Coastal Vegetation and their Functions in Reducing Tsunami Damage

Dr. MB Samarakoon,Senior Lecturer Department of Civil Engineering KDU

Prof. Norio Tanaka Department of Civil and Environmental Engineering, Graduate School of Science and Engineering Saitama University of Japan

1. Introduction

The tsunami in the Indian Ocean in 2004 caused destruction of life, property, and massive damage to the coastal ecosystem. This tsunami caused huge damage in some countries in Indian Ocean, with the destruction of hundreds of thousands of facilities, innumerable injured and missing victims and tremendous economic, social, and environmental losses (Kathiresan and Rajendran 2005; Tanaka et al. 2010). About two-thirds of Sri Lanka especially Western, Southern, and Eastern coast lines were severely damaged on a huge scale (Wijetunge 2005). These damages have highlighted the urgent need to develop methodologies to mitigate tsunami and other natural disasters in the coastal regions. Various researchers and institutions have been developing appropriate methodologies to mitigate tsunami damage especially for developing countries like Sri Lanka. As for a tsunami passing through an obstacle, Goto and Shuto (1983) experimentally studied the energy head loss to evaluate the effect of large obstacles on tsunami inundation. The obstacles, such as coastal forest, wave dissipating block, rock breakwater, and sea wall are accomplished of reducing energy associated with the tsunami (Harada et al. 2002). But, establishment of a hard infrastructure for tsunami mitigation creates adverse effects on ecology and aesthetics of the beachfront. Further, developing countries cannot bear such technologically advanced and capital-intensive solutions.

Coastal forests can be used as an alternative solution because it provides a range of protection options and economic revenue source for coastal communities. In addition, restoring green vegetation could enhance the seaside landscape. The disastrous amount of energy associated with tsunami and the severity of tsunami waves are significantly reduced by the coastal vegetation because of drag characteristics of them (Shuto 1987; Mazda et al. 1997; Kathiresan and Rajendran 2005; Tanaka et al. 2007). The significant role of coastal vegetation in reducing the energy of tsunami waves and damage to humans and coastal ecosystem were analyzed by many previous researchers (Shuto 1987; Mazda et al. 1997; Kathiresan and Rajendran 2005; Dahdouh-Guebas et al. 2005; Danielsen et al. 2005; Tanaka et al. 2007). But, any of the above studies have not investigated quantitatively the effective vegetation species that help to reduce the tsunami damage and effectiveness of combined vegetation systems in tsunami mitigation.

Therefore, the objectives of this study were to (1) identify the different types of vegetation species that help to mitigate the tsunami damage and (2) analyze the drag characteristics of different vegetation species.

2. Materials and method

2.1 Study area and research methods

Field surveys on coastal vegetation were conducted on eastern coastline of Sri Lanka. The survey method was to travel and make observations on vegetation along the coastal belt from Kalmunai to Passekudah including eleven locations (about 72 km) and from Passekudah to Kokkilai including nineteen locations (about 160 km). Locations of the investigation sites are shown in Figure 1.

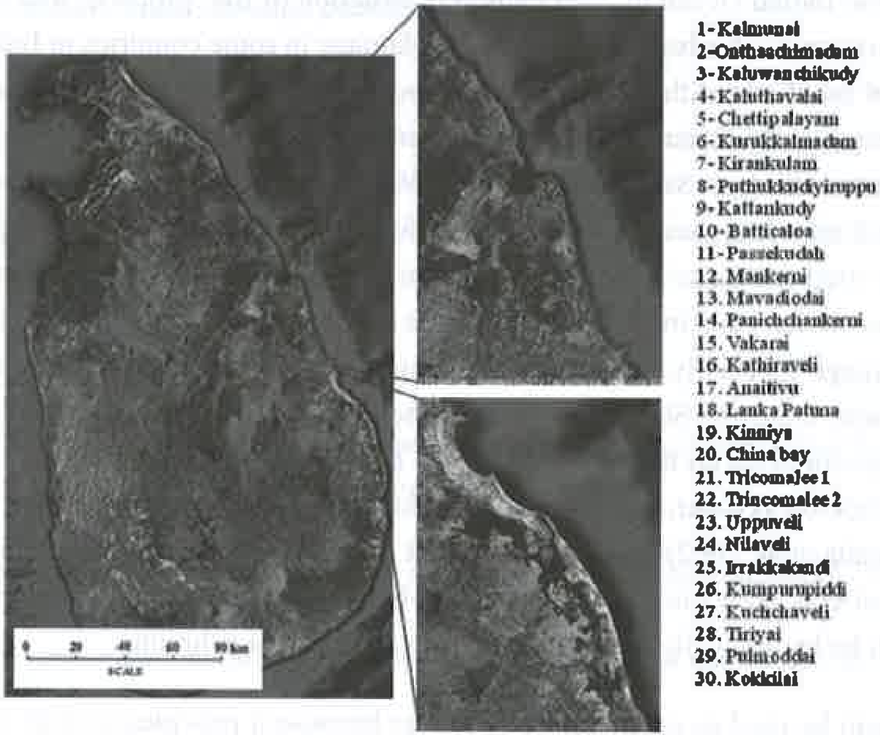

Figure 1. Locations of the investigation sites

Locations were identified where there were planted forests before and after 2004 Indian Ocean tsunami and natural forests with different vegetation species. All the investigated sites were nearly even and were higher about 0.5-3 m above the mean sea level. The soil at each site was mainly comprised of beach sand. The sites from Kalmunai to Passekudah were almost consisted with planted *Casuarina equisetifolia* forests. These forests were established by various Non Government Organizations under the consultant with the government' forest department, intended to protect people, the infrastructure and the environment from future tsunami hazards. The investigated sites from Passekudah to Kokkilai were consisted with natural coastal forests. The following information was collected from each site:

(a) Type of vegetation species

(b) Tree characteristics such as, diameter at breast height (D_{bh}), tree height (H), and tree density

(c) Forest characteristics such as, forest length (L), forest width (W), the gap between two trees in shore (l_1) and cross shore (l_2) directions, and the length from the forest to sea were measured.

(d) Georeference of the sites by hand-held GPS

2.2 Estimation of drag force coefficient using tree characteristics

The physical characteristics of coastal vegetation were considered by means of drag force of trees along a width of W (m) and a length of vegetation of 1 (m). The following equation shows the cumulative drag force acting on the forest (Tanaka et al. 2007).

$$D_{cum} = \frac{1}{2}\left(\frac{dn\alpha\beta}{100}\right)C_d \rho U^2 h \tag{1}$$

where D_{cum} is the cumulative drag force of trees a width of W (m) and a length of 1 (m), n is the number of trees in a vegetation width of W (m) and length of 1 (m), d is the reference tree trunk diameter at 1.2 m above the ground (cm), α and β are additional coefficients representing the effects of branches and leaves on the drag force, respectively, C_d is the drag coefficient, ρ is the density of salt water (kg/m^3), U is the depth-average velocity (m/s), and h is the tsunami depth (m). Coefficients α and β were chosen according to the average tree height.

Equations 2, 3, and 4 define the vertical vegetation structure, $C_{d\text{-}all}$, the effective vegetation thickness, dN_{all}(cm/ (vegetation width x 1 m^2)), and the vegetation thickness per unit area, dN_u (cm/unit vegetation area m^2), as follows (Tanaka et al. 2007).

$$C_{d-all} = \alpha\beta * C_d \tag{2}$$

$$dN_{all} = \alpha\beta * dn \tag{3}$$

$$dN_u = \frac{dN_{all}}{l^2 n} = \frac{\alpha\beta d}{l^2} \tag{4}$$

where l is the average spacing of the trees (m). Equations 2, 3, and 4 are related to the drag force in Equation 1. $C_{d\text{-}all}$ describes the characteristics of the tree itself, dN_{all} describes the characteristics including the effects of the tree structure αβ in the W (m) x 1 (m) vegetation, and dN_u describes the characteristics of a unit vegetation area.

3. Results and discussion

3.1 Classification of representative vegetation

Vegetation at the investigated sites was classified based on their habitat and the stand structures. The classified vegetation species include, (a) *Lumnitzera racemosa*, a mangrove that has a root system below the ground and grows as shrubs especially in lagoon areas, (b) *Cocos nucifera*, a plantation species in the coastal zone, (c) *Azadirachta indica*, a tree species that grows near the beach especially in dry zone, (d) *Borassus flabellifer*, a tree species in the coastal zone, (e) *C. equisetifolia*, a representative tree that grows in beach sand, (f) *Terminalia catappa*, a large tropical tree that grows in coastal zone, (g) *Rhizophora apiculata*, a mangrove that has an aerial root system and grows in lagoon areas, (h) *Pandanus odoratissimum*, a representative tree that grows in beach sand, (i) *Manilkara hexandra*, a tree species that grows near the beach especially in dry zone, and (j) *Calotropis* *gigantea*, a large shrub that grows in beach sand. The representative coastal vegetation at eastern coast line of Sri Lanka and their vertical structures are shown in Figure 2.

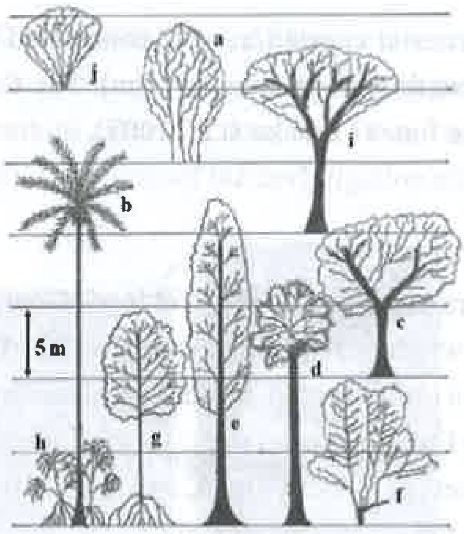

Figure 2. Classification of different vegetation species

3.2 Drag characteristics of representative coastal vegetation

Figure 3(a) shows the variation of $C_{d\text{-}all}$ that calculated with an average tree diameter with tsunami height for different vegetation species. The values of $C_{d\text{-}all}$ is greater for trees with larger leaf area density (*T. catappa*), comparatively larger crown area (*A. indica* and *M. hexandra*), and including aerial root structure (*P. odoratissimum*). *B. flabellifer* has lesser $C_{d\text{-}all}$ because the canopy of leaves spreads only at the top of the trunk. $C_{d\text{-}all}$ is approximately equal to 1 for *C. nucifera* due to absence of branches. In addition, $C_{d\text{-}all}$ of *R. apiculata*, *C. equisetifolia*, *C. gigantea*, and *L. racemosa* is varied close to 1 due to presence of branches and leaves at the height of 1.2 m from the ground. A clear difference between curves could be obtained if we include the density difference of trees, because some species such as *P. odoratissimum*, and *R. apiculata* possess aerial roots, or young *C. equisetifolia* possesses branches from the ground, can grow densely.

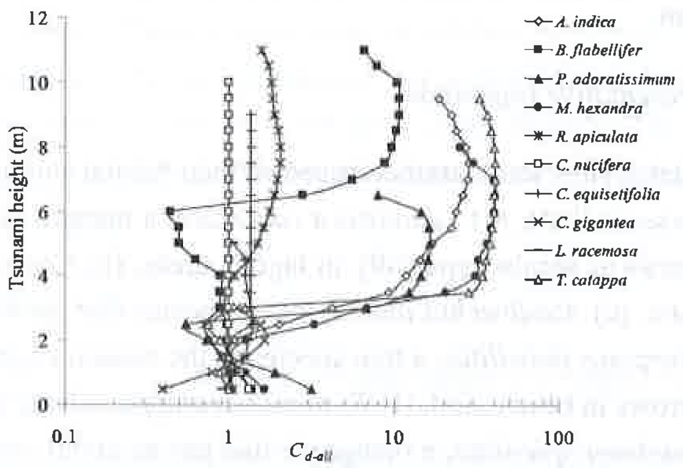

Figure 3(a) Variation of $C_{d\text{-}all}$ with Tsunami height

The present results are consistent with some previous studies. The value of $C_{d\text{-}all}$ of *R. apiculata* was close to the value obtained for mangrove trees (Wolanski et al. 1980), and the value of $C_{d\text{-}all}$ of *C. equisetifolia*, *P. odoratissimum*, and *C. nucifera* was close to the $C_{d\text{-}all}$ obtained for similar types of trees by Tanaka et al. (2007, 2009). Figure 3(b) shows the variation of dN_u with different tsunami heights. *R. apiculata* shows relatively greater dN_u values. When the forest is used for protecting from tsunami which is higher than 10 m, *R. apiculata* would be effective in comparison with other species because it grows very densely and has an aerial root structure. In addition, *B. flabellifer* is also capable of providing protection against tsunami; however the dN_u of the smaller height is very low. When the tsunami height is less than 10 m, *R. apiculata*, *P. odoratissimum*, *M. hexandra*, and *L. racemosa* forests provide most effective protection.

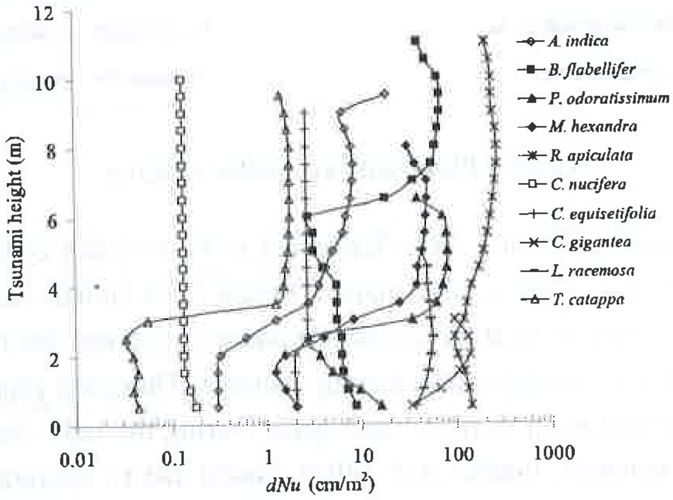

Figure 3(b) Variation of dN_u with Tsunami height

However, Tanaka et al. (2007) found although *R. apiculata* and *P. odoratissimum* were effective, they had a tendency to break when they were in the front line of the vegetation for a tsunami higher than 10 m. *C. equisetifolia* provides relatively low dN_u value in comparison with other species. Tanaka et al. (2009) reported that young *C. equisetifolia* (e.g., d=15 cm) is effective in protecting tsunami higher than 10 m because it grew densely and was not broken by tsunami. Further, they reported that the value of dN_u for large diameter *C. equisetifolia* is quite small, almost the same as *C. nucifera*. Thus, age has a quite important effect in the case of *C. equisetifolia*. In our study we selected relatively old *C. equisetifolia* trees (e.g., d=25 cm) to measure the dN_u value, therefore the obtained dN_u value was quite low. Even though the value of dN_u for *T. catappa* is small, it has another important effect during a tsunami in which people can use these trees to escape. *C. nucifera* has very low dN_u values providing little effect from any point of view.

By analyzing Figure 3(b) further, it is proposed a combination of vegetation patterns so as to get a better dN_u value. Two sets of vegetation combinations can be proposed to provide a better protection from a tsunami-type event. Set 1, *B. flabellifer* is planted with *P. odoratissimum* at the front line of the forest while *M. hexandra* is planted behind the above combination. Set 2, *C. equisetifolia* is planted with *P. odoratissimum* at the front line of the forest while *A. indica* is planted behind the above combination. The details of these two sets are shown in Figure 4(a) and (b), respectively.

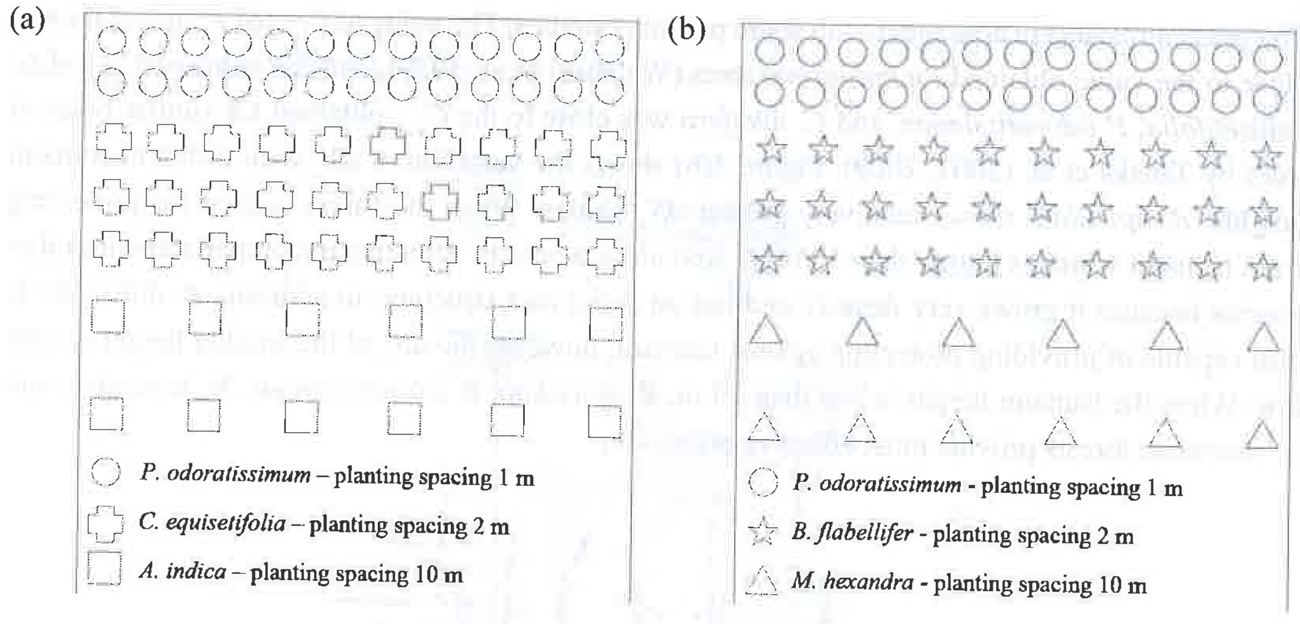

Figure 4 Proposed vegetation systems

We observed that the investigated sites from Kalmunai to Passekudah consisted with planted *C. equisetifolia* forests and some of them have planted before 2004 Indian Ocean tsunami. The gap between two forests were about 50 m at Batticaloa site and we observed that many houses and other infrastructure located within these gaps were heavily damage. Thus, it is proposed to plant another species such as *P. odoratissimum* in front of these gaps. During the field observation in Sri Lanka after 2004 Indian Ocean tsunami, Tanaka et al. (2007) found that *C. equisetifolia* and *P. odoratissimum* were mixed at the interface for a distance of about 20 m at Kalutara site. The tsunami height 60 m inland from the coast was 0.6 m, and houses located within this area were not as heavily damaged because the tsunami height was low compared to its original height. A numerical simulation also proved that the combination of vegetation is believed to be capable of playing an effective role in protection against tsunami waves (Tanaka at al. 2009). Tanaka et al. (2010) described a collaborative research project between Saitama University, Japan and University of Peradeniya, Sri Lanka. Under this project, a successful coastal vegetation site was maintained in Matara, Sri Lanka where *P. odoratissimum* was planted in the front line, with *C. equisetifolia* planted behind it. In addition, Edward et al. (2006) also expressed the effectiveness of mixed vegetation in reducing tsunami waves in Japan.

Conclusions

The drag characteristics of different vegetation species were analyzed using $C_{d\text{-}all}$, dN_u, and dN_{all}. The results revealed that trees which have larger leaf area density, comparatively larger crown area, and posses aerial root structure provide comparatively greater $C_{d\text{-}all}$ values. Therefore, to obtain better shield from tsunami-type event, it is recommended to plant trees with above properties. The results of dN_u revealed that a combination of vegetation is effective rather than planting a single species. Two sets of vegetation (set 1: *B. flabellifer* is planted with *P. odoratissimum* at the front line of the forest while *M. hexandra* is planted aft of the above combination, set 2: *C. equisetifolia* is planted with *P. odoratissimum* at the front line of the forest while *A. indica* is planted aft of the above combination) were proposed to enhance the dN_u. Accordingly, the plating situation will be improved at the investigated sites.

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