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Article

Mitigation effects of mangrove forests on tsunami impacts in Upolu Island, Independent State of Samoa - Field surveys and numerical modeling of the 2009 event

Hideaki YANAGISAWA[1], Toyohiko MIYAGI[2] , Shigeyuki BABA[3]

Abstract: We investigated tsunami mitigation effects of mangrove forests in the 2009 Samoa tsunami using field surveys and numerical models. According to our field survey in Matafaa, the tsunami height decreased from 3.2 m to 1.9 m in a 50 m-wide mangrove forest. Although mangroves were partially destroyed by strong tsunami flow at the forest front, damage became minor 10 m from the forest edge, and no damage occurred from 40 m into the forest. These results show that the strong tsunami flow was reduced by the 40 m-wide mangrove forest. In the Lotopu'e area, we found that tsunami flow depth and damage to houses were clearly different between the front and back of the mangrove forest. At the front of the forest, many houses were washed away by 2.7 to 3.5 m-deep tsunami flow. In contrast, the flow depth became 0.7 to 0.9 m at the back of the mangrove forest and caused relatively little damage to houses. Regarding the role of trapping debris, we revealed that some significant debris such as cars and house roofs was stopped by the forest. The mangrove forest protected the inland residential area from damage by drifting debris. From interviews with local people, we confirmed the role of mangrove trees in preventing people from being washed away by strong tsunami flow. Using the numerical simulation of the tsunami, including the resistance of mangrove forests, we estimated the reduction ratios with/without mangrove forests. The model results show that tsunami flow depth and hydraulic pressure are reduced by approximately 10 % and 30 %, respectively, due to the mangrove forest. From this result, we concluded that the conditions of mangrove forests in Samoa had the potential to mitigate tsunami damage during the 2009 event.

Keywords: Field surveys, Mangrove, Numerical modeling, Samoa, Tsunami

1. Introduction

On 29 September 2009, a large tsunami was triggered by a strong earthquake with a magnitude 8.1 at the Tonga Trench approximately 200 km southwest of the Samoa Islands. The tsunami propagated across the South Pacific Ocean, caused considerable damage around the Samoa Islands and resulted in casualties estimated as at least 192 people: 149 in independent State of Samoa, 34 in American Samoa and 9 in Niuatoputapu, Tonga (USGS). Maximum runup heights were 15 m at independent State of Samoa, 18 m at American Samoa and 22 m at Tonga Island (Fritz et al.,2011).

On the other hand, the Pacific Disaster Net (2009) reported that mangrove forests had a protective function against the tsunami impact in Samoa and encouraged the conservation of mangrove areas as coastal protection. Since the 2004 Indian Ocean tsunami, which caused a catastrophic disaster with 0.22 million causalities, several observations of mangroves' roles in protecting human lives and properties from the disaster have been reported (Danielson et al., 2005; Kathiresan and Rajendran, 2005). Furthermore, recent developments from laboratory experiments and numerical simulations have confirmed the tsunami reduction effect of mangrove forests (Harada and Imanumra 2000;

[1] Corresponding author: E-mail: h-yanagi@mail.tohoku-gakuin.ac.jp Department of Regional Management, Faculty of Liberal Arts, Tohoku Gakuin University, 2-1-1 Tenjinzawa, Izumi-ku, Sendai, Miyagi 981-3193, Japan

[2] The Institute for Research in Human Informatics, Tohoku Gakuin University, 2-1-1 Tenjinzawa, Izumi-ku, Sendai, Miyagi 981-3193, Japan

[3] International Society for Mangrove Ecosystems, Faculty of Agriculture, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa 903-0129 Japan

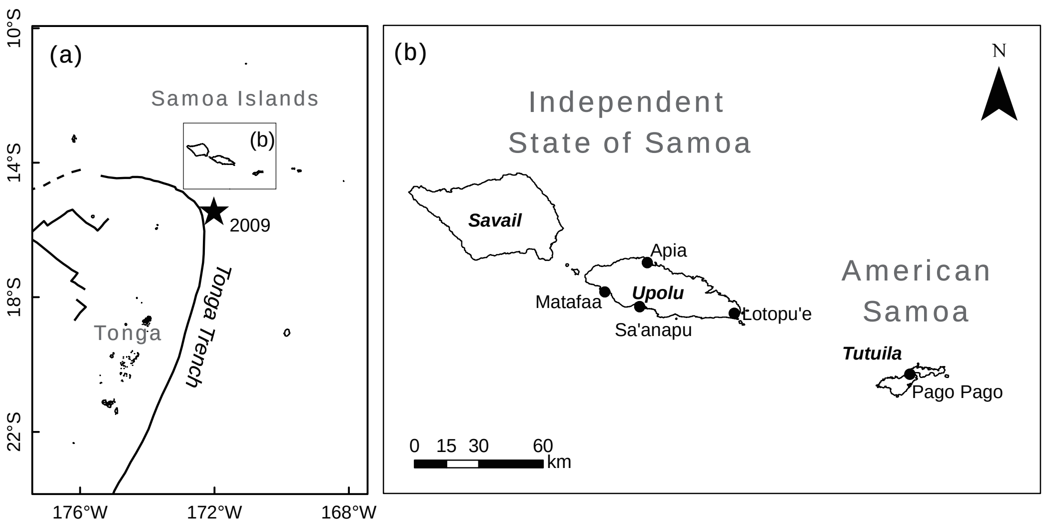

Fig. 1 Study area. (a) Epicenter of the 2009 Samoa earthquake. (b) Location of the Samoa Islands. Our study sites are on Upolu Island, Independent State of Samoa.

Yanagisawa et al. 2009; Husrin et al. 2012; Tanaka et al. 2018). Although the tsunami mitigation effects of mangrove forests have been highlighted, questions remain from preliminary survey reports of tsunami reduction in mangrove forests (Kerr et al. 2006; Vermaat and Thampanya 2006a; Kerr and Baird 2007; Bhalla 2007; Baird and Kerr 2008; Feagin et al. 2008; Srinivas et al. 2008). These studies claim that tsunami reduction depends on not only the coastal conditions with/without mangrove forests but also other coastal features such as ground elevation, topographic profile and distance from the coast. To validate preliminary reports of mangroves' protective role, detailed field surveys and analyses are required.

The protective roles of coastal trees have been studied in several tsunami disasters since the 1896 Meiji Sanriku tsunami, which killed more than 20,000 people in Japan. Based on field observations of coastal pines, Shuto (1985) reported five roles for coastal trees in tsunami mitigation: (1) reducing strong tsunami flow, (2) trapping debris, (3) providing places for emergency escapes by grabbing a tree, (4) preventing coastal erosion and (5) forming sand dunes to prevent tsunami inundation. Mangrove trees habiting wetlands could have as protective roles as other coastal trees. However, a few examples support the mitigating effects of mangrove forests.

Focusing on roles (1) – (3) above, which are direct effects to reduce tsunami damage, we investigate the mitigation effects of mangrove forests during the 2009 Samoa tsunami based on field measurements, interviews with local people and numerical simulation. Comparing detailed field data of tsunami heights and damage to houses around mangrove forests, we confirm the mitigation effect of forests against tsunami impacts. We then numerically model mangrove forests based on field data to estimate the tsunami reduction effect, simulating tsunami flows with and without mangrove forests (Yanagisawa et al. 2010). Finally, we verify the role of mangrove forests in mitigating tsunami damage during the 2009 Samoa tsunami.

2. Methods

2. 1 Study site

The Samoa Islands comprise American Samoa, which includes Turuila, Ofu, Olosega, Ta'u, and Rose and Swains atolls, and the Independent State of Samoa composed of Upolu, Savai'i and several islets. The Tonga Trench, which is located approximately 200 km south of the islands, constitutes one of the convergent boundaries between the Pacific Plate and the Tonga Plate, extends approximately 1000 km northeast of the Kermadec Trench and then takes a sharp bend to the west near the northern terminus (Fig. 1). The 2009 Samoa earthquake and the resulting tsunami occurred at 17:48:10 GMT in the northern part of the trench with an epicenter at 15.51°S and 172.03°W (Okal et al. 2010).

To study the protective roles of mangrove forests,

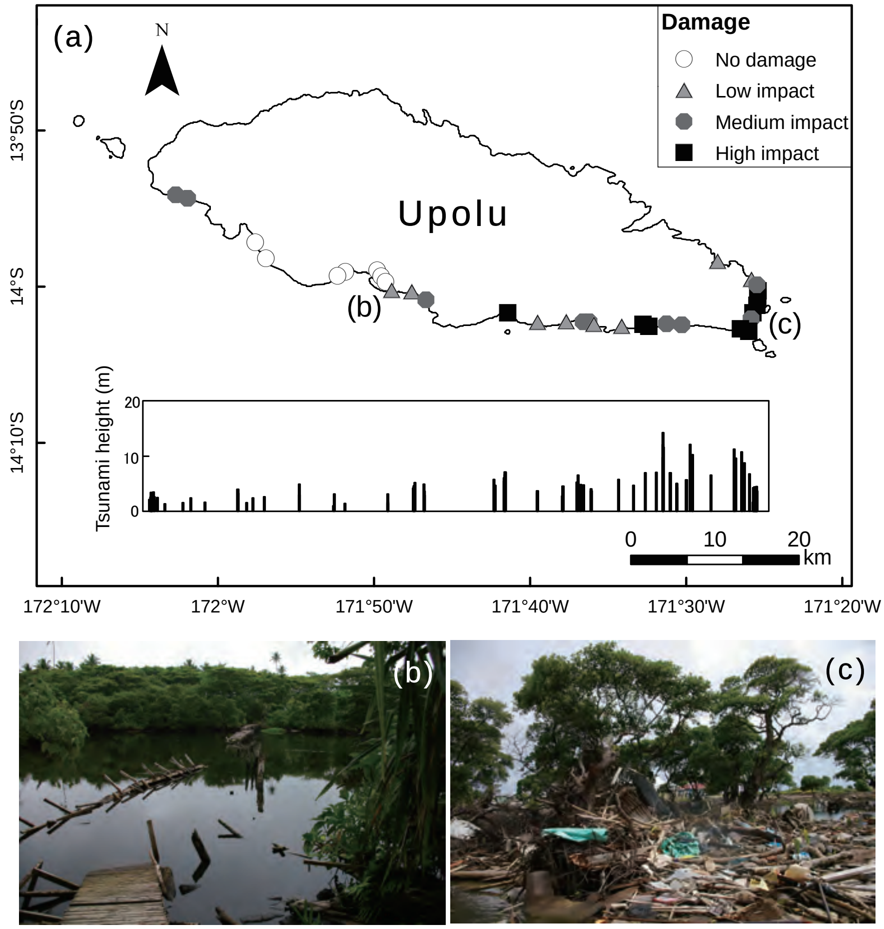

Fig. 2 Impacts of the 2009 Samoa earthquake and tsunami in Upolu Island. (a) Tsunami heights at and damage to villages on Upolu Island (Okal et al., 2010; Pacific Disaster Net, 2009) (b) Wooden boardwalks damaged by the tsunami at Sa'anapu. (c) Debris in mangrove forest at Lotopu'e.

we conducted a field survey and numerical simulation of the tsunami at Upolu Island, Independent State of Samoa. Figure 2a shows the distribution of tsunami heights measured by Okal et al. (2010) (National Geophysical Data Center (NGDC)/WDS Global Historical Tsunami Database; https://www.ngdc.noaa.gov/hazard/tsu_db.shtml) and tsunami damage in each village observed by the Pacific Disaster Net (2009). The tsunami was larger around the southeastern side of Upolu Island, where the height exceeded 10 m. As tsunami height increases, the degree of damage to villages increases. On the other hand, the Pacific Disaster Net (2009) reported that damage to mangrove forests was limited and that forests will recover in a short to medium term. According to our observations covering all of Upolu Island, we were not able to discern severe damage to mangrove forests; however, wooden boardwalks for tourists in mangrove forests around Sa'anapu village were partially destroyed by tsunami flow, and some large debris entered mangrove forests in Lotopu'e (Fig. 2b, c).

2.2 Observation

The field survey took place from 23 December 2009 to 1 January 2010 on Upolu Island, focusing on mangroves in the Matafaa and Lotopu'e areas on the southwest and east sides of the island, respectively (Fig. 1b). Both forests are mainly composed of *Bruguiera* species. In a field survey, we documented the flow depth, current direction of tsunami flow, damage to houses/trees and locations of trapped debris on mangrove trees. The flow depth was determined by the heights of water marks on houses, trapped debris, broken branches or interviews with local people. The current directions were inferred from the directions of uprooted trees or trapped debris. We

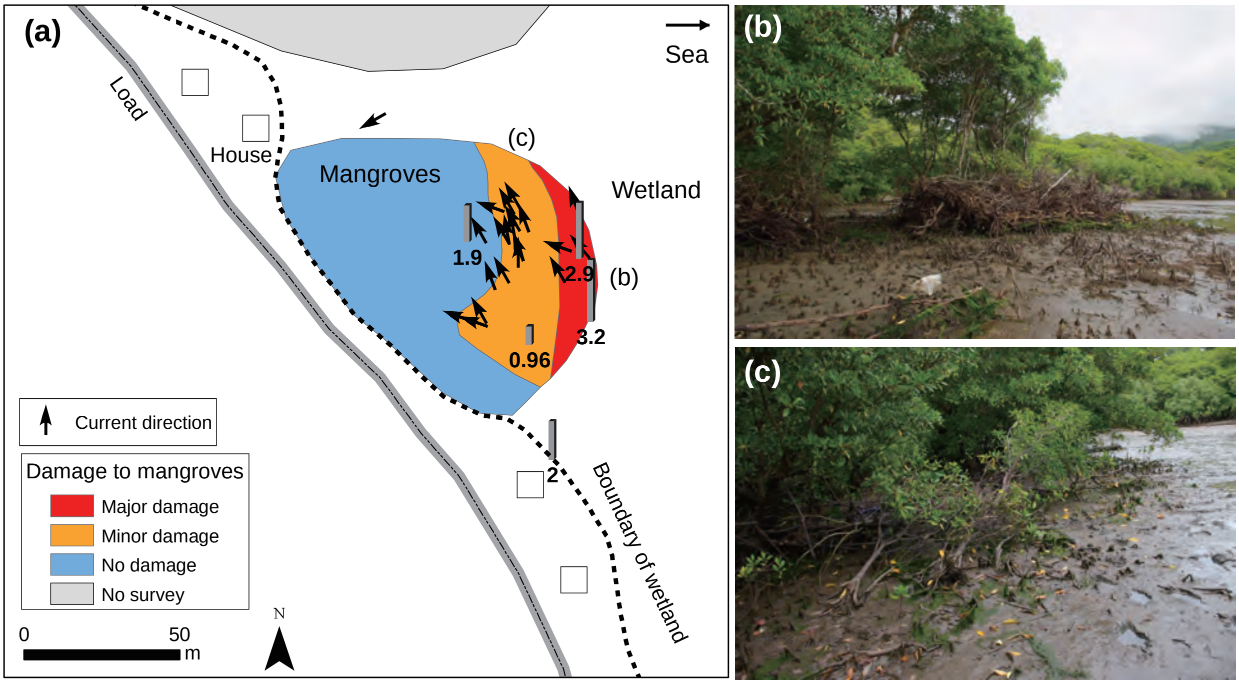

Fig. 3 Tsunami damage on mangrove forest in Matafaa. (a) Tsunami height (m), current direction (the arrows do not include a flow strength) and mangrove damage. (b) and (c) show damage to mangrove trees at (b) and (c) in map (a).

also measured the condition of mangroves, such as diameter at breast height (*DBH*) and intervals between trees as a preliminary assessment. The density of trees (trees per unit area) is assumed from averaged tree interval considering uniformed staggered pitch. The locations of the measured data were recorded using a global positioning system (GPS) and mapped using a geographical information system (GIS).

3. Results of the field survey

3.1 Tsunami reduction effect in mangrove forests at Matafaa

In the Matafaa area, we focused on the mangroves' protective roles in reducing tsunami energy and providing emergency escape places. Figure 3 shows tsunami heights (flow depth + ground level above the height of wetland), current directions and damage to mangrove trees. According to these figures, the tsunami mostly flowed toward the west, and the height decreased from 3.2 m to 1.9 m in a mangrove forest with a width of 50 m. The damage to mangroves could decrease with decreasing tsunami height. Although mangroves were largely destroyed by strong tsunami flow at the front of the forest, the damage became minor 10 m inland from the forest edge, and there was no damage even to branches or seedlings at 40 m. These results show that the strong tsunami flow was reduced in a mangrove forest 40 m wide. In contrast, local people reported that the tsunami flowed strongly in open areas between mangrove forests, which could be caused by contracted flow. According to a tree survey in the forest, the average diameter at breast height (*DBH*) and tree density (trees per unit area) are 15 cm and 270 tree/ha, respectively. Based on the field data, we determined that these mangrove conditions could contribute to reducing tsunami energy.

Furthermore, we interviewed local people about the protective role in emergency escape during the tsunami. A resident said that a child was caught by the strong backwash of the tsunami, but he snatched at a mangrove tree that saved his life. The mangrove trees contributed to preventing people from being washed away by the strong tsunami flow.

3.2 Tsunami mitigation effect of mangrove forest in Lotopu'e

Here, we focused on the protective roles of mangrove forest in reducing tsunami damage and trapping debris. Figure 4 shows tsunami flow depths, directions of flow, and damage to houses around the mangrove forest. In this area, the direction of

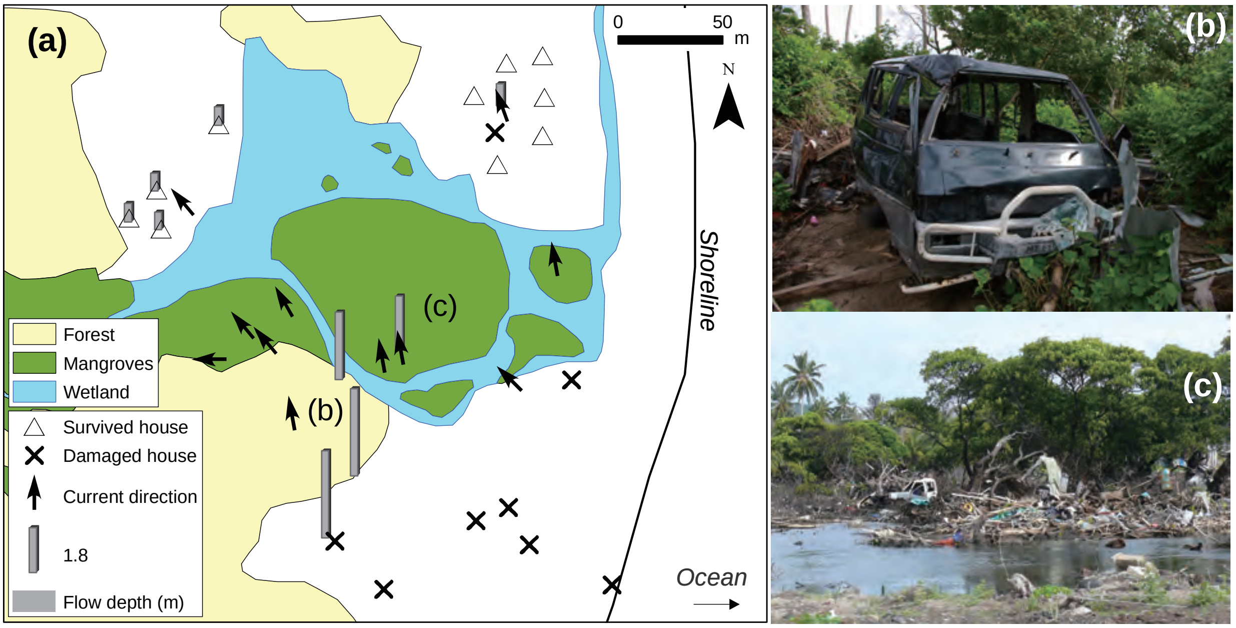

Fig. 4 Tsunami damage around mangrove forest in Lotopu'e. (a) Tsunami flow depth, current direction (the arrows do not include a flow strength) and house damage. (b) and (c) show a car and many pieces of debris drifted into the mangrove forest.

the tsunami flow was not westward, which is the perpendicular direction landward from the shoreline, but northward or northwestward nearly parallel to the shoreline. This effect could have occurred because the tsunami propagated from southwest of the Samoa Islands and ran up the village. An offshore island could also have affected the direction of tsunami flow. According to these figures, we found that tsunami flow depths and damage to houses were clearly different between the front (south side) and back (north side) of the mangrove forest. At the front of the mangrove forest, many houses were washed away by a tsunami flow 2.7 to 3.5 m deep. On the other hand, the flow depth became 0.7 to 0.9 m at the back of the mangrove forest and caused relatively little damage to the houses. Although these results imply that the mangrove forest could reduce the tsunami impact, we need to be careful with the observational data because other coastal features such as distance from the coast could affect tsunami reduction behind mangrove forests. Thus, we discuss whether the mangrove conditions can reduce tsunami impact through numerical analysis in the followings. According to a tree survey, the forest is dominated by *Bruguiera* species, which include a well-grown tree with a *DBH* of more than 80 cm. The average values of *DBH* and tree density are 39 cm and 480 tree/ha, respectively. We consider these mangrove conditions in the numerical analysis.

Figure 4b and c show some significant debris such as cars and house roofs, which are trapped by the mangrove forest. According to local people, the cars were drifted from the village south of the mangrove forest. In the village, many houses were damaged by the tsunami, and much of its debris drifted into the mangrove forest. If the debris had not been trapped by the mangrove forest, it would have drifted to the residential area behind the mangrove forest, which could have caused severe tsunami damage to human lives and property. From these results, we clarify that the mangrove forest contributed to mitigating tsunami damage by stopping drifted debris during the 2009 Samoa tsunami.

4. Discussion

4.1 Modeling of tsunami reduction effect of the mangrove forest

Our purpose here is to use numerical simulation to confirm whether the mangrove conditions at Lotopu'e have the potential to reduce tsunami impacts. To focus on the mangrove effect, we use a simplified model with cross-sectional one-dimensional nonlinear shallow-water equations. We compute tsunami generation assuming a one-side sine wave with a

10-minute period. Adjusting the amplitude of the sine wave, we produce a 3.5 m tsunami flow depth at the shoreline, which corresponds to the observed tsunami height at the front of the mangrove forest at Lotopu'e. The coastal landform for the simulation is simplified from the nearshore of the eastern side of Upolu Island (fig 5a). For the friction of the mangrove forest, we use the variable roughness coefficient estimated by the equivalent roughness model, considering the occupancy ratio of trees in a control volume/area (e.g., Yanagisawa et al. 2010). The occupancy ratio is determined from the tree density (trees per unit area) and the averaged *DBH*. Based on field data from Lotopu'e, we assume parameters of *DBH*, tree density *N* and width of the forest *Wd* for the simulation (*DBH* = 39 cm, *N* =480 tree/ha, and *Wd* = 100 m).

4.2 Discussion of tsunami reduction effect by mangrove forest

Figure 5b and 5c shows the computed maximum height and hydraulic pressure around the mangrove forest. The ratios of hydraulic pressures and flow depths with/without mangrove forest are 0.72 and 0.9 behind the mangrove forest, respectively. These results mean that the hydraulic pressure is reduced by approximately 30 % and the flow depth by 10 % because of the mangrove forest. According to previous studies (cf. Hatori 1964), hydraulic pressure correlates directly with house damage by tsunami flow. Thus, the conditions of the mangrove forest in the Lotopu'e area could have had the potential to mitigate house damage during the 2009 event.

On the other hand, when we estimate the ratio of flow depths between the front and back of the mangrove forest, the value becomes 0.59. At the front of the mangrove forest, the friction of the mangroves temporarily causes wave setup, and the tsunami height becomes larger than without mangrove forest (Fig. 5b). Consequently, mangrove forest unfavorably increases the height of the tsunami at the front of the forest, and the reduction ratio between front and back becomes higher. Although the one-dimensional numerical model could overestimate wave set-up, wave set-up is likely to be caused at the front of mangroves due to stagnation of the flow with damping of current velocity. Numerical model includes parameter and scenario uncertainty, and it is needed to validate by field observations. However, considerable attention is also required to estimate the ratio between the front and back of mangroves as a tsunami reduction effect, which is observable in data from field surveys, because the observed reduction ratio might be an apparent result estimated by the increased tsunami height due to the mangrove forest. Therefore, the integrated approach including field surveys and numerical modeling is effective to estimate the protective roles of mangrove forest.

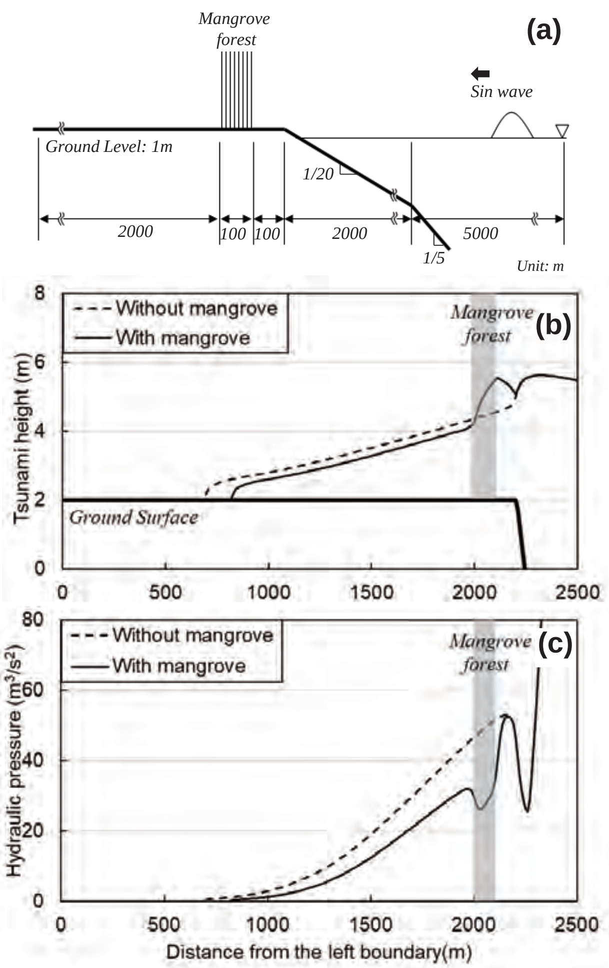

Fig. 5 (a) Numerical conditions of the cross-sectional simulation. (b) Numerical results of the maximum tsunami height and (c) hydraulic pressure with/without mangrove forest. Solid and dotted lines show numerical results with and without mangrove forest, respectively. The shaded area indicates the location of the mangrove forest.

5. Concluding Remarks

Focusing on the protective roles of mangrove forest, we investigated the tsunami mitigation effects of these forests during the 2009 Samoa tsunami by using an integrated approach with field surveys and numerical simulations. Based on a field survey in Matafaa, we clarified the effects of reducing strong tsunami flow and providing an emergency escape place. Comparing damage in the villages in front of and behind the mangrove forest in Lotopu'e, we also confirmed that house damage is relatively small in villages behind the mangrove forest due to its protective roles in reducing tsunami impact and stopping drifted debris. To validate the tsunami reduction effect of mangrove forests, we further modeled the 2009 Samoa tsunami and the reduction effect of a mangrove forest. As a result, we estimated that mangrove forests can reduce tsunami hydraulic pressure by approximately 30 %. Therefore, we concluded that the conditions of the mangrove forest in Lotopu'e had the potential to mitigate tsunami damage during the 2009 event. On the other hand, the computed reduction effect of mangrove forests related to flow depth was limited to approximately 10 %, although the observed tsunami reduction between the front and back of the forest in Lotopu'e seemed to be higher. This contrast could be an apparent reduction effect caused by the wave setup in front of a mangrove forest. These results indicated that estimating the tsunami reduction effect of mangrove forests using only field survey data is difficult. However, the recent development of numerical simulation technology can help validate the protective function of mangrove forests during tsunamis. Therefore, future studies are required to re-evaluate previous preliminary reports of mangrove protective functions using numerical models.

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