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Hydraulic functions of mangroves in relation to tsunamis

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Abstract: Through field investigations after the Indian Ocean tsunami which occurred on the 26 December 2004 and previous researches in relation to the tsunami control forests, it is believed that mangrove forests along coastal areas protect human lives from tsunamis. Tropical mangrove areas have unique physical characteristics, compared to the coastal areas in middle latitudes. Given these characteristics and the research results on this tsunami, it is suggested that mangrove forests act in two different ways, which protect human lives from tsunamis, depending on their magnitude. Firstly, when the tsunami is of moderate force, the mangrove trees remain standing, preserving their own ecosystem and protecting the human lives behind them. Secondly, when the force of the tsunami is so great to destroy the mangrove forests, the forests protect human lives by sacrificing themselves. There are, however, very few studies on the hydraulic behavior of tsunamis in relation to the peculiar characteristics of mangrove areas. It should be, further, noted that the hydraulic function of tsunami waves in mangrove areas cannot be estimated by interpolation between the previous findings about tidal waves and sea waves in these areas. In order to obtain quantitative findings of a tsunami ' s impact on mangrove forests and to protect human lives and the natural environment in tropical mangrove coastal areas, the following topics urgently need to be studied through interdisciplinary researches between topography, dendrophysics, forest ecology, sedimentology, hydraulics and tsunami engineering; 1) the mechanism of hydraulic resistance in mangrove forests in relation to the time-scale of tsunami waves, under situations not only of standing trees but also of felled trees; 2) the function of tsunami waves scouring the bottom-soil and scooping up underground roots in mangrove forests; 3) the mechanism of deformation/attenuation of tsunami waves at a reef edge and over a wide shallow tidal flat; and 4) the hydraulic criteria which can be used as a quantitative standard for planning tsunami control forests, based on the results in the above 1) to 3).

Keywords: Tsunami, Mangrove, Hydraulic function, Indian Ocean tsunami

1. Introduction

We express our heartfelt sympathy to all people who sustained damage during the disaster caused by several earthquakes and the associated tsunamis which occurred in the Indian Ocean in December 2004. Several researches have been conducted to find out the reasons for such catastrophic disaster in these areas. With a desire to prevent such a disaster from recurring in the future, we wish to highlight some important functions that mangrove forests may have played in shielding human lives from the tsunami, and to propose that a quantitative understanding of the behavior and hydrodynamics of tsunamis especially in tropical mangrove areas is needed urgently.

Danielsen *et al.* (2005) have reported their research results in Cuddalore District in Tamil Nadu, India (Fig.1) just after the Indian Ocean tsunami. A few hamlets behind mangrove forests fringing the coast survived from the attack of the tsunami, even though the waves damaged areas unshielded by vegetation.

Kathiresan and Rajendran (2005) investigated the damage by this tsunami in 18 hamlets along the south-east coast of India. According to their report, there was no loss of human lives in three hamlets, and the human death toll was low in four. All were situated behind mangrove forests. Parish *et al.* (unpublished) collected satellite images (Fig.2) of a western bay on Katchall Island belonging to the Nicobar Islands shown in Fig.1.

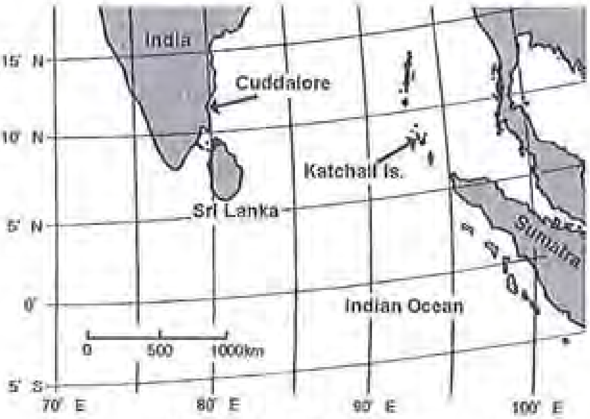

Fig. 1. Map of Indian Ocean

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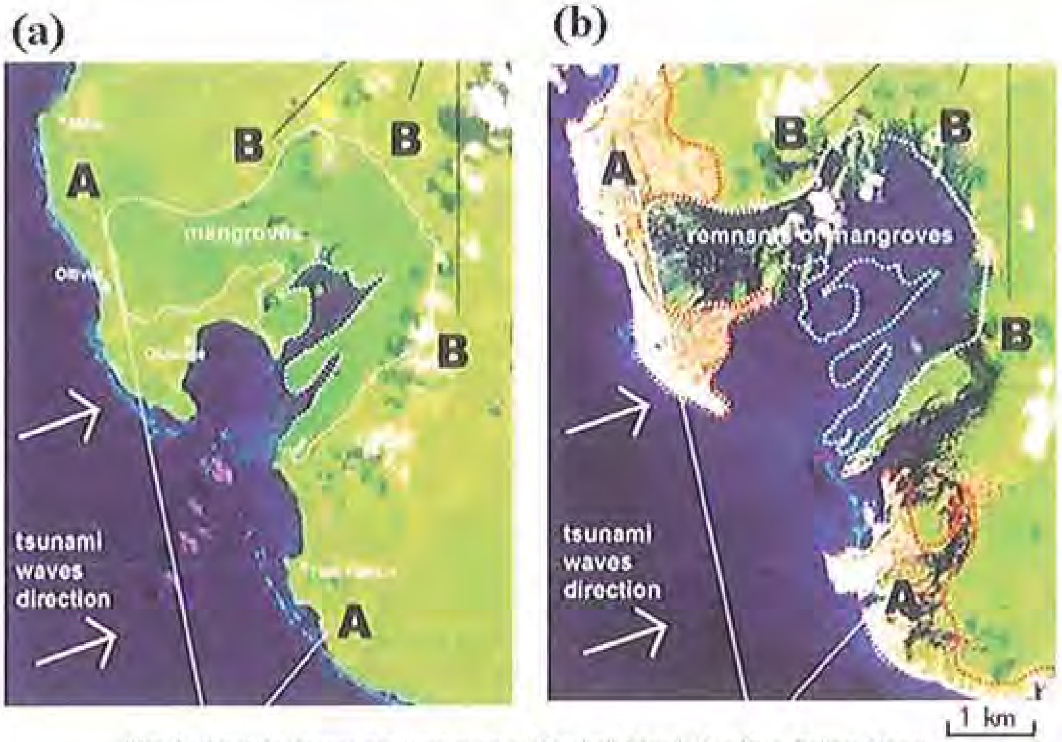


Fig. 2. Satellite images of a west coast of Katchall Island, Nicobars, Indian Ocean
(a) Before the Indian Ocean tsunami occurred on 26 December 2004
(b) After the tsunami

This figure shows the destruction of the mangroves on a large scale by the tsunami and the mangrove's potential protection function. Figures 2a and 2b are the images taken before and after the attack of the tsunami, respectively. The tsunami washed along the white arrows as shown in the figures. The bay area is bordered by a white dotted line. Before the attack by the tsunami, the bay area had been covered with mangrove canopies. After the attack, however, no mangroves could be seen in the bay on the satellite image. This means that the tsunami scoured the bottom soil in the bay and uprooted or snapped off all of the mangrove trees. After the attack of the tsunami, our assessment of satellite images suggests that vegetation and villages in the area marked "B" behind the mangroves were not badly impacted by the tsunami disaster, while villages and agricultural areas marked "A" without mangroves were destroyed or severely damaged by the tsunami. A comparison of these two satellite images suggests that the tsunami was huge, given that all of the mangroves in the bay seemed to have been destroyed. Notwithstanding that, land areas behind the mangroves were protected perhaps by sacrificing mangroves. These observational results suggest a typical function of mangrove forests protecting human lives from tsunamis. Based on these findings, we discuss the hydraulic functions of mangroves in relation to tsunami waves.

2. Systems preventing tsunami disasters

Through previous studies and the field investigation of the Indian Ocean tsunami, the following four kinds of systems, which prevent tsunami disasters, can be pointed out.

1) The system that dams up (reflects) the tsunami energy, protecting useful facilities behind the system.
2) The system that lets the tsunami energy pass through, preserving the system itself.
3) The system that disperses the tsunami energy, both preserving the system itself and protecting facilities behind it.
4) The system that is destroyed by the tsunami energy, sacrificing the system itself but protecting facilities behind it in exchange.

Examples of 1) are artificial tsunami gates and tsunami embankments that reflect the tsunami waves (Tomita, 2005). An example of 2) is a piloti. In coastal zones in Hawaii, it is recommended that the ground floors of houses should be built on stilts alone, without walls

Fig. 3. Examples of mangrove trees

(Urban Regional Research, 1988). Imamura (2005) has also reported the significant effect of the piloti on coastal buildings in Sri Lanka, based on his field research following the Indian Ocean tsunami. In Aceh in Indonesia the only buildings which survived the tsunami were mosques which had large archways and windows which allowed the wave to pass through the lower part of the building. An example of 3) is a tsunami control forest. The tsunami control forests are usually facilitated along the Japanese coasts in order to protect the residential areas from winds, sea waves and storm surges (Harada and Imamura, 2003; Harada and Imamura, 2005). Data from Cuddalore in India mentioned above (Danielsen *et al.*, 2005) also suggests an example of 3). An example of 4) is the case of Katchall Island shown in Fig.2.

In the western bay of Katchall Island, the mangrove forest and the ecosystems were entirely destroyed by the tsunami invasion. However, human lives behind the forest were protected perhaps by sacrificing the forest. Of course, the conservation of mangroves is important from the viewpoints of natural environment, food resources, wood resources and land protection (Vannucci, 1989; Hong and an, 1993). But, mangroves can recover either naturally or through reforestation, although it takes many years (Hong, 2004). As explained in detail in Section 3.2, destroyed mangroves consume tsunami energy greatly, compared to the case of 3). Thus, the function of 4) is very different to that of 3). It should be recognized that the role of mangroves as a sacrifice is very important especially in a worst case scenario such as the huge tsunami that occurred on the 26 December 2004.

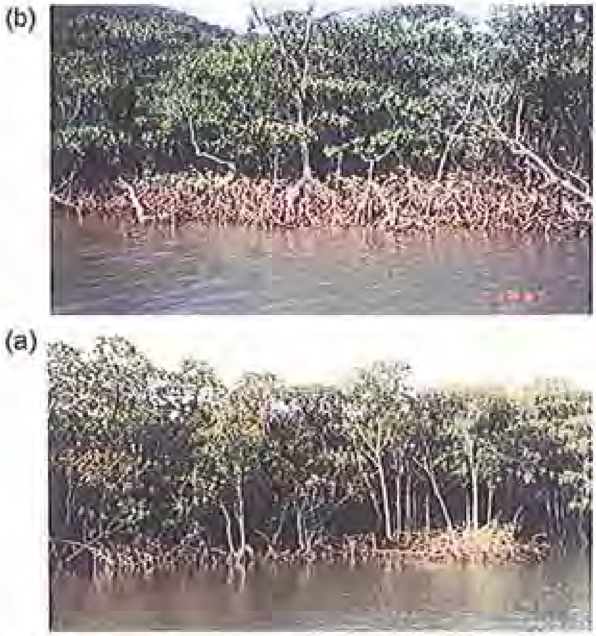


Fig. 4. Mangrove trees (*Bruguiera* sp.) scooped their underground roots and felled by ship waves, along the bank of the Nakama-gawa river in Iriomote Island, Japan

3. Hydraulic functions of mangroves

3.1 Construction of mangrove areas

Mangrove areas in tropical regions have the following unique physical characteristics, compared to coastal areas in middle latitudes.

a) Mangrove forests are reciprocally flooded and exposed to the air with a diurnal or semi-diurnal period.
b) Mangrove trees are closely entangled with each other (Nakasuga, 1991).
c) Mangrove trees have a vertical configuration with roots above and below the ground, plus trunks and canopies (Sato, 1984; Sato, 1989; Mazda *et al.*, 1997b).
d) The underground roots are confined to a shallow depth below the bottom substrate (Komiyama *et al.*, 1989).
e) The extent of spread and the spatial density of roots under the ground are comparable to the total amount of the mangrove trees above the ground (Komiyama *et al.*,

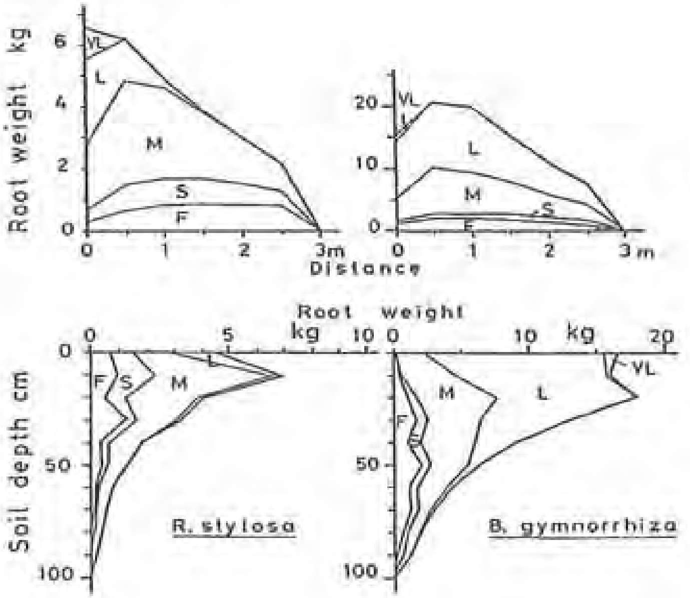


Fig. 5. Estimated root form of *Rizophora stylosa* (left) and *Bruguiera gymnorrhiza* (right) (after Komiyama *et al*., 1989).
F: fine root;
S: small root;
M: medium root;
L: large root;
VL: very large root
Top: horizontal root distribution. Bottom: vertical root distribution.

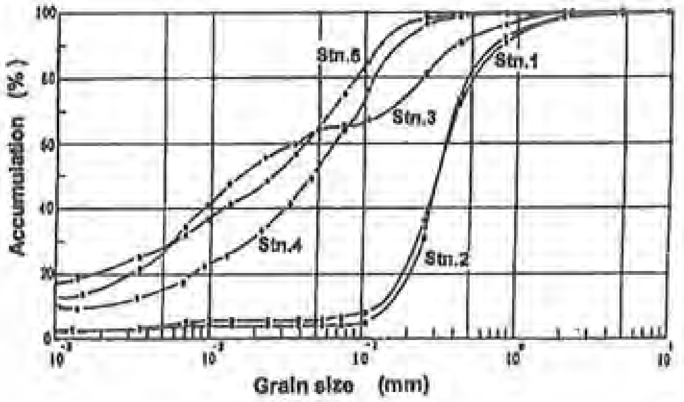


Fig. 6. Grain-size distributions of sediments in a swamp and a tidal creek of the Kesaji-gawa river, Okinawa Island, Japan (after Sato, 1975). Stns.1 and 2 are sites in the tidal creek, and Stns.3-5 are sites in the mangrove swamp.

2000).

f) The bottom soil is loose because of fine sediments, animal burrows and the reciprocating tidal flow over and under the ground (Sato, 1975; Susilo and Ridd, 2005; Mazda *et al*., 2006a).

g) Tidal flats adjacent to the mangrove forests expand widely toward the open sea, and at the end of the tidal flat such as reef edges the water deepens substantially (Mazda *et al*., 2006b).

Depending on these characteristics, mangrove areas have unique hydraulics as follows. Mangrove forests experience flooding every day. The flooding by tidal action, however, is very slow compared to that by tsunamis. The behavior of tsunamis in mangrove forests may depend on whether the tsunami occurs at high tide or at the exposure of the bottom substrate, while tsunamis in middle latitudes always overflow onto the dry land. Further, the flow in the forest depends on the vegetation density. The vegetation density in mangrove forests is very high up to 2 trees/m^2 (Nakasuga, 1991; Mazda *et al*.,1997b), while within pine forests such as tsunami control forests in Japan it is in the order of 0.3 trees/m^2 (Harada and Imamura, 2005). As can be seen in Fig.3, the configuration of mangrove roots above the ground varies by species. The roots of each species individually play an effective role in resisting water flow (Mazda *et al*., 1997a; Mazda *et al*., 2005; Mazda *et al*., 2006b). Figure 4 shows *Bruguiera* species, fringing the Nakama-gawa river in Iriomote Island, Japan. Ship waves induced by sightseeing boats have easily scoured sediment off the creek bottom and the bank, because the soil is loose due to fine sediments, animal burrows and the reciprocating tidal flow over and under the ground. As a result, the underground roots have been exposed, and trees have fallen into water, because the depth of the roots under the ground is less than 1 m (Fig.5). We can also see in Fig.4 that the extent of the spread and the spatial density of the roots under the ground are comparable to the total amount of the trees above the ground. In Fig.5

Komiyama *et al.* (1989) show the spatial distribution of the underground roots. They have stated that the underground roots extended horizontally up to 3 m. Further, Komiyama *et al.* (2000) have stated that in a *Ceriops tagal* forest, nearly 50 % of the total biomass was allocated to the underground roots, compared to 10-20 % in tropical inland forests. These values, though being measured in weight, suggest the importance of the underground roots as hydraulic resistance when the trees fell into the water. Figure 6 shows the distributions of grain size at a tidal creek on the Kesaji-gawa river and fringing mangrove swamps, Okinawa Island, Japan (Sato, 1975). As seen in the figure, generally, the grain-size in mangrove swamps is considerably finer than that in tidal creeks and adjacent coastal areas. Accordingly, the bottom soil of mangrove swamps is easily scoured and swept away by waves and water flows. Generally, mangrove forests contact to the open tidal flats which expand widely toward the open sea over 10 km, and at the end of the tidal flat such as a reef edge the water deepens substantially. This bottom profile typical in tropical mangrove regions is very different to that within middle latitudes.

The following observational results suggest the significant effects of the various characteristics listed above. On coasts in Thailand and Sri Lanka, Sasaki *et al.* (2006) have estimated that the bottom soil in mangrove swamps was scoured to a depth of up to 1 m by the Indian Ocean tsunami. Havanond (2007) has also stated that on the Andaman coast the sediment erosion due to this tsunami was 0.5-2.0 m in depth. Similarly, on an Andaman coast, Miyagi (personal communication) has estimated that the roots of *Avicenia* species were scooped up by the strong water flow caused by this tsunami. Kathiresan and Rajendran (2005) have introduced that the island chain of Surin off the west coast of Thailand escaped heavy destruction, because the ring of coral reefs and mangroves surrounding the island helped to break the lethal power of this tsunami.

3.2 Two systems in which mangrove forests protect human lives

Given the above, mangrove forests can act in two ways, i.e. 3) and 4) classified in Section 2. When the tsunami energy is moderate, the mangrove trees survive or remain standing. In this situation, the terms of b) and c) in Section 3.1 function together to disperse the tsunami energy due to hydraulic resistance. Thus the force of the tsunami doesn't reach deep into the mangrove forests, resulting in the survival of the mangrove ecosystem and the protection of human lives. The following paradox, however, should be noted. The laboratory research by Hamzah *et al.* (1999) has suggested that the water flow velocity behind the mangrove vegetation doubles because of narrowing the flow section when the mangroves vegetate too densely. Further, it is noted that in R-type mangrove forests (see Appendix) the tsunami waves propagate to a long distance upstream through the creek without energy reduction, because there is no vegetation in the creek.

On the other hand, when the tsunami energy is great, the tsunami waves deform into a bore (Sato, 1995), creating a strong water flow due to g), and digging the mangrove roots up from under the ground due to d) and f), felling trees into the water. Since the flood and exposure are reciprocal with the tidal period as stated in a), the bottom substrate always contains a lot of water, resulting in the loose bottom soil which accelerates the above effect. In this situation, considering e) and the fact that canopies dip into the water too, the tsunami energy is effectively dissipated by these strong resistances (canopies, trunks, branches, roots above and below the ground), compared to the former case when the trees stand still normally. As a result, even if the tsunami energy is so great that mangrove forests are destroyed, the land and human lives behind them can be protected by this sacrifice.

It has been pointed out that trees forming coastal forests would be destroyed and washed away by a huge tsunami, causing secondary damage by attacking houses and human lives like floating weapons (Shuto, 1987). However, given that in mangrove areas the fallen trees are restricted to being washed away because of b), it should be noted that human lives behind mangrove forests can be saved. Furthermore, Danielsen *et al.* (2005) and Parish *et al.* (unpublished) have pointed out the effect of mangroves to stop drifts such as floating wood, boats and debris, based on their field investigation just after the Indian Ocean tsunami. In conclusion, mangrove forests can act as two systems against tsunami intrusions. Firstly, when the tsunami energy is moderate, the mangrove trees remain standing, preserving their own ecosystem and protecting the human lives behind them. Secondly, when the tsunami energy is great enough to destroy the mangrove forests, the forests absorb the huge wave energy by sacrificing themselves, protecting human lives.

4. Hydraulic studies within mangrove areas

4.1 Present studies on tsunami control forests

Studies on hydraulic behavior of tsunami waves have been widely conducted (Iida and Iwasaki, 1983; Hebenstreit, 1997; Satake, 2005). As the latest works, Hamzah *et al.* (1999), Harada *et al.* (2000), Aburaya and Imamura (2002), Harada *et al.* (2002), Harada and Imamura (2003), Hiraishi and Harada (2003), Harada and Imamura (2005) and Imai and Matsutomi (2005) have discussed the effect of hydraulic force in tsunami control forests, mainly based on laboratory experiments and numerical simulations. Imai and Matsutomi (2005) have pointed out the importance not only of the drag force due to vegetation but also of the inertial force at the bore-like wave front and the wave-making force due to the shaking of tree foliage. Harada and Imamura (2005) have summarized effects of forest width, vegetation density and wave period on the reduction of tsunamis, and proposed the criteria to identify quantitatively the relation of the tsunami intensity to disaster, which can be used as a quantitative standard to design a coastal forest as a tsunami countermeasure. These studies, however, have not been specifically designed for mangrove areas. On the other hand, Hamzah *et al.* (1999) and Harada *et al.* (2000) have experimented on the behavior of the drag force taking into consideration the vertical configuration of the mangrove trees.

As shown in Appendix, Cintron and Novelli (1984) have classified the mangrove landform into three types, riverine forest (R-type), fringe forest (F-type) and basin forest (B-type). Regarding the F-type and B-type, the tsunami waves intrude into mangrove swamps perpendicular to their coastal lines. For the R-type, however, the tsunami waves go up the creek, and then inundate the mangrove swamp. The behavior of the tsunami going upstream is quite different from that when inundating the mangrove swamp. These different behaviors should be studied separately. It should be noted that since the swamp water is dragged by the flow going up the creek, thus flowing parallel to the creek, the viscous force (shear force) plays an important role as well as the drag force (Asano *et al.*, 2001; Kobashi and Mazda, 2005; Mazda *et al.*, 2005). The viscous force along the creek might reduce the tsunami energy going up the creek. There are, however, very few studies on the tsunami waves which consider these unique characteristics of mangrove areas.

4.2 Differences in the hydraulic behavior of tsunami, tidal and sea waves in mangrove areas

Figure 7 shows the hydraulic resistance of mangrove vegetation in a range of sea waves with a period of less than about 20 seconds (Mazda *et al.*, 1997a). The data was obtained at a mangrove area of *Kandelia candel* in northern Vietnam. The abscissa in Fig.7 is the water depth, which changes with tidal phase, and the ordinate is the coefficient of hydraulic resistance, i.e. the drag coefficient due to mangroves. The magnitude of this coefficient roughly means that of the reduction in wave energy. "A" is the case where there is no vegetation in the area. "B" is the case where 5-6 year old mangroves cover the area. And "C" is the case where mature mangroves cover the area. The difference between A, B and C in Fig.7 suggests that the hydraulic resistance due to mangroves depends on the growth level, i.e. the vertical configuration of mangrove trees. In addition, it seems that the hydraulic resistance depends on the amount of vegetation submerged in the water. Mazda *et al.* (2006a) have also found that the effect of the hydraulic resistance differs considerably between roots, trunks and canopies, based on observations in an area vegetated by *Sonneratia caceoralis*.

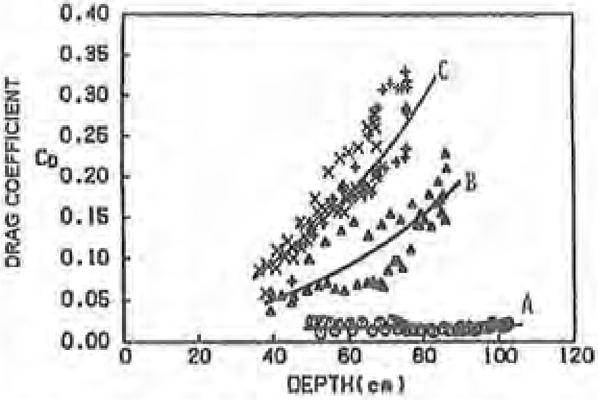
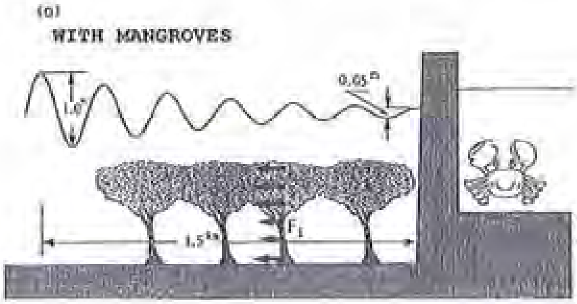


Fig. 7. Variation in the drag coefficient C_D with the water depth (Mazda *et al.*, 1997a).

Figure 8 shows a concrete effect of hydraulic resistance due to mangroves, according to Case C in Fig.7. Within the area investigated, the mangrove trees vegetate with a 1 m interval up to 1.5 km from the coast toward the open sea and 3.0 km along the coast line. The wave height at the point 1.5 km from the coast reduces to 5 % at the coast due to the resistance of the mangroves. If there were no vegetation, 75 % of the wave height at the open sea would arrive at the coast. This result suggests the effectiveness of the hydraulic resistance of mangroves against the sea waves in a typhoon that has wave periods of less than 20 seconds. However, as described below, this finding cannot be directly applied to the case of tsunami waves.

Figure 9 shows the behavior of the coefficient of hydraulic resistance due to mangroves in a range of tidal waves with a semi-diurnal period, based on field observations in many mangrove swamps individually dominated by *Rhizophora* species or *Bruguiera* species (Mazda *et al.* 2005). The abscissa is arranged according to the following parameter, i.e. Reynolds Number.



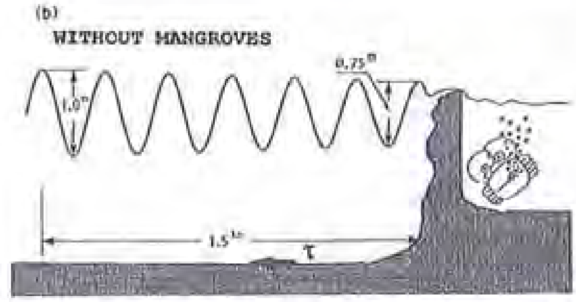


Fig. 8. Differences in the effect of wave reduction (a) with and (b) without mangroves (Mazda *et al.*, 1997a). In (a) the drag force on the plants ΣF_i occurs throughout the water depth. In (b) the bottom friction τ occurs only at the bottom floor.

$$\mathrm{Re} = \frac{uL}{\nu} \text{............(1)}$$

where ν is the kinematic viscosity, u is the water velocity in the swamp caused by the tidal motion, and L is the effective interval between trees, which depends on the vegetation density, the vertical configuration of vegetation and the water depth.

The figure shows that the coefficient of the resistance, which varies within a wide range of 0.5 to 10, depends on the magnitude of L, i.e. the effective interval between trees. On the other hand, for sea waves with periods of less than 20 seconds, the coefficient is at most 0.4, as shown in Fig.7. Further, Hamzah *et al.* (1999) have measured the magnitude of the coefficient as ranging from 0.5 to 1.5 for *Rhizophora* species, based on a laboratory experiment for tsunami waves.

The above findings suggest that the hydraulic behavior of waves in mangrove swamps greatly depends on their periods. Figure 10 shows the spectrum of waves in water areas, after Munk (1951). The abscissa is the period of waves on a logarithmic scale. The periods of tsunami, tidal and sea waves are each very different. The period of tsunami waves is in a range of 10 minutes to 2 hours, and vary different both from the sea waves(< 20 seconds) and the tides with diurnal and semi-diurnal periods. Further, it should be noted that the water velocity in tsunami waves is extremely large compared with those of tidal waves and sea waves. The tsunami thus transcends the range of the abscissa on Fig.9, which is defined by Eq.(1).

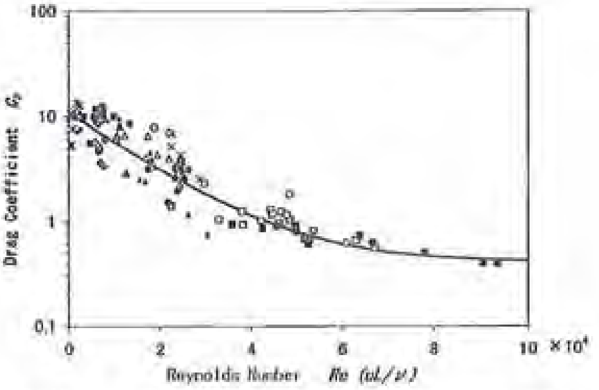


Fig. 9. The relationship between the drag coefficient C_D and the Reynolds Number *Re* (Mazda *et al.*, 2005). The marks indicate the different observation sites and species.

Within the tidal-scale hydrodynamics of mangrove swamps, the inertial force caused by the acceleration of water mass is neglected, because the tidal flow can be approximated to a steady flow (Mazda *et al.*, 1997b). However, as mentioned previously (Imai and Matsutomi, 2005), the inertial force cannot be neglected for the case of tsunami waves, because they are in a transient process with a large acceleration at the wave front. Especially, given g) in Section 3, which is a unique condition in tropical areas, it is suspected that the inertial force plays an important role as follows, compared with those in middle latitudes. Tsunami waves break at coral reef edges, twist their waveform, then arrive at mangrove forests after passing a long distance across a tidal flat as a strong flow with a sharp front like a huge bore. This strong flow with a sharp front is suspected to form a significant inertial force, resulting in great destructive energy to mangrove trees.

In conclusion, as Kathiresan and Rajendra (2005) pointed out, the hydraulic function of tsunami waves in mangrove areas cannot be estimated by interpolation between those of tidal waves and sea waves. We have to investigate separately quantitative behavior of tsunamis in mangrove areas, though the previous findings regarding the hydraulic behavior of tidal waves and sea waves in these areas can be qualitatively referred to for tsunami.

5. Future studies

According to the above discussion, the following studies

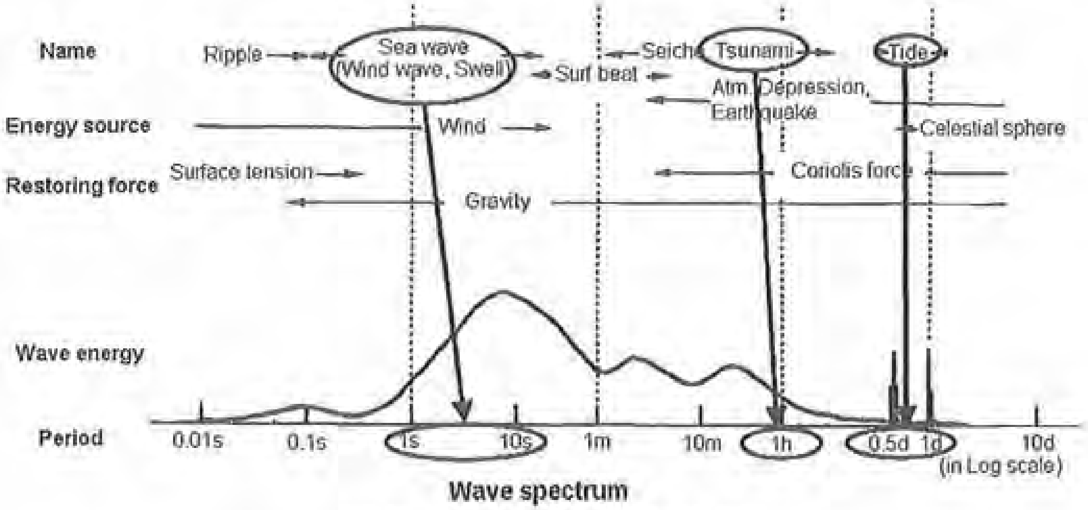


Fig. 10. Wave spectrum (after Munk, 1951).

on tsunamis should be conducted from the standpoint of mangrove hydraulics.

1) The mechanism of hydraulic resistance in mangrove forests in relation to the time-scale of tsunami waves, under situations not only of standing trees but also of felled trees.
2) The function of tsunami waves scouring bottom-soil and scooping up underground roots in mangrove forests, as well as snapping mangrove trunks.
3) The mechanism of deformation/attenuation of tsunami waves at reef edges and over a wide shallow tidal flat.
4) The hydraulic criteria which can be used as a quantitative standard for designing and establishing tsunami control forests, based on the results in the above 1) to 3).

As mentioned previously, since the fallen trees do not drift due to b) in Section 3.1, human lives behind the forest can survive. However, it depends on the vegetation density. Generally, since coconuts, palms and casuarinas in tropical coastal zones don't vegetate closely, compared to mangrove forests, the trees once destroyed by tsunamis drift away, attacking human lives like floating weapons (Shuto, 1987). Furthermore, as mentioned previously, the water flow velocity doubles behind the mangrove trees when the mangroves vegetate too densely, resulting in the destruction of human lives behind the forest. It is feared that the fallen trees play the part of a double-edged sword. In order to find the quantitative relationship between the suitable vegetation density and the force of the tsunami waves, first of all, the above mechanism 1) which controls the hydraulic resistance in densely vegetating mangrove forests have to be analyzed for each mangrove species.

The critical point that mangrove forests can tolerate the tsunami energy depends both on the magnitude of tsunami waves and the hydraulic functions of mangroves. Further, magnitude of the hydraulic function of tsunamis that scours bottom-soil and scoops up underground roots may depend on whether the bottom substrate is in an exposed condition or already in a flooded condition because of the tide when the tsunami arrives. Therefore, the function 2) and the mechanism 3) should be analyzed. Finally, in order to design the coastal mangrove forest as a tsunami countermeasure, the hydraulic criteria 4), which can be used as a quantitative standard, should be formulated according to the findings obtained through the processes 1) to 3), in consideration of the peculiar characteristics of the tropical mangrove areas.

6. Summary

In order to prevent tsunami disasters, there are four kinds of systems classified in 1)-4) of Section 2. As examples of systems 3) and 4), mangrove forests along coastal areas seem to have protected human lives from the Indian Ocean tsunami occurred on 26 December 2004.

Mangrove areas have peculiar physical characteristics, as summarized in a)-g) of Section 3.1. Given these characteristics, it is suggested that mangrove forests act as two systems 3) and 4), depending on the magnitude of tsunamis. Firstly, when the tsunami energy is moderate, the mangrove trees remain standing, preserving their own ecosystem and protecting the human lives behind them. Secondly, when the tsunami energy is great enough to destroy the mangrove forests, the forests protect human lives by sacrificing themselves.

Mangrove roots underground have great spatial density and extent of spread. When mangrove trees fall down, therefore, the underground roots create great hydraulic resistance in the water. At the same time, the resistance of the canopy is superimposed on this resistance. It should be noted, thus, that the hydraulic resistance of felled-mangrove trees plays a considerably different role in a tsunami disaster from that of standing trees.

There are, however, very few studies on the hydraulic behavior of tsunami that take into consideration the peculiar characteristics of tropical mangrove areas. It should be noted that the hydraulic function of the tsunami waves in the mangrove areas cannot be estimated by interpolation between the previous findings about tidal waves and sea waves in these areas. There is a need for interdisciplinary research between topography, dendrophysics, forest ecology, sedimentology, hydraulics and tsunami engineering, in order to obtain quantitative findings particularly of the following topics and to protect human lives and the natural environment in tropical mangrove coastal areas:

1) The mechanism of hydraulic resistance in mangrove forests in relation to the time-scale of tsunami waves, under situations not only of standing trees but also of felled trees.
2) The function of tsunami waves scouring bottom-soil and scooping up underground roots in mangrove forests.
3) The mechanism of deformation/attenuation of tsunami waves at reef edges and over a wide shallow tidal flat.
4) The hydraulic criteria which can be used as a quantitative standard for planning the tsunami control forest, based on the results in the above 1) to 3).

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Appendix

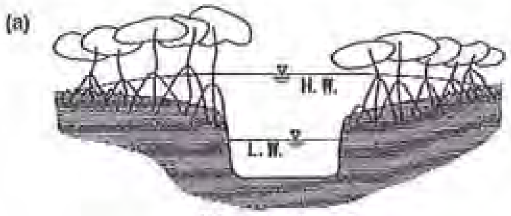
Based on topographical features of mangrove areas, Cintron and Novelli (1984) have classified mangrove landform into three types, riverine forest, fringe forest and basin forest, as shown schematically in Fig.A.

1) Riverine forest (R-type; Fig.Aa) is defined as that found on a floodplain with long tidal creeks, which is inundated by most high tides but dry up at most low tides. Most tidal creeks meander and intertwine with each other. The tidal flow goes up the creek without energy reduction, then inundates the mangrove swamp at flood tide. The swamp water in the vicinity of the tidal creek is dragged by the tidal flow of the creek, thus flowing parallel to the creek, while the flow in the swamp is predominantly perpendicular to the creek due to the water surface slope between the swamp and the creek (Kobashi and Mazda, 2005; Mazda *et al.*, 2005).

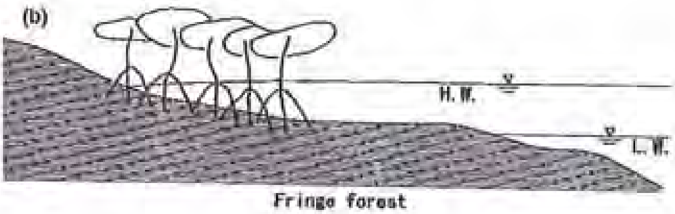
2) Fringe forest (F-type; Fig.Ab) is defined as that found on shores facing open sea, and is directly exposed to the action not only of tidal water but also of sea waves. Sea waves reduce in the swamp because of the resistance of thick mangrove trees and their roots emerging from the soil (Mazda *et al.*, 1997a; Massel *et al.*, 1999).

3) Basin forest (B-type; Fig.Ac) is defined as that found in a partially impounded depression, which is inundated by few high tides during dry season but many high tides during wet season.

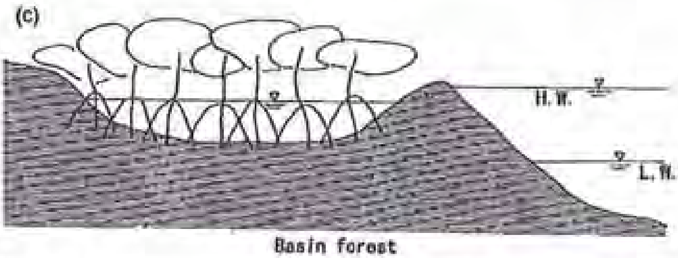
It should be recognized that the dominant water movements differ between the R-type, F-type and B-type



Riverine forest



Fringe forest



Basin forest

Fig. A. Classification of mangrove topography (after Cintron and Novelli, 1984)
(a) Riverine forest type; (b) Fringe forest type; (c) Basin forest type