Original Research

Damage to Mangrove Forest by 2004 Tsunami at Pakarang Cape and Namkem, Thailand

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Abstract

We investigated damage to mangroves from the 2004 Indian Ocean tsunami at Pakarang Cape and Namkem, Thailand. Visual inspection of remotely sensed images revealed that 12 and 20 ha of mangrove forests were damaged, respectively, at Pakarang Cape and Namkem. Field surveys revealed that mangrove trees were destroyed particularly around the river mouths and channels. Numerical simulation indicated that the flow concentrated at the river mouth and inundated mangrove forests through river channels. We concluded that the tsunami flow pattern was largely affected by local river mouth and channel topography. Damage to mangroves might be severe in such areas.

Keywords: mangrove forest, tsunami, damage, natural hazard, Thailand

Introduction

Mangroves, an important ecosystem, are densely vegetated wetlands in tropical and subtropical areas. They have a special role in protecting human life and property of people during natural disasters such as storm surges, coastal erosion, and tsunamis, while providing environmental services and timber resources to people [e.g. 1, 2]. From field observations in Vietnam, Mazda et al. [3] measured that the sea wave height during a typhoon was reduced by 20% in a 5-year-old mangrove forest with a landward width of 100 m. Mangroves also protect the coast from wave-induced erosion by absorbing wave energy [2]. Regarding the 26 December 2004 Indian Ocean tsunami, which imparted catastrophic destruction to coastal communities, some reports have described areas with coastal trees, such as mangroves, suffering considerably less damage from the tsunami than areas without them [4, 5]. Deforestation for economic development, however, has threatened mangrove ecosystems in tropical and subtropical areas [6]. After the devastating tsunami impacts, local governments and NGOs have acted to rehabilitate mangrove forests as a countermeasure against the effects of such natural disasters [7].

On the other hand, some mangroves were greatly damaged by the 2004 Indian Ocean tsunami and might have lost their disaster-mitigation effects [2, 8-10]. Although the tsunami mitigation effect of mangrove forests has been emphasized [4, 5], few studies have examined the damage to mangroves associated with the tsunami inundation flow. The damage condition of mangrove forests must be clarified to determine limitations of mangrove forests as a countermeasure against tsunamis. Yanagisawa et al. [10] recently proposed a model to estimate the damage probability to mangrove trees associated with tsunami bending stress,

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using observed damage data and numerical modeling results of the tsunami. Actually, the geographical condition around a mangrove forest might be an important factor reflecting the damage of mangrove forest simply because the tsunami inundation flow behavior depends strongly on local topographic features [11]. However, no study has examined the effect of the geographical conditions in a mangrove forest (river mouth, channel, etc.) on the damage to mangroves. For this study, we investigated the damage to mangroves resulting from the 2004 Indian Ocean tsunami at Pakarang Cape and Namkem, Thailand, using an integrated approach to analyze remotely sensed images, field surveys, and numerical modeling to clarify the relation between geographical conditions and damage to mangrove forests.

Study Area

The 2004 Indian Ocean tsunami was caused by a great earthquake of magnitude 9.0-9.3 in the Andaman-Sumatran subduction zone (Fig. 1a). The tsunami engendered massive loss of life and environmental damage along the Andaman coast of Thailand and in several other countries. The present study examined mangrove forests at Pakarang Cape and Namkem in Pang Nga province, Thailand, 60 km and 80 km north of Phuket Island, respectively (Fig. 1b). Mangrove forests are densely vegetated mudflats lining the banks of river channels in the study areas (Figs. 1c and 1d). The Pak Ko River flowing between Namkem and Kho Khao Island (Fig. 1c) extends 15 km; mangrove forests

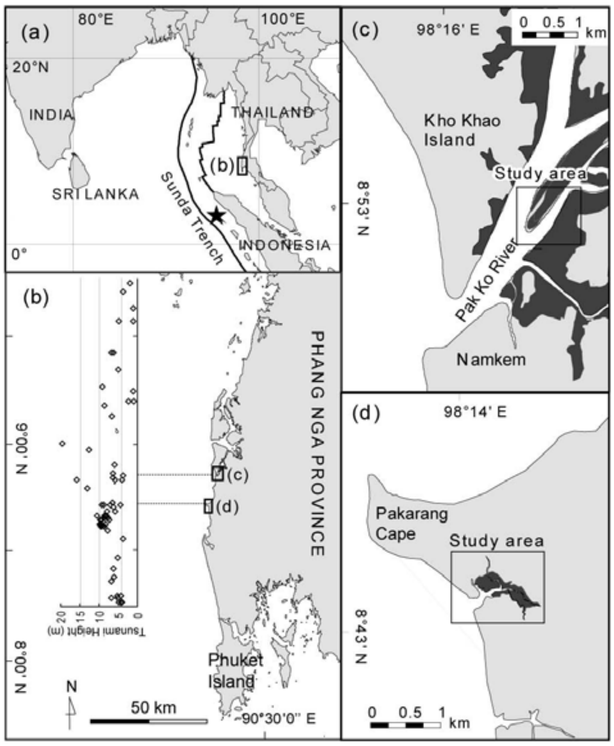

Fig. 1(a) The epicenter of the 26 December 2004 earthquake; (b) Andaman coast of Thailand with measured tsunami heights [12, 13]. Study area at (c) Namkem and (d) Pakarang Cape. The dark gray areas in (c) and (d) show mangrove forests before the tsunami event.

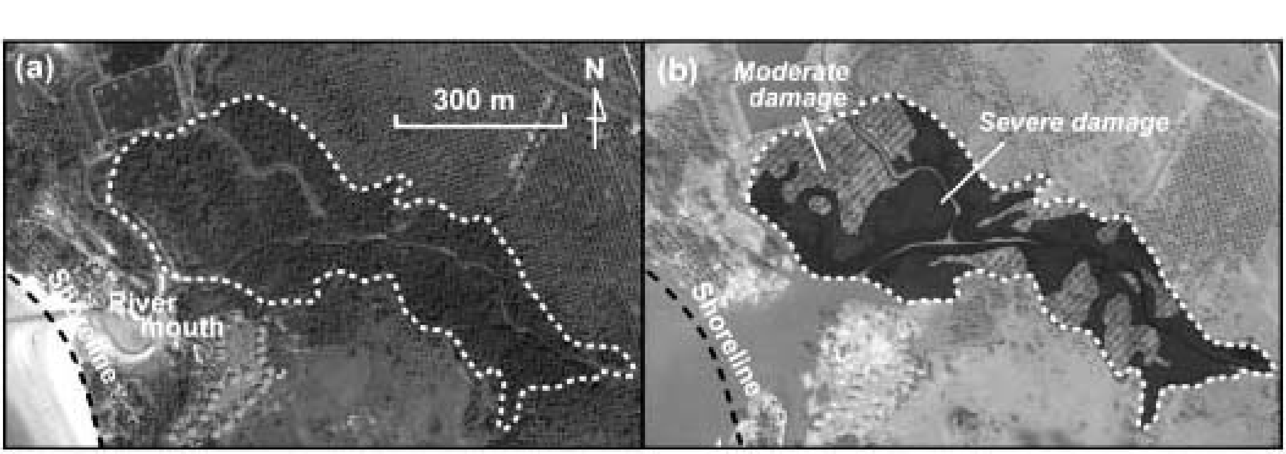

Fig. 2. Satellite images of the mangrove forest at Pakarang Cape: (a) before, and (b) after the 2004 Indian Ocean tsunami (13 January 2003 and 29 December 2004, respectively). White dotted lines in (a) and (b) show mangrove forests with minor quantities of other vegetation. The shaded area and black area in (b) respectively show a moderately damaged area and a severely damaged area. These satellite images were provided by Space Imaging/CRISP-Singapore.

covered the riverside areas (ca. 4,500 ha). The river with mangroves at Pakarang Cape, however, extends from the shoreline to 1 km inland (Fig. 1d); the mangrove forest covers only a small fraction of that area (ca. 17 ha).

The tsunami wave heights (above tide level when the tsunami hit) near the study areas at Pakarang Cape and Namkem were measured respectively as approximately 5-10 and 4-6 m [12, 13] (Fig. 1b). The devastating tsunami wave killed more than 8,300 people (including missing) in Thailand. The village at Namkem is one of the worst damaged areas: more than 1,400 people were killed and 500 houses were destroyed [14]. Although the tsunami-affected people were fewer at the coast of Pakarang Cape than at Namkem because of the smaller populated area, most hotels or houses near the coast incurred catastrophic tsunami damage [15].

Methodology

We first investigated high-resolution remotely sensed images (aerial photographs and satellite images) acquired before and after the tsunami event to assess the overall mangrove damage. We overlaid remotely sensed images before and after the tsunami event using a geographical information system (GIS) and categorized the mangrove forest into those areas with severe damage and with moderate or no damage based on visual inspection, particularly addressing differences in ground color as a consequence of erosion or destruction of vegetation by tsunami inundation. Subsequently, field surveys were conducted three times during 2005-06 to investigate ground truth related to mangrove tree damage. The conditions around the damaged mangrove trees and its locations were recorded respectively using a digital camera and Global Positioning System (GPS). In the mangrove forest, some destroyed trees or houses were trapped by surviving trees [16]; that debris provides valuable clues to infer the tsunami flow direction [17]. We assumed that the tsunami dominantly flowed front to back of the surviving trees, thereby trapping the debris in front of them. Furthermore, we considered that the direction of the fallen trees indicates the tsunami flow direction. Based on these assumptions, we measured the directions of the trapped debris or fallen trees and determined the directions of the local tsunami flow in the mangrove forest.

For this study, we simulated the 2004 Indian Ocean tsunami using the long-wave theory to examine the tsunami inundation process in a mangrove forest. A numerical model of the transoceanic propagation of the 2004 Indian Ocean tsunami was based on the linear long-wave theory incorporating the Coriolis force and using a spherical coordinate system [18]. Tsunami propagation in the coastal area was simulated based on the nonlinear long-wave theory, which includes the bottom friction term in the form of Manning's formula. For tsunami modeling, we used one-arc-minute grid (ca. 1850 m) digital bathymetry and topography data, published in the General Bathymetry Chart of the Oceans (GEBCO) Digital Atlas, for transoceanic propagation. The transoceanic propagation model is connected to the model of nearshore propagation and coastal inundation [18]. To evaluate the effect of the river mouth and channel in a mangrove forest, high-resolution numerical simulation is necessary. Therefore, we prepared 17 m grids of digital bathymetry data, which were produced through interpolation of the observed data [10], for the coastal area. The grid size (17 m) was sufficiently fine to discuss the characteristics of tsunami inundation flow at the river mouth and channels in the study areas.

For the initial condition of the propagation model, we estimated the vertical seismic deformation of the land and sea bottom using the theory of Manshinha and Smylie [19]. The tsunami source parameters of the 2004 Indian Ocean tsunami were determined following Koshimura and Takashima [20]. For bottom friction, we used the constant roughness coefficient in the form of Manning's formula, depending on land use: 0.02 for bare ground and grass, 0.025 for sea and rivers, 0.06 for buildings, and 0.05 for vegetation other than grass [21]. For the bottom friction of coastal trees, we used the variable roughness coefficient estimated using the equivalent roughness model [22].

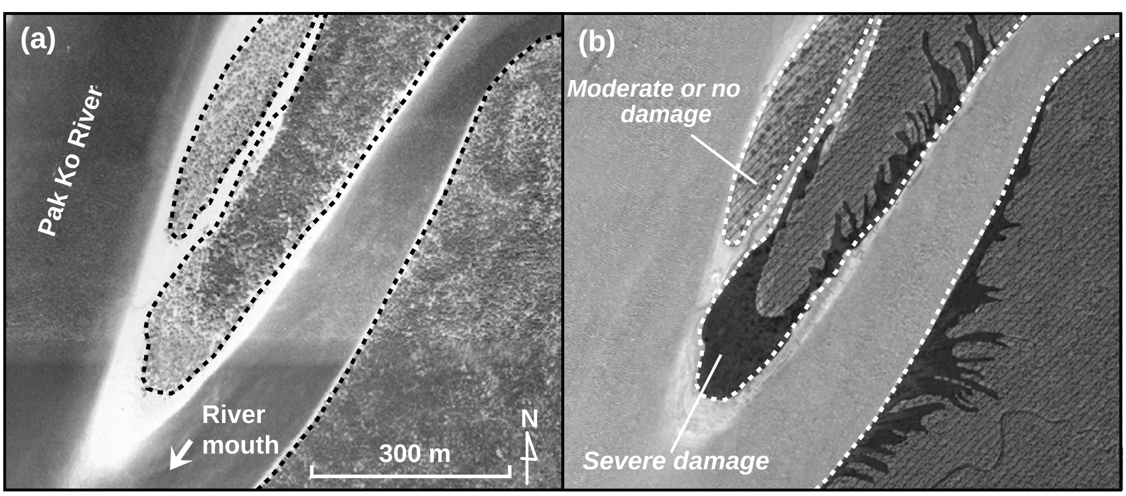

Fig. 3. (a) Aerial photograph acquired on 2002 before the tsunami event and (b) a satellite image acquired on 05 January 2005 at the mangrove forest in Namkem. The black dotted line in (a) and white dotted line in (b) show a mangrove forest. The shaded area and black area in (b) respectively show areas of moderate or no damage and severe damage.

The numerical conditions of mangrove trees were determined following Yanagisawa et al. [10]. We reproduced the tsunami propagating for more than 10 h after the earthquake, which is sufficient to reach maximum tsunami height at the study areas [23].

Results

Damage of Mangrove Forest Observed from Remote Sensing Imagery

Comparing satellite images of pre-tsunami and post-tsunami events at Pakarang Cape (Figs. 2a and 2b), we found that the tsunami severely damaged approximately 12 ha of mangrove forest (70% of the forest). Several trees in other areas of the forest (ca. 5 ha) survived the tsunami, but the forest became sparse. The mangrove area is heavily eroded along the river mouth and channel; the damage to the mangrove forest was especially severe around the eroded area (Fig. 2b).

In Namkem, mangrove trees were severely damaged along the river channels (Figs. 3a and 3b). In addition, the destruction pattern of mangrove forest shows a characteristic feature: the destruction area forms a jagged destruction pattern (Fig. 3b). We estimated that approximately 20 ha of mangrove forest were severely damaged in Namkem and that the destruction area extended up to 170 m inland.

Results of the Field Survey

Figure 4a portrays the tsunami flow direction, as inferred from the direction of trapped debris or fallen trees in the forest at Pakarang Cape. According to the figures, the direction of tsunami inundation flow was mostly toward the northeast, which was almost perpendicular to the shoreline. On the northern bank, however, some flow direction near the river mouth and channel was inland from the river channel (Fig. 4b). On the other hand, on the southern bank, distantly positioned from the river mouth, the flow directions were only toward the northeast, which was almost perpendicular to the shoreline (Fig. 4b). Figs 4c and 4d show mangrove trees affected by the tsunami, as photographed from helicopter and field surveys. Most mangrove trees were destroyed at the area facing the river mouth (points A and B in Fig. 4a): only stumps including prop roots of *Rhizophora* spec. remained (Figs. 4dA and 4dB). Several mangrove trees, however, survived the tsunami impact other than those in the area facing the river mouth (Fig. 4dC).

Regarding analysis of remotely sensed images at Namkem, the destruction of mangrove forest formed a jagged destruction pattern (Fig. 5a). Field observations revealed that the mangrove trees' destruction was concentrated on the side of small creeks in the mangrove forest. They formed a jagged destruction pattern (Figs. 5cA, 5cB, and 5cC). Figure 5c also portrays the condition of damaged mangrove trees along the line in Fig. 5b. On line D in Fig.

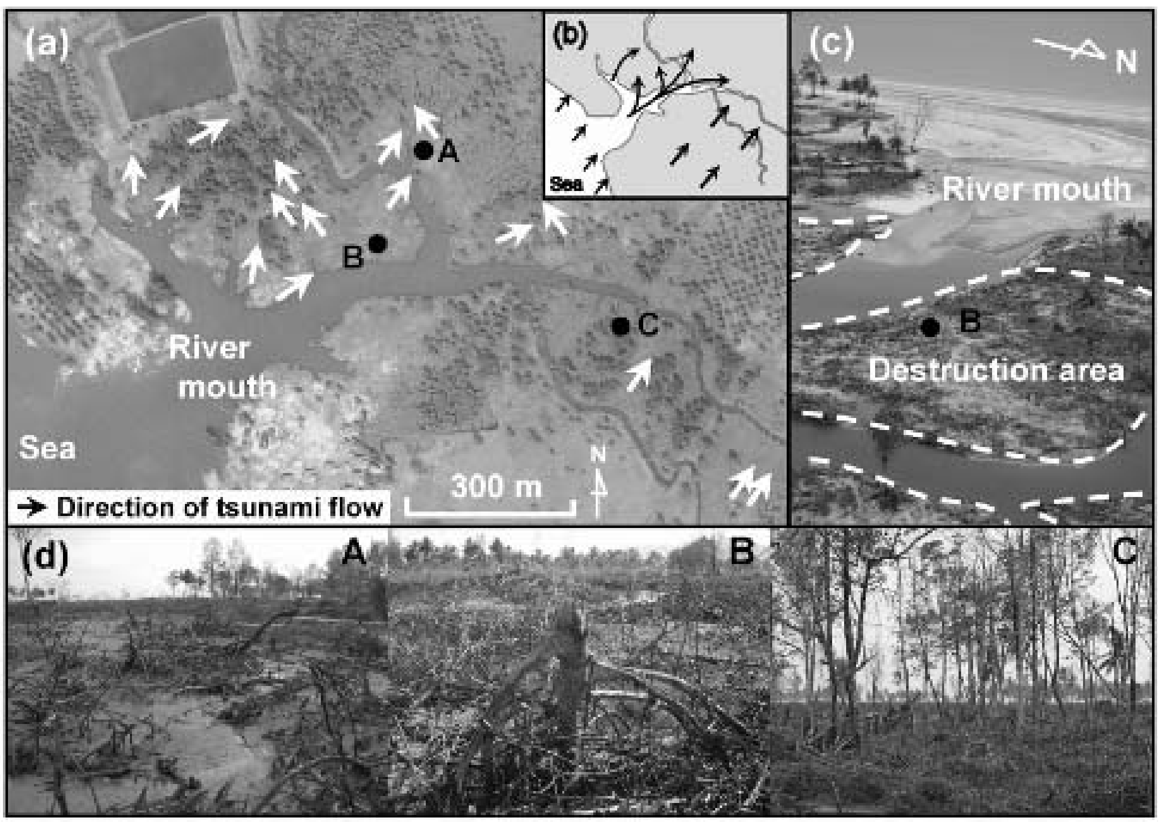

Fig. 4. (a) Satellite imagery after the tsunami event with vectors of tsunami flow inferred from the trapped debris or fallen trees. (b) Trend of the dominant tsunami flow inferred from (a). (c) The destroyed mangrove area photographed from a helicopter (February 2006). (d) Mangrove trees photographed at A, B, and C in Fig. 4a. Photographs A and B show mangrove stumps of destroyed trees; photograph C shows surviving mangrove trees after the tsunami.

5b (up to 75 m from the river channel), mangrove trees were heavily damaged and only stumps remained (Fig. 5cD). On line E (75–170 m from the river channel), however, mangrove trees were mostly inclined without breaking. Some survived the tsunami event. The direction of inclination is mostly inland from the river channel (Fig. 5cE). Tree damage (including inclined trees) was up to 170 m inland from the river channel; mangrove trees were scarcely damaged on line F (Fig. 5cF). Damage from the tsunami was strong near the river channel and weakened concomitantly with distance from the river channel inland.

Numerical Modeling Results

We simulated the 2004 Indian Ocean tsunami using nonlinear long-wave theory to investigate the local behavior of tsunami flow attributable to the topographic features. We first compared the tsunami record measured using a tide gauge at Kuraburi [23] with computed results to validate our numerical modeling result (Fig. 6a). According to the measured data, the tsunami wave with 85 min wave period and 0.76 m height reached Kuraburi 153 min after the earthquake [23]. The computed arrival time, wave period and height of the tsunami were consistent with the measured data [24] (Fig. 6a). Figure 6b also presents a comparison between observed tsunami heights [12, 13] and the maximum tsunami heights computed from our model along the southern Thailand coastline. The numerical model results were approximately consistent with the observed tsunami height, except for the greater than 10-m values observed from Pakarang Cape to Kuraburi. The exceptionally great tsunami heights measured on trees [13] might have resulted from splashes from tsunami waves [24], which are irreproducible using the numerical model. Based on these validations, we confirmed that the numerical model results are useful for investigating the local tsunami inundation pattern around the mangrove forest at Pakarang Cape and Namkem.

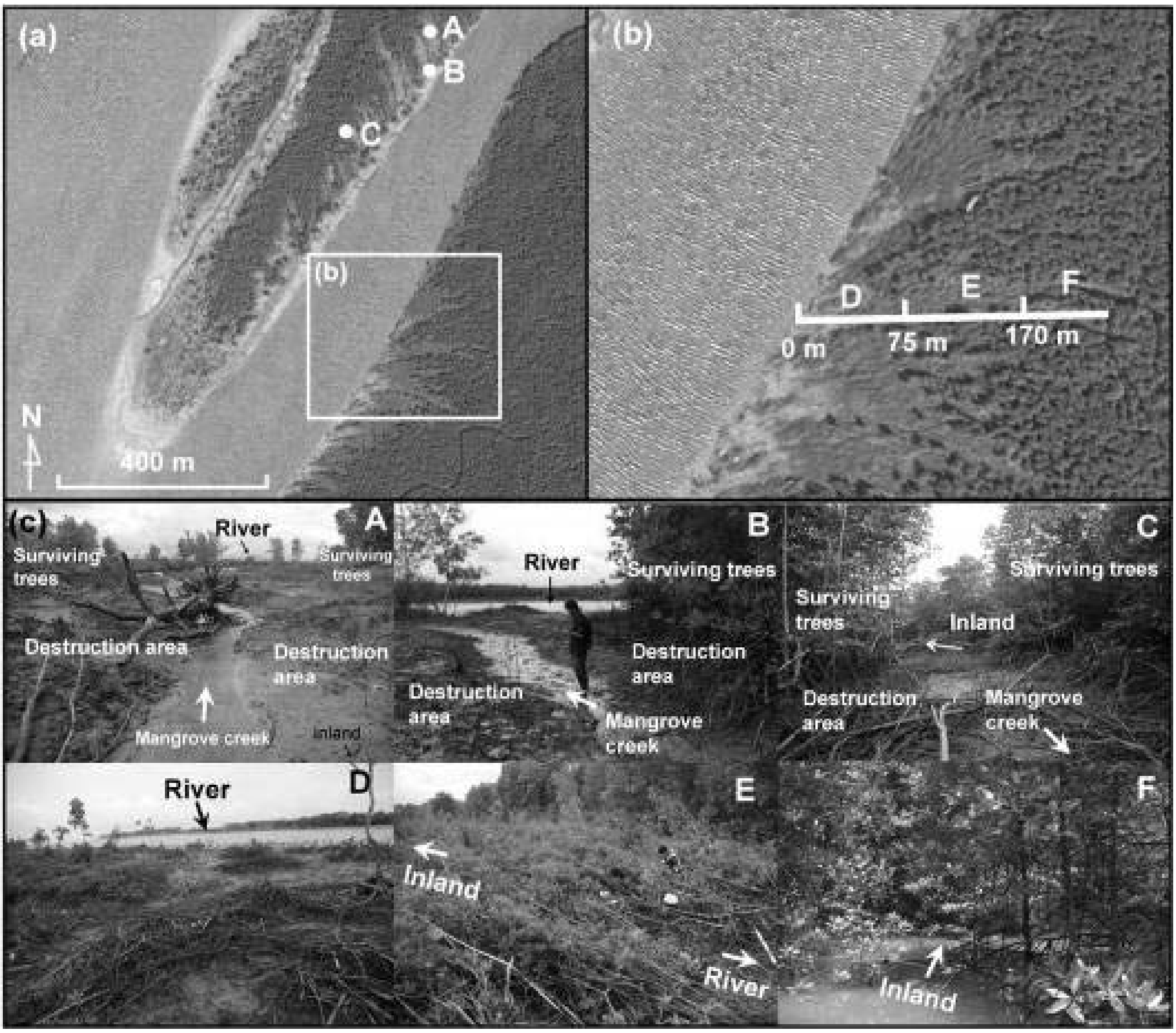

Fig. 5. (a) Survey area at Namkem. (b) The surveyed lines are the following: line A is from 0 m to 75 m from the river channel, B is 75–170 m, and C is more than 170 m inland. (c) Mangrove trees after the tsunami event, photographed at A–C points and on D–F lines in Fig. 5b. Mangrove trees were damaged severely at the side of small creeks in the mangrove forest (A–C points). In addition, mangrove trees were mostly destroyed at line A, inclined without breaking at line B, and undamaged tsunami event at line C.

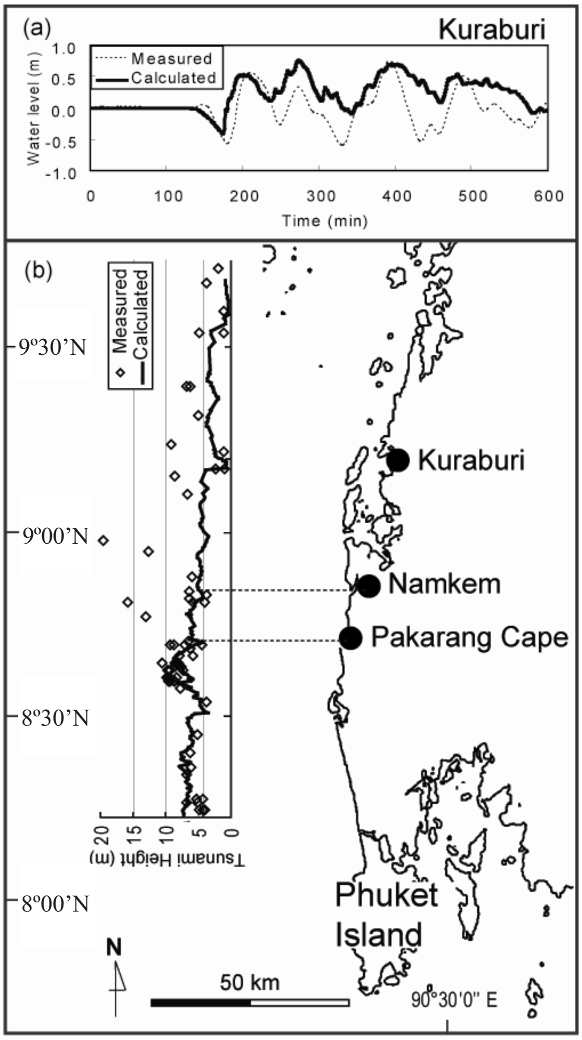

Fig. 6. (a) Comparison between the measured [23] and computed water level at Kuraburi [24]. (b) Andaman coast of Thailand with comparison between measured tsunami heights [12, 13] and computed maximum tsunami heights.

The numerical model results suggest that the first tsunami run-up reached the coastal line of Pakarang Cape 137 min after the earthquake; 10 min later, the tsunami wave reached the Namkem coastline. The computed maximum tsunami inundation depth (from the ground level) in the mangrove forest at Pakarang Cape and Namkem is, respectively, approximately 4-6 m and 2-3 m. Figs 7 and 8 show snapshots of the computed current velocity in the mangrove forests at Pakarang Cape and Namkem. According to Fig. 7, the tsunami waves attacked the coast of Pakarang Cape from the southeast (Fig. 7a). Then, the direction of tsunami inundation flow was changed depending on the topography, for example the tsunami penetrated toward the lowest ground level such as river channel and mouth (Figs. 7c and 7d). In the northern bank, the tsunami propagated from the river mouth and flooded in the mangrove forest through the river channels. In the southern bank, distantly positioned from the river mouth, the tsunami directly inundated from the coast perpendicular to the shoreline. The numerical results agreed approximately with the inundation process inferred from field surveys (Fig. 4b). The tsunami current velocity became highest along the river channels. The wave was estimated to be as fast as 5 $m \cdot s^{-1}$.

At Namkem, the waters in the sea and river receded before the arrival of the first tsunami run-up wave. Then, the tsunami run-up wave attacked the coast and propagated through the river mouth and channels. Although the tsunami partially inundated the southern edge of Kho Kao Island, the tsunami could not have covered the entire island because the ground level in the middle of Kho Kao Island is high (Fig. 8). Consequently, the inundation process into the study area was mostly from the river channels. The computed wave celerity (which is the velocity of wave propagation) to run the river channels is approximately 7 $m \cdot s^{-1}$.

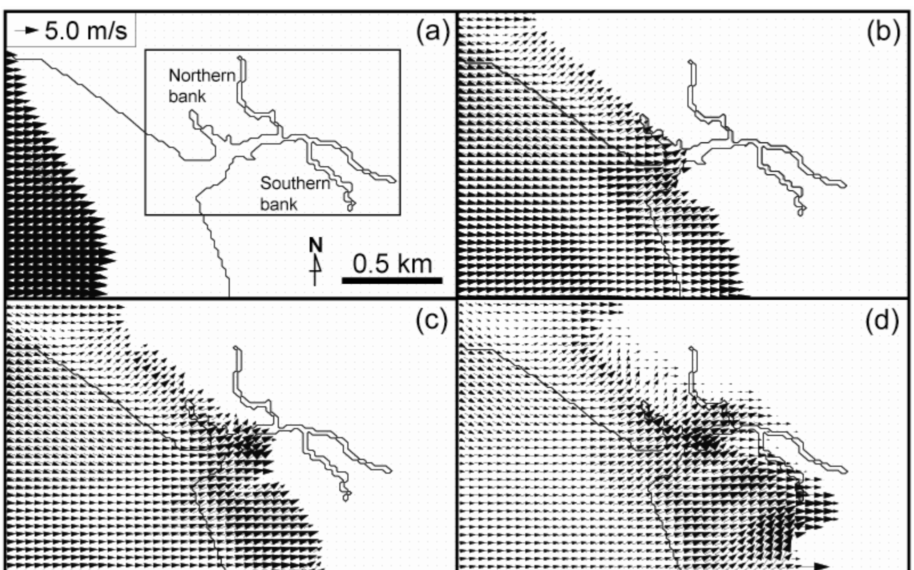

Fig. 7. Snapshots of the computed current field in the mangrove forest at Pakarang Cape at (a) 136 min 12 s, (b) 138 min 36 s, (c) 139 min 12 s, and (d) 140 min 24 s after the earthquake. The square in (a) demarcates the study area. The ground level is less than 5 m around the study area.

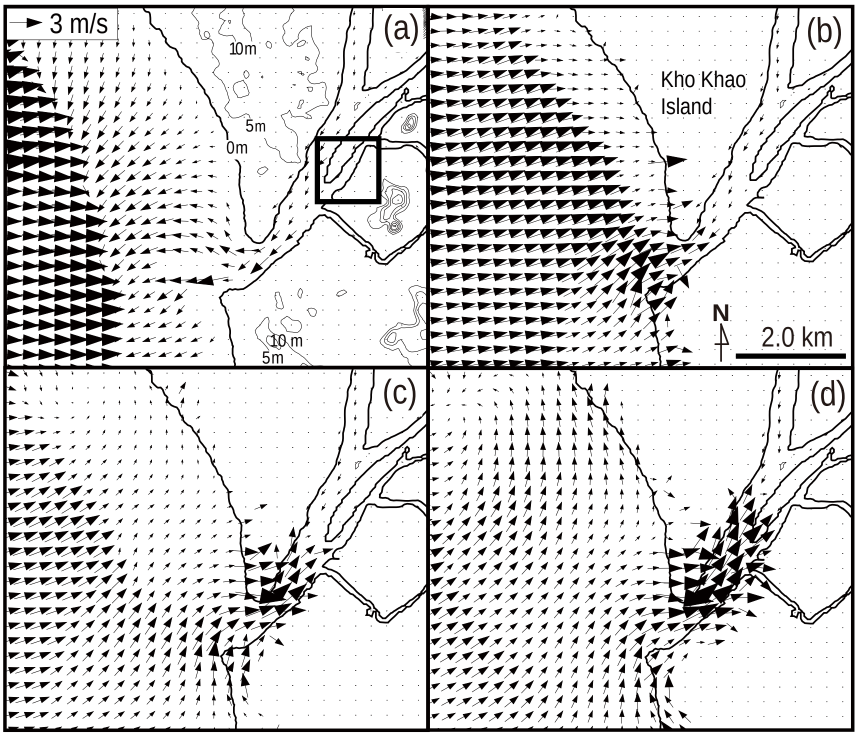

Fig. 8. Snapshots of the computed tsunami current field in the mangrove forest at Namkem at (a) 141 min, (b) 150 min, (c) 153 min, and (d) 156 min after the earthquake. In panel (a), the 5 m interval contour line shows the ground level; the square shows the study area.

Discussion

The role of mangrove forest in reducing tsunami damage to human life or homes has been proposed from field evidence [4, 5]. However, a mangrove forest might be largely destroyed by a massive tsunami impact and might have lost tsunami reduction effects [10, 25]. Therefore, it is important to examine the damage pattern of mangrove trees to find the limitations of their mitigation effects. Wolanski [2] empirically determined that mangrove trees might be mostly destroyed by more than 6 m tsunami inundation depth and that tsunami impacts cannot be reduced by mangrove forests in this case. Shuto [25] also suggested that coastal trees (Japanese pine) were partially damaged by 4 m tsunami inundation depth and mostly destroyed by 8 m tsunami inundation depth. Yanagisawa et al. [10] showed that more than 50% of mangrove trees (*R. apiculata*) with 20-25 cm stem diameter were destroyed by 4-6 m tsunami inundation depth. In this respect, the proposed tsunami heights that induce the extensive destruction of coastal trees are similar among cases. However, results of the previous studies might depend on site conditions such as specific tree condition (stem diameter, density of trees and dominant species), local behavior of a tsunami, and topography [10]. Therefore, we must carefully examine the above empirical results, collecting more field evidence in the future.

Topographic features around the mangrove forest are also an important factor affecting the destruction of mangrove trees. In general, tsunami flow concentrates in the lowest ground area and the area is prone to be damaged severely. In fact, analyses of remotely sensed images at Pakarang Cape revealed that mangrove trees around the river mouth and channels, where the ground level is the lowest, were heavily damaged. According to the tsunami flow direction inferred from the field surveys at Pakarang Cape, several tsunami flows headed inland from the river channel around the severely damaged area located near the river mouth, which is probably true because the tsunami flooded mangrove forest from the river channel and directly inundated those areas without energy consumption from the beach ridges. Our numerical model results also suggests that the tsunami partially propagated along the river mouth and channels. All these results show that the tsunami propagated through the river mouth and channels, and extended the damage of mangrove forests along those areas.

Field surveys at Namkem also indicate severe destruction of mangrove forests along the river channel and small creeks. We confirmed that the tsunami flow concentrated in the river mouth and inundated mangrove forest through the river channel, where the ground level is the lowest, using a numerical simulation. The tsunami flow concentration in the lowest ground area such as the river channel and small creeks might extend the damage to mangrove forests.

After the 2004 Indian Ocean tsunami, plantings of mangroves have been conducted in damaged areas as a tsunami disaster countermeasure [7]. However, mangrove forests might be heavily damaged by a devastating tsunami [2, 10, 25]. Particularly, mangrove trees at the river mouth, channels, and small mangrove creeks might be damaged severely. For that reason, the mitigation effect of mangrove forest in such areas must not be overestimated. To evaluate a fragile area of mangrove forest, it is important to estimate, using the numerical model [10], the mangrove areas that are prone to confront a concentrated tsunami flow and incur damage.

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