water flow), sediments and organisms, to the point of reaching the trophic chain. Furthermore, cells and tissues have also shown to be affected, impinging on growth and increasing mortality. Chirenje et al. (2004) found that fine-textured soils and soil with high amounts of organic matter had larger retention capabilities of copper, chromium and arsenic, presenting potential contamination problems. This finding became important for riverine and estuarine environments as well as wetlands, since organic matter can be found in sediment, although these types of ecosystems can also act as metal sinks which further reduces their availability.

17.2.2.2 Soil and Water Contamination from CCA in Landfill

Some studies demonstrated the impact of CCA-treated wood disposed in landfills. The leachate metals can pollute ground and surface water used for drinking purposes as C&D (construction & demolition) landfills are unlined (Weber et al. 2002). During rain, water penetrates into C&D landfills, causing leaching of wood preservatives from disposed CCA-treated wood. Rainfall is the only cause of leachate formation in these types of landfills for construction materials (Weber et al. 2002). On the other hand, Saxe et al. (2007) showed that aggregate groundwater data from 62 unlined C&D landfill sites and data from individual sites indicated no appreciable arsenic migration to groundwater, despite an estimated 12.8 million kilograms of arsenic disposal in CCA-treated wood in Florida by 2000. Nevertheless, there is increasing concern about potential environmental contamination from leaching of copper, chromium, and arsenic from treated wood in service and from wood removed from service and placed in landfills in North America (Shalat et al. 2006).

Arsenic is a major concern from a disposal point of view, with respect to groundwater quality (Townsend et al. 2004). The presence of arsenic in areas surrounding CCA-pressure-treated wood poses a danger to groundwater contamination due to runoff. Arsenic enters the environment and does not decay.

As the leachate of treated wood in landfills is genotoxic and carcinogenic, the contaminated water is dangerous for human beings and animals. It is therefore important to investigate leaching and biodegradation of treated wood. There is the potential for soil, water and the environment to become contaminated with chromium, copper and arsenic wherever chromium leaches least, despite being present in the greatest proportion. A study investigating the effects of pH, temperature, and duration of leaching showed in areas where the region is exposed to sulfuric acid rain due to sulfur dioxide emissions that there is a high risk of chromium, copper and arsenic leaching. Although most acidic rain has a pH of 4.3, the trend of decreasing pH has shown to increase the leachability of wood. Moreover, as temperatures increase, the amount of leached metals rises, arsenic in particular being the least resistant to leaching (Moghaddam and Mulligan 2008).

To assess whether landfill disposal of solid waste might impact leachate or groundwater quality, a leaching test was conducted (Townsend et al. 2005); the results indicate that weathered, CCA-treated wood might result in elevated pollutant concentrations in landfill leachates and possible groundwater impact at unlined sites. Arsenic, chromium and copper were found to be above acceptable drinking water standards and arsenic often leached above hazardous waste level limits.

CCA-treated wood storage requires soil lining particularly in the aftermath of natural disasters to avoid affecting groundwater, particularly if disposed together with construction and demolition (C&D) debris (Jambeck et al. 2008). CCA in construction debris proved to release more of its harmful elements when immersed in water (Lebow and Tippie 2000)

Other material piled up from tsunami debris such as concrete and steel were found to be unlikely to adversely affect groundwater quality in aquifers (Graham and Scott 2013).

17.2.2.3 Atmosphere Contamination

Debris incineration, handling and demolition may cause atmospheric pollution (Fig. 17.5). Hata et al. (2004, 2006) reported that the incineration of large amounts of disposed CCA-treated wood from rebuilding old houses in Japan (mainly in 1995) showed almost no arsenic volatilization when processed at high temperatures (1,000 °C). However, early works stated that zero arsenic release is not feasible (Helsen and Van den Bulck 2003). The same authors (2005) indicated that a variety of incineration options including co-incineration, low-temperature pyrolysis and high-temperature gasification would largely diminish the release of arsenic.

Fine dust is produced when CCA-treated planks are cut or sheered, requiring workers to use special respiratory and skin protection (Level 2013). Sawdust and shavings release enormous amounts of active elements as a result of a greater surface area-to-volume ratios.

On the other hand, CCA-treated wood when incinerated produces contaminated ash, requiring special treatment and or disposal to avoid soil and water contamination (Matsumoto et al. 2012). Burning CCA-treated wood waste (debris and sediments) has been considered in general to be harmful to the environment (Nakanishi 2011).

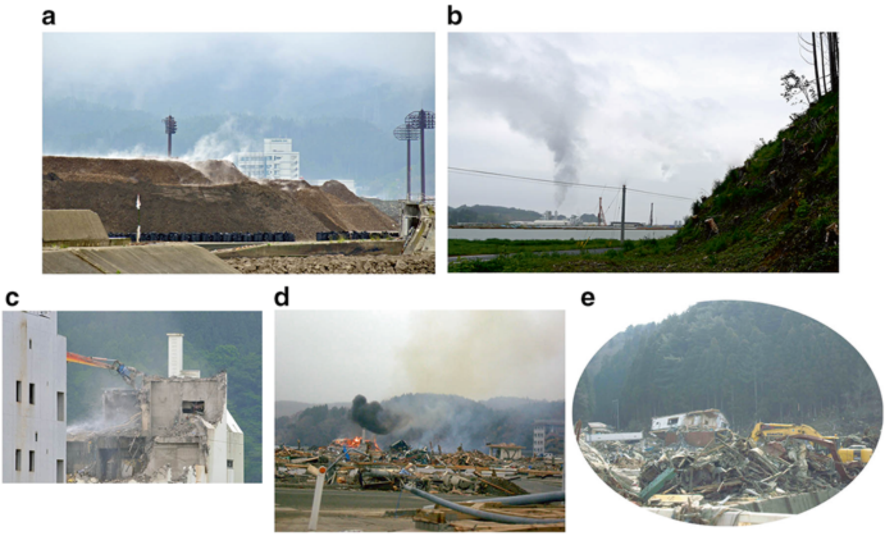

Fig. 17.5 Air pollution sources from (**a**) shredded debris (gas emissions from anaerobic fermentation processes); (**b**) incinerator emissions (CO_2, and other gases); (**c**) demolition (dust and other particles); (**d**) debris burning (hazardous gases); (**e**) cleanup (dust particles including asbestos)

17.2.3 CuAZ (Copper, Boron, and Azole) and ACQ (Ammonical Copper Quaternary)

Another preservative with a higher copper concentration than CCA also proved to be a better alternative for wood treatment due to its low leaching rate (Li et al. 2011), although Wang and Wang (2011) showed that the copper fixation rate in CuAZ-treated bamboo was similar to that of CCA, suggesting similar copper loss in both wood treatments.

In 2007, the majority of lumber in the USA was treated with ACQ, due to its reliability (Home Builders Association 2007). Likewise, this compound was widely used in Japan (Miyauchi 2008); as arsenic was not present in the formula, ACQ contains a high copper concentration, much like CuAz. Copper-leaching has shown to be continuous from treated wood due to rainfall, albeit in lesser quantities as wood weathers (Hasan et al. 2010).

The release and environmental impact of copper from ACQ- (Ammonical copper quaternary) treated wood was evaluated in a wetland boardwalk study (US-FFS 2000). Elevated levels of copper were detected in rainwater, soil, and sediment collected adjacent to sites with treated wood. The rainwater collection indicated that the release of copper peaked 6 months after construction, reaching average release rates of 35 μg per cm^2/in. of rain (US-FFS 2000). Much lower average release rates (approximately 5 μg/cm^2/in. of rain) were observed 11.5 months after construction. The relatively high release of copper during the first 6 months of this study was reflected in the concentrations of copper detected in the soil; geometric mean soil concentrations were elevated by approximately 169 kg/min (flow rate) directly under the edge of the boardwalk. Copper mobility was greater in the sediment than in the soil. Despite the accumulation of copper detected in the environment, no significant impact was detected on the quantity or diversity of aquatic insects at the site (Lebow 2004). A wide description and characteristics of ACQ is available at Treatedwood.com (2012).

17.2.4 AAC (Alkyl Ammonium Compounds) and BAAC (Quaternary Ammonium Borate)

ACC is also a component of ACQ (Ibach 1999), and its efficiency as a preservative depends on the type of tree species on which it is applied and the specific chemical formulation (Hedley et al. 1982). Although leaching inevitably occurs, it can be greatly reduced with proper chemical fixation (Ohio-DOA 2003). Due to its apparent low toxicity and biodegradability, AAC is still used in China and other countries (Huai'An Huize 2013).

Considering the low environmental impact of AC and ACQ, both are commonly used in Japan, particularly in the treatment of wooden bridges (Shuichi et al. 2001).

BAAC is reported to be widely used in Japan, too (Japan Wood Protection Association 2011); borate compounds are considered to be less harmful to the environment and mammals than CCA, but still require a good fixative to prevent leaching, which limits their use when exposed to wet environments (Canadian Wood Council 2013; Freeman et al. 2006).

Boric acid and borate salts in ammonium borate and copper compounds are soluble in water. Most boron will exist in aqueous solution such as boric acid or borate ion (ATSDR 2007). Boron cannot be destroyed in the environment. It can only change its form or become attached or separated from particles in soil, sediment, and water (ATSDR 2010). Didecyl polyoxyethyl ammonium borate (DPAB) or Polymeric Betaine, was developed as biocide for chromium-free copper-based wood preservatives in the 1980s in Europe, showing to have a valuable synergistic effect against copper-resistant fungi, as well as good fixation properties. Hence, it has continued to be used for over 20 years (Härtner et al. 2008, 2009).

Boric acid and borate salts may reach groundwater because of their relatively high water- solubility and their variable soil sorption (WHO 1998). Also pertinent to the leaching of boron and copper from ammonical formulations was a study evaluating leaching from 38 mm by 89-mm plywood planks treated with ammonical copper borate and exposed for 11 years at a test site in Mississippi, USA (Johnson and Foster 1991).

Copper is associated with fewer mammalian health concerns than arsenic. Environmental release of ecobiocides such as boron or quaternary ammonium compounds is also to be expected, but these co-biocides also have relatively low mammalian toxicity (Lebow 2004).

17.2.5 BAC (Benzalkonium Chloride) and SAAC (Quat Non-ester Pyrethroid)

BAC is also largely used in Japan (Miyauchi et al. 2008); BAC is an active component of ACQ. Under certain circumstances such as the presence of humates and the type of tree, this compound could leach in the soil (Miyauchi and Mori 2013; Miyauchi et al. 2008). Still, this compound is used in a large number of industries due to its low toxicity, high biodegradability and the fact that it does not seem to accumulate in the environment under normal conditions. Another advantage is that its active compounds can be deactivated by clay, neutralizing their toxicity in the water environment (Quat Chem 2013).

Some types of non-esther pyrethroids bearing low toxicity to fish and the aquatic environment were developed in 1992 (Meier et al. 1992), and Quat non-ester pyrethroids have been used in Japan to treat wood since approximately 2004 (Japan Wood Protection Association 2011). Depending on their particular chemistry, pyrethroid compounds have shown to be more or less toxic to the environment and mankind, therefore those with higher toxicity potentially require more careful management and manipulation (MSDS 2010; US-FFS 2013). Silafluofen, a pyretroid insecticide containing silica, has been in use since 1981 for treating timber due to its low toxicity to mammals and fish as well as its high stability under sunlight, soil and alkaline environments (Katsuda et al. 2011).

17.3 Debris Management in the Aftermath

Tsunami debris had an enormous impact in the affected areas along the coastline, creating large problems (Santiago-Fandiño 2013b). The costs involved in managing debris have been staggering; in Ishinomaki City alone, they are estimated to reach US$ 262.5 million or about 21.2 million Yen (Tisnadibrata 2013). The total amount of debris generated in the Ishinomaki block equaled about 68 years of general waste while in Watari-Natori block about 50 years (MPG 2014).

Governments need to estimate the amount of debris and also prioritize their cleanup as soon as possible as debris blocks roads, obstructing humanitarian relief and rescue efforts. Furthermore, as debris may also carry toxic and or hazardous chemicals, they present a variety of potential environmental and health hazards. Studies towards the establishment of disaster debris management based on quantitative estimation using natural hazards maps could be used in emergency response and pre-disaster planning (Hirayama et al. 2010).

If clean-up and disposal is not properly carried out, secondary impacts on the environment are likely to occur (Srinivas 2005). For example, burning construction debris in the open could produce PAH's and other toxic compounds (Bird and Grossman 2011; Japan Society for Material Cycles 2011). In the city of Minamisanriku (Miyagi Prefecture), debris containing plastics, vinyl, seawater-soaked wood, wiring and insulation materials appears to have been burned during the initial cleanup process as seen in Fig. 17.5d (Bird and Grossman 2011).

Mixed debris once stored in temporary sites are moved to new ones for further sorting and segregation, treatment, incineration, recycling and/or disposal. During this waiting period, debris tends to adhere to soil and/or sand, making further processing and incineration more difficult (MPG 2013a).

Construction materials and storage sites containing organics or gypsum, particularly in wet environments, generate methane and hydrogen sulfide gases. This is due to bacterial degradation of organic compounds. High concentrations of these gases present a serious health and fire hazard if not properly managed (Ohio-EPA 2011; ATSDR 2013). Sudden explosions have already occurred in temporary storage sites in Miyagi (UNEP 2012).

Traditional tatami mats are manufactured using a variety of vegetation products such as straw as well as other materials like clay-based dyes (Fujimoto and Muller 2004). Tatami mats are capable of maintaining high levels of moisture facilitating decomposition and generation of flammable gases, necessitating proper storage conditions to avoid further hazards or accidents (Fig. 17.6).

In terms of greenhouse (GHG) emissions and CO_2 "footprint", Cui et al. (2013) made a preliminary assessment calculating that 10.95 Mt CO_2-eq. was due to debris.

Fig. 17.6 Piled-up tatami mats awaiting to be processed in the Hajikami facility

This result, together with emissions resulting from housing reconstruction and land use change very likely could put into question commitments made by Japan under the Kyoto Protocol in terms of GHG reductions.[2]

17.3.1 Debris Management in Miyagi

In the aftermath of the tsunami, Miyagi prefecture had to deal with 18 million tons of debris (11 million considered as general disaster debris, and 7 million tons in tsunami deposits[3]), all of which was kept at 90 temporary sites, presenting an enormous potential pollution hazard. By the end of February 2013, about 90 % of the debris was already cleared and stored (56 % percent of which was general debris, while 29 % consisted of tsunami deposits); the remaining amount is expected to be dealt with by March, 2014 (MOEJ 2013a).

Thirty-three temporary incinerators and thirteen sorting and shredding facilities were built in Iwate, Miyagi and Fukushima prefectures to deal with the amount of debris, although other prefectures have also assisted in disposal processes (MOEJ 2013b). The Ministry of the Environment reported that treatment finished in 29 temporary incinerators and 13 sorting and shredding facilities by February 2014, likewise that the number of temporary storage sites decreased by 54 of 17 % (MOEJ 2014).

[2] In late 2013, Japan decided to reduce its greenhouse emissions by 3.8 % from their 2005 level by 2020 due to the shutdown of its nuclear industry (UNFCC 2013).

[3] Tsunami deposits consist mainly of soil, mud and sand.

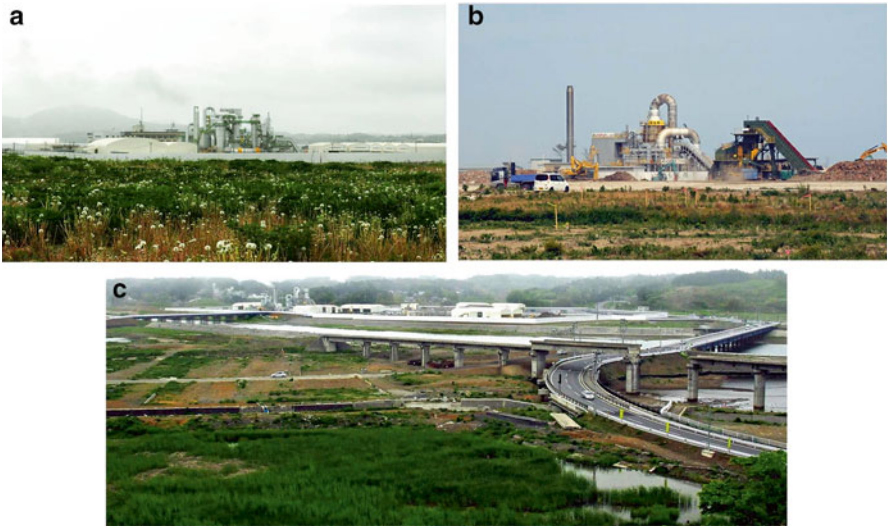

Fig. 17.7 Holding blocks and incinerator complexes at (**a**) Hajikami; (**b**) Harahama and (**c**) Koizumi, Miyagi Prefecture

Table 17.1 Kesennuma block facilities and treated weight (×1,000 t)

	Hajikami	Koizumi	Katahama	Other plants
General waste	460	230		
Tsunami debris	40	20	610	
Total	500	250	610	280

Source: Taisei Corp. Info Brochure (2013)

In Miyagi, five holding blocks, i.e. Kesennuma, Ishinomaki, Miyagi-Tobu, Sendai and Watari-Natori (MPG 2013a; Taisei Corp. 2013), were constructed (Fig. 17.7) including storage, sorting and incineration facilities, costing up to 16 billion Yen (approximately US$ 160 million at the time), each to be dismantled by April 2014 (roughly one and half years after being built). Following decommissioning, the land is to be used for various development purposes (Taisei Public Information, Hajikami Plant, Kesennuma 2013, personal communication).

The Hajikami, Koizumi and Katahama debris facilities, located in the Kesennuma block, dealt with 1.64 million tons of debris until March 2013, of which 670,000 t consisted of tsunami debris or deposits, while the rest consisted of general disaster waste or tsunami debris (Table 17.1). All of this debris was originally stored in 24 initial collecting temporary sites throughout Kesennuma City (Taisei Corp. 2013; MPG 2013a).

The main components of general disaster waste collected in the block included wooden debris, burnable and non-burnable materials, concrete, asphalt, metals, boats and plaster as well as soil, sand and mud. Out of all the materials, wooden debris totaled 120,000 t, representing the highest amount of debris to be processed and incinerated. Up to March 2013, 3 t of incineration ash and fly ash were generated from burning debris (Taisei Corp. 2013).

Dioxins, nitrogen oxides, metals and metalloids, among other compounds, may have been released during this process. To prevent the production of dioxins at the sites, debris was incinerated at 800 °C, having previously gone through removal of sand and soil by rotary and vibration screening while modifiers were also added (MPG 2013a). Products of combustion, such as nano-particles, could also have been produced and may continue to remain in solid and liquid waste (Leiva 2013).

17.4 Radiation

The earthquake and subsequent tsunami on March 11, 2011 caused the Fukushima Dai-ichi nuclear power plant south of Miyagi Prefecture to suffer severe damage as radiation spewed into the air, contaminating large areas of land and resulting in emergency evacuations and setting up exclusion zones (Cabinet Office 2012; Fukushima on the Globe 2013) (Fig. 17.8). The Onagawa nuclear plant facility in Miyagi was not affected since the plant's reactors shut down immediately following the event, initiating emergency cool-down protocols. In the case of the Fukushima Dai-ichi nuclear plant, although the reactors were shut down automatically, safety systems for reactors No. 1 to No. 4 failed to keep cooling. The earthquake damaged power lines providing energy to the facility, and soon after the independent, emergency diesel generators were flooded by the 10-m (30 ft.) tsunami waves. As a result,

Fig. 17.8 Security gate along Route 288 in Tamura city by the exclusion zone. Fukushima Prefecture

all electric equipment in reactors 1–4 were rendered useless (IAEA 2011). Venting operations had to be undertaken; hydrogen explosions in reactors Nos. 1 and 3 occurred, spewing more radioactive material such as cesium (^{137}Cs and ^{134}Cs) and iodine (^{131}I). Special measures were taken in the damaged reactors to avoid spent fuel meltdown (NISA and JNES 2011).

The total amount of released ^{131}I was calculated to be around $1.2–1.6 \times 10^{17}$Bq while in the case of ^{137}Cs was $0.8–2.0 \times 10^{16}$Bq; the highest release estimates were after the hydrogen explosions around $10–15 \times 10^{16}$Bq per hour for both. In Onagawa city (Miyagi), about 150 km from the Fukushima plant, the dose rate was measured to be up to 15 μ Sieverts per hour (μSvh^{-1}) on 13th March 2011, although in Minamisoma City the level near the plant reached 20 μSvh^{-1}. The deposition map of ^{137}Cs showed that the radiation plume was large, covering most of Miyagi and southern Iwate, albeit in low quantities (Masamichi et al. 2011; Masamichi 2012). The majority of the released radiation dispersed over the Pacific Ocean.

On the other hand, a study done in 2011 based on cesium (^{137}Cs) and xenon (^{133}Xe) readings stated that the amount of radiation from the nuclear plant was much higher than reported (Stohl et al. 2011; Brumfiel 2011). A study done by Yasunaria et al. (2011a, b) on soil contamination estimated that large areas in eastern and northeastern Japan, particularly in Fukushima and nearby prefectures had partially (^{137}Cs) estimated depositions larger than 100,000 and 10,000 MBq km^{-2} respectively.

The Nuclear Regulation Authority of Japan (NRAJ 2012) published the results of radiation monitoring of soil in a number of towns in Fukushima Prefecture after the nuclear accident focusing of strontium and plutonium (^{90}Sr and ^{238}Pu). This agency concluded that the highest contamination from ^{90}Sr occurred in Ottozawa in the town of Okuma and Koriyama in the town of Futaba being 3,070 Bq/m2 (80.8 Bq/kg-dry soil) and 502 Bq/m2 (14.9 Bq/kg-dry soil) respectively. In the case of plutonium (^{238}Pu) only Ottozawa in Okuma seemed to have been only slightly contaminated. The same authority provides detailed information about the events, damage and measures taken due to radiation exposure of different isotopes (NRAJ 2013).

Comprehensive information about emergency monitoring readings of environmental radiation levels throughout 2011 is provided by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT 2011). The Japan Reishi Association (JRA 2012), an international NGO supported by industries and government organizations provided the radiation (air dose) levels in various prefectures in eastern Japan from 2011 to 2012, and their analysis showed that while making comparisons with radiation-exposure levels found in other cities around the world, levels in Fukushima City were only slightly higher than in other locations.

In the case of Miyagi Prefecture, the Radiation Information Site of Miyagi Prefecture provides detailed, up-to-date information about radiation dosage rates considering air, tap water, agriculture, forest and marine products (MPG 2013b). As result of the nuclear accident, a variety of agricultural and forest products in northern Miyagi, including mushrooms, aralia sprout and bamboo shoots have recorded radioactive cesium (MPG 2013b). Moreover, reports by citizens watch on radioactivity in Japan showed that domestic house dust from vacuum cleaners collected from Marumori-cho in Miyagi has shown to be high in radioactive cesium (^{137}Cs and ^{134}Cs) in amounts larger than 6,000 Bq/kg (ACRO 2013).

Considering the problem of radiation and its accumulation, local authorities and citizens have expressed deep concern about incinerating debris from Miyagi Prefecture. Reports by the government claim that radiation levels are very low, for example, in the city of Ishinomaki where the largest amount of debris exists, radioactive readings were 0.055 (μSvh^{-1}), appearing to be similar to its surroundings (Recovering Tohoku 2012). Nonetheless, the city of Kitakyushu has accepted to burn 23,000 t of debris amid strong opposition by its citizens (Japan Today 2012).

The Environment Ministry has set further safety guidelines for ash originating from debris incineration in contaminated areas, stating that up to 8,000 Bq/kg of radioactive cesium can be buried safely like any other type of waste (The Asahi Shimbun 2012).

Radioactive materials from the Fukushima nuclear plant has contaminated soil and waterways in Miyagi, likely creating some radioactive "hotspots". For example, studies have shown the Murone and Yagoshi mountains along the Okawa river watershed ending at Kesennuma have a certain amount of radiation, raising concerns about dispersion of radioactive elements and their potential impact (Tanaka M, International Institute for Advance Studies, Kyoto University, Japan, 2012, personal communication). Although figures vary according to sources at the time of sampling, it is clear that radioactive contamination appeared to have occurred in Miyagi Prefecture as result of the Fukushima Dai-ichi nuclear plant disaster.

17.5 Environmental Contamination and Toxicity

Toxic effects of pollutants could result in death or ailments in the short, medium and long-term. Moreover, depending on the type of exposure and the level of response, they could be considered acute or chronic (Environmental Health and Safety 2013; University of Toronto 2013). The degree of toxicity depends on the particular type, concentration, activity-reactivity, physicochemical characteristics, persistence of the compounds as well as the target (species) and exposure time. Moreover, combined mixtures of pollutants could result in stronger (potentiated and synergistic) or weaker (antagonistic), toxic effects (VKM 2008).

Toxic effects may produce growth abnormalities and teratogenesis, cell and tissue damage, chromosome mutations or changes in behavior as well as alterations in reproductive rates, among many other problems (US-EPA 2011). A large number of studies have been carried out on the effects of toxic substances on species and compiled in metadata such as the ECOTOX Database focusing on aquatic, terrestrial plants and wildlife (USA-EPA 2014).

Considering the type of chemicals spread by the tsunami in Miyagi Prefecture from industries, processing factories, warehouses, households, garages, hospitals, etc. as well as those potentially released from wooden debris, the likelihood of environmental and human health risk hazards could be high. This would be particularly

Fig. 17.9 Debris storage sites in lowlands along the coastline (**a**) shredded; (**b**) mixed; (**c**) wooden and (**d**) composite (partially submerged). Miyagi Prefecture

important in areas along the coastline where toxic "hot spots" have been created. Studies by Komai et al. (2013) on evaluation risk assessment undertaken in certain areas of northern Miyagi and Iwate Prefectures showed that toxic substances (mainly arsenic and lead) present in tsunami deposits pose a relatively high level of risk requiring appropriate management before being stored or utilized.

Primary and secondary debris collecting sites (Fig. 17.9) can be considered as toxic hot-spot sources of pollution as they lack ground lining. Moreover, shredders and crushers in direct contact with the soil as well as howling trucks continuously transporting debris from and through collecting sites are responsible for spreading large amounts of dust and other contaminated particles in large areas.

Furthermore, as sea salt must be washed off of debris prior to incineration in order to improve performance and reduce dioxin production, the practice increases soil salinity; salt accumulates mainly in the cortex of wooden deposits, taking up to 80 cm of cumulative rainfall to remove almost 97–99 % of the salt (Nakanishi 2011).

It is important to highlight the fact that soil salination in tsunami-hit areas is mainly due to its inundation of seawater rather than from salinated debris; this is particularly conspicuous in certain areas along the Sendai plains in Miyagi where deposited sea salt has been found to be as far as 15 cm below the tsunami-deposited sediment (Chagué-Goff et al. 2012a).

As soil types vary along Miyagi's coastline, i.e. Fluvic, Brown (Cambisols) and Fulvic Andosols as well as Korosuko (Andosols), Red Yellow and Regosol (Soil Science 2014; Yagi 2012; Kanno et al. 2010), the likelihood of pollutants seeping deep into the soil also varies. The possibility of pollutants contaminating aquifers could be high at locations where high soil permeability and porosity exist. Moreover, contaminated groundwater could in turn contaminate coastal waters through submarine ground discharge (SGD) as shown by Slomp and Van Cappellen (2004), Swarzenski and Gibbons (2009) and Kontar et al. (2013). Hazardous and toxic substances leached from debris stock piles and treated wood in certain areas or hot spots are likely to have seeped into the ground as well, eventually reaching bottom coastal waters through SGD aside of surface water flows.

To reduce the possibility of contamination of aquatic environments by chemically-treated wood debris, proper management must be undertaken. Countries such as the USA and Canada have developed some guidelines; Canada has recommended keeping treated wood debris and related chips and sawdust away from aquatic environments, particularly in low-flow riparian systems as well as covering the ground (Government of British Columbia 2013). This practice may also apply to temporary debris storage sites. Kakitani et al. (2006) proposed the use of bioxalate solution with sodium hydroxide to reduce the risk of pollution by heavy metals and arsenic present in CCA, ACQ and CUAZ treated wood.

The areas along Tohoku's coastline hit by the tsunami are considered a " Na-tech" disaster (Young et al. 2003). These events contaminate inland and marine waters (Fig. 17.10) posing a high risk to the environment due to the presence of pollutants,

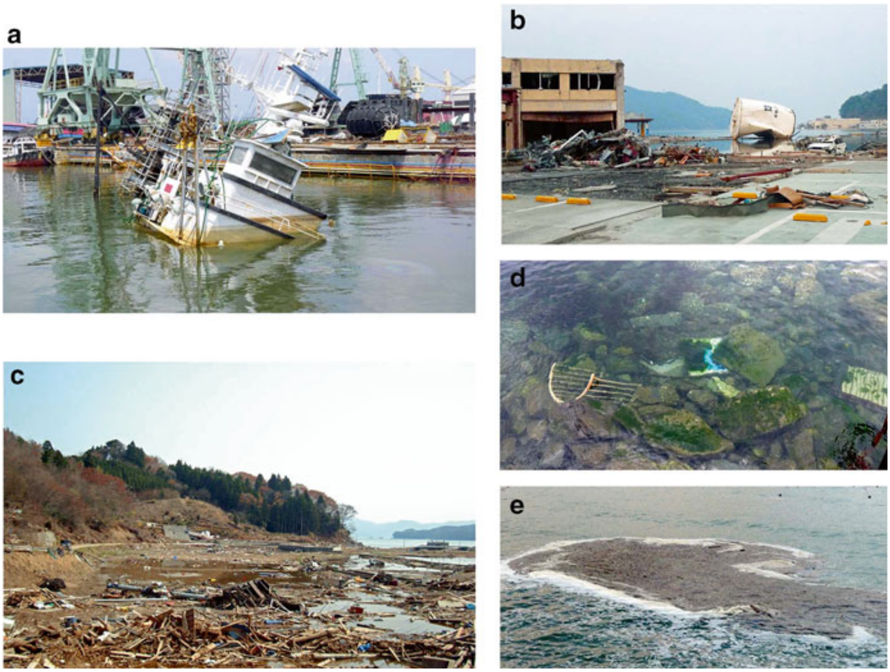

Fig. 17.10 Post disaster scene in Ishinomaki port (**a**), Onagawa town (**b**) and Shizugawa beach side (**c**). Submerged (**d**); and floating (**e**) debris in Minamisanriku city. Miyagi Prefecture

Fig. 17.11 Torrential rains along the coastline in Miyagi Prefecture

although toxic interaction would be very difficult to assess accurately (Andreadakis et al. 2012). Tsunami water and backwash contain a large number of compounds and materials from multiple origins, complicating the resulting mixture and interactions; harmful effects are likely to have multiple impacts on local ecosystems, flora and fauna to various degrees. Likewise, the effects in the short, medium and long-term would be very difficult to accurately identify and measure; nevertheless, studies are required to evaluate their impacts, particularly in coastal wetlands and lagoons which act as natural sinks for pollutants.

It is very difficult to assess the impact of pollutants on the environment, species and communities as the contaminants have been diluted by the rain, snow melt and water currents since the event took place (Fig. 17.11). It should be highlighted, however, that even fairly low levels of chemical and hazardous compounds could cause severe toxic effects, particularly in the early stages of development and growth in organisms, resulting variations in behavioral patterns, biodiversity of composition and alterations in plankton and benthos communities.

17.6 Conclusions

As a result of the earthquake and tsunami of 2011, a total of 15,833 people lost their lives, in addition to 2,656 missing and 6,145 injured, totaling 18,489 casualties (NPAJ 2013). The economic impact on the country amounted to 17 trillion Yen or about US$ 221 billion, 10.4 trillion Yen (US$ 11 billion) of which consisted of damage to housing, offices and machinery, among others (RAJ 2012). The tsunami alone caused nearly 39 % of the total direct economic loss in Japan for 2011 (Daniell and Vervaeck 2011).

Industrial development has brought an enormous amount of wealth to Japan while also an enormous amount of hazardous and toxic compounds, posing dangerous ecosystem and health risk hazards. Moreover, as a country where wood is largely used for construction materials, its treatment may also add to environmental problems; less aggressive wood treatment construction methods such as the *Shou Sugi Ban* have disappeared as result of the development of the chemical industry. Ironically, this traditional method to preserve wood is highly regarded in stylish and modern architecture (Guralnick 2013).

Enormous amounts of mixed debris, including treated wood and deposits resulted from the 2011 tsunami destruction along Tohoku's coastline, requiring their removal and further treatment to ensure a sound recovery process and to comply with the reconstruction management cycle (JICA 2008). Concomitant to its accumulation, removal and cleanup of contaminated debris, as well as its treatment and proper handling should be enforced, while an assessment of the hazards to the environment and human health should be undertaken as part of the disaster management policy. Considering that a number of public works plan to recycle debris in projects such as coastal and river embankments restoration, agricultural field restoration, fishing port projects and disaster prevention forest restoration and parks (MOEJ 2013a, b, 2014), comprehensive environmental and health risk assessment would have been advisable prior to their implementation. Radiation may have further added to pollution problems in Miyagi and surrounding prefectures, complicating risk assessments of impacts on the environment from non-radioactive components.

The costs of contamination are likely to be enormous, both economically and environmentally. Exposure to radiation is more conspicuous in Fukushima prefecture, while in Miyagi devastation of industrial complexes can be found in many locations along its 850 km of Pacific coastline. The difficulty in obtaining an accurate estimate of the real environmental cost lies in the difficulty of identifying and measuring the effects of toxic and hazardous compounds from a variety of sources including the impact of chemically-treated wood debris on key ecosystems, fauna, flora and microorganisms, which in turn reflects the impossibility to evaluate the potential loss of ecosystem services unless thorough and comprehensive research is undertaken.

The assessment of the levels of accumulation and impact in the soil, fauna and flora, other debris and water bodies including groundwater is of upmost importance as contaminated materials may be used for building purposes while chemically tainted water sources for commercial, industrial or human consumption throughout the reconstruction process.[4]

Disasters like the Great East Pacific Earthquake and Tsunami of March, 2011 have brought tremendous economic and social losses, and unless accurate, comprehensive evaluations of environmental impacts of pollution and its costs in terms of ecosystem services and resource impacts are brought to center-stage, any plan for sound rebuilding and recovery is likely to fall far short of reality.

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[4]Although available information was not found while preparing the present Chapter, studies on the subject are likely to be ongoing by research institutions and the academia amongst others.

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Chapter 18
The Agri-Reconstruction Project and Rapeseed Project for Restoring Tsunami-Salt-Damaged Farmland After the GEJE – An Institutional Effort

Yutaka Nakai, Takeshi Nishio, Hiroyasu Kitashiba, Masami Nanzyo, Masanori Saito, Toyoaki Ito, Michiaki Omura, Miyuki Abe, and Yukie Ogushi

Abstract The Graduate School of Agricultural Science, Tohoku University, launched an Agri-Reconstruction Project in 2011 immediately after the March 11 Great East Japan Earthquake disaster, and this continues to date. The project's objective is to support the agricultural, forestry and fisheries reconstruction process in the tsunami disaster area. The activities have been implemented through more than 40 research projects along the Tohoku region including the Rapeseed Project for Restoring Tsunami-Salt-Damaged Farmland.

Immediately after the disaster, damaged farmlands were surveyed and salt-tolerant rapeseed varieties from Brassicaceae and related species were used to restore the soil. The plants came from the gene bank developed at the Graduate School of Agricultural Science, and were planted on damaged farmland in Sendai, Iwanuma and Higashi Matsushima cities. The varieties used to restore the soil depended on the specific damage.

As part of the project, the production and sale of edible as well as fuel oil obtained from rapeseed plants was organized in coordination with the Miyagi Prefecture Sendai City government, a number of private companies and other partners. This enterprise continues to date.

Besides using the salt-tolerant varieties of Brassicaceae plants in tsunami-damaged fields they are also used overseas in the rehabilitation of salt-damaged farmlands.

Keywords Great East Japan Earthquake • Tsunami • Reconstruction • Support • Rapeseed • Salt damage • Farmland • Biogas

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18.1 Background to the Establishment of the Project

Many lives were lost and horrendous damage was caused by the Great East Japan Earthquake and tsunami disaster of March 11, 2011. Severe losses were incurred at the Graduate School of Agricultural Science's Amamiya Campus in Sendai City. The Kawatabi Field Centre in Osaki City was also contaminated with radioactive material. Efforts to fully restore these facilities are ongoing (Saito 2011). The Onagawa Field Centre in Onagawa Town was also completely destroyed as the tsunami waves overwhelmed the two-storied building. The lack of fuel plus harsh weather conditions made it very difficult for researchers to work, but support for the local population and research activities soon began to take shape (Nakai 2013).

The Graduate School of Agricultural Science launched the Agri-Reconstruction Project in March 2011, soon after the disaster (Nakai 2011). Due to existing difficulties a relatively small number of experts participated during the first stages, expanding to a larger number as the project developed.

Following a request from the Sendai City authorities, an initial soil survey was undertaken at Arahama in Wakabayashi Ward, where the tsunami had completely destroyed the coastal village and its pine forest. Thereafter, Project members visited Higashi Matsushima City as well as the Graduate School of Agricultural Science Onagawa Field Center in Onagawa Town, where massive destruction occurred and a large number of people lost their lives.

Analysis of soil samples taken at Arahama were rapidly completed. After discussions, it was decided that the salt damage fields could be restored by washing the plow layer with water after removal of several centimeters of surface soil. This approach was welcomed by the local community and farmers. This in turn encouraged the local people to keep looking forward despite the difficulties.

18.2 The Agri-Reconstruction Project

The project is based at the Graduate School of Agricultural Science in a consortium-like group of independent researchers. The project leader and the management group provide guidance and coordination support related to the restoration activities by (1) providing support and experts upon request, (2) providing support for new ideas and activities of individual researchers, (3) summarizing research achievements, and (4) providing information to the disaster-affected areas.

By March 2012, 37 individual research topics were being carried out at the Graduate School of Agricultural Science (Table 18.1). Thirteen reports have been published so far (http://www.agri.tohoku.ac.jp/agri-revival/).

A large number of project activities have been carried out in close cooperation with local residents. Among these is the Project to Support the Restoration of Japanese Oyster Farming, where Tohoku University acted in a coordinating role between industry and the government. The institution took charge of the analysis

Table 18.1 Main contents of the 37 individual research topics being carried out at the Graduate School of Agricultural Science in March 2012

Field	No. of projects	Main content
Agriculture and forestry	15	Soil surveys for salt damage and pollution by radioactive substances, rapeseed, soil washing (flushing), surveys of damage to coastal forests and windbreak forests, forestry restoration, and environmental impacts
Livestock production	4	Research on feed rice contaminated by radioactive cesium, protection and radiation dose survey of cattle within the 20 km zone from the nuclear accident site, and infection by soil-originating bacteria
Marine products industries	15	Research on the restoration of Japanese oyster culture farming, subsurface surveys, plankton, *arame* [*Eisenia bicyclis*] and other species
Education and urban restoration	3	Community support, regional revival, and support for high school education

and well-being of oysters seeds and succeeded in restoring the devastated oyster seed production in a very short time. This activity indicated the pivotal role institutions can perform in the industry-government-academia complex relationship. Another important activity was the Project to Protect Cattle Remaining within the Fukushima Nuclear Power Station 20 km Evacuation Zone. This project ensured that the status of the livestock remaining in the Evacuation Zone will be publicized and also considers activities for temporarily impounding the cattle to divert them from experimental or exhibition purposes.

The Rapeseed Project for Restoring Tsunami-Salt-Damaged Farmland became the foremost project of the institution supporting the restoration of damaged lands and restoring agricultural activities.

18.3 Rapeseed Project for Restoring Tsunami-Salt-Damaged Farmland

18.3.1 Project Activities

The Graduate School of Agricultural Science is a leading research institution in Japan in the field of genome sequencing of Brassicaceae plants and holds a renowned gene bank of phyletic lines specializing in Brassicaceae-related plants.[1]

Brassicaceae related species include *Raphanus* (radish), *Capsella* (shepherd's purse), *Eutrema* (Japanese horseradish) and others. The genus *Brassica* alone

[1] Over the last 50 years the gene bank has sampled and managed roughly 800 phyletic lines from 177 species in 58 genera, gathered from research institutions and so on overseas.

includes *B. juncea* (mustard, mustard greens, Sichuan vegetable (*zha cai*), *B. oleracea* (cabbage, cauliflower, Brussels sprouts and others), *B. napus* (rapeseed) and *B. rapa* (Chinese cabbage, turnips, Japanese mustard spinach (*komatsuna*), potherb mustard (*mizuna*) and others) (Table 18.2).

The soil restoration team group included soil and cultivation specialists as well as specialists in the life cycle assessment of energy production (Rapeseed Project for Restoring Tsunami-Salt-Damaged Farmland: http://www.nanohana-tohoku.com/).

Soon after the disaster, the Japan Science and Technology Agency (JST) called for project proposals under the Support Program for Emergency R&D Achievements and Responses to the Great East Japan Earthquake Disaster. This prompted the action by the Graduate School based on the fact that 10,000 ha (revised later to 14,300 ha) of wet rice fields had been damaged in Miyagi Prefecture alone. A damage survey of wet rice fields in Wakabayashi Ward (Sendai City) was undertaken in collaboration with the Sendai City municipal government. The survey showed that

Table 18.2 Representative examples of Brassicaceae plants

Genus	Species	Variety
Brassica	*B. rapa*	*chinensis (pak choi), japonica (mizuna), olerifera (rapeseed), pekinensis (Chinese cabbage), perviridis (komatsuna), rapa (turnip), etc.*
	B. oteracea	*acephala (kale), alboglabra (Chinese kale), botorytis (cauliflower), capitata (cabbage), gemmifera (Brussels sprout), italica (broccoli) etc.*
	B. nigra	
	B. napus	*napobrassica (rutabaga), napus (rapeseed)*
	B. juncea	*cernua (mustard), integrifolia, tumida (Sichuan vegetable)*
	B. carinata	
Arabidopsis	*A. thaliana*	
	A. lyrata	
Raphanus	*R. sativus* (radish)	
	R. raphanistrum	
Sinapis	*S. alba*	
	S. arvensis	
Alyssum, Capsella, Cardamine, Diplotaxis, Draba, Eruca, Erucastum, Eutrema (Japanese horseradish), *Iberis, Lepidium, Matthiola, Moricandia, Nasturtium, Orychophragmus, Rorippa, Thlaspi, etc.*		

the pine coastal forest had been leveled to the ground and the rice fields engulfed in mud, thus requiring restoration.

Prior to the submission of the project proposal to the JST, a number of surveys were implemented in coordination with Miyagi Prefectural research institutes, the agricultural technology extension office, farmer's cooperative staff and other partners.

The project objectives included soil surveys of the affected farmlands and selection of Brassicaceae plants suitable for the level of salt damage. Moreover, it included sowing these seeds on the damaged land, planting yellow rapeseed flowers to improve the landscape and to symbolize the agricultural revival and eco-energy development. Oil was obtained from the harvested rapeseed to produce biodiesel fuel. This fuel is used to operate machinery for the restoration of the affected areas, and run school buses for children living in disaster-stricken communities (Nakai 2012).

It was considered that the construction of a regional autonomous energy supply system making use of rapeseed would play a useful role in the restoration of the disaster-affected areas (Fig. 18.1).

As a complementary objective, it was hoped that through the cultivation of rapeseed local farmers would be encouraged to resume farming at the earliest possible time, as this would lead on to the revival of the farming economy.

To implement the project, the affected farmland in Miyagi Prefecture was divided up into a 1 km^2 mesh. Soil surveys were then carried out at 344 locations. Cultivation tests conducted using Brassicaceae plants showed that the seeds were unable to germinate in the tsunami mud layer. Transplanted seedlings also withered and died.

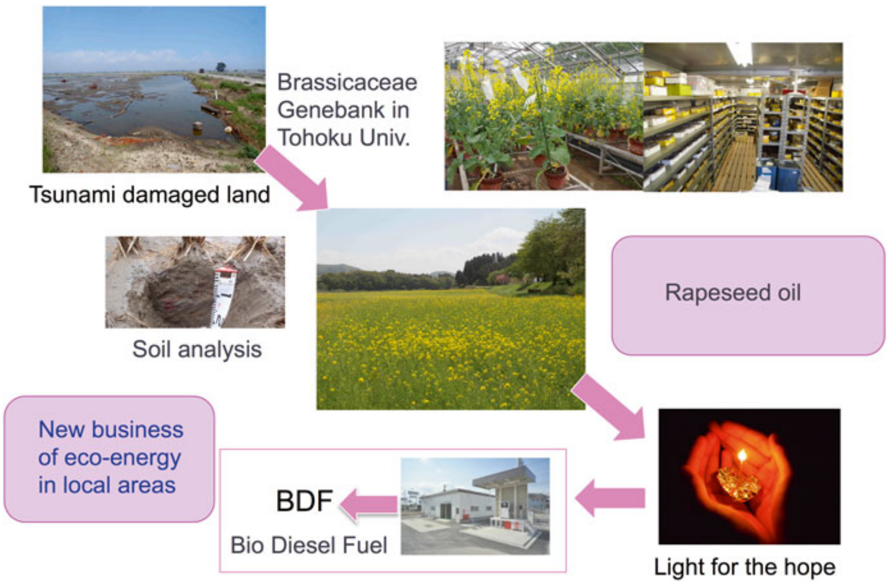

Fig. 18.1 Concepts of rapeseed (Nano-hana) project for restoring tsunami-salt-damaged farmland

However, it was found possible for these plants to grow in the plow layer below the tsunami mud.

The Graduate School of Agricultural Science selected 56 lines of *B. napus* and 36 lines of *B. juncea* to test for differences in their salt tolerance through cultivation trials. The trials were performed in soil with differing levels of common salt concentrations to discover plant lines whose growth was least suppressed in comparison with control plot soil (no added salt). As a result, four lines of *B. napus*, two lines of *B. juncea* and one line of *hamadaikon* (*Raphanus sativus* var. *raphanistroides*) were selected as salt-tolerant lines. These were planted out on the cultivation trial farmland (Fig. 18.2). The cultivation trials were carried out at three locations: (1) an affected upland field (roughly 0.07 ha at the Sendai City Agricultural and Horticultural Center), (2) an affected paddy rice field (roughly 0.4 ha at Arai, Sendai City), (3) on farmland dedicated to the production of commercial edible vegetable rapeseed or rapeseed plants (roughly 1.4 ha in Iwanuma City and 0.9 ha at Shichiga-hama District). Water was drained from the wet rice fields and the fields furrowed for protection purposes.

In collaboration with volunteers, weeding and removal of the mud layer deposited by the tsunami were performed on 0.2 ha of tsunami-affected fields with the purpose of cultivating ordinary, non-salt-tolerant, species. Salt-tolerant species were cultivated in experimental plowed plots without removing the tsunami-mud deposit (Fig. 18.3).

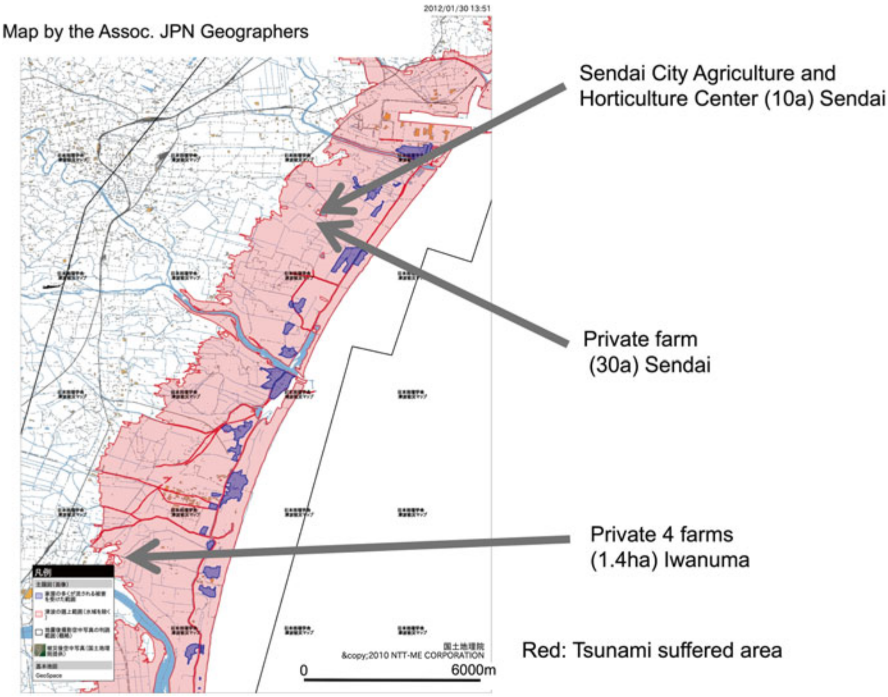

Fig. 18.2 Field trials of cultivation of rapeseeds on tsunami damaged farmlands

Fig. 18.3 Removal of weeds and the mud layer deposited by the tsunami supported by 120 volunteers; 30th July 2011. Wakabayashi Ward, Sendai City (Source Photo: Shusei Yamada)

Typhoons flooded the rice fields at the end of September. Thus drainage was greatly delayed by damage to the drainage channels and drainage pumps. However, it was later possible to sow rape plants. These showed good growth in paddy fields, unaffected by the salt levels (Fig. 18.4).

An unforeseen event occurred when a trial field was badly damaged by the presence of migratory wild swans, which completely devoured the leaves. Although Brassicaceae plants are rarely damaged by birds, it is thought that the birds fed on the plants due to the unavailability of unharvested grains and other type of food.

The rapeseed restoration project has been implemented with the support of a large number of cooperating institutions, authorities and companies (Table 18.3). Produced rapeseed was sold as food, edible oil and biodiesel fuel (BDF). Support was also obtained from group members who devised specific methods for the sale of rapeseed oil and BDF, and from students and companies that designed events for the cultivation of rapeseed plants. This project began from the desire to assist farmers, but exceeded the framework of the coordination between the institutions and farmers to involve large numbers of people and reveal an extensive social component.

By the winter of 2012 a total of 2.67 ha of land had been cultivated with a yield of 2–4 t per ha. A total of roughly 4.5 t of rapeseed was harvested, and 63 l of edible oil was bottled. With the exception of seed for sowing, oil was pressed from the remaining seed to produce approximately 4 t of BDF.

The hope for restoration of damaged fields was symbolized by the blooming of the rapeseed plants beside the Iwanuma expressway interchange. The *Kizakinonatane* (*kizaki* rapeseed) that was almost completely eaten by the swans also bolted in the

Fig. 18.4 Mustard and rapeseed showed well growth in the damaged paddy field (10th December 2011; Wakabayashi Ward, Sendai City. Source Photo: Yutaka Nakai)

Table 18.3 Support received from partner organizations cooperating with the rapeseed restoration project

Partner organization	Type of support
Miyagi Prefecture	Soil surveys
Sendai City	Demonstration trials
Chida Cleaning, Ltd.	Demonstration trials and BDF production
EAC Corporation	Soil surveys and others
Miyaka Co., Ltd.	Demonstration trials, rapeseed vegetable sales
Local farmers	Demonstration trials: Arai, Wakabayashi Ward and Oshiwake, Iwanuma City
Kinari Inc.	Donations from the sale of eco-bags
Kureha Corporation	Donations from the sales of wrapping films and others
Kirin Co., Ltd.	Donations from beer sale and others

spring, and although the stems were short, the field was filled with yellow flowers.[2] Harvested before full bloom, the *kizakinonatane* sold well as edible vegetable rapeseed, and a food preparation method was developed for the plant. A technique was devised for manufacturing preserved flowers from pre-flowering Brassicaceae

[2] One of the project's major achievements was a comment by a neighboring farmer, who stated, "Despite the almost total devastation, I was greatly encouraged by the rapeseed flowers that sprang up strongly, just as we have done."

plants and the experimental production of solid candles and soap from rapeseed oil was also carried out.

Considering the results of this project, the following activities have been planned. It is thought that these activities will be carried out over about the next 10 years:

1. To analyze the mechanisms and genes involved in the breeding of salt-tolerant Brassicaceae plants.
2. To establish methods for the stable production of Brassicaceae plants and a cultivation system for soil improvement in the affected farmlands.
3. To establish sales methods for rapeseed oil as BDF and edible oil.
4. To construct a local-production-for-local-consumption energy system for BDF production and so on from rapeseed oil.

18.3.2 Synopsis of the Specific Project Activities

18.3.2.1 Soil Surveys of the Farmland Affected by the Tsunami

From March 2011, immediately after the earthquake disaster, a detailed and wide-ranging soil survey covering the entire 14,300 ha of tsunami-affected farmland in Miyagi Prefecture was carried out in coordination with Miyagi Prefectural research institutes, the agricultural technology extension office, farmer's cooperative staff and other partners. Three hundred and forty four locations were selected for the survey (Nanzyo 2013). There were significant differences in the damage from region to region. In some places, the soil surface had been covered to a depth of 10 cm by a tsunami deposit consisting of mud (Fig. 18.5), while in others the plow layer was covered in a thick deposit of sand. In other places, the topsoil had been washed away, making a revival of agriculture impossible without soil dressing. There were places where the land had simply been immersed in seawater and could not be recovered without salt removal. There were also places where the windbreak forest had been uprooted and the roof tiles of houses had been scattered over the land. It was clear that the farmland restoration method would differ according to the type of damage found in each area. Soil analyses were performed in detail with reference to the vertical distribution of salt. Salt removal projects have been carried out during the 2 years thus far, but it has been confirmed that the following issues still remain (Ito 2013; Ito and Kanno 2012).

1. In fields where salt removal has been completed, sodium adsorbed by the soil particles still remains and the concentration of bioavailable calcium is reduced (Fig. 18.6).
2. The mud deposited by the tsunami contains a high concentration of salt. According to our research on tsunami-muds distributed in northern part of Miyagi prefecture (Shima et al. 2012), they showed the electric conductivity of 3.5–24.9 as the averaged values of the three areas, measured by water to mud ratio of 5. The values of electric conductivity are very high compared to the critical

Fig. 18.5 Paddy fields covered by tsunami-deposit (mud). Paddy fields located near the branch of the Kitakami River were covered to a depth of 10 cm by tsunami deposit. The clayey muddy materials are cracked after drying out. Ishinomaki City, Miyagi prefecture; 11th May 2011 (Source Photo: Takehiko Yamamoto)

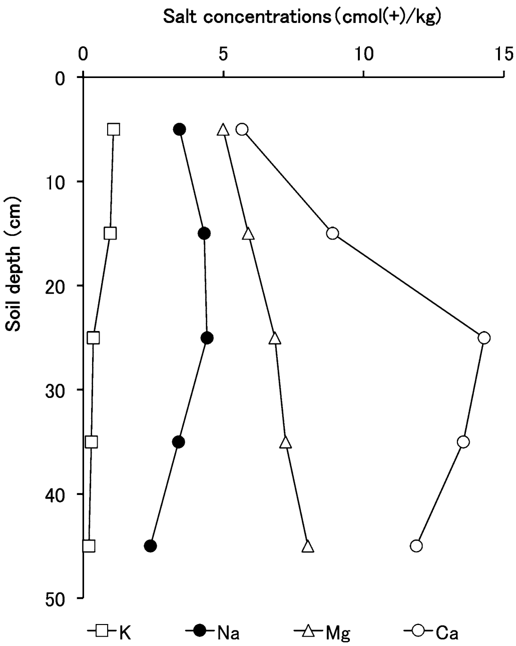

Fig. 18.6 Salt distribution in the tsunami-affected soil after salt removal operation. The figure shows concentrations of salts in the tsunami-affected paddy soil collected in Ishinomaki City on 12th April 2012, 2 years after a salt removal operation. The salt concentrations are the mean sum of water-soluble bases and bases adsorbed by soils. Even after salt removal operations, sodium, toxic to crops, still remains in the soil. On the other hand, calcium is reduced in the surface soil layers

value (0.5) that can induce salt injury to rice plant. If this were simply abandoned in the environment, tsunami deposit having a high salt concentration would damage rice plants due to salt injury as the tsunami deposit was heavily mixed into the soil.

3. The mud deposited by the tsunami contains a high concentration of sulfide. If tsunami-deposited mud containing large amounts of sulfides (iron sulfide, iron disulfide) is incorporated into the farmland soil, there is a possibility of acidification problems occurring on upland soils due to sulfuric acid being formed as the oxidation product of the sulfides. For example, plow layer soil showed strongly acidic (pH 3.8) after 5 cm of tsunami-mud was incorporated into the soil in Soma City, northern Fukushima (Inagaki et al. 2012). Paddy rice root injury may also occur due to hydrogen sulfide formed in the reduced condition.
4. Restoration methods for fields where the topsoil has been washed away will need to be carried out with due care. When poor soils are dressed into the fields, considerable time may be taken to recover good soils with high productivity.

We intend to continue the research for resolving these problems in the future (Kitamura et al. 2012).

18.3.2.2 Salt Tolerance Experiments with Brassicaceae Plant Crops

Lines showing strong salt tolerance were selected from among the *B. napus* and *B. juncea* genetic resources held by the Graduate School of Agricultural Science. The dry weight ratio after salt treatment cultivation and an index of the cumulative dry weight ratio were used to evaluate the degree of salt tolerance. Of 38 lines of *B. napus* examined, five lines exhibited relatively strong salt tolerance, as did four lines of the 28 *B. juncea* lines examined. Excerpts from the data are shown in Table 18.4 (Nasu et al. 2012).

The amount of sodium absorbed from the upper layer of the soil was then determined. Regardless of the degree of the salt tolerance, the Na concentration per unit dry-weight increased as the treated salt concentration rose. No significant difference between the lines was observed for Na concentration at equivalent salt treatment concentrations (Table 18.5). Nevertheless, a trend of increased Na accumulation per plant was seen in strongly salt-tolerant lines of both *B. napus* and *B. juncea* when compared with weakly salt-tolerant lines. Strongly salt-tolerant lines of both *B. napus* and *B. juncea* accumulated 1.5–2 times more Na than weakly salt-tolerant lines. This lead us to believe that a certain degree of salt-removal effect could be expected from the strongly salt-tolerant lines.

18.3.2.3 Cultivation Trials on Salt-Damaged Farmland

In early October 2011, the growth, yields and so on of the *B. napus* and *B. juncea* that had been planted on affected wet rice fields (Arai, Wakabayashi Ward) and affected upland fields (Sendai City Agricultural and Horticultural Center) were

Table 18.4 Dry weight of aerial parts of plants cultured with liquid media containing 50, 100 and 200 mM NaCl

	50 mM	100 mM		200 mM	
Lines	Dry-weight ratio[a]	Dry-weight ratio	CRI[b](100)	Dry-weight ratio	CRI(200)
Brassica napus					
N-343	0.98	0.96	1.94	0.90	2.84
N-127	1.10	1.04	2.14	0.69	2.83
Westar	0.95	0.83	1.78	0.67	2.45
N-503	0.89	0.78	1.67	0.47	2.14
N-119	0.89	0.75	1.63	0.48	2.12
Kizakinonatane	0.57	0.66	1.23	0.41	1.64
Kirariboshi	0.61	0.54	1.15	0.41	1.57
Brassica juncea					
J-105	1.03	0.88	1.91	0.49	2.40
C-639	0.97	0.61	1.57	0.36	1.93
J-130	0.70	0.66	1.37	0.57	1.93
J-138	0.72	0.69	1.42	0.43	1.84
J-601	0.57	0.48	1.05	0.21	1.26

[a]The average of dry-weight (n = 3 to 6) in each salt-treatment was divided by the average at 0 mM
[b]CRI (cumulative ratio index) represents a cumulative value of dry-weight ratios

Table 18.5 Na uptake (mg/g•dw) in salinity-tolerant and salinity-sensitive lines

	0 mM	50 mM	100 mM	200 mM
N-119	11.3	30.8	44.1	53.2
Kizakinonatane	9.1	25.3	26.8	46.9
Kirariboshi	9.1	33.5	45.9	47.6
J-105	5.3	32.8	50.8	58.8
J-601	5.5	31.3	36.0	54.5

surveyed. A part of the *B. juncea* had died due to damage from cold and snow. The *B. napus* cultivated in the affected wet rice fields had been damaged due to feeding by swans, but had resumed good growth in early spring. This crop approached harvesting in mid-June to July.

Here we indicate a part of the data on comparative results of plant length and yields obtained in the experimental cultivation plots (control upland field, affected upland field, affected wet rice field) for each of the *B. napus* lines. The data for the control upland field plot in the experimental fields of the Graduate School of Agricultural Science, the affected upland field plot at Sendai City Agricultural and Horticultural Center, and the affected wet rice field plot at wet rice fields at Arai, Wakabayashi Ward, Sendai City are experimental results, and the "Tohoku Agricultural Research Center" data are values from papers by the Tohoku Agricultural Research Center.

Table 18.6 Plant height, yield of seeds and weight of a thousand seeds of the *B napus* lines

	Control	Salt-damaged farmland	Salt-damaged paddy filed	Standard field
Plant height (cm)				
N-119	168.9	163.9	144.7	
Kizakinonatane	192.1	165.0	152.0	143–155
Yield of seeds (t/ha)				
N-119	4.2	4.3	3.2	
Kizakinonatane	7.4	5.5	5.8	3.5–4.1
Weight of a thousand seeds (g)				
N-119	4.2	4.7	4.9	
Kizakinonatane	3.8	4.2	3.6	4.3

Control: Graduate School of Agricultural Science/Faculty of Agriculture, Tohoku University; Salt-damaged farmland: Sendai City Agricultural and Horticultural Center; Salt-damaged paddy filed: Wakabayashi Ward in Sendai City. Standard Field: Average of 5 years data at normal farmland Of Tohoku Agricultural Centre (Ishida et al. 2007)

All lines indicated a trend for reduction of plant length due to salt damage. Although yields (t/ha) showed a tendency to be reduced, no statistically significant difference was seen between the trial plots (Table 18.6). Measured by thousand kernel weight, N-119 showed absolutely no sign of impact from salt damage. The values for *Kizakinonatane* in the affected upland field and affected wet rice field are almost equivalent to the values (Ishida et al. 2007) reported by the Tohoku Agricultural Research Center, showing that sufficient growth and seed harvest could be expected even on farmland affected by the tsunami.

B. juncea lines judged by the pot experiments to be strongly salt tolerant showed dramatically reduced yields in both the affected upland field plot and affected wet rice field plot. Considering seed yields based on the trial cultivations, *B. napus* is appropriate for salt-damaged farmland. It was believed that approximately standard harvests could be expected from the cultivation of either the salt-tolerant N-119 or *Kizakinonatane* on farmland in the vicinity of the trial plots.

It was also found from these trial cultivations that *B. napus* can easily adapt to the climate in the area around Sendai City. At the same time, it was discovered that the *B. juncea* lines used in the experiments could not be expected to give sufficient seed yields, perhaps due to snow damage and other reasons.

18.3.2.4 Elucidation of the Salt Tolerance Mechanism

Plants have protective mechanisms that act against environmental stresses such as salinity, low temperature and aridity. These mechanisms work through genes that come into play to provide stress tolerance (Chinnusamy et al. 2004). Several such genes are already known with respect to Brassicaceae plants. The variation in gene expression between the strongly salt tolerant *B. napus* N-119 and the weakly salt tolerant *kirariboshi* was examined. When treatment with a high salt concentration was carried out, it was found that both lines show a rapid increase in the gene expression for LEA (Late Embryogenesis Abundant) protein (Dalal et al. 2009), but with the expression level of N-119 being seven times higher than that of *kirariboshi*. N-119 might excel in the induced ability to protect other proteins from osmotic damage. At present, a wide range of genes that alter their expression under saline stress are being surveyed in an attempt to comprehend other factors that may determine differences between lines.

18.3.2.5 Development of Strongly Salt-Tolerant *B. napus* Lines

Based on the results of the pot experiments for salt tolerance, intercrossing was carried out between strongly salt-tolerant lines in spring 2012 to obtain the F_1 generation. This F_1 generation is currently being grown out and it is expected that the seeds of the F_2 generation (the following generation) will be harvested in 2013. The existence of individual plants showing even stronger salt tolerance is anticipated in the F_2 generation. We believe that it will be possible to perform the actual selection of lines in the following season, after consideration of the assessment method for salt tolerance.

18.4 A Regional Resource Recycling System with an Added Biogasification of Organic Materials

Rapeseed oil can be used as the raw material for BDF, either directly or after use as edible oil (so-called waste vegetable oil, WVO). When BDF is produced, waste glycerin is also generated as a by-product. We attempted to retrieve energy through the methane fermentation (anaerobic digestion) of this waste glycerin (Nakai et al. 2012).

Treated effluent sludge from a food products factory was placed in a 50 t methane fermentation tank once each week. The amount of added waste glycerin required for the efficient production of methane gas was examined by pouring in a certain amount of waste glycerin once per day.

The upper limit possible for the amount of waste glycerin added per day for stable and continuous operation was 0.1 %/day (a rate of addition of 0.1 % (v/v) per day with respect to the volume of the fermentation liquid).

As a result of this research (Baba et al. 2013), by the addition of 30 l of waste glycerin per day to the 30 m^3 of fermentation liquid, it was possible to obtain a total monthly production of methane of roughly 140 m^3. This is equivalent to the volume of town gas used monthly by 16 ordinary households. The energy (methane gas) produced in this way exceeded the energy consumed in operating the fermentation tank. Converting this surplus energy obtained into the distance over which a vacuum car can be operated, it was found to be equivalent to sufficient energy to operate the vacuum car for approximately 1,200 km. Transporting the sludge and digested sludge within these limits would result is a positive energy balance (energy generated/energy consumed). The economics of retrieving the produced methane gas for power generation or exhaust heat recovery was also positive, and the cost of diesel fuel capable of operating the vacuum car for an annual distance of 1,900 km was obtained as surplus funds.

When the value of the digested sludge remaining after methane fermentation of the waste glycerin as fertilizer was examined, a fertilizer application effect of 1.2 times was confirmed in comparison with non-application of fertilizer.

In the future, we anticipate the construction of a resource recycling system consisting of rapeseed oil → BDF → waste glycerin → digestive liquid remaining from methane fermentation → cultivation of rapeseed.

18.5 The Future of the Rapeseed Project

In June 2013, all of the 194 tsunami-affected areas planned for the collective relocation of local residents by Miyagi Prefecture received government approval. The aim is to complete land improvements by FY2015, and although collective relocation alone does not resolve all the issues, a pathway has opened up towards the reconstruction of the daily lives of the people affected by the disaster. At the same time, with regard to farmland, of 2,700 ha of affected farmland in Sendai City, agricultural work resumed on 500 ha in FY2012. Agricultural production is scheduled to resume on 900 ha in FY2013, and 400 ha in FY2014 (Sendai City 2013).

Of the 251 strawberry farmers in Watari District, 232 were affected by the tsunami. At present seedling nurseries and vinyl cultivation houses covering a total area of roughly 70 ha are under construction in three locations is the district. A “strawberry estate” is expected to be completed by the summer of 2013 at a total project cost of 11 billion yen. With farmers expanding to larger scale production regimes, and under the banner of conversion to the Sextiary Sector (fusion of the primary, secondary and tertiary industries), the area surrounding Sendai City gives a sense of the rapid progression of reconstruction projects, while the resumption of agriculture in Iwate Prefecture and Fukushima Prefecture is only just beginning.

The Graduate School of Agricultural Science project is supporting the cultivation of rapeseed in upland fields in Ofunato City, Iwate Prefecture, and also in flower beds that have been affected by the tsunami along the coastal National Route 45. In Minamisoma City, affected by both tsunami salt damage and pollution by radioactive substances, the institution is also providing seeds, performing trial cultivation on farmland polluted by radioactive substances, and field work with the objective of assessing the migration of radioactive substances to the plant body and seeds. This is particularly important in Minamisoma and other areas, where the production of food is problematical on farmland contaminated with a high concentration of radioactive substances. The cultivation of *B. napus* for the production of BDF is thought to be effective in this case.

A survey was conducted on the production of rapeseed in 2011 by the Fukushima Agricultural Technology Centre. This survey also covered rapeseed that was sown in the fall of the year prior to the Fukushima Daiichi Nuclear Power Station accident. The seeds were studied between the end of June and the beginning of July 2011 (Crop Horticulture Department of Fukushima Agricultural Technology Center 2011).

The survey showed that rapeseed leaves growing at the time of the accident were contaminated by the nuclear fallout. Likewise, radioactivity exceeding the provisional standard (500 Bq/Technology) at that time was detected in the seeds.

It has been reported that when seeds containing 667.4 Bq/kg of radiation were mechanically pressed to obtain the oil, the level of radioactive cesium in the oil was 3.63 Bq/kg, indicating that almost none of the radioactive cesium in the seeds migrated to the pressed oil. Nevertheless, it will be necessary to accumulate further data through field work to ascertain the amount of radioactive cesium absorbed from the soil and the amount of radioactive cesium contained in the rapeseed oil produced from the seed. However, since the amounts of radioactive cesium remaining in the BDF manufactured from the rapeseed oil are extremely small, it is thought that the BDF can be used as vehicle fuel in the local area.

In the future, rapeseed will not only be cultivated on farmland where salt removal operations have not yet begun, but will be put to use in accordance with the actual situation in each area. This would include, for instance, the production of oil in order to build up a regional energy self-sufficiency system. In locations which have been polluted by radioactive substances, the cultivation of rapeseed may also be carried out as a raw material for the production of BDF (Fig. 18.7).

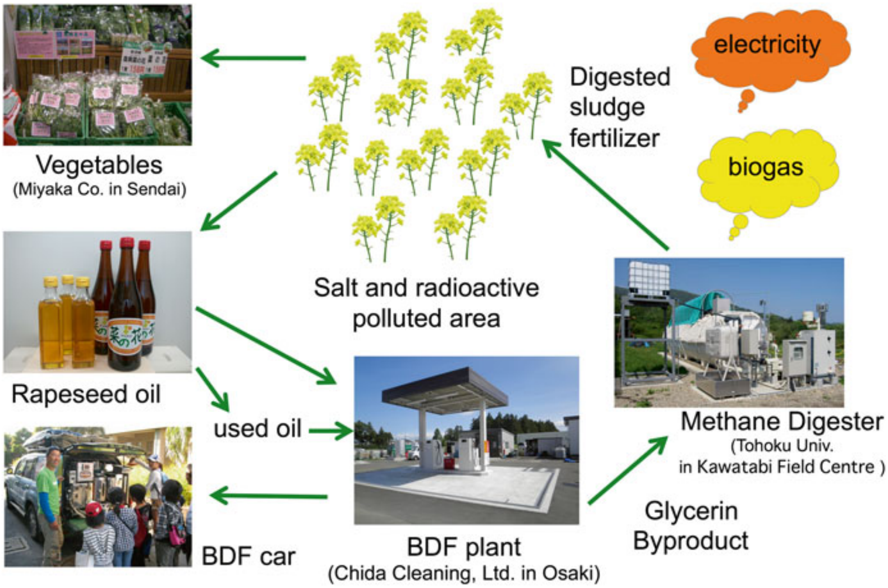

Fig. 18.7 Restoration of agriculture and production of eco-energy by rapeseed

For the Rapeseed Project, as well as carrying out support for these activities, the institution plans to continue breeding research such that salt-tolerant *B. napus* will find uses not only on farmland within Japan, but in all locations in the world where salt damage has occurred.

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Chapter 19
Observations of Natural Recruitment and Human Attempts at Mangrove Rehabilitation After Seismic (Tsunami and Earthquake) Events in Simeulue Island and Singkil Lagoon, Aceh, Indonesia

Ben Brown, Woro Yuniati, Rio Ahmad, and Iona Soulsby

Abstract The December, 2004 tsunami and March 2005 earthquake along the Sunda Megathrust off the Western Coast of Aceh, Sumatra, Indonesia not only resulted in catastrophic losses of life and livelihood, but also changed the very shape of the land and coast. The effects of this rapid change in coastal geomorphology are well expressed in a pair of locations, the remote Island of Simeulue, relatively unknown even in Indonesia before the tsunami, and the district of Singkil, which includes a mainland section as well as the *Banyak* (Many) Islands. Simeulue and Singkil effectively straddle the Sunda Megathrust, yet experienced the cumulative effects of the tsunami and earthquakes differently, with Simeulue Island undergoing seismic uplift while coastal mainland Singkil subsided. After the seismic events, at least 163 separate institutions (government agencies, local and international non-governmental organizations) planned and implemented mangrove rehabilitation activities in Aceh, including over a dozen in Simeulue and Singkil districts. (Brown and Yuniati 2008) Despite a great deal of commitment from such organizations to bringing back mangroves in the affected areas, the majority of the rehabilitation attempts, which mainly relied on hand planting methods, failed to restore mangrove forests. All the while, mangroves were naturally recruiting seismically repositioned intertidal surfaces, and growing well. Near to total mortality was observed in 6 out of 7 planting sites in the two districts, while recruitment rates, stem densities and species diversity in nearby intertidal zones indicated that natural recovery was well underway. When comparing

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the "success" of natural recovery versus planted sites, we see that practitioners are still faced with significant challenges. This paper makes the case that observation and monitoring of natural regeneration, and calculation of rates of recruitment after a major disturbance event is equally or more important than mangrove planting, from not only ecological but also social and economic points of view.

Keywords Natural revegetation • Post-tsunami • Rehabilitation • Mangrove

19.1 Background: The Impact of Aceh's Seismic Events (Earthquake and Tsunami) on Mangrove Populations

19.1.1 Simeulue District

The Sunda Megathrust occurs along the Western Coast of Sumatra, and extends northwards to Myanmar and Southeast along the Southern coast of Java and Bali, terminating near Australia. It is a volatile region, as it represents the interface between the overriding Eurasian plate and the subducting Indo-Australian plate (Briggs et al. 2006). Numerous large seismic events have occurred along this megathrust, including the eruption of Krakatau, and the 2004 tsunami which claimed over 225,000 lives. (Chlieh et al. 2007).

By reading the corals, much like foresters read tree-rings in temperate latitudes; researchers have been able to tell that major seismic uplift has occurred in 1370, 1600, 1797 and 1833, meaning this occurrence of tectonic emergence is cyclical (Briggs et al. 2006). Subsidence after uplift events occurs in each instance as the Indian Ocean plate sinks and curves under the land mass of Sumatra. This submergence takes somewhere between 75 and 150 years to return the islands to their pre-earthquake position, after which the spring is again loaded and the plate ready for another large earthquake (Briggs et al. 2006).

Prior to the 2004–2005 seismic events, mangrove distribution on Simeulue island occurred nearly entirely along the northern coast of the island, which is protected from the strong waves and currents experienced on the southern coast (Fig. 19.1). As a result of the March 2005 earthquake, the island rose on average 100–150 cm on the Eastern and Western ends, and around 25–75 cm along the central portion (Fig. 19.2). The entire annual tidal range of Simeulue Island, from Lowest Gravitational Tide (LGT) to Highest Gravitational Tide (HGT) is only roughly 78 cm. Approximately 24 species of mangroves have been identified on the island, all of which must exist within that limited tidal range. In fact, the extent of their habitat is narrower still, as they exist only from around Mean Sea Level (MSL) up to HGT, or about 38 cm above LGT up to 78 cm above LGT. The author obtained data points for uplift around the Simueule island, as well as recent tidal data directly from Sieh K (2013, California Institute of Technology (USA), personal communication), enabling the understanding of mangrove re-establishment.

Along the NE and NW coasts of Simeulue, the mangroves as a system were lifted completely out of the intertidal zone in which they must live. A new intertidal zone was

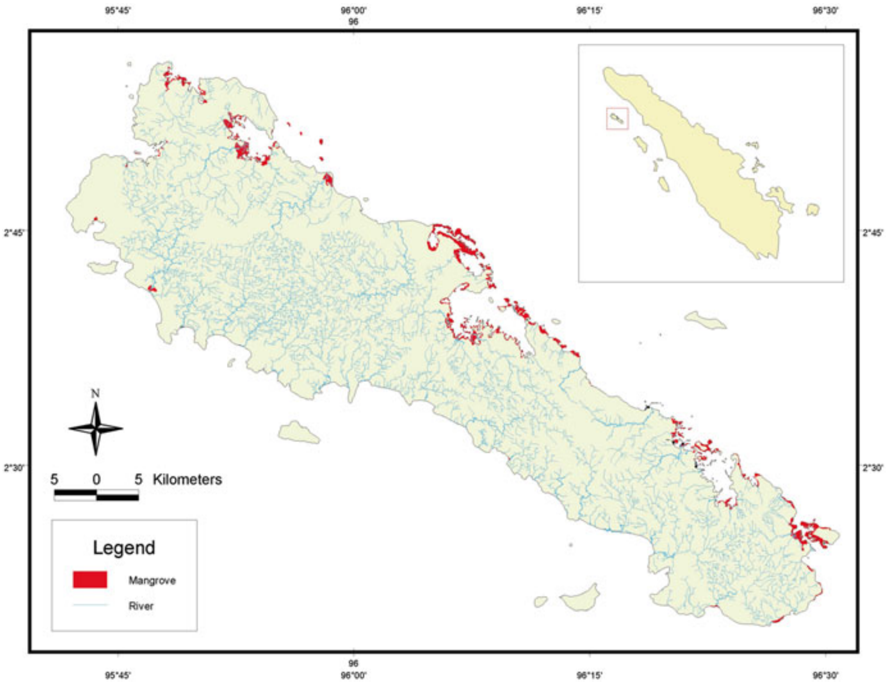

Fig. 19.1 Pretsunami mangroves distribution in Simeulue island (Source: Blue Forests)

formed, in essence, further out to sea. In order for mangrove forests to continue to exist in Eastern and Western Simeulue, their propagules (mangrove fruits and seeds) needed to colonize the new intertidal zone, establish themselves and grow. In NE and NW Simeulue, this process was arduous at first, as the majority of adult trees had been uplifted and began to die. They died both due to desiccation and also due to intense competition with terrestrial vegetation more suited to this new uplifted environment (Fig. 19.3). Only a relatively small number of adult mangrove survived, those which occurred either very low in the tidal profile, near MSL, or those situated directly adjacent to river mouths and tidal creeks. This differed from the North Central coast of Simeulue, in the area known as Teluk Dalam (deep bay). Here a significant number of adult mangroves persisted, as the amount of seismic uplift was less than the tidal range (Fig. 19.3). These adult tress continued to produce and disperse propagules, and, initially, the newly uplifted intertidal zone was colonized at a much higher rate than NE or NW Simeulue.

19.1.2 Singkil District

Whereas Simeulue Island was uplifted between 25 and 150 cm, mainland Singkil experienced seismic subsidence of between 25 and 50 cm. When mangroves are submerged or flooded for an extended period, they succumb to high levels of H_2S in the soil (a by-product of anaerobic respiration). Different species of mangroves,

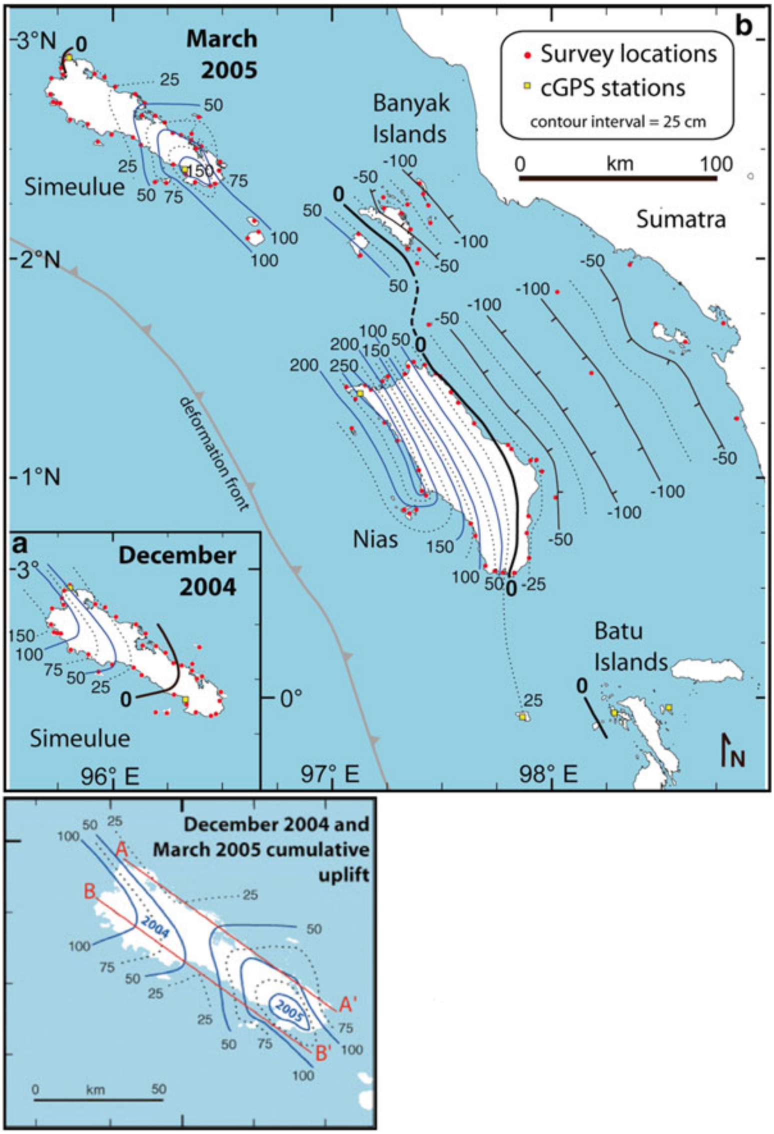

Fig. 19.2 Vertical deformation contour map of Banyak islands after the 2004 and 2005 earthquakes. The zero value (0) line indicates the uplift while the lines on the *right* subsidence (Briggs et al. 2006). The saddle shape uplift in Simeulue island shown on the *right* meant that mangroves on NE and NW coast where lifted entirely out of the intertidal zone, while mangroves in the north central bay (Telum Dalam) largely survived as they were not displaced far from the original intertidal position (Source: Briggs et al. 2006)

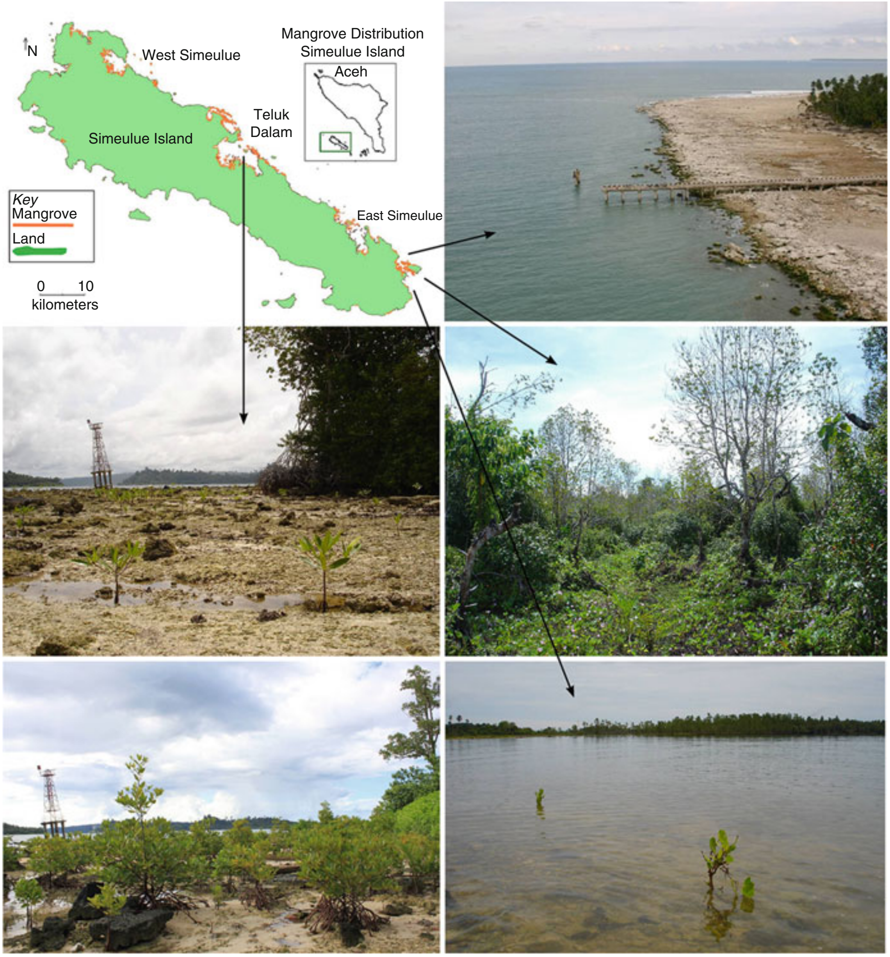

Fig. 19.3 The mangroves in Teluk Dalam, north central Simeulue island have already reached a coverage of 2,268 stems per hectare due to the relative small uplift (*left*). Larger uplift occurred in the Eastern side of the island taking the mangroves away from the original intertidal zone resulting in low level of natural recruitment (*right*) (Source: Blue Forests/author)

have differential tolerances to inundation, a major factor in the apparent zonation of mangroves from based on substrate elevation (from MSL – HGT).

A transect walk through the mangroves on the seaward edge of "Anak Laut" lagoon in Singkil reveals the pattern of mangrove mortality and rejuvenation. *Rhizophora apiculata* is dominant at the lowest elevations adjacent to the open water of the lagoon. As one continues further inland, species dominance changes with substrate elevation in the following pattern;

- Zone 1: *Rhizophora apiculata (*with *Aegiceras corniculatum* in the upper estuary*)*
- Zone 2: *Brugueira gymnorrhiza* with some *Nypa fruticans*
- Zone 3: *Sonneratia caseolaris*

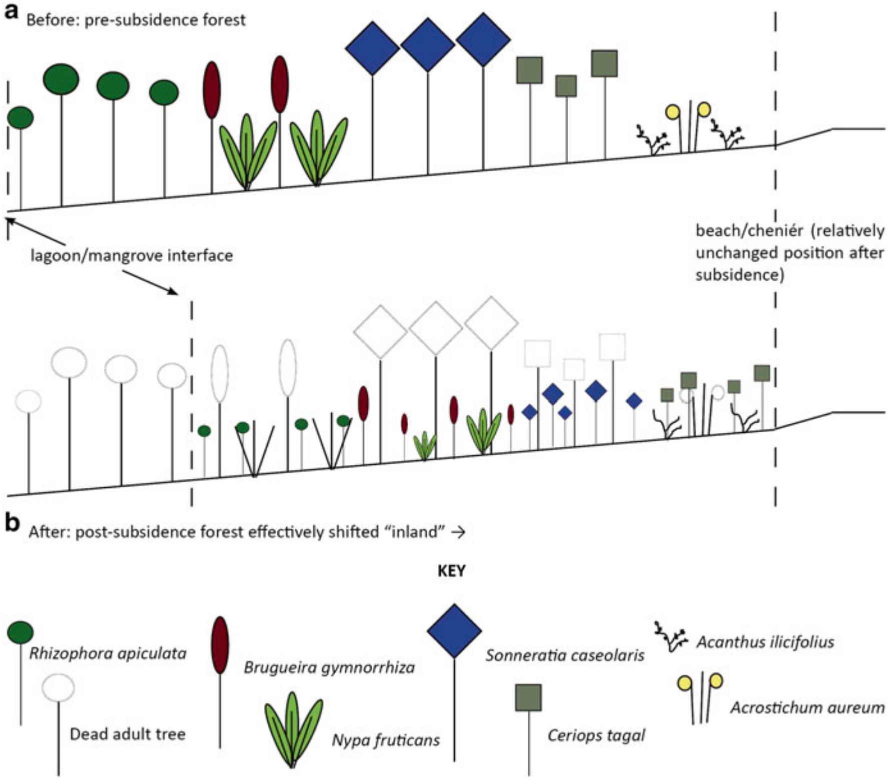

Fig. 19.4 Mangrove forest at Singkil Lagoon before and after subsidence. The original zonation was shifted "inland" after subsidence; the most upland species of mangroves *A. ilicifolius* and *A. aureum* ran out of room to shift inland as the beach/chenier occurred in relatively the same original geographical position before and after subsidence (Source: Blue Forests/author)

- Zone 4: *Ceriops tagal*
- Zone 5: *Acrostichum aureum* and *Acanthus ilicifolius*

After the seismic events and tectonic subsidence, a clear shift took place, with the die off of adult trees, and the establishment of seedlings precisely one zone "upwards."

Adult *Rhizophora apiculata* die off in Zone 1, with adult *Brugueira gymnorrhiza* die off in Zone 2 and establishment of young *R. apiculata* in zone 2 under the dead *B. gymnorrhiza*. This pattern is depicted in Fig. 19.4.

At the highest intertidal elevation, adjacent to the chénier formation that separates the lagoon from oceanic coast, *Acrostichum aureum* and *Acanthus ilicifolius* were forced to retreat onto the submerged sands of the former chénier – which is only a very narrow zone as the chénier itself continues to build due to the action of winds, currents and waves depositing sand. Therefore, these two species were reduced in relative abundance, as their habitat was effectively squeezed.

It must be noted, that this pattern of subsidence and upward migration of mangroves merits further study, as it provides an accelerated analogue of the anticipated effects of sea level rise on mangrove distribution.

19.2 Methods

Ten, 20 m × 5 m vegetation plots were temporarily established shore-left in a random stratified design (Duke 2011). Within each 100 m^2 plot total counts of trees (dbh > 2.5 cm, height > 130 cm, saplings (dbh < 2.5 cm, height > 100 cm) and seedlings (height < 100 cm)) of each species were determined. Girth of each tree was recorded using a tape measure and from this the cross-sectional area, or basal area (BA), was calculated to give an indication of growth and dominance. Tree height was recorded using an extendable height stick. Height of the first ten saplings and seedlings encountered were recorded.

A pair of sits (Teluk Dalam – Mercu Suar and Teupah Selatan) were monitored twice at a 12 month interval. The relationship between average stem densities over time for these two sites were examined with correlation analyses. Changes in density between pre-rehabilitation survey and most current survey data per site were analyzed with paired student T-tests using months since rehabilitation and average densities as group factors at 95 % confidence levels. The remaining four sites were only measured once, and a rate of recruitment was calculated simply by dividing the average stem density by the 7 years since the most recent major seismic disturbance (March 2005).

In all, six sites were measured, four of which had not experienced any degree of mangrove planting and two of which had been previously planted as part of the earlier rehabilitation attempts:

Never planted

1. Teluk Dalam-Mercu Suar (TDMS)
2. Teupah Selatan (TS)
3. Singkil Lagoon 1 (SL1)
4. Singkil Lagoon 3 (SL3)

Previously planted

5. Teluk Dalam-Sambay (TDS)
6. Singkil Lagoon 2 (SL 2)

To better understand stakeholder perspectives, non-formal interviews, formal interviews and focus group discussions were conducted with 200 villagers in partner villages in Simeulue Island and Singkil, as well as government agents from District Level Forestry Department, and Environmental Agency. Data was not analyzed, but anecdotes are used below.

19.3 Reflection on Human-Assisted Mangrove Rehabilitation in Changing Intertidal Zones (from Social – Economic and Environmental Perspectives)

It was reported that the 2004 tsunami in Aceh destroyed 32,000 ha of mangroves along the Aceh coast (Department of Fisheries and Oceans, 2005; and NAD Province Department of Forestry, 2005 as cited in Purwanto 2008). In response to this loss, 164 institutions, both government and non-governmental, (including only those registered with the Nanggroe Aceh Darussalam Bureau of Reconstruction and Rehabilitation), engaged in mangrove rehabilitation in the affected areas (Brown and Yuniati 2008). A pair of these mangrove planting projects is discussed below.

The Australian Red Cross (ARC) initiated the planting of 60,000 mangrove seedlings at five sites on the North Coast of Simeulue Island in 2006. Project monitoring 1 year later, in 2007 indicated total mortality at three sites, 25 % survivorship at a 4th site and 70 % survivorship at the 5th site (ARC Simeulue Office – project report, 2007). At this point, ARC contacted Mangrove Action Project – Indonesia, who was contracted to undertake a rapid assessment leading the recommendation that an Ecological Mangrove Rehabilitation (EMR) training be initiated with eight villages who were involved in planting the five sites. The training occurred in 2007, participated in by 30 women and men from the 8 villages. Evaluations of the training revealed that the majority of community members wished to attempt follow-up activities to rehabilitate mangroves in replanted sites, using techniques of propagule distribution and some hydrological repair; however, the 3 year ARC project came to an end, and no further action was taken by ARC, MAP or the local communities.

Between 2010 and 2013 a project under the USAID CADRE program[1] engaged Lutheran World Relief to continue mangrove rehabilitation and conservation activities in five villages on the North Coast of Simeulue Island, and five villages around Singkil Lagoon. In the project plan, mangrove rehabilitation sites were to be chosen after social (land tenure, stakeholder support) and ecological feasibility studies were undertaken. However, in practice, project managers pre-selected all ten villages before the feasibility study was conducted. In Simeulue, the five villages selected were all located in Teluk Dalam, where natural recruitment was already estimated as “recovering.”

It was determined to take baseline surveys of natural recruitment in order to revise recommendations of potential rehabilitation sites. In both Simeulue and Singkil Lagoon, baseline surveys would reveal that natural recovery rates were already higher than the project’s success criteria (see Sects. 4.1 and 4.2 below), and that no genuine mangrove rehabilitation sites existed at selected project locations. A genuine rehabilitation site was considered a site where natural recruitment, without human intervention, would not be sufficient to effectively restore mangrove populations. In search for viable rehabilitation sites (so that project targets of 400 ha of mangrove rehabilitation could be met) it was hypothesized that newly uplifted intertidal areas in Eastern Simeulue would not be recruiting at sufficient rates to repopulate mangroves in the near-term, and that human intervention was needed to

[1] Increasing Coastal Resiliency & Climate Change Mitigation through Sustainable Mangrove Management in Sumatra.

expedite the process before permanent alterations to the landscape (infrastructure development) were made. A baseline survey was also called for, to determine natural recruitment rates in Eastern Simeulue at an area known as Teupah Selatan.

In terms of government policy, mangrove rehabilitation in Indonesia is planned and budgeted for annually, in each province and coastal district. Processes include site selection, community awareness building, nursery development and planting at 1 m – spacings (BPDAS and South Sulawesi 2013). All activities are to take place within a single year. Monitoring occurs within 3 months after planting. Two such government planting practices were observed in Simeulue and Singkil during the timing of the ARC and CADRE projects. A 2005 forestry department planting event in Linggi Village, Simeulue promoted 100 ha of direct planting. One year after the event, only 0.5 ha of planted mangroves are evident (Fig. 19.5). Government officials

Fig. 19.5 Mangrove planting at Linggi Village, Simeulue. Out of 100 ha planted in 2005 only 1 ha of seedlings were evident in 2006 (*upper left*). Wooden stakes are the only remnant of around five additional hectares of wrongly planted *R. appiculata* at the landward edge of the intertidal zone were the species cannot grow (*middle left*). In the *bottom lower* picture thriving natural recruits of *S. caseolaris* are found amongst a graveyard of dead planted *R. apiculata*. Pioneers species such as *S. caseolaris* should be consider for human assisted propagule distribution, to colonize appropriate substrate as the first step in the rehabilitation of disturbed mangrove forest. In 2011 only 0.5 of the original 100 ha remained alive (*top right*) (Source: Blue Forests/author)

interviewed sited poor planting practices, poor species selection, poor condition of seedlings and herbivory by water buffalo as reasons for failure. Herbivory fails to explain the living 0.5 ha or thriving natural recruits at the site.

A similar planting took place in Singkil Lagoon in 2011. This planting took place on micro-deltas formed at the Southern end of the lagoon, and at the time at appropriate substrate elevations. However, rapid sedimentation took place over the course of the following year, and planted *Rhizophora apiculata* were 100 % "replaced" with naturally recruiting *Casuarina* sp., a common beachfront pioneer species.

Economically indeed, there must be a better way to use money earmarked for mangrove planting. It is reported that Ecological Mangrove Rehabilitation costs on average $600–1,500 per hectare when implemented in Indonesia and has a high success rate (Lewis and Brown 2014). In many cases, the benefit of such as process is simply to recommend that a site not be restored due to social or ecological reasons. Post-tsunami, villagers from Jaring Halus in North Sumatra provided over 1,000,000 seedlings per year (Fig. 19.6) for 3 years out of their 42 ha village forest, packed and shipped overland to Aceh to an unknown fate (Brown and Yuniati 2008).

Some local NGO's and members of communities have expressed their doubts about the effectiveness of mangrove planting as the trees are able to come back on their own. An example was the case of the Banyak islands where many mangroves died after the Nias earthquake but started to grow back naturally (Bpk. Zukifli, 2013, Department of Forestry. Singkil, personal communication).

Fig. 19.6 One batch of the one million seedlings shipped annually from Jarig Halus to Aceh (Source: Mangrove Action Project – Indonesia/author)

19.4 Observed Natural Recruitment

19.4.1 Simeulue

Of all the sites measured, the previously un-planted sites at Teluk Dalam exhibited the highest stem density (2,859 stems/ha), average annual rate of recruitment (408.4 plants/year), and total species diversity (12). Teupah Selatan, an un-planted site in Eastern Simeulue hypothesized as "in need of human assisted propagule distribution" exhibited lower average stem density (2,117 stems/ha), average annual rate of recruitment (302.5 plants/year), and total species diversity (7), exceeding expected results. With a rate of recruitment expected to add 900 plants/ha over 3 years, this site was re-evaluated as "not requiring human assistance for rehabilitation," as natural recruitment would exceed CADRE project targets (1,250–2,500 seedlings/ha after 3 years of intervention).

The final site measured in Simeulue was an ex-planting site at Teluk Dalam, Sambay. This site was planted twice since the tsunami, both with qualitatively high mortality. At the time of sampling, it was difficult for the team to distinguish planted material from natural recruits for *Rhizophora apiculata*, yet the other six species present were all natural recruits as they were not planted by either planting project. The overall stem density at the time of sampling was 467 stems/ha with a recruitment rate over 7 years of 66.7 comprised of seven species. Results are summarized in Table 19.1.

19.4.2 Singkil

Mangrove stem densities, recruitment rates and species diversity were also surveyed at a trio of sites in Singkil Lagoon; SL1, SL2 and SL3.

SL 1 is located near a newly cut channel between the sea and the lagoon and exhibited a mean density of Mean density of 2,980 plants per hectare. This site exhibited the pattern of a shift of species to higher elevations after seismic subsidence described in Sect. 2.2. SL2, includes areas previously planted, and then succeeded by *Casuarina* due to rapid sedimentation. The mangrove stem density at this site was 160 plants/ha. SL3 was not formerly mangrove forest, and has been colonized by *Acrostichum aureum* after subsidence, indicating this site is now at the upper intertidal limit for mangrove distribution. The local community with support from the CADRE project has planned an intervention for this area, razing the *Acrostichum aureum*, digging in tidal channels to facilitate water exchange with the lagoon, and planting woody mangrove species. Findings for all three sites at Singkil Lagoon are also summarized in Table 19.1.

Table 19.1 Stem density and species diversity for four un-planted and two planted sites in Simeulue and Singkil Districts

	Area	Site	Size (ha)	Stem density	Statistics	Species present	No. & size of plots
Simeulue island							
1	TelukDalam	MercuSuar	14	$0.29/m^2$ 2,859/ha	Standard deviation = 0.22 Variance = 0.05	Total = 9 (12) *A. aureum* *B. gymnorrhiza* *C. tagal* *L. littorea* *P. acidula* *R. apiculata* *R. mucronata* *S. alba* *X. granatum* Observed at site but not sampled: *A. ilicifolius* *A. speciosum* *B. sexangula*	n = 13 100 m^2 (5 m × 20 m)
2	TelukDalam	Sambay	1.65	$0.047/m^2$ 467/ha	Standard deviation = 0.039 Variance = 0.002	Total = 4 *B. gymnorrhiza* *C. tagal* *R. apiculata* *R. mucronata*	n = 6 100 m^2 (5 m × 20 m)
3	Teupah	Teupah Selatan	99.99	$0.212/m^2$ 2,117.39/ha	Standard deviation = 0.18 Variance = 0.03	Total = 7 *A. aureum* *B. gymnorrhiza* *C. tagal* *L. littorea* *N. fruticans* *R. apiculata* *R. mucronata*	n = 23 100 m^2 (5 m × 20 m)

Singkil							
4	AnakLaut Lagoon	SL1	8.10	0.30/m^2 2,980/ha	Standard deviation = 0.10 Variance = 0.01	Total = 4 *B. gymnorrhiza* *R. apiculata* *S. caseolaris* *A. aureum*	n = 5 100 m^2 (5 m × 20 m)
5	AnakLaut Lagoon	SL2	6.06	0.02/m^2 160/ha	Standard deviation = 0.02 Variance = 0.0002	Total = 4 *L. littorea* *R. apiculata* *S. caseolaris* *A. aureum*	n = 5 100 m^2 (5 m × 20 m)
6	AnakLaut Lagoon	SL3	6.12	0.11/m^2 1,080/ha	Standard deviation = 0.04 Variance = 0.0013	Total = 3 *R. apiculata* *S. caseolaris* *A. aureum*	n = 5 100 m^2 (5 m × 20 m)

Source: MAP; Indonesia/author

19.5 Discussion

Improper selection of mangrove rehabilitation sites took place frequently after the seismic displacement of the intertidal zone. Even where experienced mangrove rehabilitation practitioners were enlisted, the mechanisms of post-disaster project planning and project management superseded careful assessment.

Although this paper is largely anecdotal, one single monitoring event's worth of evidence of natural recovery versus planting success was undertaken, however it was not performed as an academic study, but rather in the context of disaster relief programming. What is notable, is that natural recovery, in some sites, had already exceeded success criteria of the rehabilitation project. Stem densities per hectare were higher than project targets in sites chosen for rehabilitation at both Simeulue and Singkil. Species diversity was certainly higher due to natural recruitment than planting alone, but should be described as a percentage of known local species diversity present in nearby reference forests. Rate of recruitment was calculated simply by dividing species density over time since disturbance, but should be tracked through several monitoring events to develop a more realistic linear progression. A pair of assessment methods are given in the conclusions to assist project managers in more deliberate planning.

In Teluk Dalam, Simeulue, natural recruitment was expected, as seismic uplift was less than the tidal range, and significant numbers of adult trees were noted not only to have survived the disturbance event, but to have remained fecund. In Eastern Simeulue, however, it was hypothesized that stem density would be significantly lower and natural recruitment rates significantly slower than Teluk Dalam, as many adult mangrove forests were uplifted entirely out of the zone of tidal influence. Enough trees, however, remained both alive and fecund, and stem densities of greater than 2,000 stems per hectare were encountered.

In Singkil Lagoon, which underwent seismic subsidence, adult trees died, but enough remained alive and fecund in order to colonize newly attenuated intertidal surfaces. Essentially, mangroves were noted to have shifted "upwards" along with the tidal frame. Mangroves planted in the micro-deltas formed at the far end of the lagoon grew initially but died off within a year due to rapid sedimentation, evidenced by colonization of *Casuarina*. Caution needs to be taken at all times when attempting to plant mangroves, so that their habitat requirements are met, but an extra degree of caution is needed in the case where a coastline is resettling after a period of disturbance. Such is the case in Aceh, where the subduction of tectonic plates begins anew, and displaced substrates are in a state of flux, due to geomorphological deformation, changing patterns of sedimentation (Fig. 19.7), compaction and other factors.

Fig. 19.7 Natural mangrove recruits *B. gymnorhizza* buried alive by rapidly changing sedimentation patterns (Source: Blue Forests/author)

19.6 Conclusion

It is clear that increased attention is paid to use of proper assessment methods when selecting mangrove rehabilitation sites. Examples of appropriate assessment tools include; (a) assessment chapters in *Ecological Mangrove Rehabilitation – A Practitioner's Manual* (Lewis and Brown 2014), and (b) *Tsunami Damage to Terrestrial Coastal Ecosystems Common Guidelines and Methodology for Rapid Field Assessment* (IUCN 2005).

In a post-disaster scenario, rapid assessments methods are required, but for obvious humanitarian reasons, rehabilitation planning should take place only after stabilization and resolution of major humanitarian issues (trauma, water, food and shelter). In cases where drastic geomorphological change has taken place, a long period of observation may be necessary before action taking. Resource intensive activities, such as nursery development and mangrove planting should not be considered in an initial period, if at all. Human assistance in collecting and distributing propagules to promote natural regeneration should be considered, coupled with careful monitoring of human assisted versus natural recruitment (Fig. 19.8).

Where mangrove planting projects have been attempted by governments, NGO's, and communities, without rigorous methodologies, failure can lead to

Fig. 19.8 Periodic human assisted propagule distribution to reestablish mangroves on appropriate intertidal surfaces and monitoring in collaboration with local communities (Source: Blue Forests/ author)

apathy amongst local stakeholders, where concerns over maintenance of annual government budgets, or short-term cash-for-work supersedes genuine intentions to restore mangroves as a vital coastal ecosystem. Economically, funds for repeated planting projects, without monitoring and feedback mechanisms can result in large-scale wastes of public and private financial resources and the detriment of the rehabilitation of mangroves in tsunami hit areas.

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