VEGETATION BIO-SHIELD FOR TSUNAMI MITIGATION: REVIEW ON THE EFFECTIVENESS, LIMITATIONS, AND MANAGEMENT

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ABSTRACT

This paper reviews the findings in previous and our research activities on the vegetation bio-shield in relation to the effects and limitations of coastal vegetation for tsunami mitigation. A two-layer vegetation structure with *Pandanus odoratissimus* and *Casuarina equisetifolia* was proposed to increase the drag force and to trap floating objects. Considering all the findings during the post tsunami researches, we proposed the establishment of a pilot-scale coastal plantation in the Matara Thotamuna area which was severely affected by the Indian Ocean tsunami. Parallel projects were also carried out by many government institutions and NGOs, in an effort to establish a coastal vegetation barrier for tsunami mitigation. A survey was conducted to assess whether coastal vegetation barriers fulfilled the requisites of the bio-shield concept. Some of the projects were not successful due to lack of maintenance. For the proper design of bioshield, more study is needed to clearly elucidate the effects on how vegetation behaves in combination with other physical barriers (i.e. artificial or natural embankments or the raising the elevation of coastal roads) by considering the cumulative vegetation length. It should also be noted that in certain cases the existence of a road or river could accentuate tsunami propagation towards the land.

KEYWORDS: tsunami, vegetation barrier, hybrid barrier system, maintenance of coastal vegetation

1. INTRODUCTION

Coastal vegetation is recognized as a comprehensive strategy to mitigate the destructive force of tsunami events, although it cannot completely stop the tsunami itself and the effectiveness depends on the magnitude of the tsunami and the vegetation structure. Shuto (1987) analyzed the effects and limitation of coastal vegetation in the historical records of tsunamis in Japan. Especially after the 1998 Papua New Guinea tsunami (Dengler and Preuss, 2003), many researchers have begun investigating the effect of coastal vegetation in tsunami mitigation using the water flume experiment (Harada and Imamura, 2000), and field investigations and numerical simulations (Hiraishi and Harada, 2003). After the Indian Ocean tsunami on 26 December 2004, much research was carried out to elucidate the effectiveness of coastal vegetation (Danielsen et al., 2005; Kathiresan and Rajendran, 2005; Harada and Imamura, 2006; Tanaka and Sasaki, 2007; Tanaka et al., 2006, 2007) and coral reefs (Fernando et al., 2005) for minimizing the damage and protecting human lives and the environment. Danielsen et al. (2005) pointed out that mangroves and other coastal vegetation have been cleared or degraded along many coastlines, increasing their vulnerability to storm and tsunami damage and suggested that establishing or strengthening greenbelts of mangroves and other coastal forests could play a key role in reducing the effect of future extreme events. Therefore, natural methods that employ coastal vegetation together with other natural features such as sand dunes and submerged reefs have been studied because they involve relatively little capital investment in comparison to artificial measures, provide human-friendly beach fronts and also enhance inter-relationships with other ecological systems. However, when there was an open gap in the coastal vegetation belt, the tsunami damage could become severe (Fernando et al., 2008, Thuy et al., 2008, 2009). Development of design and management guidelines for coastal vegetation is needed if these new establishments are to be successful projects (Tanaka, 2009).

For the optimal planning of natural systems, we need to elucidate the vegetation effect on reduction in tsunami potential quantitatively. Therefore this paper reviews the findings related to vegetation bio-shield concept in relation to the following areas: 1) effectiveness, 2) limitations, 3) planting situation in Sri Lanka, 4) management, and 5) future research needs. In addition, numerical simulation results in Saitama university are explained from the points of; 1) the appropriate parameters that express the vegetation effect with the change of land slope, 2) effect of the combined system of vegetation and embankment for the application under land-use limitation, and 3) open gap effect on tsunami current. In addition, this paper addresses the effects in reduction of run-up height using a one dimensional numerical simulation model.

2. EFFECTIVENESS OF COASTAL VEGETATION

Energy dissipation effect is discussed mainly by numerical simulation, and it is reviewed in 2.1-2.3. Other than that, Tanaka et al.(2007) described the possible functions that coastal vegetation can potentially perform during tsunami. For any future coastal vegetation management or land-use planning project, the functions below other than energy dissipation should be considered (Fig.1).

(1) Soft-landing effect: People caught up in the waves can have a better chance of survival by landing on tree branches if a tree species has dense branches and leaves.

(2) Trapping effect: During a tsunami, man-made debris (cars or pieces of destroyed property) will also be washed away injuring people. However, large-diameter trees can trap such debris. In particular, if a mangrove forest is located behind a sand dune, it could trap most of the debris and prevent the buildings behind the forest from being damaged.

(3) Escape effect: People can also ride out the tsunami by climbing trees. The effective trees types in this regard are *Thespesia populnea*, *Pongamia pinnata*, and *Terminalia catappa*.

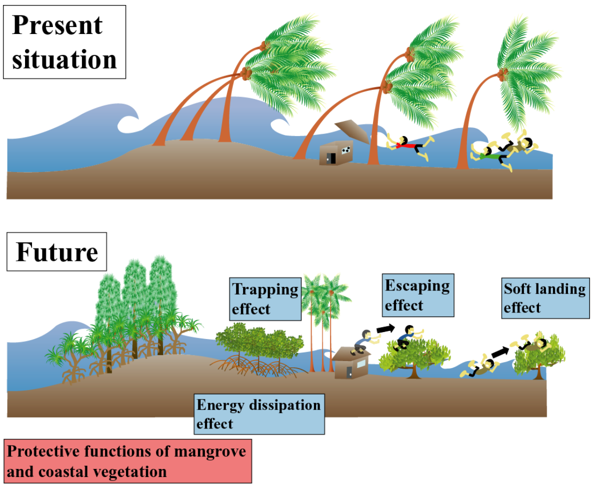


Figure 1 Functions of coastal vegetaion for tsunami (modified from Tanaka et al., 2007)

2.1 Numerical simulation1(N1): bed slope and species difference on tsunami reduction (Iimura & Tanaka, 2008)

2.1.1 Governing equations

One dimensional depth averaged equations were developed with the drag force correction to analyze the flow through vegetation as follows.

Continuity equation

$$\frac{\partial \zeta}{\partial t} + \frac{\partial Q}{\partial x} = 0 \tag{1}$$

Momentum equation

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{h+\zeta}\right) + g(h+\zeta)\frac{\partial \zeta}{\partial x} + \frac{\tau_b}{\rho} + \frac{f_D}{\rho} = 0 \tag{2}$$

Where, ζ = water surface elevation, Q = flow rate (discharge per unit width), h = still water depth, τ_b = bed resistance per unit area, f_D = drag force per unit area, g = gravitational acceleration, ρ = density of sea water. Bed resistance in Eq. (3) and drag force in Eq. (4) are reformulated compatible to the governing equations as follows.

$$\tau_b = \frac{\rho g n^2}{(h+\zeta)^{7/3}} Q|Q| \tag{3}$$

$$f_D = \gamma \frac{1}{2} C_{D-all} d_{ref} \frac{Q|Q|}{h+\zeta} \tag{4}$$

Where, n = Manning's roughness coefficient (=0.025 in this study), γ = tree density (number of trees per unit area), d_{ref} = reference width of the tree trunk at 1.2m above the ground level and $C_{D\text{-}all}$ (for more details refer Tanaka et al.(2007)) is defined as follows.

$$C_{D-all} = \frac{1}{h+\zeta} C_{D-ref} \int_{-h}^{\zeta} \frac{C_D(z)}{C_{D-ref}} \frac{d(z)}{d_{ref}} dz \tag{5}$$

Where, $C_{D\text{-}ref}$ = reference drag coefficient (= 1.0), $d(z)$ = width of the tree at the height of z from the ground and $C_D(z)$ = coefficient of drag at the height of z from ground respectively.

2.1.2 Tsunami and topography conditions

This section also introduces the results by Iimura and Tanaka(2008). Fig.2 and Table 1 show the schematic of the bed topography and vegetation type used in the simulation, respectively. Vegetation belt is set in two regions. Incident wave height at the input boundary is 3m, 5m and 7m. Wave period is set constant at 20 min in all cases.

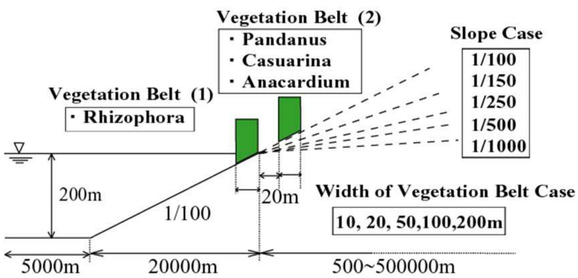


Figure 2 Schematic of the bed topography and vegetation type used in the simulation

Table 1 Species characteristics (Tanaka et al., 2007) used in Iimura & Tanaka(2008)

specie	tree height	reference tree diameter at height, 1.2m	distance between trees	tree density (triangle)
	(m)	(m)	(m)	(number/m^2)
Pandanus odoratissimus	6	0.16	1.7	0.403
Rhizophora apiculata	10	0.12	2.2	0.247
Anacardium occidentale	5	0.30	7.1	0.023
Casuarina equisetifolia	8	0.18	3.3	0.104

Tanaka et al. (2007) investigated the effectiveness of the classification by Shuto (1987). The damage situation of *Casuarina equisetifolia* almost satisfied the criteria using vegetation thickness, *dn* (*d*: trunk diameter at breast height, *n*: number of trees in stream-wise direction in unit cross-stream length). However, the *dn* of *Anacardium occidentale* and *Avicennia alba*, broad leaved trees and *Pandanus odoratissimus* or *Rhizophora apiculata* that has aerial roots were not well classified because the large diameter branches or aerial roots adds additional drag that Shuto (1987) have not been considered. Thus, for distinguishing the effect of tree species, Tanaka et al. (2007) recommend effective vegetation thickness, dN_{all} (cm/(vegetation width (m) ×1 m)) as below:

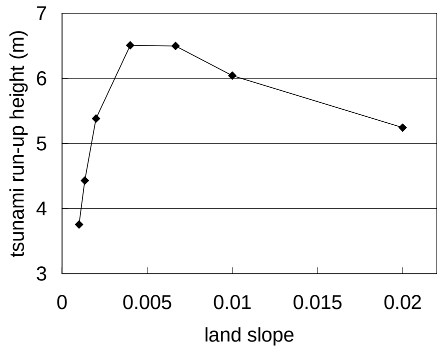
$$dN_{all} = dn \times \frac{1}{h}\int_0^h \alpha(z)\cdot\beta(z)dz = dn \times \alpha\beta \qquad (6)$$

Where, h is the tsunami water depth, $\alpha(z)$, $\beta(z)$ are additional coefficients that expresses the effect of cumulative width of a tree in each height on the drag, and the effect of leaves or aerial roots on the drag, respectively, $\alpha\beta$ is about 1.3, 2, 3 and 3.5 for *C. equisetifolia*, *A. occidentale*, *R. apiculata* and *P. odoratissimus*, respectively for 3-5 m tsunami.

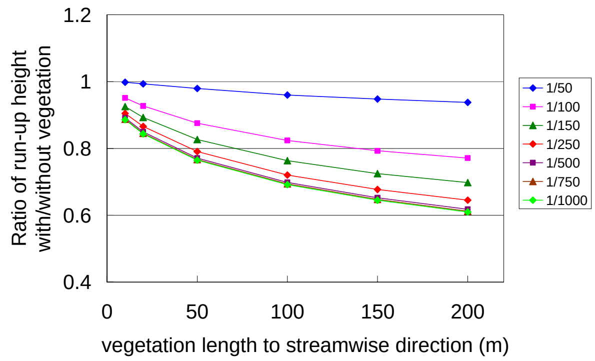
2.1.3 Effectiveness of the cumulative vegetation length to streamwise direction dN_{all}

The effect of vegetation on tsunami run-up height is calculated as shown in Fig.3. Without vegetation, the run-up height has a peak when landslope is around 0.05 with the simulated condition. The difference by vegetation species is large as shown in Fig.4a, however, the difference is only slightly, if we use dN_{all} for evaluating the vegetation effect (Fig.4b).

Moreover, dynamics of tsunami with coastal vegetation effect of the ground slope are discussed in relation to Nandasena et al.(2008b). Further results are described in Iimura et al. (2009a).

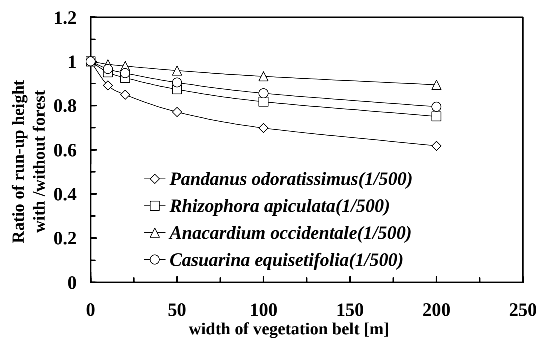


(a)

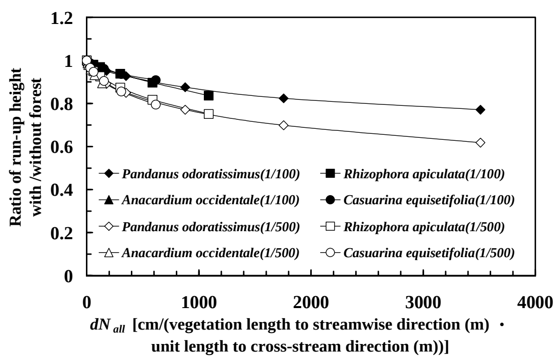


(b)

Figure 3 Tsunami run-up height with different ground slope, (a) without vegetation, (b) ratio of the runup height with/without vegetation



(a)



(b)

Figure 4 Ratio of the run-up height with and without vegetation in relation to; (a) vegetation length to tsunami direction, (b) dN_{all}

2.2 Effect of the combination of coastal vegetation and embankment (road) (Iimura & tanaka, 2008)

The governing equation is the same as the one used in the N1 simulation. Figs. 5 and 6 show the schematic of the topography, and the combination of the embankment and coastal vegetation. *P. odoratissimus* was selected as the vegetation. Embankment height was set 4 cases, 0.5m, 1.0m, 1.5m and 2.0m. Tsunami height at shoreline was set 2 cases, 3m and 5m, and wave period was 20 min. As the width of road was not a sensitive parameter, the width was set 10m for all cases. All the results were compared at the first wave.

Fig. 7 shows the variation of tsunami run-up height. As for the combination of vegetation and embankment, the tsunami defense effect becomes more prominent when the embankment is behind the vegetation (land side, Case2). When the banking height is 1.0-2.0m, run-up height decreases by 4-30% (tsunami height at coast = 3 m) and by 1-7% (tsunami height at coast = 5 m) compared to the effect of coastal vegetation alone where tsunami heights at coast were 3m and 5m respectively.

Moreover, as for the banking effect of road, tsunami defense effect becomes larger with increasing the banking height, but the width of road has no influences on the tsunami defense effect. When banking height is 1.0m, run-up height decreases by 5% and maximum fluid force decreases by 20%, compared to the effect of coastal vegetation alone. When the road is located in front of vegetation (sea side, Case1), water is dammed up by the vegetation and water depth increase in front of the vegetation. Therefore, tsunami defense effect by banking of road becomes small. The arrangement of road and vegetation does not change much for the delay in tsunami arrival time. In addition, as tsunami height at coast becomes large, tsunami defense effect becomes small. Further results are described in Iimura et al. (2009b).

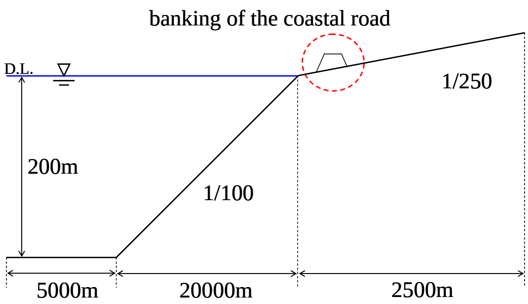


Figure 5 Cross section of topography for simulations (Iimura&Tanaka, 2008)

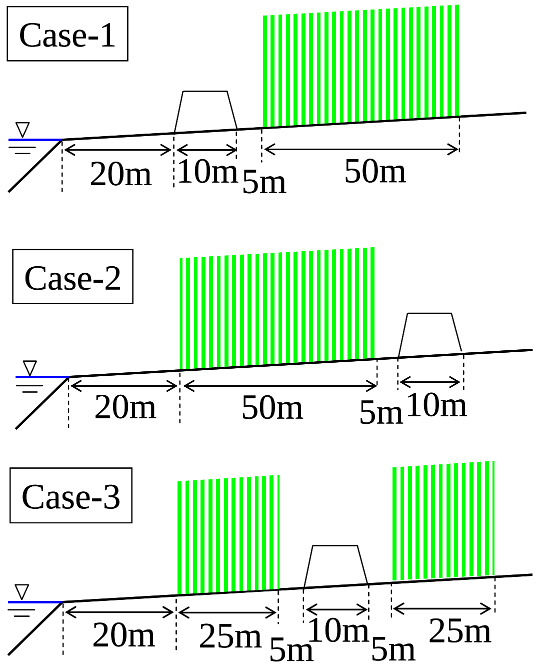
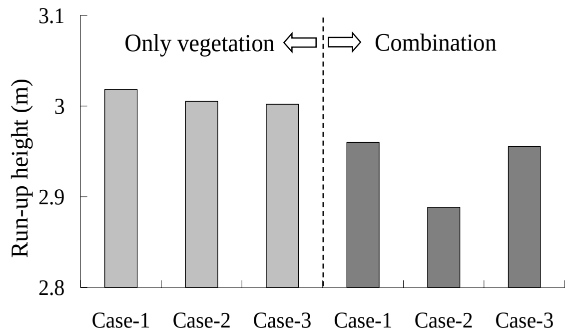
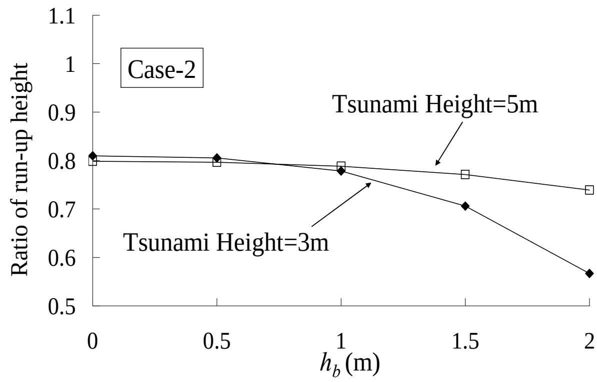


Figure 6 Schematic of the combination of the embankment and coastal vegetation (Iimura&Tanaka, 2008)



(a) difference by the combination of vegetation and embankment (tsunami height at shoreline = 3m)



(b) ratio of tsunami run-up height with the change of h_b and tsunami height

Figure 7 Effect of the combination of coastal vegetation (50 m) and embankment on tsunami runup height (Iimura&Tanaka, 2008)

2.3 Effect of the Vulnerability of sand dune, coastal vegetation and coral reef: Open gap problem (road)

A gap in the coastal belt zone is reported to increase risks and potential damage. Gaps are found in naturally, such as the sand dunes vegetation, river mouths and mangrove channels opening onto the sea. But they can also be artificial due to construction of access roads to the beach or sand mining (FAO, 2007; Mascarenhas and Jayakumar, 2008), and coral reefs for constructing headlands or embankments (Fernando et al., 2005). The flow through the gap can accelerate as it moves into a constricted area (FAO, 2007; Fernando et al., 2005, 2008).

When the gap is narrow, there is a tendency for the velocity to increase immediately behind the gap although the water depth will actually decrease in most cases (Nandasena et al., 2008a). The areas behind coastal forest can still be protected from the tsunami (FAO, 2007; Thuy et al., 2008), but the gap increases the hazard in the besides of gap line (Fernando et al., 2005, 2008). As it is not realistic to consider a coastal forest without any gap in the barrier, careful planning is required for the actual design process of a coastal forest to incline the gap or to make it in a staggered pattern to reduce the velocity through the gap.

Further results are described in papers in our research groups (Thuy et al. 2009; Tanimoto et al. ,2008, 2009). A straight open gap perpendicular to the shoreline was used to investigate the effect of gap width (Thuy et al., 2009). As the gap width increases, the flow velocity at the end of the open gap first increases, reaches a maximum, and then decreases, while the run-up height increases monotonously. The maximum velocity in the condition was 1.7 times the maximum velocity without a coastal forest. The effects of different gap arrangements in the forest on tsunami run-up were also investigated in the paper. The flow velocity at the end of an open gap can be reduced by a staggered arrangement.

3. BREAKING CONDITIONS OF FORESTS AND A TREE

Tanaka et al.(2007) discussed the relationship between tsunami height and cumulative vegetation length to tsunami stream length, dN_{all}.
In the Fig. 8, the classification followed was according to Shuto (1987).
A: Main trunks are not broken and the trees can trap debris, but they have no effect on water velocity or distance of inundation from the shoreline.
B-1: Trees are tilted or bent over, but they may be expected to trap debris.
B-2: Trees are cut down, and no effect is expected.
C-1: Both trees and undergrowth are undamaged. Soil in a forest may remain intact without scouring.
C-2: Some trees on weak soil or at the fringe of the forest may be damaged and the soil around the trees may be scoured, but the damage does not affect the whole forest.
D-1: Neither the trees nor soil is damaged.
D-2: Surface soil may be scoured and damaged to some extent, but the current velocity and inundation depth are reduced and the degree of damage is reduced.

R. apiculata or *P. odoratissimus* cannot be classified by *dn* but can be expressed well by dN_{all}. Thus, the dN_{all} is useful for distinguishing the effect of tree species (Tanaka et al., 2007).

Tanaka et al.(2007) indicated that *P. odoratissimus* can provide significant drag compared to other sparsely vegetated trees (*Cocos nucifera* or *C. equisetifolia*). However, regarding the breaking condition of each tree, Tanaka and Sasaki (2007) found that *P. odoratissimus* can break easily if the tsunami height exceeds 80% of the plant height (Fig.9).

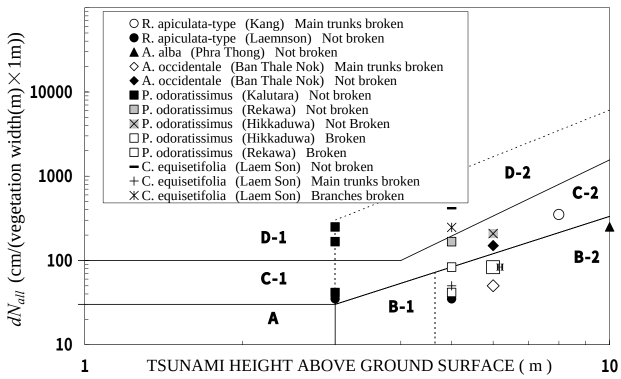


Figure 8 Breaking condition of forest. For details, please see Tanaka et al. (2007)

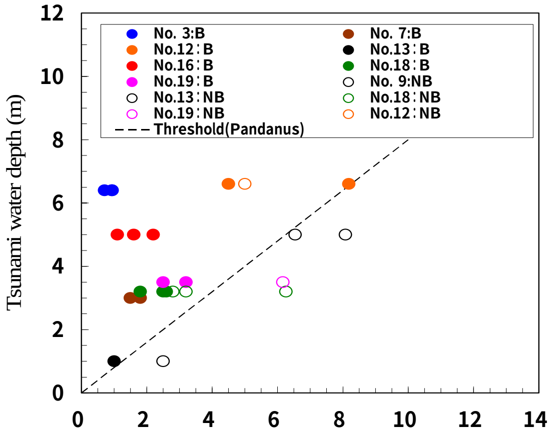


Figure 9 Breaking condition of *P. odoratissimus* (Tanaka and Sasaki (2008)
B:broken, NB:not broken

4. COASTAL VEGETATION ESTABLISHMENTS AND ITS SUSTAINABILITY IN SRI LANKA

A survey was conducted to compile the present establishment situation of coastal vegetation for tsunami protection in Sri Lanka (Fig.10). Many government institutions and NGOs along the southern and western coasts of Sri Lanka have undertaken such projects (Fasley et al., 2008). An evaluation was carried out to assess whether the coastal vegetation establishments fulfilled the functions such as dissipation of wave energy, trapping effect, escaping effect and soft landing effect (Tanaka et al., 2007). Fifty percent of the vegetation barriers are planted in one or two rows due to land availability constraints in areas main roads or railway tracks. It was noted that more than 75% of the sites were established by NGOs. Continuous maintenance is ensured only for 50% of sites with community participation (Fasley et al., 2008). Dissemination of knowledge and coordination with government institutions and research institution are very important for effective establishment and management of coastal vegetation for tsunami protection with community participation. More details will be discussed in Tanaka et al.(2010).

The findings from Tanaka et al.(2007) suggested several options for coastal vegetation management that could effectively reduce the impact of tsunamis and other natural disasters in future. Accordingly, the team comprising with Saitama university and University of Peradeniya (SU-UOP team) proposed establishing a pilot-scale coastal plantation in the Matara Thotamuna area which was severely affected by the 2004 tsunami (Fig.11(a), (b)). *C. equisetifolia* and *P. odoratissimus* were planted in a mixed culture and their growth was monitored continuously. The average height and diameter of the plants are around 92.2cm and 117.1cm for *P. odoratissimus* and 627.5cm and 4.0 cm for *C. equisetifolia*, respectively after 18 months from planting (Perera et al., 2008).

Figure 10 Planting situation of coastal vegetation (50% of the projects were failed because of the lack of maintenance)

The project was very successful and effective compared to similar projects where poor maintenance and operation resulted in failure. The experience indicated that support from local authorities and communities are vital to make such programs successful. The management of the site was handed over to the local temple (Fig.11(c)). That is an option for long term maintenance as suggested by Tanaka (2009).

(a)

(b)

(c)

Figure 11 Pilot project in Matara city. (a) notice board, (b)growth situation after 18 months, (c) long term maintenance by local temple

5. IMPLICATIONS OBTAINED FROM FIELD INVESTIGATION, NUMERICAL SIMULATIONS, AND PLANTING PROJECTS

5.1 Effective vegetation structure

Considering the effectiveness and the limitations, Tanaka et al. (2007) proposed two layers of vegetation in the vertical direction with *P. odoratissimus* and *C. equisetifolia*. This configuration exhibits strong potential for decreasing the damage behind the vegetation cover. These findings are supported by the numerical simulation by Tanaka et al. (2008).

A horizontal forest structure with small and large diameter trees is also assumed to be effective because the densely populated small diameter trees (d > 0.1) could reduce the velocity of the tsunami current, while the large diameter trees (d >0.3) could trap the broken branches and man-made debris. The vertical structure also provides an effective soft-landing for people washed away by the tsunami or for climbing when the tsunami waves hit (Tanaka et al., 2007).

5.2 Sustainable maintenance and utilization

De Zoysa (2008) assessed the impact of a *Casuarina* shelterbelt from economic (agricultural crop, household goods, timber production, fuel supply), social (prevention of illegal settlements, attraction of tourists, prevalence of anti-social activity), and environmental (wind speed reduction, sand dune formation, impact on undergrowth, aesthetic value) viewpoints, and concluded that the environmental and social impacts are larger than the economic impacts. Integrated coastal zone management by the residents, city council, and tourist board is recommended in order to increase the benefits of coastal shelter belts.

Considering the Matara project by the SU-UOP team and the research by De Zoysa (2008), Tanaka (2009) recommended an integrated coastal vegetation management system. With the growth of trees, the tsunami energy mitigation effect of the vegetation may be reduced, because the tree spacing becomes larger and effective cumulative tree diameter in the stream-wise direction dN_{all} is reduced (Tanaka et al., 2007). To keep the forest dense, proper management is needed by using the forest as a source of firewood or for timber production to thin it, and maintaining various-aged stands of trees by replanting (FAO, 2007). In particular, the front line of the forest close to the sea should be dense vegetation (i.e., a *Pandanus-Casuarina* belt) as Tanaka et al. (2007) proposed. *C. nucifera* has many uses, i.e. fruit production, fuel, timber, and coconut fiber is used as water storage and water purification materials in the substrate of manmade wetlands (Tanaka et al., 2008a). Thus, it is not necessary to remove *C. nucifera* from the coastal region if it is kept at the backside of coastal sand dunes or combined with dense *Pandanus* forest, even though the contribution of *C. nucifera* to increasing the overall drag coefficient by itself is not large.

6. SUMMARY

The effects and limitations of coastal vegetation for tsunami mitigation were investigated in Sri Lanka following the 2004 Indian Ocean tsunami. Two layers of vegetation in the vertical direction with *Pandanus odoratissimus* and *Casuarina equisetifolia* were proposed to increase drag, and to trap floating objects, broken branches and people. Accordingly, a pilot scale coastal plantation in Matara Thotamuna area was established. The success of our site in comparison to other unsuccessful projects suggests that proper maintenance is essential. Support from local authorities and communities are vital to make such programs successful. Considering land availability in coastal regions of Sri Lanka, more study is needed for identifying the effect of vegetation in combination with other physical barriers (i.e. embankments or raising road height (like an embankment) considering cumulative vegetation length). It should also be noted that in certain cases the existence of a road or river could accentuate tsunami propagation towards the land. This is also an aspect that needs detailed investigation.

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