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Planning and Design of Tsunami-mitigative Coastal Vegetation Belts

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Coastal vegetation belts have actual benefits environmentally and economically as well. For tsunami prone areas, these benefits will be extended if vegetation belts are designed according to tsunami disaster mitigation conditions. In order to facilitate coastal vegetation belt design that fulfills the conditions of tsunami disaster reduction, guidelines are necessary.

This report intends to give general guidelines on the planning and design of coastal vegetation belts for tsunami disaster mitigation according to presently available knowledge. The contents include description of the general roles and limitations of coastal vegetations in tsunami disaster mitigation, description of basic steps in planning and design, data requirement and collection, design parameters and calculation procedure, and example of calculation processes as well. Notes on the requirement of combination with other structures and the importance of good governance for the sustainability of tsunami-mitigative coastal vegetaion belt are also described.

However, the fact that research results on this theme are limited and the available graphs and diagrams were dependent a lot on empirical data, many additional field data, especially related to vegetation characteristics are much required to enhance the applicability of this Guideline.

Keywords: coastal vegetation, tsunami disaster, mitigation, design, guideline

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1. Introduction

1.1 Objective

Coastal vegetation belts have actual benefits environmentally and economically as well. For tsunami prone areas, these benefits will be extended if vegetation belts are designed according to tsunami disaster mitigation conditions. In order to facilitate coastal vegetation belt design that fulfills the conditions of tsunami disaster reduction, guidelines are necessary.

Although further investigation is necessary on the behavior of various types of coastal tree in mitigating tsunami disasters, presently available knowledge has explained the resistance mechanism of coastal vegetation belts against tsunami flows in the beach mostly based on empirical and laboratory experimental results. Supported by the results from several post tsunami disaster field investigations, presently available knowledge can be used, to some extent, to give guidance on the possible application of coastal vegetation belts as one of tsunami disaster mitigation measures.

This report intends to give general guidelines on the planning and design of coastal vegetation belts for tsunami disaster mitigation according to presently available knowledge.

1.2 Expected users

This report is an attempt to provide as simple guidelines as possible that enable the planning and design of anti-tsunami coastal vegetation belts for government officers, community leaders or those who have responsibility for providing alternative solutions for coastal disaster reduction.

1.3 Limitations

These guidelines have been developed based on presently available knowledge and open to further development. The guidelines need to be corrected and enhanced along with progress in related fields. Especially more extensive data on vegetation characteristics are necessary to enhance the accuracy of related graphs and diagrams for design and calculation.

2. Roles and limit of coastal vegetation belt in tsunami disaster mitigation

2.1 Roles of coastal vegetation belts in tsunami disaster mitigation

The roles or functions of coastal vegetation belts in tsunami disaster reduction can be summarized as follows (Tanaka [2007]; Shuto [1987]):

1) Trapping effect: the effect to stop driftwoods (fallen trees, *etc.*), debris (destroyed houses, *etc.*) and other floatages (boats, *etc.*)
2) Energy dissipation effect: the effect to reduce water flow velocity, flow pressure and inundation water depth
3) Soft-landing effect: the effect to provide a life-saving means for people to catch tree branches when carried off by tsunamis
4) Escaping effect: the effect to provide "a way" of escaping by climbing trees from the ground or from the second floor of a building
5) Barrier effect: the effect to collect wind-blown sand and raise dunes which act as natural barriers against tsunamis

2.2 Limit of coastal vegetation belt capacity against tsunami forces

At present only limited data are available to adequately formulate the coastal vegetation belt capacity against tsunami forces. Nevertheless, several investigation results have given knowledge about this matter and can be used as a base for designing anti-tsunami coastal vegetation belts.

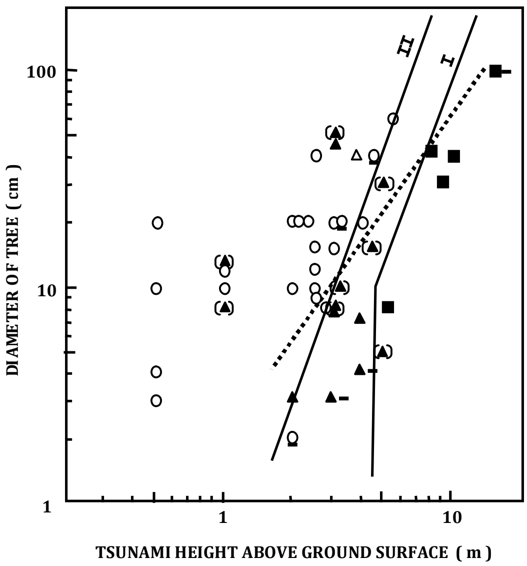
From presently available knowledge, it can be concluded that in general:

(i) coastal vegetation belts provide no or little mitigation effect against tsunami inundation greater than five meters (Shuto [1987] and Tanaka *et al.* [2006, 2007]), and

(ii) coastal vegetation belts never provide a hundred percent protection even if the inundation height is less than five meters (Harada and Imamura [2003], Harada and Kawata [2004], Yanagisawa *et al.* [2008]).

The survival capacity of a coastal vegetation belt depends on the single-tree capacity within the belt. The effective resistance decreases along with decrease in survived tree numbers (Shuto [1987]; Tanaka *et al.* [2007, 2008]; Yanagisawa *et al.* [2008]). Once trees are broken or collapsed, they have no longer capable of reducing tsunami force. Yanagisawa *et al.* [2008] concluded that until the mangrove trees were destroyed by tsunami they possibly acted as a resistance against tsunami flow, however, the reduction of tsunami energy during tree destruction process is considered to be minor because tsunami has a long wave period and penetrates continuously across the vegetation belt area long after the trees have been destroyed.

Tree capacity against tsunami force is related to trunk diameter. Shuto [1987] provided the graph in Figure-1 based on more than forty-five examples collected from five major tsunami events in Japan.



Data label:
○ – no damage to tree with the effect of stopping floatages
⦶ – no damage to tree with the effect of stopping floatages when a tsunami behaves as a standing wave
● – damage to some of the trees with the effect of stopping floatages
■ – cut down of the tree and no effect
△ – reduction of the current velocity and inundation depth with no damage in the forest
▲ – reduction of tsunami energy behind the forest with the damage to the forest
Underline – dense undergrowth
Bracket – damage to trees in poor condition
Horizontal bar – actual tsunami height being bigger than the values indicated in this figure

Figure-1 Degree of damage to tree in terms of trunk diameter and tsunami height above the ground surface [*Source: Shuto (1987)*]

The graph shows damage to pine-tree forests (mostly black pine trees with a small portion of red pine trees) in terms of trunk diameter and tsunami height above the ground surface.

Curve I in Figure-1 is given by Shuto [1987].

$$\left.\begin{array}{ll} H = 4.65 & \text{for } d<10 \\ d = 0.1H^3 & \text{for } d>10 \end{array}\right\} \quad (1)$$

where d is the tree trunk diameter at breast height in cm, and H is the tsunami height above the ground surface in m. Here, the "breast height" refers to 1.20m from the ground. To the right of the curve, the trees were completely ineffective against the tsunamis.

Curve II is also given by Shuto [1987].

$$d = 0.37H^3 \quad (2)$$

The curve gives another boundary, and no damage to trees is expected when they are plotted to its left. Unless soil at the fringe or at sparse places of a forest is severely scoured due to intensive water flow, trees will not tilt or turn over. Between Curves-I and II, trees may tilt or turn over if scouring occurs in the midst of a forest.

Shuto [1987] concluded that Equation 1 gives the smallest trunk diameter with which trees are able to stop floatages brought by tsunamis with inundation depth H.

Tanaka *et al.* [2006] provide the graph in Figure-2 that shows a correlation between the trunk diameters of several other trees (*Exoecaria agallocha*, *Casuarina equisetifolia*, *Rhizopora apiculata*, *Pandanus odoratissimus*, *Lumnitzera racemosa*) and the tsunami heights at the breaking of those trees. The tsunami heights at the breaking of the trees refer to the maximum tsunami inundation heights available at the disaster locations where the trees were found to be collapsed or broken in the aftermath of the tsunami disasters. These data were collected during the post tsunami field investigations at Sri Lanka and Thailand.

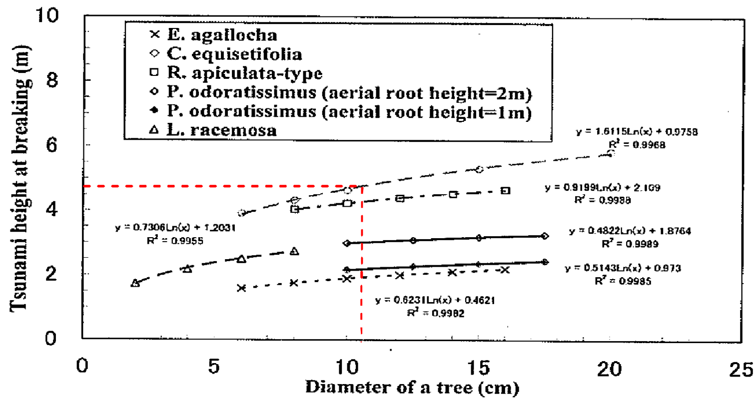


Figure-2 Tsunami heights at the breaking of the trees in relation to the diameters at breast height [*Source: Tanaka et al. (2006)*]

3. Effect of coastal vegetation belt on tsunami flow

The effects of coastal vegetation belts on tsunami flow reduction so far reported are mostly related to the reduction of run-up and inundation depth and that of flow speed and force. The reduction of run-up and inundation depth will reduce the area of destruction behind a vegetation belt in the vertical direction. The reduction of flow speed will give a considerable span of time for evacuation before a tsunami flow reaches residential areas behind a vegetation belt. The reduction of flow force will diminish the destructive force of tsunamis to structures or human bodies.

3.1 Factors involved in the interaction between tsunamis and coastal vegetation belts

The interaction between tsunamis and coastal vegetation belts is mainly influenced by tsunami characteristics and vegetation belt characteristics. At the same time, the effects of ground slope, soil type and ground cover are also important and indirectly influence the interaction between tsunamis and coastal vegetation belts. Table 1 shows the summary of factors involved in the interaction between tsunamis and coastal vegetation belts as well as the expected effects of coastal vegetation belts on tsunami flow reduction.

Table 1. Factors involved in the interaction between tsunamis and coastal vegetation belts and the expected effects of coastal vegetation belts on tsunami flow reduction

<table>
<tr><th>TSUNAMI CHARACTERISTICS</th><th>VEGETATION BELT CHARACTERISTICS + TOPOGRAPHY</th><th>EXPECTED EFFECT</th></tr>
<tr><td rowspan="3">▪ Inundation depth
- Wave force
▪ Period/wave length
▪ Wave direction</td><td>- Single tree breaking moment capacity</td><td rowspan="3">▪ Flow velocity reduction
▪ Run-up and inundation depth reduction
▪ Impact force reduction</td></tr>
<tr><td>- Vegetation belt width
- Vegetation belt density
▪ Tree numbers
▪ Tree size and structure
• Trunk diameter
• Tree height
• Root-trunk-canopy composition
▪ Vegetation combination</td></tr>
<tr><td>Ground slope, soil type, ground cover *etc.*</td></tr>
</table>

Tsunami characteristics are influenced by tsunami wave force, tsunami period/wave length and incoming wave direction. Among these tsunami characteristics, tsunami wave force is considered as the main factor. In many analyses, tsunami inundation depth is used to determine the wave force working onto coastal vegetation belts (*e.g.,* Shuto [1991], Harada and Imamura [2003], Tanaka [2008]).

Vegetation belt characteristics depend on the single-tree breaking moment capacity as well as the capacity of vegetation belts. The capacity of vegetation belt is influenced by vegetation belt width and density. The vegetation belt density is dependent on the tree counts, tree size and structure (trunk diameter, tree height, root-trunk-canopy composition) and vegetation combination.

3.2 Effects of coastal topography

At the beach, effects of coastal topography on tsunami flow are seen in the effect of ground slope on tsunami run-up, which simultaneously affects flow velocity, flow forces and inundation depth.

Figure-3 shows the relationship between run-up height and land slope based on numerical simulation results from Tanaka & Iimura [2009]. According to this simulation results, tsunami run-ups reach their peaks at a slope between 0.004 and 0.005 (1/250 and 1/200). On the ground with slope steeper than 0.005, the disturbance by the high reflected waves are considered to cause tsunami run-up height reduction.

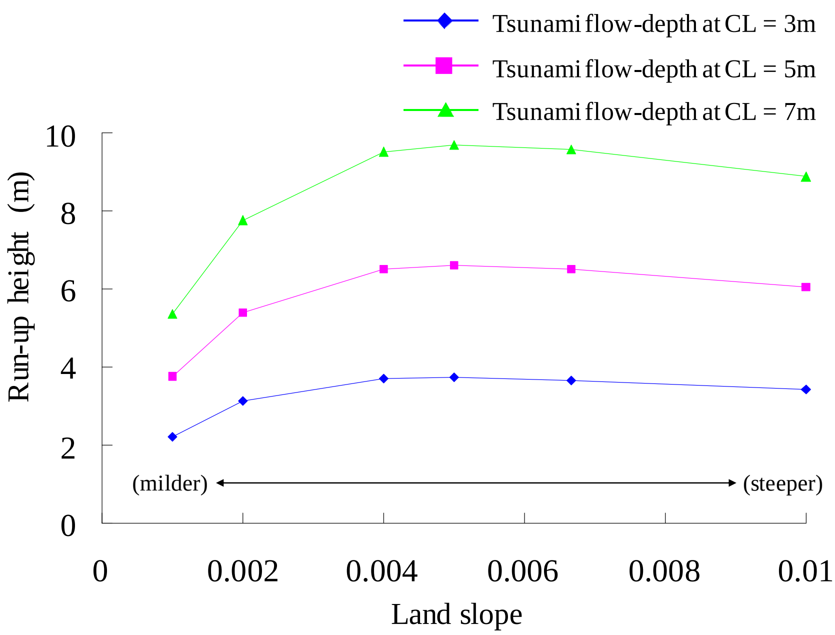


Figure-3 Tsunami run-up on various ground slopes without a coastal forest based on numerical simulation results from Tanaka & Iimura (2009).

3.3 Effect of vegetation belt density

Vegetation belt density is determined by individual tree size (including root, trunk, branches and leaves) and the number of trees per unit area (Shuto [1987]; Harada & Kawata [2004]; Dinar *et al.* [2006]; Tanaka *et al.* [2007, 2008]; Yanagisawa *et al.* [2008]). The higher the product of these two factors, the higher the density of a coastal vegetation belt.

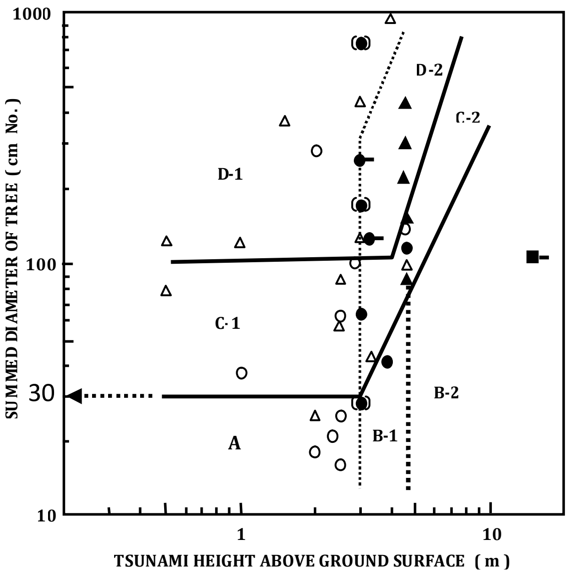
The vertical structure of trees, *i.e.,* the vertical distribution of density, which is influenced by the composition of tree root, trunk and canopy, affects the effectiveness of vegetation belts in tsunami flow reduction in term of tsunami flow depth.

If a tsunami flow depth is lower than the lowest height of the canopy (*i.e.,* branches and leaves), the vegetation belt density is calculated based on the trunk diameter only. An example of this calculation method was done by Shuto [1987], in which he introduced the term of “summed diameter” to evaluate the effectiveness of pine-tree forests in the reduction of tsunami energy. Shuto [1987] considered that the hydraulic resistance of a forest can be determined by evaluating the hydraulic resistance of a tree and summing that up for the number of trees in the direction of a water flow. Considering that the resistance of a tree is proportional to the product of the projection area *dH* and the square of flow velocity v^2 (velocity v is assumed to be equal to gH; g is the gravitational acceleration) and n is the average number of trees in the direction of the water flow, Shuto [1987] proposed the following expression of tsunami energy reduction:

$$d\,H\,v^2\,n \simeq d\,n\,H^2 \tag{3}$$

where H^2 is the representative characteristics of the tsunami at the site, and *dn*, which is called "summed diameter", is the major component of the resistance of the forest.

Based on the above approach, Shuto [1987] provided a graph on the effect of, and damage to, a tsunami control forest in terms of tsunami height and summed tree diameter as shown in Figure-4.



Data label:
○ – no damage to tree with the effect of stopping floatages
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▲ – reduction of tsunami energy behind the forest with the damage to the forest
Underline – dense undergrowth
Bracket – damage to trees in poor condition
Horizontal bar – actual tsunami height being bigger than the values indicated in this figure
Slant bar – damage caused by concentrated forces such as a boat

Figure-4 Effect of, and damage to, a tsunami control forest in terms of tsunami height and summed diameter of the trees [*Source: Shuto (1987)*]

Shuto (1987] concluded that a forest whose summed diameter value (*i.e.*, *dn*) is less than 30 has no effect on tsunami flow reduction but stopping floatages. The higher the *dn* value, the higher its reduction effect on tsunami flow.

For several mangrove species with a considerable volume of prop or aerial roots (*e.g., Rhizopora apiculata*, *Rhizopora mucronata*), the root-resistance effect should be well recognized. The effect of the roots can be treated as a friction coefficient against tsunami flow [Yanagisawa *et al.*, 2008] or as a hydraulic resistance related to the drag force coefficient [Tanaka *et al.*, 2006, 2007, 2008].

When tsunami flow depths reach the canopy part (branches and leaves) of a tree, flow resistance caused by them should be included. Since each type of tree exhibits its own unique vertical structure, each type should also affect tsunami flow in its own unique way for each different tsunami flow depth. Tanaka *et al.* [2007] analyzed that the vertical structure of a tree significantly affect its total drag coefficient working against tsunami flow. Figure-5(a) shows the correlation between the total drag coefficient of each representative tree ($C_{D\text{-}all}$) and tsunami height.

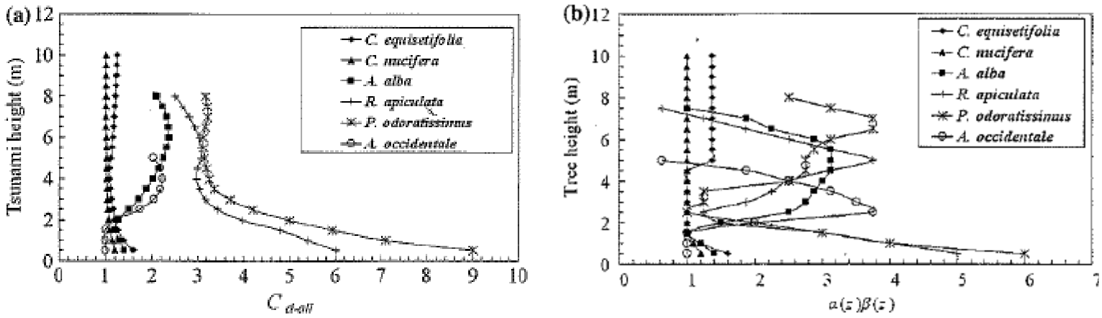


Figure-5 (a) $C_{d\text{-all}}$ values of each representative tree in term of tsunami height. (b) Vertical distribution of the effects of branches and leaves, $\alpha(z)\beta(z)$ [*Source: Tanaka et al. (2007)*]

The plotted values of $C_{D\text{-all}}$ were calculated according to the following equations [Tanaka *et al.*, 2007].

$$C_{D\text{-all}} = \alpha\beta \times C_D \quad (4)$$

$$dN_{all} = C_{D\text{-all}} \times dn \quad (5)$$

$$dN_u = dN_{all} / W = dN_{all} / l^2 n = \alpha\beta d / l^2 \quad (6)$$

$$n / W = 1 / l^2 \qquad \text{[trunk density/m}^2\text{]} \quad (7)$$

$$\alpha\beta = \frac{1}{h}\int_0^h \alpha(z)\beta(z) = \frac{1}{n}\sum_{i=1}^{n} \alpha_i \times \beta = \frac{1}{n}\sum_{i=1}^{n}\frac{dA_i}{dA_{1.2}} \times \beta \quad (8)$$

$$dA_i = \sum_{m=1}^{m=i_{max}} dA_{im} \quad (9)$$

In Equation 4 to 9, W(m) is the width of a coastal vegetation belt in the direction of tsunami flow, n(trunk/m^2) is the number of the trees in the vegetation belt W(m) wide and 1m long, l(m) is the average spacing between the trees, d(cm) is the trunk diameter at 1.2m above the ground, h(m) is the tsunami flow depth, dn(cm/vegetation belt width-m^2) is the cumulative tree diameter of the vegetation belt in the tsunami direction, called "vegetation thickness", α is the branch effect on C_D, β is the leaf effect on C_D, dA_i(m^2) is the area the tree parts cover, $dA_{1.2}$(m^2) is the area of the trunk at 1.2m above the ground. Further, $C_{D\text{-all}}$ is the drag coefficient including the vertical vegetation structure, dN_{all} (cm/vegetation belt width-m^2) is the effective vegetation thickness in the W(m) x 1m area of the vegetation belt, dN_u (cm/unit area-m^2) is the vegetation thickness per unit area. Additional drag by leaves was taken as constant $\beta = 1.25$ (in leaf-bearing layers) or $\beta = 1$ (in leafless layers). The products of $\alpha(z)\beta(z)$ in terms of tsunami height for the representative vegetations are shown in Figure-5(b).

Making use of the above calculation approach, Tanaka & Iimura [2009] conducted numerical simulation and provided the graphs in Figure-6 that show the reduction rates of tsunami run-up, flow force and propagation time delay in terms of vegetation belt density, dN_{all}, and ground slope variations. The effect of a coastal vegetation belt on run-up reduction (see Figure-6, upper left) is significant under the mild-slope condition. On steeper slopes, the slope effect on run-up reduction is more dominant than the effect of a coastal vegetation belt.

The graphs in Figure-6 were derived for the vegetation types of *Pandanus odoratissimus*, *Casuarina equisetifolia*, *Rhizopora apiculata* and *Anacardium occidentale* under the conditions shown in Table 2.

Harada & Kawata [2004] also conducted numerical simulation for the case of Japanese pine trees with the fixed tsunami height of 3m, seafloor slope of 1/200, inland slope of 1/500, forest density variations of 10, 30 and 50 trees/100m^2, and forest width variations of 50, 100, 200 and 400m. The simulation results are shown in Figure-7. The tsunami flow reduction rate of each forest width changes only slightly at the forest density variations of 10, 30 and 50 trees/100m^2.

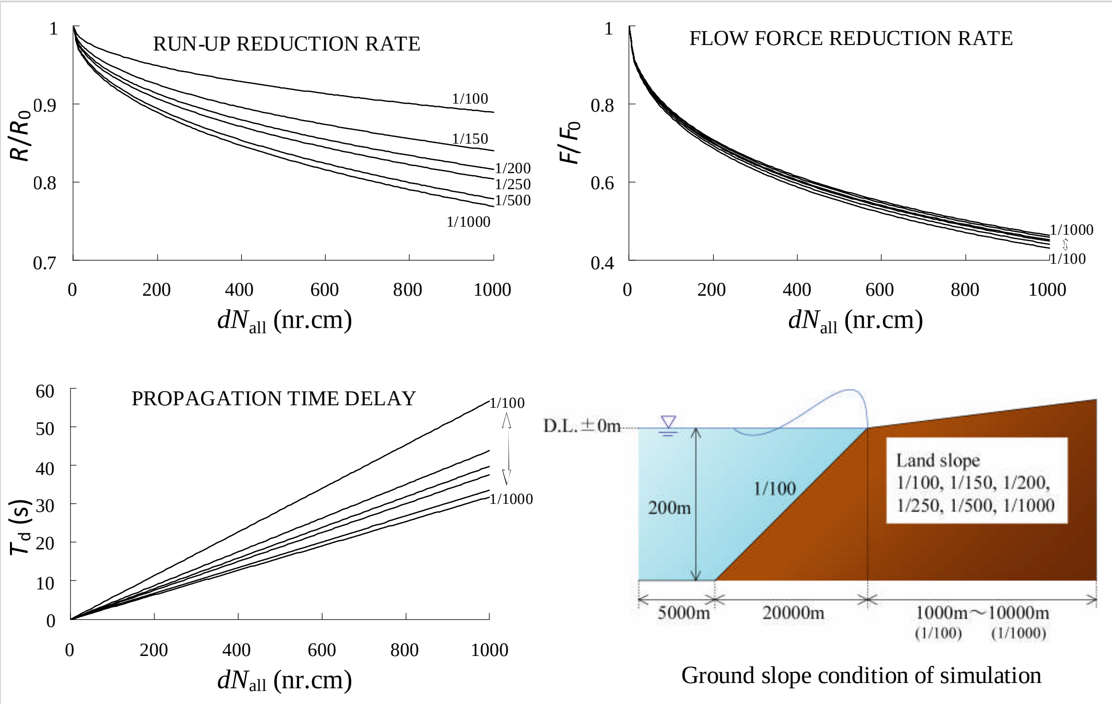


Figure-6 Numerical simulation results on the reduction rates of tsunami run-up, flow force and propagation time delay in terms of forest density, dN_{all}, and ground slope variations [*Source: Tanaka & Iimura, 2009*]

Table 2. Conditions of vegetation species used for numerical simulation to derive graphs in Figure-6 [*Source: Tanaka & Iimura, 2009*]

Vegetation-species	Tree height (m)	DBH (cm)	Average spacing (m)	Vegetation belt density (trees/m^2)
Pandanus odoratissimus	6	15.5	1.692	0.403
Anacardium occidentale	5	29.7	7.100	0.023
Casuarina equisetifolia	10	12.4	2.160	0.247
Rhizopora apiculata	8	17.7	3.336	0.104

Shuto [1987] used the term "undergrowth" for this complementary vegetation. Although no quantitative description on the effect of undergrowth on tsunami flow, he found data that a forest with dense undergrowth would reduce current velocity and suffer little or less damage from a tsunami attack. Tanaka *et al.* [2007] found in Kalutara, Sri Lanka, in the aftermath of the 2004 Indian Ocean Tsunami that two layers of vegetation, *i.e., Pandanus odoratissimus* and *Casuarina equisetifolia,* provided effective protection to the area behind a forest. The vertically dense structure of *Pandanus* reduced the flow effectively, while the strong and high *Casuarina* stopped floatages and reduced the flow velocity in the upper space.

In this regard, the vertical variation of a vegetation belt should be considered in the design of a tsunami-mitigative coastal vegetation belt to provide maximum protection effects.

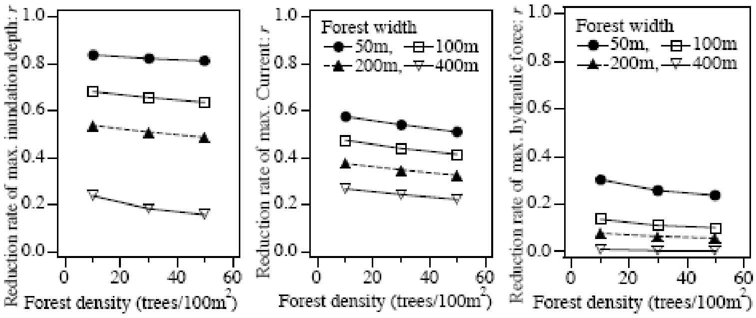
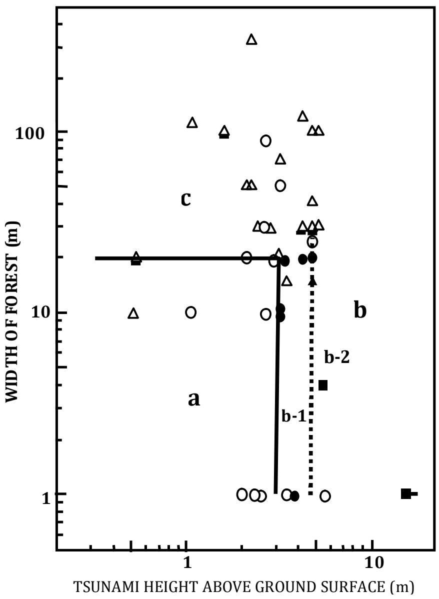


Figure-7 Effects of forest density to tsunami reduction (tsunami period 10min) [*Harada & Kawata, 2004*]

3.4 Effect of vegetation belt width

The tendency of the vegetation belt width effect on tsunami flow reduction was initially shown by Shuto [1987] qualitatively in the case of pine-tree forests in Japan. Statistically, the average conditions of the analyzed forests were the forest width of 23m, trunk diameter of 13 cm and inter-tree distance of 1.6m. He found that with its width 20m or less, a forest has no capacity of reducing tsunami flow but stopping floatages. As long as a tsunami flow depth is less than 3m, a forest of more than 20m width is capable of reducing tsunami flow. Flow reduction increases as forest width increases. However, when a tsunami flow depth is greater than 4.65m, the width of a coastal forest does not have much effect on tsunami flow reduction although it may trap floatages effectively. The graph in Figure-8 shows the effectiveness of the width of a pine-tree forest in reduction of tsunami energy [Shuto, 1987].



Data label:

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Underline – dense undergrowth
Bracket – damage to trees in poor condition
Horizontal bar – actual tsunami height being bigger than the values indicated in this figure

Figure-8 Effectiveness of the width of a pine tree forest on reduction of tsunami energy [*Source: Shuto (1987)*]

Several laboratory experiments as well as numerical simulations were carried out by many researchers to investigate the effects of vegetation belt width variation on tsunami flow. The numerical simulation results from Harada and Kawata [2004] show that the variation of forest width gives greater effect on tsunami flow reduction rate than that of forest density. In Figure-7, with the same forest width of 50m, the forest density of 10, 30, and 50 trees/100m^2 gave the inundation rates of 0.83, 0.82 and 0.81 behind the forest, respectively. But when the forest width is 400m, the inundation rates behind the forest with the forest density of 10, 30, and 50 trees/100m^2 are 0.23, 0.18 and 0.15, respectively. This shows that inundation rate reduction can differ greatly between two different conditions in vegetation belt width, whereas it may change only slightly under different vegetation belt densities. Here, the inundation rate refers to the inundation elevation behind a coastal vegetation belt, which is non-dimensionalized by the inundation elevation at the same point without a coastal vegetation belt.

3.5 Considering the effect of gaps along a coastal zone

Gaps in a coastal zone, such as construction of access roads to beaches or sand mining sites, the mouths of rivers, and mangrove channels open to the sea [FAO, 2007], are reported to increase risks and potential damage. Water flow accelerates as it passes through those gaps. When a gap is narrow, water flow increases the velocity immediately behind the gap, although the water depth will actually decrease in most cases [Nandasena *et al.*, 2008]. Areas behind a coastal vegetation belt can still be protected from tsunamis [FAO, 2007; Thuy *et al.*, 2009], but such gaps increase hazards in the wave run [Fernando *et al.,* 2005, 2008; Thuy *et al.,* 2009]. As it is not realistic to consider a coastal vegetation belt without any gap, careful planning is required in the design of an actual coastal vegetation belt. It can be done by inclining the gap direction away from the tsunami current direction or to stagger the gap to reduce the water velocity through gaps [Tanaka, 2009].

4. Planning of coastal vegetation belt for tsunami disaster mitigation

4.1 Basic Steps in Planning and Design of Tsunami Mitigative Coastal Vegetation Belts

Basic steps in planning and design of tsunami mitigative coastal vegetation belts consist of assessment of site suitability for coastal vegetation belt implementation and determination of coastal vegetation belt variables, mentioned in Table 1. Figure-9 shows a flowchart of basic steps in planning and designing tsunami mitigative coastal vegetation belts.

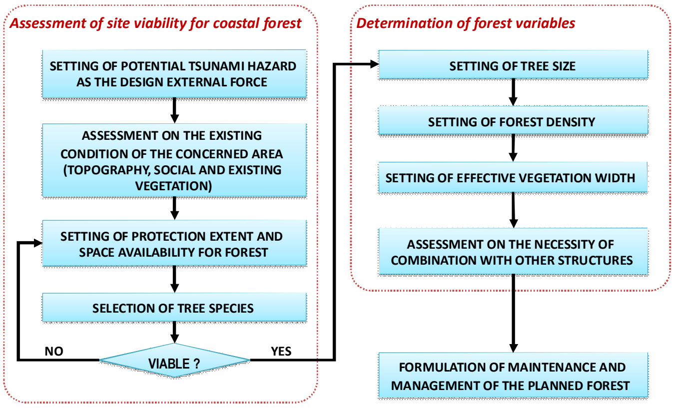


Figure-9 Flowchart of basic steps in planning and design of tsunami mitigative coastal vegetation belt

In the assessment of site suitability, analysis should be conducted on potential tsunami hazard, assessment of existing coastal conditions, setting of protection level and selection of tree species. Subsequently, tree size and vegetation belt density and width should be determined after the assessment of site suitability. Within this second group of activities, any requirement for combination with other structures should be assessed, too.

The last important step is the formulation of vegetation belt management and maintenance after the project commencement. Vegetation belt management and maintenance is the most crucial issue to ensure the sustainability of the vegetation implementation program.

4.2 Data requirement and collection

4.2.1 Potential tsunami hazard

Potential tsunami hazard means possible maximum tsunami inundation depth in a concerned area, which should be determined based on historical data or numerical simulation. This information is significantly important to get an idea about the required coastal protection capacity against a potential tsunami.

Historical records should be given the first priority since they are the records of actual hazards. If no historical records are available, approximation should be done in reference to available records of nearby coasts as long as those nearby areas are considerably similar to the concerned area in topography and bathymetry.

At present, several historical tsunami databases are available for free access. However, considerable discrepancies are still found among available databases. Thus, historical data should be collected from as many accessible sources as possible to compare and select them to create the most appropriate dataset. Data definition should be also cautiously reviewed whether data are tsunami wave heights at the nearshore, tsunami water levels at the coastline, or tsunami flow depths above the ground. Data should also be checked for their relative positions to tide water level.

Prediction of tsunami inundation heights by using numerical simulation or analytic calculation will be an alternative if no historical records are available or historical data of nearby coasts are not applicable. However, utilization of numerical models to determine tsunami inundation depths may not be practical for many expected end users, *e.g.,* local municipality officers, community leaders, or individuals. In order to facilitate these end user, the following procedure to determine tsunami inundation depths should be considered.

(i) Historical records of tsunami inundation depths in the concerned area are the most authentic data to be utilized. In this regard, those data should be publicly available and easily accessible for free access..

(ii) If data on the concerned area is not available, data on the nearest location can be used after careful consideration about similarity of conditions such as bathymetry, topography and coastal morphology between the two locations. In this case, expert suggestions are indispensible.

(iii) The central government carries out thorough investigation on the historical records of tsunami inundation all over the country. Numerical simulation of potential tsunami inundations in tsunami-prone coastal areas should also be conducted to provide data for areas with no historical data. Those potential tsunami inundation data from historical as well as simulated events should be publicly open and made accessible freely.

4.2.2 Coastal morphological and tidal data

Coastal morphological data include coastal inland elevation (topography), coastal bed elevation (bathymetry) and coastal environment classification (such as wetland, sandy beach, estuary delta, *etc.*) as well.

Topography and bathymetry data are required to determine ground slope and to run tsunami inundation simulation. Beach slope has significant effect on run-up reduction. For tsunami inundation simulation purposes, maps as detailed as 1:1.000 are necessary.

Coastal environment data, especially ground soil type and land cover (*e.g.,* wetland, sandy beach or muddy tidal flat), are very important since they are associated with vegetation habitat. Together with data on existing vegetation, these data are indispensible to determine suitable vegetation for coastal protection.

If no map is available yet, terrestrial topography and bathymetry measurement should be carried out to provide required data and maps.

A simple measurement method of beach slope gradient is illustrated in Figure-10. A beach slope in a concerned area should be measured at several points including ones at the maximum and minimum beach width. Ground level should be measured gradually inland from the coastline.

Along with this, tidal graph record is necessary to connect topography and bathymetry data to the reference datum. Mean highest water level (HWL), mean water level (MWL) and mean lowest water level (LWL) are the standard information on tide. These tide level data can be confirmed by interviewing local residents and coast administrators or by referring to available port and beach planning data or existing tide observation data, *etc.*

Tide elevation record is also important for tsunami run-up simulation and determination of effective areas for coastal vegetation belt development.

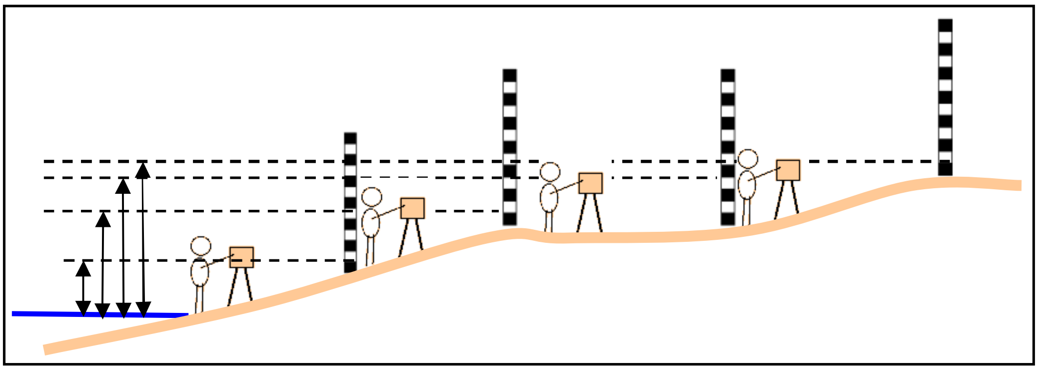


Figure-10 Simple measurement method of beach slope gradient

4.2.3 Existing vegetation

Availability and type of vegetations in a concerned area or its nearby coast is important information to identify site suitability for coastal vegetation belt implementation. These data will also give an initial picture on a possible mitigation level by the existing coastal vegetation belt. Survey on vegetation belts should cover variables including the items of vegetation front, species, trunk diameter, tree height, vegetation shape factor (*i.e.,* composition of root, trunk, branches and leaves), number of tree per unit square and forest width. The vegetation front refers to shrubs and semi-tall trees, which grow on the ocean side of the vegetation.

Table 3 describes vegetation survey, showing survey items and purposes, whereas Figure-11 gives illustration of vegetation survey items.

Table 3. Description of vegetation survey items

Item	Description of survey
Vegetation front	To confirm the location of vegetation growing near the planning point, measure the width between the coastline and the vegetation front. The vegetation front is the ocean side of vegetation belts in which typically shrubs and semi-tall trees grow. (as indicated in Fig.10)
Tree species	To decide effective tree species for a plan, main tree species are investigated in the vegetation area. Dominant tree species are categorized into classifications of tall trees, semi-tall trees and shrubs.
Tree density	To estimate the tree density in a plan, the number of growing trees in an area of 10 x 10 m^2 is counted according to species.
Tree height	To estimate each tree species' tolerance to tsunami wave height in a plan, the average tree height is measured according to tree species.
Vegetation belt width	To determine the practical, effective width of vegetation belt, the existing maximum and minimum widths of vegetation belt are measured. The width of vegetation belt is measured perpendicular to the coastline, from the most outer tree trunk position at one side to the one at the opposite side.
Soil material	Check the soil material in the investigated area.

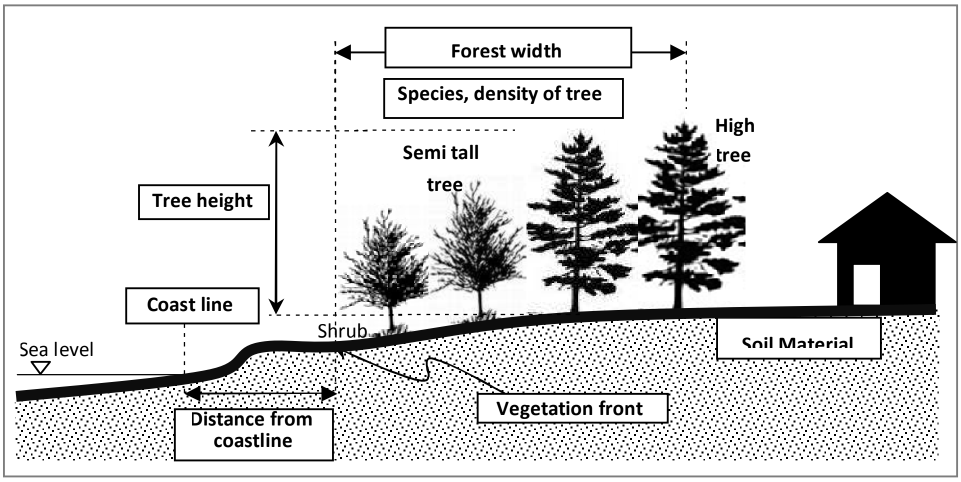


Figure-11 Illustration of vegetation survey items

4.2.4 Land use situations and social conditions

Land-use situations and local social conditions include existing and future plans for coastal land-use situations and the daily livelihood of residents. Land-use data are required to determine the expected protection and available space for a coastal vegetation belt. Further, livelihood situations (*e.g.,* record on the interaction of local residents with an existing forest, whether they are utilizing forest materials for their daily life, *etc.*) are very important to assess forest sustainability as well as its future management and maintenance viability. The housing material information is also important to decide required flow force reduction to a safer level for surrounding houses. Description by Shuto [1992] in Table 4 shows the correlation between tsunami inundation height and potentially generated damage.

Table 4. Tsunami force and its related disasters [*Source: Shuto, 1992*]

Tsunami strength	0		1		2		3		4		5	
Tsunami height (m)	1		2		4		8		16		32	
Tsunami form	Gentle slope	Rising on the shore		Water wall at offshore Second breaking wave		Increase wave which is breaking at the tip of it		Even first wave causes a surging wave breaking				
	Steep slope	Fast current speed		Fast current speed								
Sound					Continuous soundby front wave breaking							
						Big blare by surging wave breaking at shore (Thunder blare, not recognized in distant place)						
							Big blare conflicting in a cliff (distant thunder, heard to the far places)					
Wooden house		Partial destruction		Full destruction								
Stone house		Holding						Full destruction				
Reinforced concrete building		Holding										
Fishing boat				Damage		Damage ratio 50%		Damage ratio 100%				
Damage of forest		Damage reduction				Partially damage		Full destruction				
Effect of forest		Tsunami reduction		Draft prevention		Draft prevention						
Cultured raft		Damage										
Coast village				Damage		Damage ratio 50%		Damage ratio 100%				
Run-up (m)	1		2		4		8		16		32	

The availability of land space along the coastline for coastal vegetation should be clearly confirmed since a tsunami-mitigative coastal vegetation belt needs a considerable width of space to work effectively. In examining this, high resolution satellite images will be very helpful to make initial identification before conducting field investigation to check data. Available area along the coastline for coastal vegetation is measured from a limit point of wave run-up to the inland side. The limit point of wave run-up will be confirmed during site investigation. Several coastal features can be used to identify this limit point, *e.g.,* in the case of a sandy beach with low frequency of wave run-up, it is the starting point of the growth of ground cover vegetation; or, in the case of an erodible beach due to high-wave regime, it is the seaside point of beach bank or beach cliff. Interviewing local residents will be very helpful to grasp this information.

4.3 Design parameters and calculation procedures

4.3.1 External forces

Many researchers suggest the use of tsunami inundation depth to represent external force based on which tsunami velocity and forces are calculated (*e.g.,* Shuto [1991], Harada and Imamura [2000], Tanaka [2008]).

Tsunami inundation depth is the depth of tsunami inland flow at any particular point. For the standard design purpose, the values at coastline points should be applicable as the representative values. Figure-12 illustrates the definition of inundation depth.

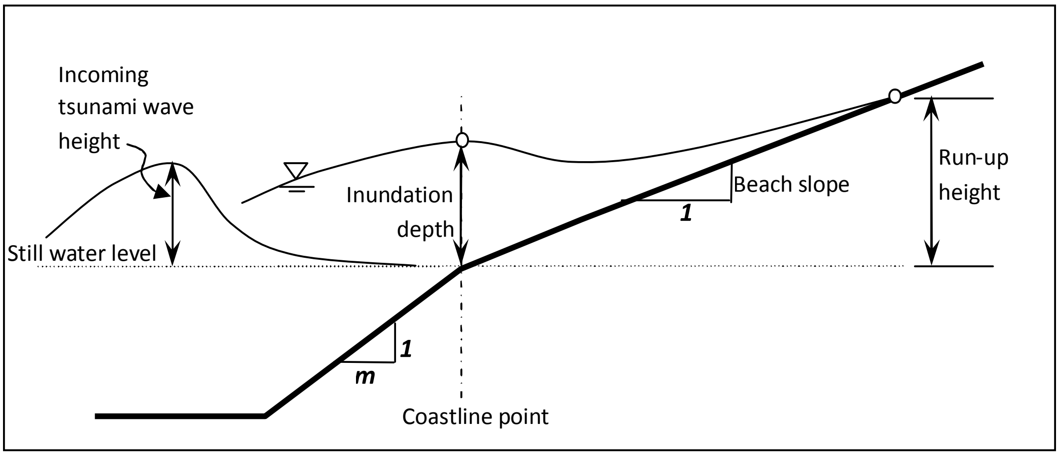


Figure-12 Illustration of tsunami inundation depth measure

The design tsunami inundation depth should be the possible maximum value among available data (Refer to the Section 5.1.1 in selecting the design inundation depth).

In an actual situation, coastal topography is usually irregular and thus tsunami inundation depths will vary within a stretch of beach due to the wave refraction effect. In such a case, calculation should be carried out in a segment-wise manner by considering the uniformity of waves, land slope and vegetation belt conditions. In this respect, detailed records of tsunami inundation are quite important. Figure-13 gives an illustration of this segmentation approach. Segmentation and the number of segments will be site specific and determined based on site investigation.

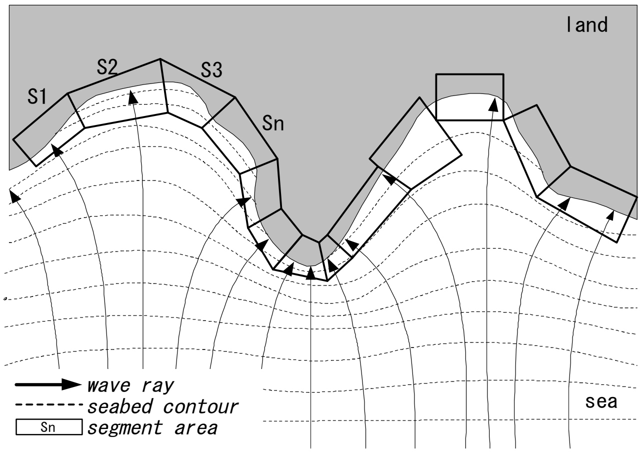


Figure-13 Illustration of alongshore segmentations for the design of coastal forests according to the field conditions of wave, land slope and forest.

4.3.2 Determination of the width of coastal vegetation belt

Available knowledge informs that vegetation belt width in the tsunami flow direction has significant effect on tsunami flow reduction. Thus, as long as space is available, a coastal vegetation belt should be built as widely as possible to provide maximum protection. At a minimum condition, a 20m width coastal vegetation belt, which consists of pine trees with median trunk diameter of 13cm and the average interval between trees of 1.6m will stop floatages but has no effect on tsunami flow reduction [Shuto, 1987].

In the lack of more comprehensive data on the behavior of various types of vegetation, numerical simulation results from Harada and Kawata [2004] in Table 5 can be used as an initial approach in determining the requirement of vegetation belt width. It should be kept in mind that the values displayed in Table 5 were based on simulation under the following conditions: maximum tsunami inundation depth of 3m, tsunami period of 10 minutes, vegetation belt density of 30 trees/100m^2, trunk diameter of 0.15m, tree height of 10m, lowest canopy of 2m from the ground, and ground slope of 1:500.

Table 5. Tsunami reduction effect by coastal vegetation belt [Harada and Kawata, 2004]

Tsunami inundation depth (m)			1	2	3
Coastal control vegetation belt [Shuto, 1987]			Mitigate damage, stop floatage, reduce tsunami		
Run-up distance	Vegetation belt width (m)	50	0.98	0.86	0.81
		100	0.83	0.80	0.71
		200	0.79	0.71	0.64
		400	0.78	0.65	0.57
Inundation depth	Vegetation belt width (m)	50	0.86	0.86	0.82
		100	0.76	0.74	0.66
		200	0.46	0.55	0.50
		400	-	0.11	0.18
Current	Vegetation belt width (m)	50	0.71	0.58	0.54
		100	0.57	0.47	0.44
		200	0.56	0.39	0.34
		400	-	0.31	0.24
Hydraulic force	Vegetation belt width (m)	50	0.53	0.48	0.39
		100	0.33	0.32	0.17
		200	0.01	0.13	0.08
		400	-	0.02	0.01

4.3.3 Selection of tree species

Suitable tree species will be determined from the results of vegetation survey considering the combination of high and low trees and the maximum density of vegetation.

Very few studies have been conducted to identify the behavior of coastal trees in response to tsunami inundation flow. Appendix-1 lists characteristics of several tree species growing in coastal areas of Sri Lanka, Thailand and Indonesia for tsunami protection (extended from data provided by Tanaka *et al.* [2005a, 2005b], Sasaki *et al.* [2005], Matsumura [2006], ICHARM [2009]).

【Species and structure of trees' effect on tsunami wave height reduction】

Tanaka *et al.*(2005b) show from field survey that effective species for tsunami protection is ones that develop very thick aerial roots and also shrub species with a large trunk (such as Cashew nuts trees). Both species are assumed as effective for less than 5-m tsunamis.

Tanaka *et al.*(2005b) explain that in a sandy beach area, a mixed-aged *Casuarina* forest and a two-layered forest having *Casuarina* and *Pandanus* in the vertical direction may be effective to decrease damage behind the forests against 10-m class tsunamis.

The effect of mixed trees on wave height reduction is under experimental verification at the moment. Tanimoto *et al.*(2007) investigated the tsunami protection effect of combinations of four different species such as *Pandanus*, *Casuarina*, Cashew nuts and Mangrove by numerical calculation.

Based on the results of the above mentioned tsunami inundation modeling, it was found that in case of a tsunami with the 15-minute period and 5-m height at the coastline, the first run-up became 1.6m lower than the original tsunami and delayed 65 seconds in arrival time at the inland end of the forest. The maximum current speed decreased from 3.1 to 1.7m/s, and the tsunami force decreased from 14 to 3.3kN/m.

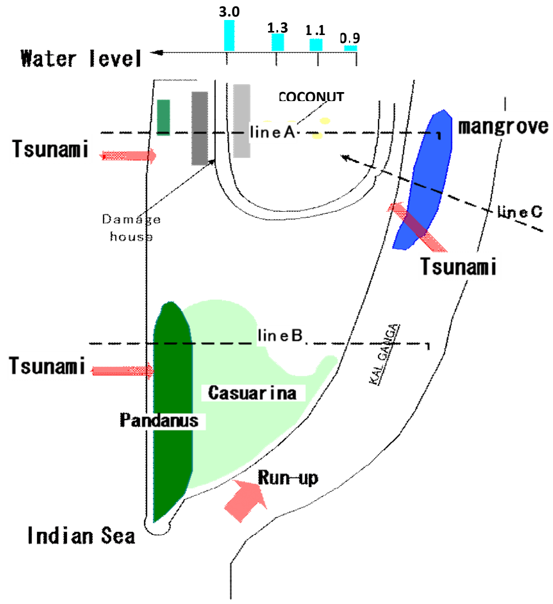
The above study further suggests that, based on repeated invetigative verification, the tsunami reduction effect may increase depending on actual conditions.

【Example of wave reduction effect (Sri Lanka)】

It was reported that the tsunami height was about 3.5m at the Cal. Ganga river mouth in Kalutara located southwest of Sri Lanka. However the following knowledge was obtained about an area located at the tip of the sand-spit (2.6 m in height) near the river mouth.

【line A】

The tsunami hit the coast and reached the housing area in the back land while knocking down coconut trees along the coast and damaging houses behind the trees up to 100m from the coast. Only one-line vegetation belt of *Pandanus* and Coconut trees existed along the coastline, which was 50m away from the nearest inland houses. The tsunami is thought to have passed between the Coconut trees. The height of the tsunami reduced only from 3.5m to 3m at the 60m spot from the coast (see the figure on the right-hand side).



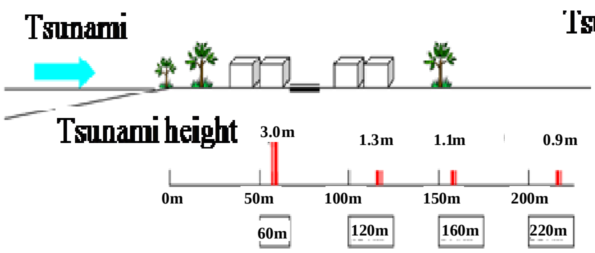
【line B】

There was a 60m-wide, mixed forest of *Pandanus* and *Casuarina* trees around the Cal. Ganga river mouth to the southern side of Line-A. No housing damage was observed behind this forest. The height of the tsunami around these houses located 60m from the coastline dropped to 0.6 m from the original 3.5m at the coastline at the 60m spot from the coast (see the figure below).

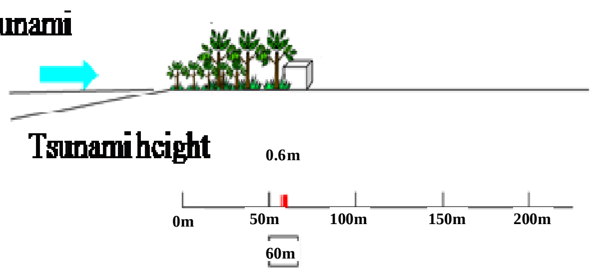
【line C】

The tsunami propagated upstream through the Cal. Ganga river mouth, but caused no damage around the flood plain area where a mangrove belt existed.

【lineA】



【lineB】

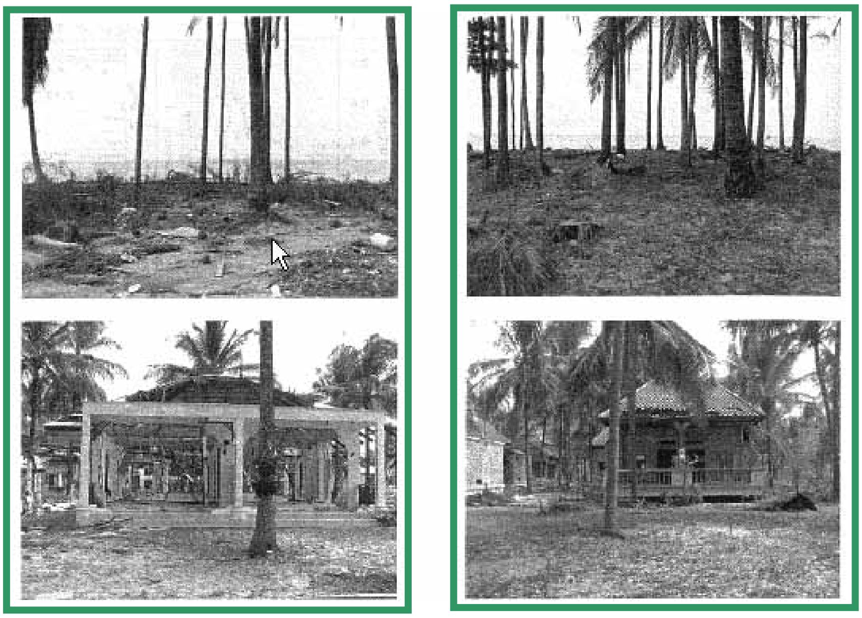


Source: JACE [2005]; Tanaka *et al.* [2005b]; Tanaka *et al.* [2007]

【Example of wave reduction effect (Thailand) 】

In the southern region of Khao Lak Beach of Thailand, a little difference was acknowledged in inland tsunami inundation height between two nearby locations where the vegetation (coconuts trees) on their seaside vary in width and density. The inundation height was 4.9m at the location with the vegetation width of 14m and density of 0.27% (Fig-A), whereas it was 4.6m at the other location with the vegetation width of 28m and density of 0.42% (Fig-B). Considering that the wave height in these two areas were same, it can be thought that the 0.3m difference in inundation depth was due to the difference in vegetation width and density between the two locations. By assuming that the wave was equal to 4.9m, the reduction rate of inundation depth due to the vegetation belt at location B is about 0.94.

A – Tree density is small. B – Tree density is medium.



The density of coastal trees and the damage of the houses behind

Source: Tanaka *et al*. [2005a]; Tanaka *et al.* [2007]

4.3.4 Determination of trunk diameter

Initial setting of trunk diameter

Field data show that ” being cut-off or broken” are the most frequently seen in trees after a tsunami attack among various damage patterns (*e.g.,* Tanaka *et al.* [2007], Yanagisawa *et al.* [2008]]. In this regard, it is very important to ensure the trunk capacity to stand against tsunami force.

Many researchers use trunk diameter as a representative variable to analyze the trunk capacity. Shuto [1987] found a correlation between the tsunami height above the ground surface (*i.e.*, tsunami inundation depth) and the diameter of a tree from the damage of pine-tree forests after tsunami disasters in Japan (Figure-1).

Tanaka *et al.* [2006] conducted field tests to investigate the force needed to break trees grown in several local vegetations in Sri Lanka after the 2004 Indian Ocean Tsunami. He then converted the tree-breaking force into an equivalent tsunami height that is supposed to generate the equal force and breaking moment effect. Based on the test results, Tanaka *et al.* [2006] illustrated a correlation between the tree diameter and the corresponding tsunami height (Figure-2).

The above mentioned correlations provided by Shuto [1987] and Tanaka *et al.* [2006] are redrawn in a logarithmic scale by using the template of Shuto [1987] as shown in Figure-14. For each kind of vegetation, a trend line was drawn and its related equation and R^2 value were displayed as well.

Figure-14 shows that trunk diameter at breaking of *P. odoratissimus*, *L. racemosa* and *E. agallocha* satisfy the approximate boundary (Curve II) given by Shuto [1987], whereas *R. apiculata*-type and *C. equisetifolia* have higher breaking capacities although still below or around Curve I, which according to Shuto [1987] is the maximum limit of the tree capacity against tsunami force. In accordance with this, we can set Equation 2 as an initial approximation value in determining the design trunk diameter for vegetation type similar to *P. odoratissimus*, *L. racemosa*, *E. agallocha* and pine trees, while using Equation 1 to determine the initial design trunk diameter of vegetation similar to *R. apiculata*-type and *C. equisetifolia*. However, the design trunk diameter should not be less than 10cm to stand against tsunami force [Shuto, 1987].

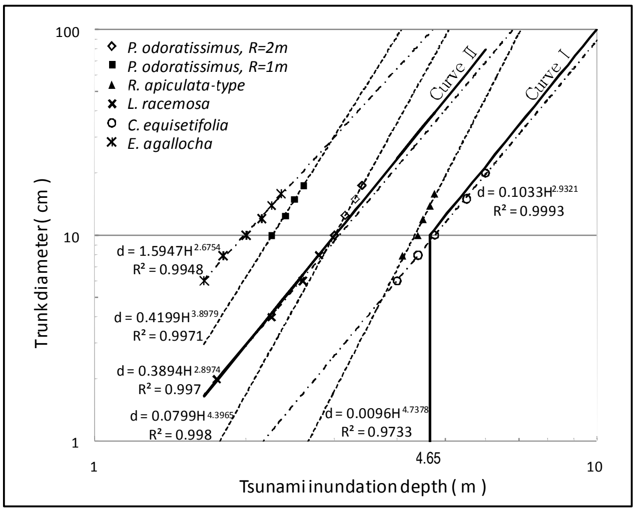


Figure-14 Trunk diameter at breaking and its related tsunami inundation depth (redrawn from data of Shuto [1987] and Tanaka *et al.* [2006]).

Wave-induced bending moment and breaking moment limit of the tree

The capacity of a tree against tsunami force should be examined according to the breaking moment limit of the tree. If the bending moment imposed by a tsunami on a tree trunk is greater than the trunk's maximum bending moment resistance, the failure mechanism is initiated (*e.g.,* Tanaka *et al.* [2008], Matsutomi [2008]).

Yanagisawa *et al.* [2008] provided the following equations to calculate the wave-induced bending moment on a tree.

$$M_d = 0.5\,F\,(h - H_R) \tag{10}$$

$$F = 0.5\,C_D\,\rho\,A_0\,u^2 \tag{11}$$

where M_d is the bending moment (in Nm), h is the tsunami inundation depth (m), F is the hydraulic drag force acting on the tree, C_D is the drag coefficient, ρ is the water density, A_0 is the vertical projection area of the inundated part of the tree, and u is the depth-averaged tsunami flow velocity. H_R is related to the position of the bending moment center of rotation. It is the height of the prop roots (m) above the ground in the case of vegetation with prop roots or aerial roots, whereas it should be zero for hard trunk-type trees, *e.g., Casuarina*, pine, *etc.,* since most damages are uprooting [Yanagisawa *et al.*, 2008].

In Equation 10 and 11, a tree stem is assumed to be cylindrical. The inertial force is neglected because the inertial force due to the velocity acceleration du/dt is comparatively much smaller than the drag force (*e.g.,* Harada & Kawata [2004], Yanagisawa *et al.* [2008]).

Referring to Shore Protection Manual [1984], Yanagisawa *et al.* [2008] suggested the following equations to calculate C_D when a tree has prop-roots with only the main trunk inundated (considered as a single cylinder).

$$C_D = \begin{cases} 1.2 & \text{for} \quad Re \leq 2 \times 10^5 \\ 1.2 - 0.5\left(\frac{Re}{3\times 10^5} - \frac{2}{3}\right) & \text{for } 2 \times 10^5 \leq Re \leq 5 \times 10^5 \\ 0.7 & \text{for} \quad Re \geq 5 \times 10^5 \end{cases} \tag{12}$$

$$Re = \frac{|u| \times d}{\nu} \tag{13}$$

$$u = \sqrt{gh} \tag{14}$$

where Re is the Reynolds number, ν is the kinematic viscosity, g is the acceleration of gravity, h is the tsunami inundation depth and d is the representative trunk diameter. Usually, d is the diameter at breast height (sometimes written as *dbh*).

In the case of a tsunami inundating most parts of the trees, including prop-roots, trunks and canopies, Tanaka *et al.* [2007] proposed $C_{D\text{-all}}$ for the integral drag coefficient, instead of $C_D\,A_0$, which is calculated as follows:

$$C_{D\text{-all}} = \alpha\beta \times C_D \tag{15}$$

$$\alpha\beta = \frac{1}{h}\int_0^h \alpha(z)\beta(z) = \frac{1}{n}\sum_{i=1}^{n} \alpha_i \times \beta = \frac{1}{n}\sum_{i=1}^{n} \frac{dA_i}{dA_{1.2}} \times \beta \tag{16}$$

$$dA_i = \sum_{m=1}^{m=i_{max}} dA_{im} \tag{17}$$

$$dA_{1.2} = \frac{d}{100} \times z_t \tag{18}$$

where h (m) is the tsunami inundation depth, α is the branch effect on C_D, β is the leaf effect on C_D, dA_i (m^2) is the summation of the vertical projection area of the tree at the layer i^{th}, $dA_{1.2}$ (m^2) is the vertical projection area of the trunk at 1.2m above the ground, z_t is the determined thickness of the partial layer at the relevant position. Additional drag by leaves was taken as constant $\beta = 1.25$ (in leaf-bearing layers) or $\beta = 1$ (in leafless layers).

For examination purposes, this bending moment force should be compared with the breaking moment limit of the tree. Unfortunately the breaking moment limits of coastal trees have not been well investigated. Within this limited information availability, the breaking moment equation derived by Tanaka *et al.* [2008] can be used for approximation. The equations was derived based on the field tests in Sri Lanka after the 2004 Indian Ocean Tsunami on several representative coastal vegetations (*i.e. Pandanus odoratissimus*, *Scaevola sericea*, *Lumnitzera racemosa*, *Rhizopora mucronata*, *Casuarina equisetifolia*, and *Avicenia marina*), as shown in Figure-15. The vegetations were classified according to their elasticity and habitation, *i.e.,* coastal vegetations (including *Pandanus odoratissimus*), flexible trees (including *Rhizopora mucronata*) and trees with hard trunks (including *Casuarina equisetifolia*).

The breaking moment equations are respectively written as M_{GP1}, M_{GP2} and M_{GP3R} as follows,

$$M_{GP1} = 4.45 \text{ x } dbh^{2.62} \quad (19)$$

$$M_{GP2} = 20.52 \text{ x } dbh^{2.83} \quad (20)$$

$$M_{GP3R} = 4.9 \text{ x } (1.5dbh)^3 \quad (21)$$

where *dbh* is the diameter (cm) of a tree at the breast height [Tanaka *et al.*, 2008].

Trunk diameter should be recalculated until the breaking moment capacity of the tree overcome the tsunami bending moment.

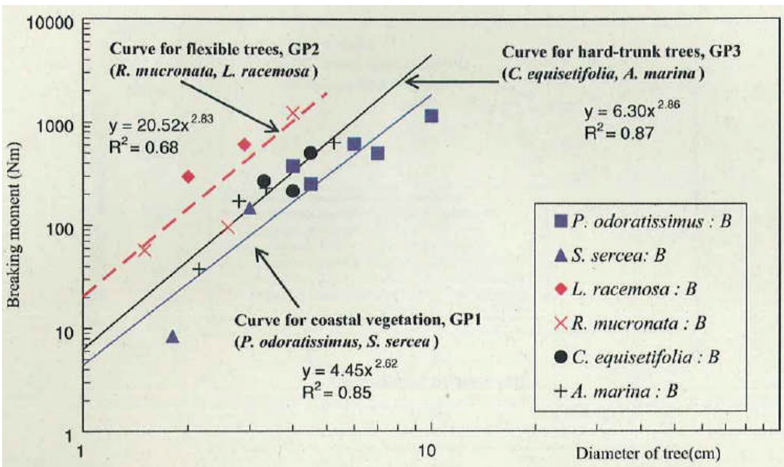


Figure-15 Breaking moment graph of representative coastal vegetation as a function of tree diameter; B=broken [*Source: Tanaka et al. (2008)]*

4.3.5 Determination of coastal vegetation belt density

After the type of vegetation and the capacity against tsunami force are ensured for the selected trunk diameter, the next step is determination of vegetation belt density. Vegetation belt density is the product of individual tree size (including root, trunk, branches and leaves) and tree numbers within the vegetation belt.

In the following, determination of tree numbers will be discussed based on the empirical relation between representative trunk diameter and average inter-tree spacing or tree numbers per unit area in combination with the concept of "summed diameter" [Shuto, 1987].

Determination of tree numbers (*n*)

Forest ecology science informs that there are certain allometric relationships among tree faculties (Asano [2007], Yokozawa and Hara [1995]), *e.g.*, between tree height and trunk diameter (Dauda *et al.* [2004]), between trunk diameter and canopy diameter (Zuhaidi [2009], O'Brien *et al.* [1995], Hemery *et al.* [2005]), which affect the composition of tree structure and tree numbers within a certain area. These allometric relationships are unique for each type of vegetation at an instantaneous period of time (Yokozawa and Hara [1995]). Good understanding on the relationships enables the design of optimum composition and arrangement of forest stand for an effective tsunami-mitigative coastal vegetation belt. For example, since usually canopy diameter is greater than trunk diameter, the distance between trees is determined based on canopy diameter. If the allometric relationship between canopy diameter and trunk diameter can be formulated, various combinations of canopy diameter, inter-tree spacing and trunk diameter can be compared to find the maximum vegetation belt density of by assuming that vegetation belt density is the product of tree numbers and trunk diameter. At present, however, knowledge about the allometry of coastal tree vegetation is not well established yet. So far only Oak trees (*Querqus* sp.) have been assessed for this relation (Hemery *et al.* [2005]). Therefore, research on this matter for coastal trees is considered to be urgent in the very near future.

In this relation, the graphs provided by Harada and Kawata [2004] and Tanaka *et al.* [2007] can be used for reference. Harada and Kawata [2004] draw an empirical relation between trunk diameter and vegetation belt density (trees/100m^2) based on Japanese pine-tree forest data (Figure-16 (left)). Tanaka *et al.* [2007] used field data collected in Sri Lanka to correlate trunk diameter and average inter-tree spacing for *Casuarina equisetifolia*, *Cocos nucifera*, *Avicenia alba*, *Rhizopora apiculata*, *Pandanus odoratissimus* and *Anacardium occidentale*. Rearrangement of the data from Tanaka *et al.* [2007] resulted in the forest density (the number of trees in 10x10m^2) in terms of trunk diameter for the related vegetations (Figure-16 (right)). Since both graphs were drawn based on the data collected from natural forests, it is expected that the effect of canopy size on inter-tree spacing has been included.

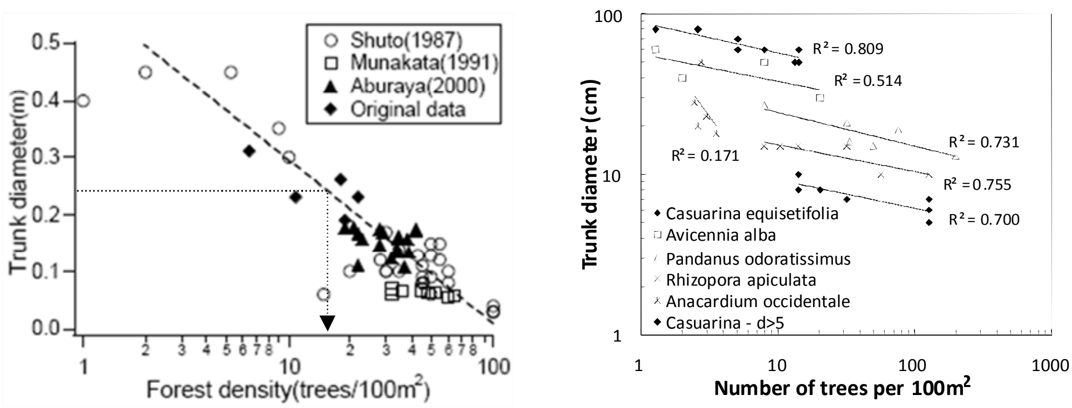


Figure-16. *(left)* Relation of forest density and trunk diameter for pine trees [Harada & Kawata, 2004]; *(right)* Relation of forest density and trunk diameter for Casuarina equisetifolia, *Cocos nucifera*, *Avicenia alba*, *Rhizopora apiculata*, Pandanus odoratissimus and Anacardium occidentale (plotted from the rearranged data of [Tanaka *et al.*, 2007]).

Let's take an example examination on pine trees. For an inundation depth (*h*) of 4m, the average trunk diameter (*d*) is initially approximated by using Equation 2 to obtain the minimum value of 23.68cm, or roughly 24cm. By using Figure-16 (left), the number (*n*) of pine trees with this trunk diameter is identified to be 15 per $100m^2$, or 0.15 per m^2. This density equals to an average spacing of about 2.9m.

The applicability of the calculated tree numbers *n* must be rechecked whether tree numbers *n* with trunk diameter *d* are actually possible within a unit area; in other words, whether there is really enough space available for a certain number (*n*) of trees with trunk diameter *d* to grow in a unit area. This condition can be related to canopy or crown size, which affects natural tree spacing within a vegetation belt. Local field survey results on average inter-tree spacing or the allometric relation between trunk diameter and canopy size is quite important to adjust tree numbers derived from the above graph. For example, if the survey results show that the maximum canopy diameter of pinus thumbergii is about two meters for the trunk diameter of about 20-25cm, the average spacing between trees should be at least one meter. Thus, in the above example case, there is still a possibility for the number of trees to increase, which will give the maximum product of *dn*.

<u>Examination of summed diameter (*dn* = *d*×*n*)</u>

Shuto [1987] uses a term "summed diameter" to express forest density, which is the product of average trunk diameter (*d*) and tree numbers (*n*) within a forest. This is a simple and useful variable for preliminary judgment or assessing the tsunami flow reduction capacity of existing vegetation belts before going to the complex measurement of all tree size (including roots, trunks, branches and leaves).

The classification in Table 6 is described based on Shuto [1987] and can be used to assess qualitative effectiveness of a design vegetation belt in reducing tsunami flow. A given tsunami inundation depth (*h*) is limited up to 5m since many pieces of evidence show full destruction of coastal vegetation belts after a tsunami inundation greater than 5m.

Table 6. Classification of vegetation belt effects on tsunami in terms of inundation depth (*h*) and summed diameter (*dn*) based on Shuto [1987]

Inundation depth (*h*) in meter	Summed diameter (*dn*) in cm	Vegetation belt response to tsunami			
		Damage	Stop floatage	Reduce velocity	Ground soil damage
h < 3	*dn* < 30	No	Yes	No	Possible
	30 ≤ *dn* < 100	No	Yes	Expected	No
	100 ≤ *dn* < 300	No	Yes	Yes	No
3 ≤ *h* < 5	*dn* < 30	Partial	Yes	No	Possible
	30 ≤ *dn* < 100	Partial	Yes	Yes	Possible
	100 ≤ *dn* < 300	Partial	Yes	Much	Possible

It is very important to note that *dn* in Table 6 is the total value within a rectangular vegetation belt area of one meter length alongshore by *W*-meter width in the tsunami flow direction [Shuto, 1987]. It means that if we take *W* to be 100m, *dn* is distributed evenly within $100m^2$ of the vegetation belt. Returning to the previous example that gave $n = 15/100m^2$ for $d = 24cm$, the value of summed diameter *dn* is obtained to be 15x24 = 360nr.cm within $100m^2$, which satisfies the classification given in Table 6.

5. Combination of coastal forest with other structures

Combination of coastal vegetation belts with other structures should take precedence over single protection by coastal vegetation belts by considering that:

(i) all post tsunami disaster investigation results have shown that coastal vegetation belts have no mitigation effects for tsunami inundation greater than 5m (Shuto [1987], Tanaka *et al.* [2006], Tanaka *et al.* [2007]). Thus, for areas with potential tsunami inundation deeper than 5m, coastal vegetation belts provide little protection. In such cases, coastal vegetation belts can be utilized as a supplement to or in combination with other protection structures such as seawall, *etc.*

(ii) even for tsunami inundation less than five meters, coastal vegetation belts never provide a hundred percent protection. Therefore, depending on the necessity, combination with other types of mitigation measures is quite important to give a higher level of disaster risk reduction.

(iii) a tsunami-mitigative coastal vegetation belt needs a considerable width to work effectively, whereas many tsunami vulnerable coastal areas have been occupied by settlements and have been developed for various purposes (industry, urban and residential development, tourism and recreation, transport, fisheries and agriculture), which has left only limited space between the land and the sea. Resettlement policy is usually unsuccessful without serious persuasion efforts and good planning and management of resettlement. When only limited space is available, a smart combination with other types of structural protection must be elaborated. One possibility is to include tsunami protection function in the design of coastal area infrastructure development. For example, coastal rural roads can be used for tsunami flow reduction together with coastal vegetation belts.

(iv) when combining coastal vegetation belts and hard structures, it is efficient to arrange coastal vegetation belts on the ocean side and hard structures on the land side (Iimura *et al.* [2008]). Design of a hard structure is based on external force due to a tsunami after it flows inland through a vegetation belt. This inland hard structure, *e.g.,* embankment, may be designed and used as an infrastructural road. Figure-17 gives an illustration of such a combination.

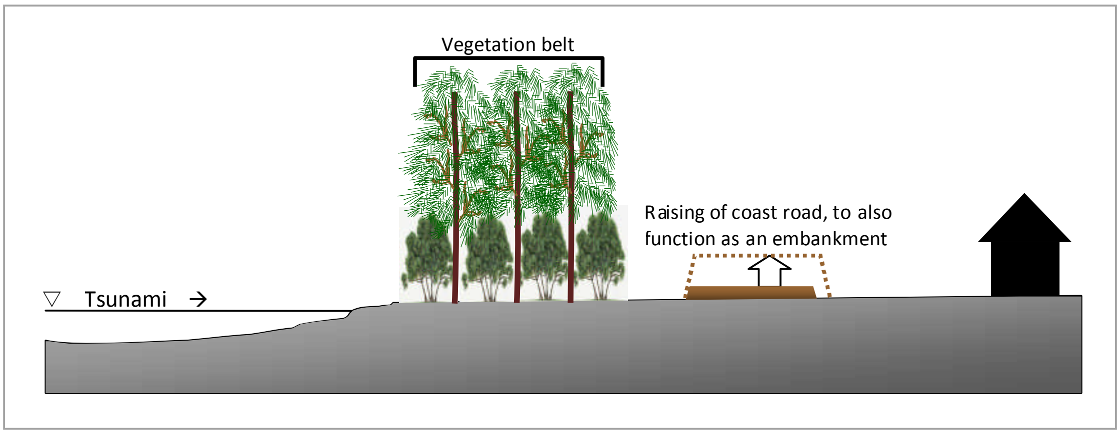
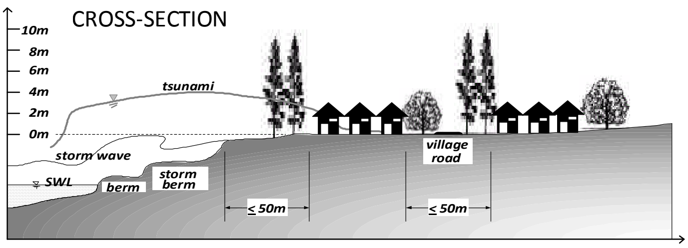


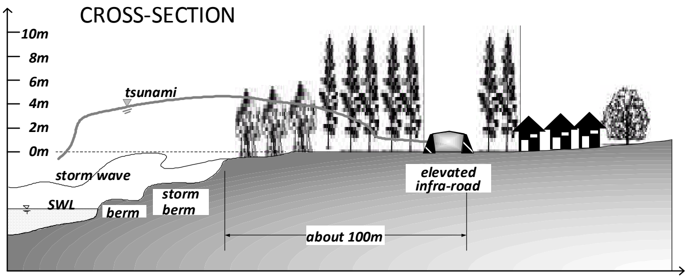
Figure-17. Illustration of combination arrangement between coastal forests and hard structures

Referring to the above mentioned potential constraints as well as the maximum capacity of coastal vegetation belts in reducing tsunami flow, several ideas on the potential application of coastal vegetation belts are proposed in Table 7.

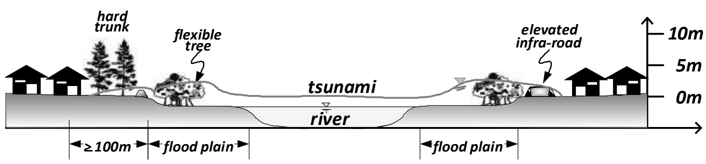
Table 7. Potential applications of coastal vegetation belts in combination with other structures



Constraint	Function and vegetation-type	Forest position and dimension
▪ Residential housing occupies most of the nearby coastline; ▪ Very limited space for a vegetation belt	▪ The least function of float trapping and escaping means; ▪ Combination of hard-trunk and flexible vegetation	▪ Coastline; around houses; between blocks; 20m-width; *dn*=30; *dbh*=13cm



Constraint	Function and vegetation-type	Forest position and dimension
▪ Limited space are available (100m) ▪ Partially are used for infra-road	▪ Float trapping and flow reduction ▪ Combination of hard-trunk and flexible vegetation ▪ Road as a flow breaker	▪ Between coastline and the road width ≤ 50m; *dn* >200



Constraint	Function and vegetation-type	Forest position and dimension
▪ River mouth and flood plain along river	▪ Floatage trapping and flow reduction ▪ Mangrove	▪ Marsh and tidal area; flood plain area width ≤ 50m; *dn* >200

6. Good governance for the sustainability of coastal vegetation-belt

6.1 General

Whereas the sustainability of coastal vegetation belts is very important to keep their continuous disaster mitigation function, vegetation belt maintenance is a challenging task since a large part of coastal areas are generally already used for direct purposes of human live.

In this respect, the following measures should be considered important in governing the sustainability of coastal vegetation belts.

(i) Community based coastal forest development in combination with incentive scheme. This scheme includes the selection of vegetation types that fulfill both tsunami mitigation function and economic demand of local villagers [Tanaka, 2009] and a clear description on the authority and responsibility of stakeholders in forest maintenance and cultivation. If necessary, local community groups of forest management can be developed in a voluntary way.

(ii) Since the 2004 Indian Ocean Tsunami, many affected countries have prepared coastal area development plans, which include land use and development zonation based on tsunami disaster risk reduction principles. However, implementation of the development plans is in many cases impossible due to miscoordination among coastal zone development stakeholders and strong objection by fishery groups who insist to live in their original coastal areas. Therefore, careful planning should be emphasized for land use regulation, coordination and law enforcement.

(iii) Along with strong enforcement and good governance of well planned land use regulation, public education on tsunami disaster should be continuously conducted to increase public understanding and awareness on tsunami dangers and tsunami disaster risk reduction as well. Without correct understanding and proper awareness, any disaster risk reduction-based development plan will face long-term objection in its actual implementation.

6.2 The Idea on Sustainable Utilization and Plantation Scheme of Vegetation

According to many empirical data, *e.g*. Tanaka *et al.* [2005], dense coastal vegetation belts consisting of vegetations with prop roots or low trees with large trunks were known to effectively reduce tsunami flow below five meter in depth. In places hit by 10m-high tsunami flows, there were indications that sand dunes covered by vegetation belts of mixed-aged *Casuarina equisetifolia* trees or combination of *Casuarina equisetifolia* and low trees with large trunks and branches (such as *Pandanus odoratissimus*) were effective in reducing tsunami flow.

In order to develop coastal vegetation belts of such structures mentioned above, selection of tree species and plantation schemes and schedule suitable for respective locations are important. The plantation schedule should refer to the growth speed and growth season of vegetation.

Especially, since tsunami disasters are not typically a frequent event, sustainable maintenance is a major challenge if maintenance responsibilities and practical uses of tree products out of tsunami prevention purposes are not mutually agreed in advance. In this respect, selection of vegetations that have more benefits to local residents should be considered, for example trees for food, medicine and daily use (*e.g.*, house materials). Suitability for tourism planning should also be considered, for example, by initially planting *Pandanus odoratissimus* on the sea front side to accumulate sand dunes along the coastline and then followed by plantation of *Casuarina equisetifolia* on the inland side.

An example scheme of periodical cultivation of vegetation products while maintaining the effective width of a vegetation belt is illustrated in Figure-18.

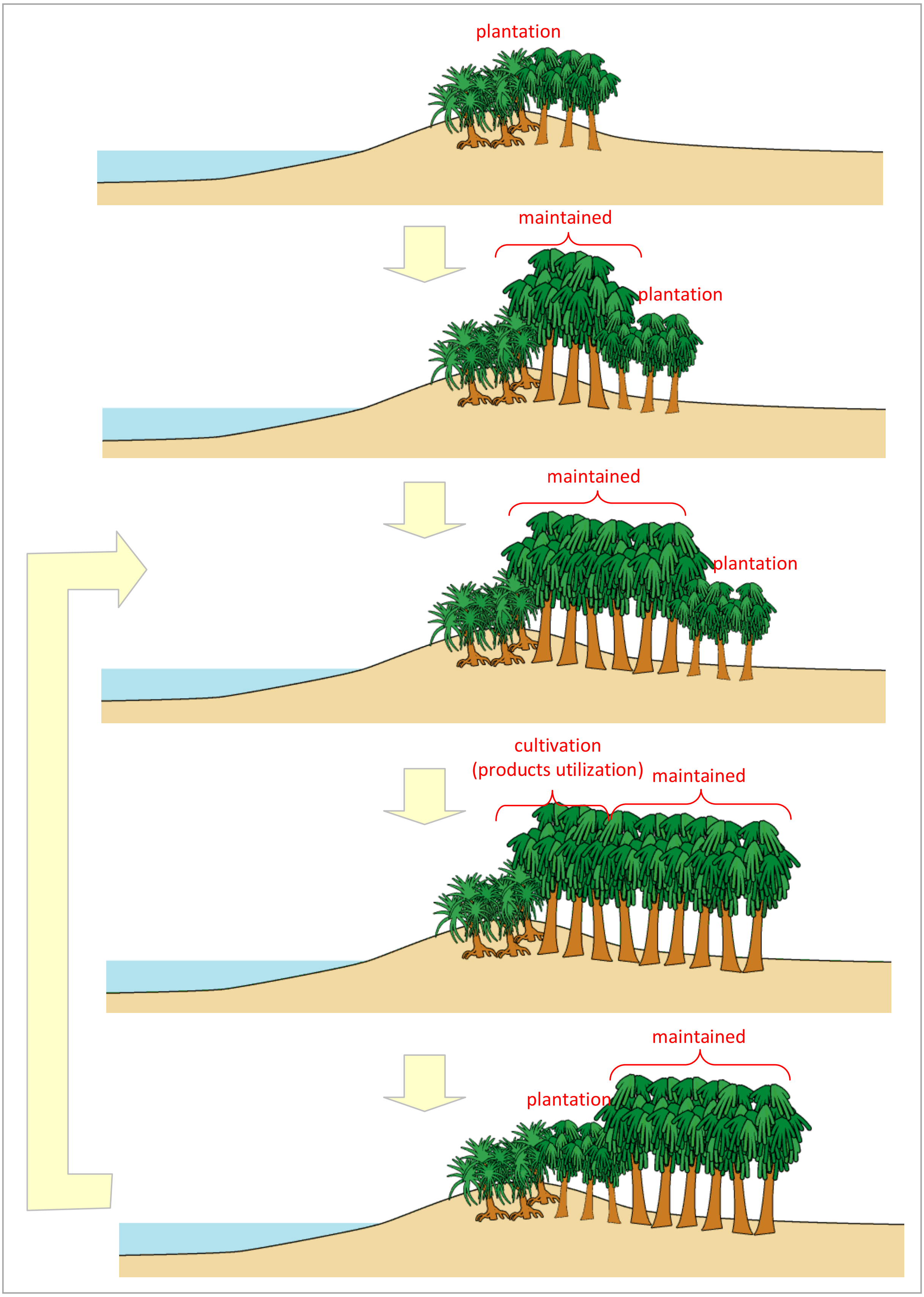


Figure-18. Illustration of an example scheme of periodical cultivation of vegetation products while maintaining the effective width of a vegetation belt. (*PCI Report to PWRI, 2009*)

7. Example of calculation

7.1 Description of location and setting of potential tsunami hazard

In this calculation, a coastal area of Galle City in Sri Lanka is selected as an example.

The Galle coast is located in southwest Sri Lanka (N6.037°, E80.224°). The morphology of the coast formed a small bay in which a city port was developed to serve the area. The sandy beach area in the Galle coast is narrow about 20-30m, and the elevation increases inland up to an altitude of 2-3m where the area is crowded with houses. Mixed vegetations of *Casuarina* and *Pandanus* types are found at the Cal. Ganga river mouth in Kalutara located south of Galle. Figure-19 shows a location map of the Galle coast (bottom, right) as well as an expanded Google's bird view map.

Figure-19 Location map of the Galle coast as well as an expanded Google's bird-eye view map

According to the NOAA-NGDC tsunami run-up database, which is partly quoted in Table 8 (see also Appendix 2), the Galle coast was inundated by an about 4.7m-deep tsunami flow during Indian Ocean tsunami 2004. So far no other historical record is available about the ancient tsunami before that of 2004. Therefore, this inundation data from NOAA-NDGC should be selected as the design tsunami inundation depth.

Table 8. Record of Indian Ocean Tsunami 2004 inundation depth at several points along the Sri Lankan coast, including record of inundation at the Galle coast. (*Source: NOAA-NGDC*)

Tsunami Runup Location								Tsunami Runup Measurements				
Country	State/ Province/ Prefecture	Name	Latitude	Longitude	Distance from Source	Travel Time Hrs	Travel Time Min	Max Water Height	Max Inundation Distance	Type	Per	1st Mtn
SRI LANKA		MATARA	5.943	80.55	1736			5.82		1		
SRI LANKA		PANADURA FISHERY PORT	6.717	79.902	1822			5.59		1		
SRI LANKA		DICKWELLA	5.963	80.693	1721			5.54		1		
SRI LANKA		BENTOTA NORTH	6.424	79.995	1805			5.5		1		
SRI LANKA		MARATUWA	6.748	79.89	1824			5.5		1		
SRI LANKA		S. COAST	5.941	80.494	1742			5.5		1		
SRI LANKA		BALAPITIYA BEACH	6.274	80.036	1798			5.3		1		
SRI LANKA		ADDACACHCHENA	7.25	81.864	1624			5		1		
SRI LANKA		NILAVELI	8.677	81.203	1740			5		1		
SRI LANKA		GALLE FORT	6.028	80.219	1773			4.89		1		
SRI LANKA		WALIGAMA	5.964	80.421	1750			4.86		1		
SRI LANKA		BERUWALA FISHERY PORT NORTH BEACH	6.479	79.983	1808			4.82		1		
SRI LANKA		GALLE PORT SOUTH BEACH	6.034	80.237	1772			4.79		1		
SRI LANKA		HIKKADUWA FISHERY HARBOR	6.142	80.099	1789			4.73		1		
SRI LANKA		AMBALAGODA BEACH	6.229	80.053	1795			4.72		1		
SRI LANKA		GALLE PORT NORTH BEACH	6.037	80.224	1773			4.71		1		
SRI LANKA		AKKARAIPATTU	7.209	81.86	1623			4.5		1		
SRI LANKA		KATUKURUNDA (KALUTARA S.)	6.566	79.951	1813			4.5		1		
SRI LANKA		RATHGAMA/DOANDUWA	6.086	80.146	1783			4.5		1		
SRI LANKA		WADDUWA RESORT	6.678	79.921	1819			4.5		1		
SRI LANKA		MORATUWA BEACH	6.755	79.89	1824			4.4		1		

7.2 Setting of protection level and space availability for vegetation belts

Setting of protected area

An area hit by the Indian Ocean tsunami in 2004 is set to be protected as indicated in Figure-20. Since most of the houses within the protected area are wooden houses, a vegetation belt should be planned to reduce tsunami inundation depth down to 1.0m downstream, which is expected to save and stop the full destruction of those wooden houses (Table 4).

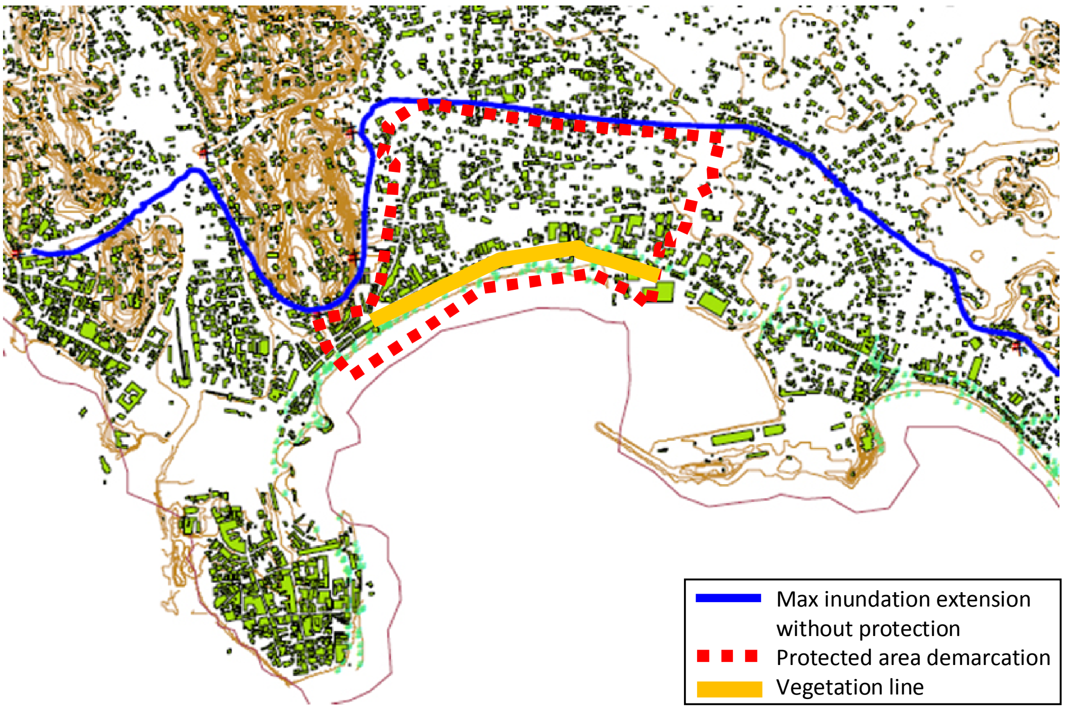


Figure-20. Setting of a protected area at Galle City; the blue line shows the maximum extension of inundation by the Indian Ocean tsunami in 2004; the red dotted-line marks the plan protected area; the yellow line indicates the plan location of a coastal forest (Source: Post Tsunami Survey for Hazard Map

Setting of effective width of a coastal vegetation belt

The planning width of vegetation should be set to be at least 50 to 100m. Since the original width of an open space for a coastal vegetation belt is only about 20 to 30m, relocation of residents' houses to further landward areas is necessary. The length of coastal vegetation belt protection in the coastline direction is set to be 700m, which is considered to protect the coast including the relocated dwelling sections. In this plan, a tsunami inundation depth of 4.7m is assumed to be applied to all points along the 700m-long protection area.

Selection of tree species

Mixed woods of *Casuarina* and *Pandanus* are considered as the most appropriate tree species according to the availability of such types of vegetation in the nearby coast.

7.3 Planning of vegetation for tsunami protection

7.3.1 Determination of trunk diameter and tree height of vegetation

Trunk diameter at breast height is determined based on tree-breaking criteria given by Shuto [1987] and Tanaka *et al.* [2008]. In this respect, the graph in Figure-14 (here redrawn as Figure-21) can be used as a useful tool. When the inundation is 4.7m, the graph suggests that the minimally required trunk diameter of *Casuarina* is 12cm. However, it cannot suggest an appropriate trunk diameter of *Pandanus* for the design inundation depth. Tanaka *et al.* [2008] reports that the maximum trunk diameter of *Pandanus* found in Sri Lanka was about 17cm.

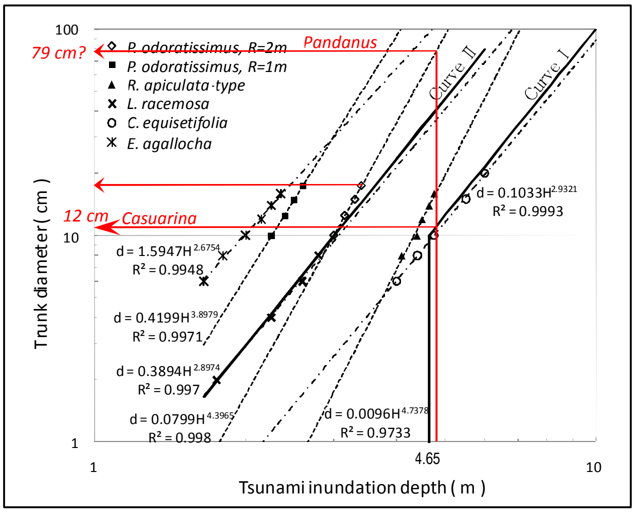


Figure-21. Determination of trunk diameter of the selected trees by using the correlation between trunk diameter and the depth of tsunami inundation that caused tree breaking. (refer to Figure-14).

Based on the above results, a trunk diameter between 15 and 20cm is selected for *Casuarina* trees as the main vegetation. Further consideration will be made later in reference to effective vegetation belt density. Although the breaking capacity of *Pandanus* trees is low at this inundation depth, they are still applicable as the second vegetation species with the expectation of reducing the lower layer of tsunami flow. *Pandanus* with a trunk diameter of 15 cm is selected for this design.

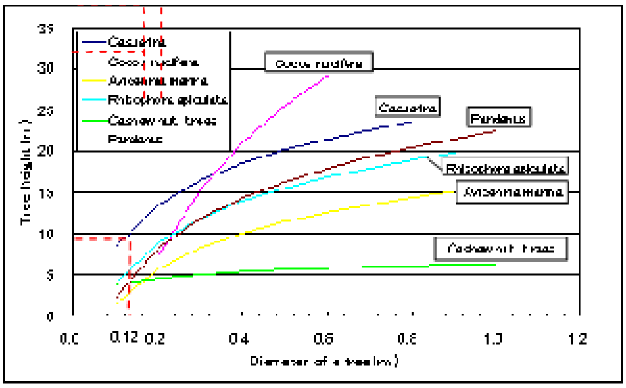


Figure-22. Relation between height and trunk diameter of 6 representative trees [*Source: Tanaka et al., 2005*]

Further, tree height information is necessary to analyze the potential breaking moment to work onto trees. Figure-22 provides a graph that relates trunk diameter and height of several trees [Tanaka *et al.,* 2007]. According to this figure, 15cm and 20cm trunk diameters of *Casuarina* are related to 12m and 14m heights, respectively. For *Pandanus*, this graph gives a tree height of 6m for a trunk diameter of 15cm.

If vegetation characteristics are different from those available in the graph, it is necessary to analyze wave-induced bending moment in comparison with the breaking moment limit of the tree trunk. In this respect, the allometric data of the trees are very important.

7.3.2 Determination of tree counts

If a coastal forest exists in or nearby the concerned area, the vegetation belt density should be determined based on the existing forest conditions. This is very important since the ground soil as well as local climate affect the vegetation grown there. It is certainly possible for the same type of vegetation to grow different forest characteristics from place to place. However, if the required data are hard to find, the graphs presently available can be used.

Figure-23 (top) correlates tree height and tree spacing, by which the average spacing between trees in a vegetation belt can be determined. Once the average spacing is understood, the number of trees within a square unit of vegetation belt can be calculated.

The graphs at the bottom in Figure-23, which are same as Figure-16, both provide the correlation between trunk diameter and tree numbers per 100m^2. The left one is for pine trees and the right for other trees.

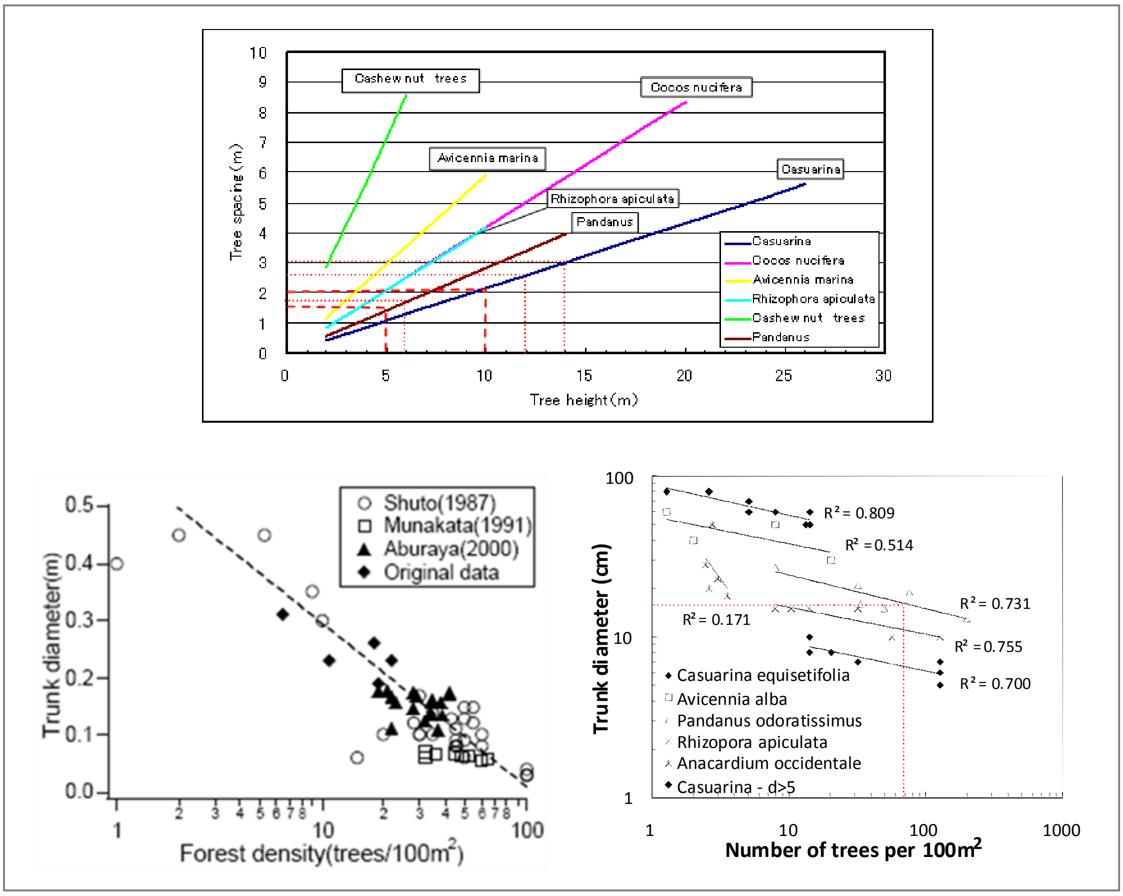


Figure-23. (top) Tree-height and tree-spacing correlation for several tree-species [Tanaka *et al.*, 2005]; (bottom) Correlation between trunk diameter and tree numbers per 100m^2 for pine-trees (left) [Shuto, 1987] and other trees (right) [Tanaka *et al.*, 2007]

According to Figure-23 (top), the average spacing for 12m and 14m-tall *Casuarina* trees are 2.6m and 3m, respectively; 6m-high *Pandanus trees should have* an average spacing of 1.7m. Based on these, tree numbers per unit square can be calculated by using the following approaches:

- For "square arrangement" :

Casuarina, 12m-height, (tree /m^2) = 1.000 / (average spacing)^2 = 1.000/(2.6)^2 = 0.148
(tree/100m^2) = 100 x 0.148 = 14.8
Casuarina, 14m-height, (tree /m^2) = 1.000 / (average spacing)^2 = 1.000/(3.0)^2 = 0.111
(tree/100m^2) = 100 x 0.111 = 11.1
Pandanus, 6m-height, (tree/m^2) = 1.000 / (average spacing)^2 = 1.000/(1.7)^2 = 0.346
(tree/100m^2) = 100 x 0.346 = 34.6

- For "equilateral triangle arrangement":

Casuarina, 12m-height, (tree /m^2) = 1.155 / (average spacing)^2 = 1.155 /(2.6)^2 = 0.171
(tree/100m^2) = 100 x 0.171 = 17.1
Casuarina, 14m-height, (tree /m^2) = 1.155 / (average spacing)^2 = 1.155 /(3.0)^2 = 0.128
(tree/100m^2) = 100 x 0.128 = 12.8
Pandanus, 6m-height, (tree/m^2) = 1.155 / (average spacing)^2 = 1.155 /(1.7)^2 = 0.40
(tree/100m^2) = 100 x 0.40 = 40

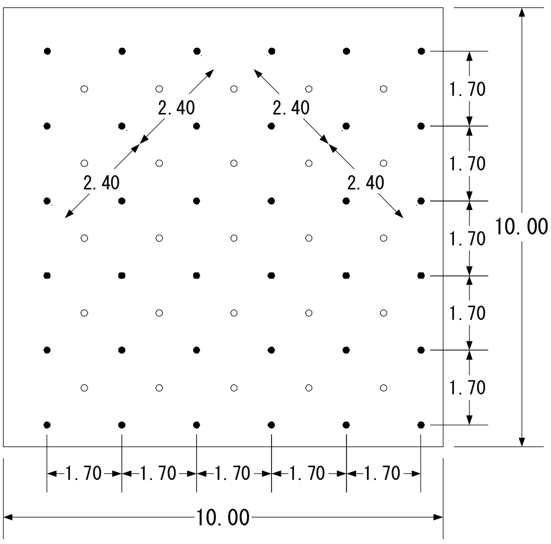


Figure-24 Plot of planned tree arrangement within a 100m^2 coastal forest; ● = Pandanus; ○ = Casuarina

As a comparison, by using Figure-23 (bottom), we found that tree numbers per 100m^2 for 15cm *Pandanus* (6m-heigth) is 70, whereas the number is not available for 15cm and 20cm *Casuarina* trees. From this, we can expect that a *Pandanus* vegetation belt with the 15cm trunk diameter may be denser with 40 to 70 trees per 100m^2.

Based on the above calculation results, a plot of tree arrangement within a 100m^2 coastal vegetation belt is illustrated in Figure-24. For example, the arrangement will be the combination of the "square arrangement" of 15cm (6m-height) *Pandanus* and the "equilateral triangle arrangement" of 15cm (12m-height) *Casuarina*. By this arrangement, the diagonal spacing between the Casurina trees is shortened to be 2.4m.

7.3.3 Examination of summed diameter (dn = d x n) and flow reduction potential

The effectiveness of a coastal vegetation belt can be appraised in a qualitative or quantitative way. In a qualitative way, the empirical approach of Shuto [1987], which correlates the "summed diameter" (*dn=dxn*) of a vegetation belt and its effect on tsunami flow reduction, may be utilized since it is based on extensive data of five major tsunami events in Japan. In this approach, the total summed diameter is calculated for vegetation within a rectangular area bordered by a unit length of shoreline and by the width of vegetation belt along flow direction. For the present example, the coastal vegetation belt widths are set to be 50m and 100m.

Referring to Figure-23, the total number of trees within $100m^2$ is 36 of 15cm *Pandanus* and 25 of 15cm *Casuarina*. Accordingly, tree numbers per square meter are 0.36 for *Pandanus* and 0.25 for *Casuarina.*

The summed diameter per unit length of shoreline is approximated as follows:

$$dn = 1m \times (\text{forest width in the flow direction}) \times (\text{trees}/m^2) \times \text{trunk diameter} \quad (22)$$

For the present example, since the vegetation is a combination of *Pandanus* (P) and *Casuarina* (C), it is calculated as linear summation as follows:

$$dn = 1m \times (\text{forest width in the flow direction}) \times \{ (n_p \times d_p) + (n_c \times d_c) \} \quad (23)$$

Where n_p and n_c are, respectively, the counts for *Pandanus* and *Casuarina* per m^2, and d_p and d_c are the trunk diameter in cm of *Pandanus* and *Casuarina,* respectively. Therefore;

For a 50m-width vegetation belt: dn = 1m' x 50m x { (0.36 x 15) + (0.25 x 15) } = 457.5 cm and

For a 100m-width vegetation belt: dn = 1m' x 100m x { (0.36 x 15) + (0.25 x 15) } = 915 cm.

In reference to Table 6 (Chapter 4), a summed diameter between 100 and 300cm ($100 \leq dn < 300$) will be partially damaged but capable of stopping floatage and reducing the velocity of tsunami inundation as deep as 3-5m ($3 \leq h < 5$). Since the present example gives dn of 457cm and 915cm, which both are far greater than 300cm, it is expected that the design vegetation belt density will effectively reduce tsunami flow.

7.3.4 Examination of vegetation thickness (dN_{all}) and flow reduction

A tool for quantitative calculation of tsunami flow reduction potential by a coastal vegetation belt is provided by Tanaka & Iimura [2009] for limited application. They proposed the graphs shown in Figure-6 under the conditions listed in Table 2. The graphs in Figure-6 correlate dN_{all} with run-up reduction rate, flow force reduction rate or propagation time delay. In spite of the limited vegetation species used to derive the mentioned graphs, the application of these graphs to other similar types of vegetation can be made possible by allowing interpolation.

Vegetation thickness dN_{all} can be calculated by the following formula (Tanaka & Iimura [2009]).

$$dN_{all} = \gamma \times C_{D\text{-}all} \times b_{ref} \quad (24)$$

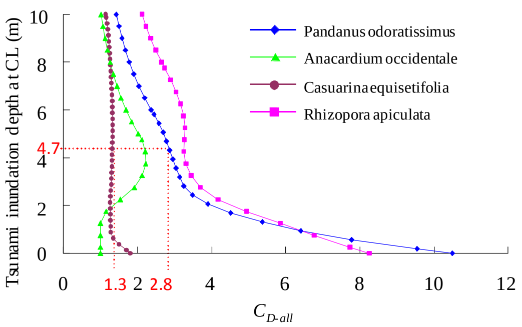


Figure-25. $C_{D\text{-}all}$ value of a whole-single tree in terms of tsunami inundation depth for *Pandanus odoratissimus*, *Casuarina equisetifolia*, *Rhizopora apiculata* and *Anacardium occidentale* under the conditions shown in Table 2.

where γ is the tree numbers within a rectangular area bordered by a unit length of coastline and by vegetation belt width in the tsunami flow direction, b_{ref} is the trunk diameter at breast height in cm and $C_{D\text{-}all}$ is the whole-single tree drag coefficient. $C_{D\text{-}all}$ were calculated at various tsunami inundation depths for the above mentioned tree species and is provided as a graph in Figure-25. Tsunami inundation depth at the coastline is used for this calculation.

For the design tsunami inundation depth of

4.7m, Figure-25 gives $C_{D\text{-}all}$ values of 2.8 and 1.3 to *Pandanus* and *Casuarina,* respectively.

Tree numbers, γ, is calculated as follows:

$$\gamma \quad = \quad 1\text{m x (vegetation belt width in the flow direction) x (trees/m}^2\text{)} \qquad (25)$$

	Pandanus	*Casuarina*
50m-width forest	γ = 1m x 50m x (0.36/m^2) = 18	γ = 1m x 50m x (0.25/m^2) = 12.5
100m-width forest	γ = 1m x 100m x (0.36/m^2) = 36	γ = 1m x 100m x (0.25/m^2) = 25

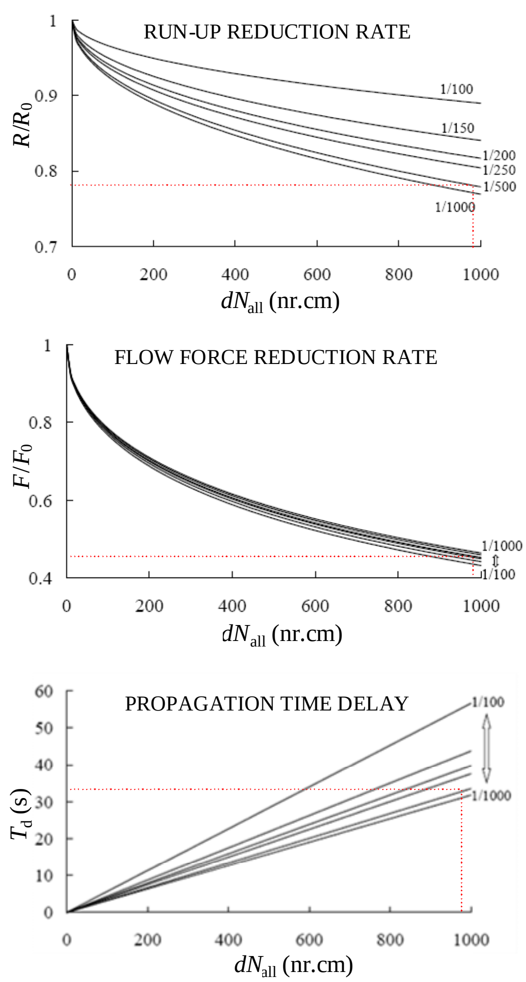
Since b_{ref} is set to be 15cm for *Pandanus* as well as *Casuarina*, eventually the value of dN_{all} of the vegetation belt can be calculated as follows:

For 50m-width forest: $dN_{all} = (\gamma \times C_{D\text{-}all} \times b_{ref})_{Pandanus} + (\gamma \times C_{D\text{-}all} \times b_{ref})_{Casuarina}$

dN_{all} = (18 x 2.8 x 15) + (12.5 x 1.3 x 15) = 999.75

For 100m-width forest: $dN_{all} = (\gamma \times C_{D\text{-}all} \times b_{ref})_{Pandanus} + (\gamma \times C_{D\text{-}all} \times b_{ref})_{Casuarina}$

dN_{all} = (36 x 2.8 x 15) + (25 x 1.3 x 15) = 1999.5



Having the above results, the run-up reduction rate, and flow force reduction rate and propagation time delay should be determined by using the graphs in Figure-6, which are redrawn on the left side.

If the land slope at the beach is 1/500, it reveals:

For 50m-wide forest: dN_{all} = 999.75 →

R/R_0 = 0.78; F/F_0 = 0.45; T_d = 33 sec.

When the forest is 100m wide, dN_{all} will be 1999.5, but the available graphs do not provide the values of R/R_0, F/F_0 and T_d. However, it can be expected that the 100m-wide vegetation belt will be more effective than the 50m-wide vegetation belt. A rough reference can be made based on the experiment results from Harada & Kawata [2004], as shown in Figure-7. The graph shows that the maximum inundation depth reduction rate of a 100m-wide vegetation belt is 0.15 higher than that of a 50m-wide vegetation belt. In this regard we may expect a similar trend for run-up reduction, which means that for a 100m-wide vegetation belt, R/R_0 = 0.78-0.15 = 0.63.

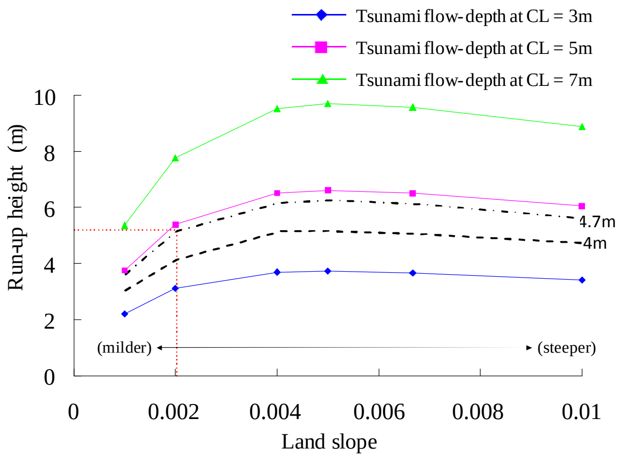


Figure-26. Tsunami run-up height in term of land slope change in case of no-vegetation. [*Source: Tanaka & Iimura, 2009*]

The graph in Figure-26 (Tanaka & Iimura [2009]) provides the numerical simulation results of tsunami run-up height on various beach land slopes without a vegetation belt. By carrying out interpolation for a 4.7m tsunami flow-depth at CL (coastline), the related tsunami run-up over a 1/500 (= 0.002) land slope without a vegetation belt is given to be 5.2m. Accordingly, the run-up after applying 50m and 100m-wide vegetation belts will be, respectively:

R_{50} = 0.78 x 5.2m = 4.056m, and

R_{100} = 0.63 x 5.2m = 3.276m

7.3.5 *Plotting of run-up calculation results on the map*

In order to check inundation areas after the application of a designed coastal vegetation belt, plotting of run-up calculation results onto the map is required.

At topographically complicated places, a simple way of plotting approximation is the level flooding method. This method can be carried out by delineating a topographic map with isoline of the maximum run-up height. A summary of the level flooding method is described in the following.

It is necessary to examine the datum line of run-up height and topography altitude when carrying out the level flooding method. Since run-up height is calculated based on the still water level (SWL), this still water level should be leveled out to match the datum line of the topography altitude.

In the calculation of tsunami runup, the mean high water level (MHWL) is preferably used as the base of calculation since it gives the potential maximum hazard. If the topography altitude was drawn according to the mean water level (MMWL), plotting of run-up height onto the map should consider the level difference between MWHL and MMWL.

For example, if MMWL is set at ±0.00, HHWL at +1.50, and the run-up height, for example, at 4.056m for R_{50} and 3.276m for R_{100}, the run-up isoline on the map should be set at +5.556 (=4.056+1.50)m for R_{50} and at +4.776 (=3.276+1.50)m for R_{100}.

Figure-27 illustrates the principle of plotting runup calculation results onto the map based on the above example.

The above calculation results show that a planned coastal vegetation belt of 50m to 100m-width is not adequate to provide safe protection to an area behind the vegetation belt. Because of limited availability of space, plantation of more than 100m is impossible. In such a case, combination with hard structures should be considered.

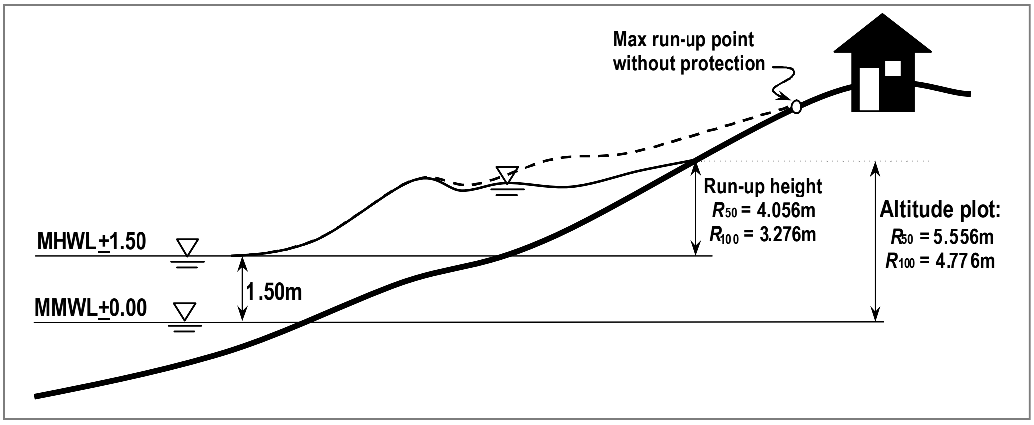


Figure-27. The principle of plotting run-up calculation results onto the map based on an example calculation

Acknowledgement

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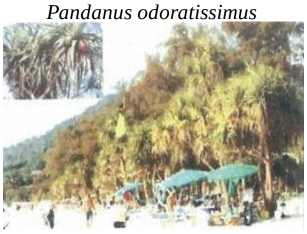
Appendix 1:

Characteristics of several coastal trees and its protection function related to past tsunami disaster events

Appendix-1. Characteristics of several coastal trees and its protection function related to past tsunami disaster events

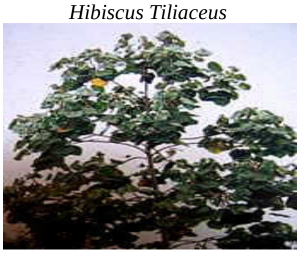
Species	Form	Characteristics	Protection function related to past tsunami disaster events [1),2),3)]
Casuarina equisetifolia 	Typical coast woods on sand dunes in the subtropics; equivalent to black pine woods in Japan; found a lot in Thailand where they often grow 20-40m tall and 160 cm in trunk diameter.	Growing environment Sand Maximum tree height 20-40 Saltwater tolerance possible	Tsunami attenuation effect was valid in the case of a two-layer shrub structure in which *Pandanus* grow under *Casuarina*. However, no tsunami wave attenuation effect was shown by tall *Casuarina* tree forests (trunk 0.5m). In the case of big trees intermingled with saplings (trunk 0.1m), saplings were fallen down but not carried away and there was also a spot where a broken branch of a big tree was trapped. Several trees looked tilted due to scouring around the roots. This phenomenon was conspicuous for *Casuarina*s on the forefront side.
Pandanus odoratissimus 	Evergreen tall trees of a screw pine family; Growing up to 10m tall in mixture with mangrove; the aerial roots around a trunk characteristically serve as props, which prevent the trees from falling down by wind force.	Growing environment Sand Maximum tree height 10 Saltwater tolerance good	*Pandanus* trees of dense clumps had high attenuation effect on tsunami even when the trunks were only about 0.1 m in diameter. Their root system structure is complicated and breeds in high density. The effect will be higher when a forest belt is formed in two-layer shrub structure with *Pandanus* grown under *Casuarina*; but they will not be effective when mixed with Coconut trees.
Cocos nucifera 	*Cocos nucifera* typically grow up to about 30m tall with 5m-long leaves; each leaf has a slender lobule on both sides from the bottom to the tip by a pinnately compound leaf. The leaves are collected at the upper tip part of a stem in crowd with the fiber.	Growing environment Sand Maximum tree height 30 Saltwater tolerance possible	Coconuts tree cultivation was widely spread along the coastline with a considerable width; Tsunamis passed through the vegetations without attenuation effect; however, several drifting fishing boats were seen trapped by the trees. The trees remained standstill although branches and leaves were greatly damaged. In several cultivation areas, parts of the base roots and some of the surface roots were about to be exposed because of bed soil erosion;
Arenga pinnata Meer 	Native to tropical Asia, from eastern India toward east to Malaysia, Indonesia, and the Philippines. This type of tree can grow up to 12m to 20m tall with the maximum diameter of about 30 cm. They have about 7m pinnate leaves with dark green lobules, which stick and take on yellowness densely.	Growing environment Sand Maximum tree height 12 Saltwater tolerance poor	The effect is on par with coconut trees and weak in salt water.

1) *Sasaki, Tanaka, et al.: Investigation on the damage by Indian Ocean Tsunami at the southern coast in Sri Lanka: The Science and Engineering Reports of Saitama University, No.38, 2005*

2) *Tanaka, Sasaki, Yutani: Effect of forest width and tree-species' difference for Tsunami protection considering the disaster caused by the Indian Ocean Tsunami at Thailand. Annual Journal of Coastal Engineering, JACE, Vol.52, 2005*

3) *Sasaki, Tanaka, et al.: Investigation on Effect for Vegetation by Tsunami in that Case of Sumatera Earthquake, Southern part of Thailand. The Science and Engineering Reports of Saitama University, No.38, 2005*

Appendix-1. Characteristics of several coastal trees and its protection function related to past tsunami disaster events (continuation)

Species	**Form**	**Characteristics**	**The protection function related to a past tsunami disaster event** [1),2),3),4)]
Terminalia catappa L. 	Its original distribution is in southern Okinawa. The branches spread sideways and usually used as shade trees. Preferring sunny places, the trees grow fast up to about 20m and show strong resistance to sea breeze, thus suitable for vegetation near the coast.	Growing environment Sand Max. tree height 20 Saltwater tolrnc. poor	Almost no trunk breaks were reported by tsunami except some cases of falling down by scouring of rootstock at sandy soil; difficult to fall down because of its strong root; The trees were effective for people to make a soft landing on and to escape from tsunamis because of their branches widely extending outwards from the lower part through the top of the trunks.
Pongamia pinnata 	This kind of evergreen tall tree sometimes exceeds 20m in height if growing near the coast. They are originally from India and Taiwan.	Growing environment Sand Max. tree height 20 Saltwater tolrnc. good	According to the interviews with residents in Thailand, the trees' canopies helped survivors in soft landing and escaping; however, it is now considered that at that time these functions the trees provided for people were supported by shrubs growing under Pongamia trees in the forest. They worked to increase the drag coefficient and reduce the flow speed.
Anacardium occidentale 	*Anacardium* genus is evergreen tall trees of the cashew family; they originate in the north and northeast of Brazil. Growing at the beachfront, the height reaches about 10-12m. They are often grown in coastal areas as cultivation forests. The trunk diameter at 1m high from the ground is about 0.5m on average.	Growing environment Sand Max. tree height 10-12 Saltwater tolrnc. poor	Since the tree spacing was large, the trees provided little effect on tsunami height reduction, but they survived against tsunami force. Some lost their leaves and some were killed due to the inundation. The forest deterred the destruction of houses located 450m behind, whereas serious damage was done to the housing area 700m inland without a forest. The functions of soft landing and escaping have been confirmed too.
Scaevola frutesches 	*Scaevola frutesches* form shrub evergreen forests; Their seeds are wrapped in cork-like substance and float in water, which enables far field distribution up to the west Pacific Ocean coast, Australia and Indian Ocean coast. Yakushima and Tanegashima Islands are the northern limit. The height reaches 1-2m.	Growing environment Sand Max. tree height 1-2 Saltwater tolrnc. good	The trees are often found in sand dune areas in Sri Lanka and are supposed to have protected sand erosion during tsunami attack. It performed frontline protection and increased friction against tsunami inundation flow.
Hibiscus Tiliaceus 	This tree type is distributed over Melanesia, Micronesia and Oceania in Polynesia islands. The evergreen trees about 6-9m in height and 30 cm in trunk diameter, have big leaves and shaggy branches. They are used for building houses and furniture.	Growing environment Sand Max. tree height 6-9 Saltwater tolrnc. good	During the tsunami event in 2000 at a village in Banggai District, Sulawesi, a house behind Waru trees remained standing without any damage while houses without any barrier in the front were completely washed out. The trees were stable even after tsunami attack. [Hiraishi and Harada, 2003].

1) *Sasaki, Tanaka, et al.: Investigation on the damage by Indian Ocean Tsunami at the southern coast in Sri Lanka: The Science and Engineering Reports of Saitama University, No.38, 2005*

2) *Tanaka, Sasaki, Yutani: Effect of forest width and tree-species' difference for Tsunami protection considering the disaster caused by the Indian Ocean Tsunami at Thailand. Annual Journal of Coastal Engineering, JACE, Vol.52, 2005*

3) *Sasaki, Tanaka, et al.: Investigation on Effect for Vegetation by Tsunami in that Case of Sumatera Earthquake, Southern part of Thailand. The Science and Engineering Reports of Saitama University, No.38, 2005*

4) *Matsumura: How to utilize the function of vegetation for disaster prevention and reduction: J.JSNDS,25-3, 2006*

Appendix-1. Characteristics of several coastal trees and its protection function related to past tsunami disaster events (continuation)

Species	Form	Characteristics	The protection function related to a past tsunami disaster event
Acacia auriculiformis 	*Acacia auriculiformis* are fast-growing, crooked, gnarly and thorny trees. They are native to Australia, Indonesia, and Papua New Guinea and grow up to 12 m. [5]	Growing environment Sand Max. tree height 12 Saltwater tolrnc. good	No data are available related to a past tsunami disaster event. However, the results of a breaking-test field measurement[6] show that their breaking moment capacity is similar to that of Casuarina equisetifolia trees.
Borassus flabellifer[7] 	*Borassus flabellifer* can reach a height of 30 m, with a canopy of leaves spreading 3 meters across. Their large trunks resemble those of coconut trees in a hard, black trunk and a skirt of dead leaves underneath the crown. They are seen in India, Sri Lanka, Southeast Asia and New Guinea[7]	Growing environment Sand Max. tree height 30 Saltwater tolrnc. good	No data are available related to a past tsunami disaster event. These trees' performance in tsunami flow reduction can be equivalent to that of Cocos nucifera. However, skirts of dead leaves that cover almost half the bottom part of the trunk may increase its friction coefficient against tsunami flow.

[5] *Gilman,E.F., Watson,D.G. Institute of Food and Agricultural Sciences, Univ. Florida, accessed on 2010/4/29 from [http://hort.ufl.edu/trees/ACAAURA.pdf]*
[6] *ICHARM and Gadjah Mada University: Data Collection and Analysis of Coastal Vegetation Characteristics for Tsunami Disaster Mitigation at Southern Coast of Java Indonesia, ICHARM Internal Technical Report, unpublished, March, 2010.*
[7] *Palm & Cycad Societies of Florida, Inc. ©1998-2006, accessed on 2010/5/11 from http://www.plantapalm.com/vpe/photos/Species/borassus_flabellifer.htm*

Appendix 2:

Examples of Forms used in the field investigation of coastal vegetation characteristics

Breaking Moment Test Data Form

Observer Name: **Date:** **Page:** **from**

Number/ Code	Name of tree/Species (Indonesia & Latin)	Root height from the ground – HR (for the trees which have aerial root)	Trunk diameter /perimeter at 30cm above root height – DR30 (for the trees which have aerial root)	Trunk diameter/ perimeter at breast height (1.3m from the ground) - DBH	Elevation of forcing point from the ground - ELF	Elevation of breaking node from the ground - ELB	Length between forcing point and breaking node - l_{arm}	Deflection - Def	Force - F (kg) / Gauge Serial Number	$EI = \left(\frac{l_{arm}^3}{3}\right)\left(\frac{F}{Def}\right)$	Note (Location, Break/Not Break, etc.)
1	2	3	4	5	6	7	8 = (6-7)	9	10	11	

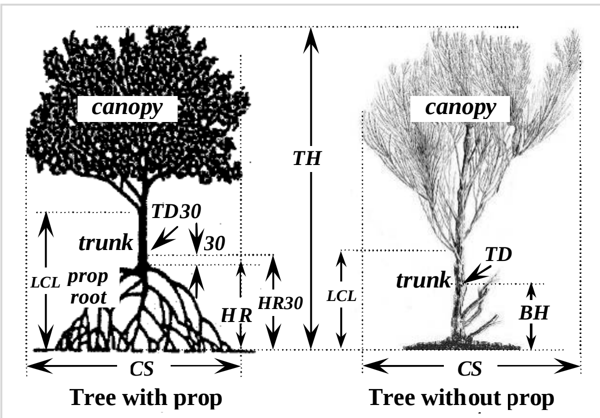
TABLE FORM OF COASTAL VEGETATION FACULTIES MEASUREMENTS

Name of location :
Name of tree species :
Surveyors :
Date of survey :
Plot number : Position coordinates of plot :

Nr.	TD (cm)	TD30 (cm)	LCL (m)	TH (m)	HR30 (cm)	HR (cm)	Distance to the next nearest tree of same species (m)		Average distance to the nearest trees (m)	CS (m)	Shape of canopy
							x	y			
1											
2											
3											

note:

TD is trunk diameter at breast height (for tree without prop root)
TD30 is trunk diameter at 30cm above prop root (for tree with prop root)
LCL is height of lower canopy from the ground
TH is total height of tree from the ground
CS is canopy average diameter
HR is height of top-end of prop root (for tree with prop root)
HR30 is height of trunk from the ground at 30cm above prop root (for tree with prop root)



The measured parts of tree for allometry analysis purpose