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Do mangroves have the potential to mitigate tsunami damage?

−A case study of Godawaya on the southern Sri Lankan coast after the 2004 Indian Ocean Tsunami −

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Abstracts: We investigated a 20 m-wide mangrove forest that was said to have mitigated damage from the 2004 Indian Ocean Tsunami in Godawaya on the southern coast of Sri Lanka. The narrow mangrove forest along a lagoon, which was located on the landward-side of a sand dune, was observed to weaken the tsunami wave that came over the sand dune area between the sea and the lagoon. A family living inland on the opposite side of the lagoon from the mangrove forest said that the forest appeared to reduce the force of the tsunami that came over the lagoon and hit their house. We investigated the characteristics of the mangrove forest which mitigated the tsunami damage and determined whether the mangrove trees that were uprooted or broken by the tsunami were swept inland had caused extensive damage. To determine whether the mangrove diminished the strength of the tsunami at the time the tsunami hit, we attempted to compare inundation height and/or the damage caused by the tsunami between two areas along the lagoon: one with mangroves, and another without. Despite not being able to locate a site without mangrove forest, we identified one case in which the tsunami swept across an area of sand dunes and a mangrove forest before hitting a house. Based on this evidence we propose that mangroves are important for reducing the force of tsunamis and should be maintained as barriers against tsunamis, even in instances where the mangroves are not facing the open sea, particularly in areas where the original coastal vegetation has been lost due to anthropogenic pressure.

1 Introduction

We have been investigating the effects of coastal forests against the Indian Ocean Tsunami of 2004 and the Solomon Islands Tsunami of 2007 (Hayashida *et al*., 2009; Inoue *et al*., 2007; Okada *et al*., 2009; Sakamoto *et al*., 2008a; Sakamoto *et al*., 2008b). In August 2006, we were told that a mangrove forest had mitigated the force of a tsunami in Godawaya, Sri Lanka (Figure 1). This mangrove forest was located along the lagoon behind a sand dune area. There were houses on the opposite side of this forest across the lagoon. A family considered that the mangrove had provided a kind of protection against the tsunami that came over the sand dune area. We investigated this forest as a case study of the potential of mangrove forests to mitigate tsunami damage and whether mangrove trees that were uprooted or snapped off by the tsunami and swept inland had caused extensive damage.

Many reports have written about the Indian Ocean tsunami of 2004 and they mentioned that coastal ecosystems, including mangroves, reduce the devastation caused by the waves (Asian Development Bank, 2005; Bambaradeniya, 2005; Braatz *et al*., 2007; Dahdouh-Guebas, 2006; Dahdouh-Guebas *et al*., 2005; Danielsen *et al*., 2005; Harakunarak and Aksornkoae, 2005; Kathiresan and Rajendran, 2005; Forbes and Broadhead, 2007; Kruse,

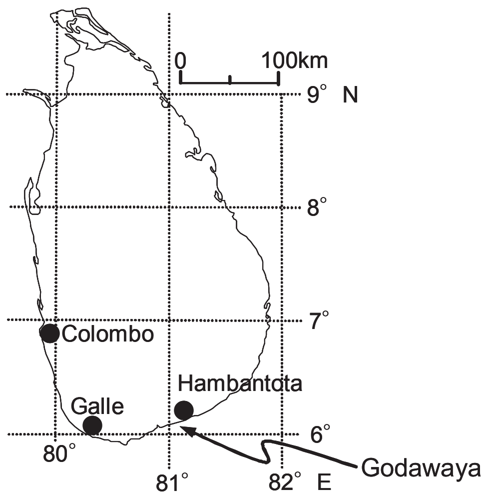

Figure 1: The location of the study area

2005; M.S.Swaminathan Research Foundation [19]; Tanaka *et al*., 2006; Toepfer, 2005; UNEP [28]; United Nations Environment Programme and Ministry of Environment and Natural Resources of Sri Lanka, 2005) and healthier ecosystems have been less affected by the tsunami (Asian Development Bank, 2005; UNEP [28])

Coastal reforestation projects after the tsunami have been promoted based on such reports. As Kerr and Baird (2007) stated, however, “the science upon which these coastal reforestation projects are based is unconvincing; nearly all of the primary accounts supporting a mitigating role for vegetation during the 2004 tsunami are anecdotal.”

For example, Kerr *et al*. (2006) pointed out that the statistical analysis by Kathiresan and Rajendran (2005) was not adequate and concluded “given hamlets of equal elevation and distance from the sea, differences in

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vegetation area did not mitigate human mortality caused by the tsunami." Kathiresan and Rajendran (2006) responded to the remarks, but apparently it was not sufficient.

On this issue, Vermaat and Thampanya (2006) re-analyzed the original data with another statistical method and concluded "the original conclusion of Kathiresan and Rajendran (2005) holds", but they added that "we deduce that mortality was most strongly and significantly reduced with increasing elevation above mean sea level, whereas property loss was governed by distance to the shore." It appears to us that Vermaat and Thampanya (2006) support Kathiresan and Rajendran (2005) but not absolutely.

Danielsen *et al*. (2005) were criticized by Dahdouh-Guebas and Koedam (2006) for concluding that the coastal vegetation acted as a barrier while including a caveat that they did not use important factors. Danielsen *et al*., (2006) replied to the remarks, but it appeared to us that it was not deemed sufficient.

In addition, Chatenoux and Peduzzi (2007) stated "during the present study it was impossible to find patches of mangrove forests located on the coast directly facing open sea" and "the mangrove forests identified in the study were all located in sheltered areas, thus preventing [the investigation of] the potential protecting role of mangrove forests".

While the barrier function of coastal vegetation has been pointed out, it has also been noted that coastal forests sometimes have negative effects (Kruse, 2005); namely, coastal trees, including mangroves, can be uprooted or snapped off at mid-trunk by strong tsunamis and swept inland, potentially causing extensive damage, especially if the coastal forest is narrow.

Thus many reports support the hypothesis that coastal forests, including mangroves, can mitigate damage from tsunamis, but most of them have not sufficiently explained how much protection can be expected from a particular vegetation type from a tsunami of a particular height at the coast.

The report of Tanaka and Sasaki (2007) is one of the exceptions. They quantitatively investigated the effects of coastal vegetation against tsunamis and calculated that the threshold tsunami water depth for bending or breaking of *Pandanus odoratissimus*, a typical species of coastal vegetation, based on field measurements carried out after the 2004 Indonesia tsunami and the 2006 Java tsunami.

Yanagisawa *et al*. (2007) is also one of the exceptions. They estimated destruction limit of mangroves using the relationship between the stem diameter and computed the tsunami bending moment based on field observations and numerical simulations, and they evaluated the potential mitigating effect of mangroves using the numerical model with the destruction limit considered. Using numerical models is practical for further development of this field, because they can consider the influences of differences of some factors. However, the level of knowledge and understanding of the functions of forests and trees in coastal protection is still insufficient (Braatz *et al*. (ed.s), 2007), so it is still necessary to conduct case studies.

2 Survey area and method

2.1 Description of the survey area

The survey area is Godawaya which is a small fishing hamlet located 8 km west of Hambantota in the southern Sri Lanka [32] (Figure 1). We conducted surveys in August and December 2006, December 2007 and October 2008. Tsunami height marks of 3.8 m above the sea level were recorded at Tangalla, which is located 30 km west of the survey area, and 7.4 – 10.3 m at Hambantota (Shibayama *et al*., 2006).

The west side of the survey area is coastal terrace (Figure 2 : T1). A west − east width of the terrace is less than 0.5 km, and the elevation of it is less than 15 m. An old temple (Gotapabbatha Rajamaha Viharaya, Ggodawaya, Gotapabbatha Temple) and some communities are located on the coastal terrace. It was said that about 2000 people from the Hambantota area stayed at that night to avoid the terror of the tsunami. The southeast side of the terrace is a rocky coast 0.5 km long. A wide alluvial plain along the Walawe Ganga (G) is located in the west side of the coastal terrace. Natural levee (NL) protrudes into the marsh (M).

A 1.5 km long sand beach stretches from the coastal terrace to the cape near the Oasis Hotel (Oasis Ayurveda Beach Resort). A 0.6 km wide sand dune area (D1) has developed from the beach to the lagoon (L1 and L2). The elevation of the sand dune is 2 - 6 m. The eastern part of the sand dune area D1 is higher and the elevation decreases toward the inland side. A run-up wave washed slightly over a sand dune D2 covered with *Casuarina equisetufolium* near the Oasis Hotel but the hotel behind the dune was not damaged.

The inlet of the lagoon L1 that was located between the coastal terrace T1 and the west end of the sand dune D1 was shut by a 2.0 m high and 50 m long beach ridge. The tsunami intruded along the lagoon. The house whose residents thought that mangrove mitigated the

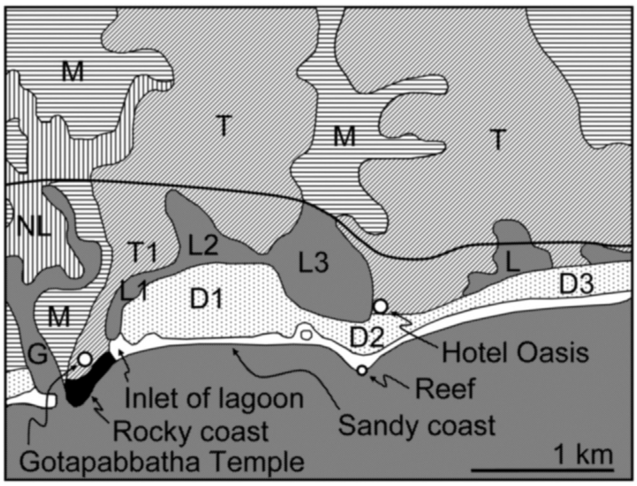

Figure 2: Topographic classification around the study area
T: coastal terrace, NL: natural levee, L: lagoon, M: marsh, D: sand dune, G: ganga (river)

tsunami damage was located 220 - 230 m inland from the inlet of the lagoon (Figure 3: C, Figure 4). The width of the lagoon was 60 - 80 m near the house (Figure 5). This

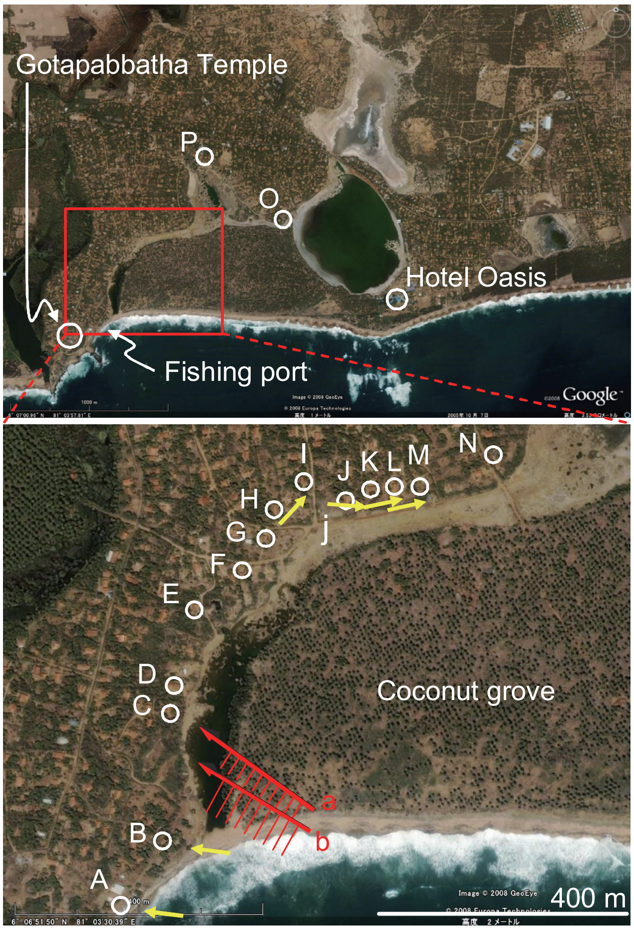

Figure 3: Study area and estimated direction of the tsunami

Yellow arrows: the direction of the tsunami based on the testimonies

Red arrows: the north east margin and the direction of the tidal wave that flowed through the coconut palm grove

a: based on the testimony of the resident of House C and our survey,

b: based on the testimony of the young man who explained in the coconut palm grove

The image was sourced from Google Earth.

lagoon turns east at 430 m point from the shoreline and connects to a 0.11 km^2 lagoon (L2) at 850 m point and a 0.42 km^2 lagoon (L3) at 1300 m point (Figure 2, Figure 3-Upper).

There were mangroves (*Rhizophora apiculata*) growing along the eastern side of the lagoon L1. There was a coconut palm (*Cocos nucifera*) grove on the sand dune area D1. The height of the *Cocos nucifera* was 20±1.3 m and the diameter at breast height was 30±8.3 cm, when we measured 10 sample trees in a standard area. The tree density was 115±12.3ha^{-1}, when we counted it in 4 quadrates (50 x 50 m) at the places where the tsunami flowed on Google Earth.

2.2 Investigation

We recorded eyewitness accounts of the events that occurred along the lagoon (Figure 3). In addition, we interviewed an old man who watched the tsunami at the

Figure 4: The mangrove and the coconut grove along the lagoon,

A: view from the beach ridge shutting the inlet of the lagoon, B: view from near House C

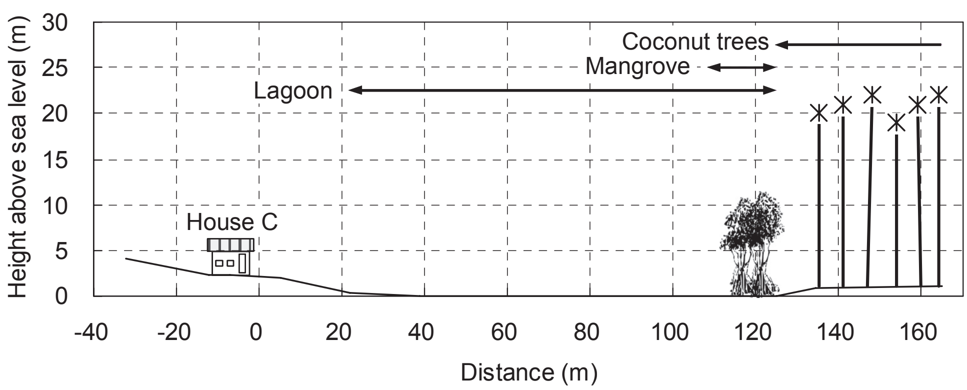

Figure 5: Layout of the mangrove forest and House C

fishing port (Figure 3-A). We asked eyewitnesses about how far the tsunami reached, the direction of the tsunami, the tsunami height, the run-up height, the points the tsunami reached, the changes in the mangrove forest and so on. We also asked the eyewitnesses where they were and what they did when the tsunami came in order to confirm that they had watched the tsunami themselves and were not repeating hearsay, because they sometimes out of kindness offered what they had heard in addition to what they had actually watched. A local interpreter participated in the interviews.

We surveyed the mangrove stand that was believed to have mitigated the tsunami force. We measured the height and diameter of individual trees, and the density and width of the stand, among other things. We also investigated marks from the tsunami that still remained on the mangroves. TruPulse 200 (Laser Technology, Inc., USA), Compass Glass (Shakujii Keiki Seisakusho, Tokyo) and leveling lasers (LP31: Sokkia Topcon Co., Ltd, Kanagawa) were used for the survey.

We measured the topography, the tsunami height and inundation points. The elevation above sea level was adjusted for the tide level at the time the tsunami hit. Model WXTide328 [33] was used to find the tide level correction using the tide level at Galle Anchorage (80°13.0' E, 6°2.0' N).

3 Results and discussion

3.1 Testimonies

A young man whom we met in the coconut palm grove said, "I was on a rock at the fishing port when the first wave came. I was swept way and climbed up into a boat, which was swept way with me but did not capsize. The shoreline went about 100 m seaward after the first wave hit. The second wave brought the boat to the west of Gotapabbatha Temple. When the third and biggest wave came, I was still on the sea. After that, I started the engine of the boat and came back to the coast and escaped to the temple. All fishing huts, about 15-20, were washed away." As we measured the direction that he pointed as the direction of the tsunami, it was about 125 °. He also walked in the coconut palm grove with us and showed us the border or edge marking where the tsunami had flowed from the sea to the lagoon across the sand dune area. According to the information on a web site [32], there were 37 fishing huts.

An old man whom we met near the harbor (Figure 3, A) said, "I escaped to Gotapabbatha Temple before the second wave hit and I watched the tsunami from there. The waves hit five times and the last one was the biggest. Three houses were completely destroyed and the fifth waved washed everything out to the sea." This man was the only person who said that the 5th wave had been the largest. The direction that he pointed as the direction of the tsunami was about 100 °. The height of the coconut palm trees that he pointed out as being the highest wave was 5.5 – 6.0 m above the ground. As the elevation was 4.8 m, we assumed that the height of the maximum wave was more than 10 m. Some debris that may have been brought by the tsunami remained on a branch of a tree (*Casuarina equisetufolium*) 3.1 m above the ground.

A young man who lived near the coast (Figure 3, B) said, "The first wave came from the east. I realized that something unusual was occurring by the sound and escaped from the house before the first wave hit. The seawater went offshore after the first wave. I watched the second wave and others from Gotapabbatha Temple. I think the first wave was the biggest. My house remains, but some windows were broken and one of the walls of the home cracked. A house that was located seaward of my house was completely destroyed by the tsunami. Judging from the inundation marks on the wall, I'd say the tsunami height was 205 cm above the floor." "A sand dune whose width was about 100 m had closed the outlet of the lagoon. That sand dune was higher than the present one. The tsunami connected the lagoon and the sea. The sand dune had been cut to connect the lagoon with the sea for draining inland floods in the past." As we measured the ground height, 205 cm above the floor was 8.2 m above the sea level. The direction that he pointed as being the direction of the tsunami was about 100 °.

A young man who lived in House C (Figure 3, C) told us of his mother's experience. "The tsunami came through the coconut palm grove and a mangrove stand that were located to the east of the lagoon, as well as from the lagoon mouth. The tsunami wave coming through the coconut palm grove and the mangrove forest was as high as half of the mangroves. The tsunami hit five times and the second wave was biggest. The house was inundated to a height above the front door. A table and a cabinet were washed away, though the house was not destroyed. Trees in the garden were not damaged except for Tamarind (*Tamarindus indica*). Some of them were broken. The road located between the lagoon and the house was destroyed. Although there had been many *Excoecaria agallocha* trees between the lagoon and the road, they disappeared. Some of the mangroves along the east bank of the lagoon were washed away upstream and the edge of the mangroves was set back about 3 m. The lagoon became shallow and narrow because of sand deposits." The direction that he pointed as being the direction of the tsunami was about 130 °. According to our measurements, half of the mangrove height was about 6 m above the sea level.

A late-middle-age woman who lived on the coastal terrace behind House C said "I heard a voice for help and I tried to run down the road between House C and House D to House D with a few men. I witnessed the tsunami from the road. While I watched the tsunami, the wave reached the bottom of the window (80 cm above the ground, 3.1 m above the sea level). I thought that the wave at the lagoon was as high as my height (about 1.4 m). The first wave went upstream very fast with a big sound. Then the seawater moved off-shore very fast. I witnessed it from Gotapabbatha Temple before the second wave came. I saw two tsunami waves and the second one was bigger. I was told that there were three tsunami waves, but it seems like I did not see the second of the three waves." She continued, "Although the sea and the lagoon had been divided by the sand dune, they were connected by the tsunami. About one month after the tsunami, I could walk between the lagoon and the sea because sand had been deposited at the outlet of the lagoon. I have been here since 1976 and the lagoon and the sea had not been connected. I was told that people had dug a trench at the sand dune to get rid of inland flood water in the past."

A man in his sixties who lived in House E (Figure 3, E) said, "One tsunami wave reached here. Water reached the lower end of the window frame. The wave also reached to where a faucet was on the inland side. The floor of the house cracked." According to our measurements, the height of the lower end of the window frame was 103 cm above the ground and 4.0 m above the sea level, and the ground height where the faucet was located was 3.1 m above the sea level.

A late-middle-age woman who lived in House F (Figure 3, F) said "I heard the sound of the first wave, but I did not witness it. The inundation height of the second wave was 30 cm above the floor. The wave was too fast to describe. The house was not damaged." Our measurements showed that 30 cm above the floor was equivalent to 2.9 m above sea level.

A young man who lived near House G told us where the tsunami reached. Our measurements of the ground heights that he pointed on the road near Houses G and H (Figure 3, G, H) as the wave reached were 2.8 m and 3.0 m above the sea level, respectively.

A man in his sixties who lived in House I (Figure 3, I) pointed to the height that the wave reached on the fence at the entrance from the road to his garden. The height was 85 cm from the ground and it was equivalent to 3.2 m above the sea level. "The tsunami seemed to go through the garden parallel to the lagoon rather than climb up from the lagoon". According to our measurements, the direction that he indicated as being that from which the tsunami was coming was 225 °. "The tsunami returned to the sea as fast as it came. The mangroves that were flowing had roots that were covered with mud . Cactus flowed into the garden. Sand was deposited in the lagoon. Local residents carried out some deposited sand as building material. The mangroves which were floating in the lagoon were later collected as firewood." He continued, "The sea and the lagoon were connected by the tsunami. The sand dune will be excavated to drain water from the lagoon during future floods. The lagoon had not been connected to the sea from 1969 until the last tsunami."

A middle- age man who lived in House J (Figure 3, J) said "There were 4 or 5 waves between 9:30-16:00. The tsunami water was flowing along the lagoon but it did not rise as it moved toward my house. The first and second waves came from the outlet of the lagoon. They did not cross the coconut grove in front of my house. The second wave was larger. The inundation height of the second wave was 50 cm above the ground at my house." According to our measurements, 50 cm above the ground was equivalent to 3.0 m above the sea level. The man continued, "The speed of the tsunami seemed to me that the wave reached in about one second from that rock about 100 m apart from the house. The wave returned to the sea at a speed that was as fast as people could run. I felt that the wave flowed upstream to the wider part of the lagoon and returned slowly. The second wave flowed faster than the first one. The damage to the house was rusting of steel parts. Big marine fish were carried toward my house, while mangroves were flowing. Pieces of cactus were carried by the wave into my house and utensils were washed away. Marine mud, 5 cm thick, was deposited in the house after the tsunami."

A middle-age woman who lived in House K (Figure 3, K) said, "The tsunami went across the garden but did not reach the house." We measured the ground heights where the wave reached. They were 2.1 – 2.4 m above the sea level. "The wave that went through the garden seemed to come from the direction of House J (277 °) rather than from the lagoon. The height of the wave was over the height of lower coconut palm trees at the lagoon. I witnessed mangroves being toppled by the wave. The tsunami water stayed in the lagoon several days and it seemed to go upstream rather than return to the sea. The tsunami carried sand from the sea to make the lagoon shallow. A road along the lagoon was destroyed by the tsunami."

A middle-age man who lived in House L (Figure 3, L) said "The tsunami wave came onto my property, but it did not reach the house." According to our measurements, the ground height at the place the man pointed as being where the wave went through was 2.1 m above the sea level. "Three waves came and the first one was biggest and was flowing for about two or three minutes." The direction which he pointed as being where the tsunami had flowed from was 261 °.

A middle-age man who lived in House M (Figure 3, M) said "There were two tsunami waves. The first wave was larger. It came onto my property, but it did not reach the house. Sand was deposited in the lagoon. The wave did not come from the coconut palm grove on the opposite shore of the lagoon." The direction which he pointed as being that from which the tsunami had flowed was 261 °. According to our measurements, the ground height at the place he pointed as being where the wave went through his garden was 2.0 m above the sea level.

A late-middle-age man who lived in House N (Figure 3, N) said "I witnessed the tsunami from my property and the road. Although four waves came, I did not witness the first one since I was at a higher place when it came. The tsunami wave containing sand returned to the sea. The tsunami water stayed in the lagoon for two or three days. The tsunami came into the sand dune area and the coconut palm grove, but only the seaward part. Cactus was being carried away, but mangrove trees were not. A boulder that was too big to move by hand was deposited there from downstream by the tsunami. Although black clay was deposited, sand was not and the lagoon did not become shallow." We measured the ground height at the place he pointed as being where the wave went through. It was 1.3 m above the sea level.

A late-middle-age woman who lived in House O

(Figure 3, O) said, “The tsunami reached my house once. Furniture, cactus and other things were being carried toward the house. The tsunami water stayed for about one day. Something like black clay was deposited. Parts of the lagoon became shallow.”

A late-middle-age woman who lived in House P (Figure 3, P) said, “Only one mangrove with roots was carried toward my house. Two boats had drifted ashore. Sand was not deposited but something like black clay was deposited. The tsunami water stayed for about 2 hours but did not reach the shore.”

3.2 Mangrove stand

The mangrove stand was composed of a kind of Indo-West Pacific stilt mangrove (*Rhizophora apiculata*). The mangroves were growing in a strip about two or three mangroves wide along the lagoon at the part where the mangrove trees had not been disappeared by the tsunami. The width of the mangrove stand along the cross line from the sand dune area to the lagoon was 8.3 - 13.6 m. Our count of the mangrove trees at three places along the lagoon showed that there were 10 trees/24 m, 15 trees/24 m and 8 trees/20 m, namely 2.4 m/tree, 1.6 m/tree and 2.5 m/tree, respectively. That is, the area of aerial roots of the average mangrove tree was smaller along the lagoon and larger across the lagoon. Our measurements of the elliptical areas occupied by the aerial roots of mangrove trees showed the length to be 3.2 -6.8 m along the major axis and 2.4 - 4.2 m along the minor axis.

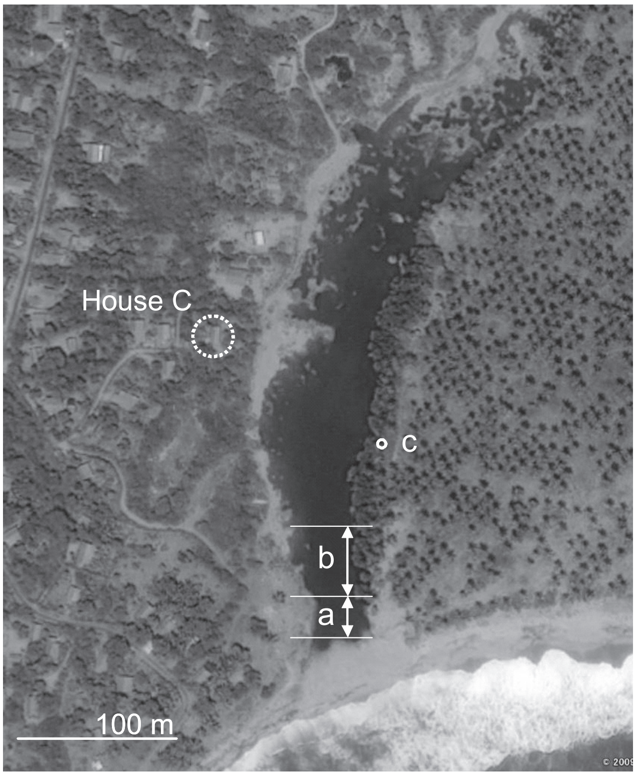

Figure 6: The area where mangrove trees were washed away
a: The mangroves were completely washed away.
b: The mangrove trees by the side of the lagoon were washed away.
c: Tsunami marks were found.
The image was sourced from Google Earth.

The mangrove trees were 9.5 - 12.5 m high and their aerial roots were 2.5 - 3.0 m high. Our count showed 17, 8, 9, 12, and 9 aerial roots in five 50 cm x 50 cm quadrates, respectively. That is, the density of the aerial roots was 44 ± 14.7 per square meter. The diameters of the aerial roots were 3.1 ± 0.7 cm.

There was testimony that a part of the mangrove stand was destroyed by the tsunami, and it was witnessed that the mangroves were flowing at the 550 m and 600 m points (Houses I and J). At the 550 m point (House I), witnesses said that mangroves with roots were flowing.

Judging from the situation of the mangrove stand and the topography, it appeared that before the tsunami, mangroves had been growing from the seaward edge of the existing mangrove forest to 22 m seaward (Figure 6). In addition, mangrove trees by the side of the lagoon were washed away from the seaward edge of the existing mangrove forest to 46 m inland. This is in agreement with the testimony from the House C resident that “the edge of the mangrove was set back about 3 m”. It appears that these mangrove trees were seen flowing at the upstream points. There was no testimony about the swept mangrove trees causing extensive damage.

Tsunami marks, namely from cactus and the husks of coconuts, were found on the branches of the mangroves. We did not find any situation in which the tsunami which came over the sand dune area had knocked down a mangrove or had receded along the coconut palm grove side. However, mangrove stands that were by the side of the lagoon were partially or completely washed away.

There was no testimony about the coconut palm grove suffering from tsunami damage, and no damage could be found there.

3.3 Overview of the tsunami

We will reconstruct the tsunami by integrating the testimonies and the results of field surveys. As some testimonies contradicted each other, we focused on the common elements to grasp the general characteristics of the tsunami.

3.3.1 Number of waves

It seemed that the tsunami could be divided into five waves by integrating the testimonies, although the number of waves was not the same among the witnesses. The tsunami, however, seemed to reach House O which was located at the mouth of a big lagoon, 1300 m from the shoreline along the lagoon, only once. After some discussion, our consensus was that the second wave seemed to be largest, although there was an inconsistency in testimonies.

3.3.2 Direction of the tsunami

The tsunami seemed to come from 100 °, according to the witness at the coast (Point A) and at House B which was near the coast. According to the testimony of those who witnessed it from either the seashore or the sea, it was about 125 °. There was testimony from the resident of

House C, 225 m from the shoreline, that the wave had come through the coconut palm grove in the sand dune area that was located east of the lagoon in addition to the wave coming up along the lagoon. The direction of the tsunami at House C was 130 °.

Although the lagoon went north almost perpendicular to the seashore near the outlet of the lagoon, it had turned sharply eastward between the 430 m point (House F) and 550 m point (House I). As the directions of the witnessed tsunami were 225 ° at House I, 277 ° at House K, and 261 ° at Houses L and M, the tsunami seemed to flow along the lagoon and change its direction

Because only the resident of House C had said that a wave had come through the coconut palm grove and the mangrove, the testimonies did not clarify the position where the wave which came through the coconut palm grove and the mangrove reached along the west of the lagoon. It seems to have been seaward of House C that was on the extension of the wave which had come through the coconut palm grove and mangrove, and there was no direct influence of the wave which had come through the coconut palm grove upstream of House C, based on the mark left along the mangrove stand and the testimony about the mark that the tsunami left in the coconut palm grove.

3.3.3 Height of the tsunami

According to the accounts about the road along the coast (Point A), the highest points of the inundation were 5.5 - 6.0 m above the ground. These heights exceeded 10 m above the sea level. In addition, the inundation height at House B seemed to be 8.2 m above the sea level based on the testimony about the tsunami mark on the wall of the house. As Shibayama *et al*. (2006) recorded a tsunami inundation height of 5.1 - 7.0 m at Hambantota, about 8 km to the east, a larger tsunami than Hambantota might have hit the study area.

As the inundation height was 2.3 m above the ground (4.5 m above the sea level) at House C which was 225 m inland along the lagoon, it was much lower compared with Point A and House B which were near the coast. Although the inundation height decreased to 0.8 m above the ground (3.2 m above the sea level) at House D (260 m point), there was a possibility that it was higher, because the information about the inundation height at House D was not acquired at the time when it was highest.

We measured an inundation height of 4.0 m above the sea level on the wall of the house and a run-up height of 3.1m above the sea level in the garden at House E. If the wave had hit the house wall and risen along the wall, then the actual height might be close to the value in the garden. That is, it may be more suitable to assume that the inundation height at House D was underestimated and the inundation height at House E was overestimated. If that was the case, then the reduction of the tsunami from House C to House F becomes more continuous than that which is illustrated in Figure 7.

The most likely reason why the tsunami height increased from 2.8 m to 3.2 m above sea level between the 505 m point (House G) and the 550 m point (House I) was the influence of the eastward curve of the lagoon . That is, it seemed that the wave which came north along the lagoon did not turn east immediately but it went straight on and ran up the slope of the curved corner. It can be interpreted that the directions of the wave, namely 225 ° at the 550 m point (House I), 277 ° at 635 m (House K) and 261 ° at 670 m (House L) and 720 m (House M), also indicate that the wave swelled outside at the curved area of the lagoon.

The tsunami height decreased gradually to 2.4 – 1.3 m above the sea level along the straight part, 635 – 830 m (Houses K - M) upstream from the curved area.

According to the eyewitness accounts, the tsunami flowed across the gardens and the roads which went inland rather than running up the slope which continued from the lagoon at the 550 m point (House I) and points upstream. Therefore, they were interpreted as the inundation heights rather than run-up heights even if the points where the tsunami reached were on the ground surface at the 505 m point (Point G) and upstream. The testimony of the resident of House J, who said that the tsunami water was flowing along the lagoon but did not rise as it moved toward his house from the lagoon also supported this.

As mentioned above, the tsunami that hit House C was clearly higher than that which hit houses further upstream, indicating that the tsunami which came through the coconut palm grove and mangrove hit House C, whose

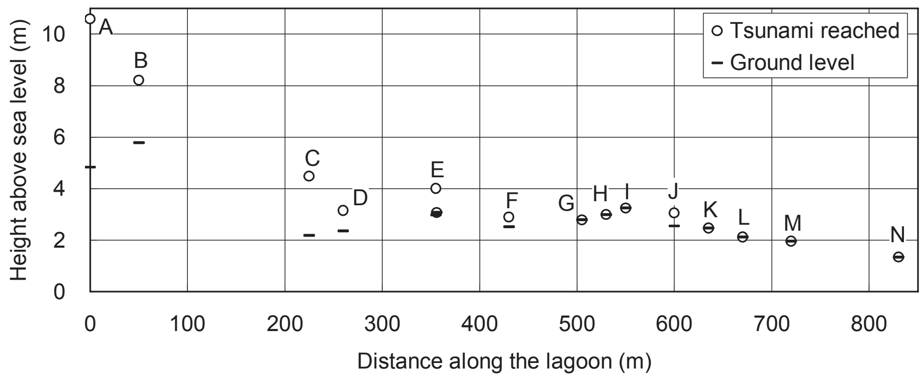

Fig. 7 Ground height and the tsunami height

residents stated that the mangrove on the opposite shore mitigated the tsunami force.

3.3.4 Floating debris and sand deposits

Mangroves and cactus were observed as floating debris. However, there was no testimony that this debris increased the damage caused by the tsunami. Sand was also carried by the tsunami. According to the eyewitness accounts, sand was deposited in a long area from 225 to 720 m point (Houses C – M) and the lagoon became shallow.

3.3.5 Rupture of the beach ridge

The lagoon and the sea were divided by the beach ridge when we conducted our survey. However, since there were accounts that the tsunami returned with remarkable speed, it was assumed that the lagoon had been connected to the sea at that time. Therefore we asked at House B, D and I whether the lagoon was connected to the sea before or at the tsunami hit. We were told that the beach ridge was destroyed by the tsunami.

4 Conclusion

To determine whether the mangrove diminished the strength of the tsunami at the time the tsunami hit, we attempted to compare inundation height and/or the damage caused by the tsunami between two areas along the lagoon: one with mangroves, and another without. Despite not being able to locate a site without mangrove forest, we identified one case in which the tsunami swept across an area of sand dunes and a mangrove forest before hitting a house (House C). Although we were unable to obtain sufficient data to make a direct comparison about the tsunami damage mitigation effect of the mangroves, we could assume that the force of the tsunami had decreased to some extent by the time it came through the mangrove.

As mangrove forests are by nature located in sheltered areas such as in estuaries, areas sheltered by stretches of coastline or in protected bays and are not located along the coast facing open sea directly (Chatenoux and Peduzzi, 2007), mangroves are not located against tsunami so effectively as original seashore or dune vegetation, whose importance as a bio-shield or a barrier against tsunamis could be higher than that of mangroves.

The surveyed mangrove forest was distinctive that it had worked against the tsunami coming over the sand dune area, not against the tsunami coming from the inlet of the lagoon as local residents had stated. Based on this evidence we propose that mangroves are important for reducing the force of tsunamis and should be maintained as barriers against tsunamis, even in instances where the mangroves are not facing the open sea, particularly in areas where the original coastal vegetation has been lost due to anthropogenic pressure.

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