Planning and Design of TSUNAMI-MITIGATIVE COASTAL VEGETATION BELTS

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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 vegetation 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.

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

\[
\begin{align*}
H &= 4.65 & \text{for } d < 10 \\
\frac{d}{10} &= 0.1H^3 & \text{for } d > 10
\end{align*}
\] (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].

\[d = 0.37H^3\] (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 (Exocarca agallocha, Casuarina equisetifolia, Rhizopora apiculata, Pandanus odorattissimus, 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
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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>
<thead>
<tr>
<th>TSUNAMI CHARACTERISTICS</th>
<th>VEGETATION BELT CHARACTERISTICS + TOPOGRAPHY</th>
<th>EXPECTED EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inundation depth</td>
<td>- Single tree breaking moment capacity</td>
<td>Flow velocity reduction</td>
</tr>
<tr>
<td>- Wave force</td>
<td>- Vegetation belt width</td>
<td>Run-up and inundation depth reduction</td>
</tr>
<tr>
<td>- Period/wave length</td>
<td>- Vegetation belt density</td>
<td>Impact force reduction</td>
</tr>
<tr>
<td>- Wave direction</td>
<td>- Tree numbers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Tree size and structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Trunk diameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Tree height</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Root-trunk-canopy composition</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Vegetation combination</td>
<td></td>
</tr>
<tr>
<td>Ground slope, soil type, ground cover etc.</td>
<td></td>
<td></td>
</tr>
</tbody>
</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](image)

**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:

$$d H v^2 n \approx d n H^2$$  \hfill (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.

![Figure-4](image-url)

**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
- Slant bar – damage caused by concentrated forces such as a boat

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 ($C_D$) and tsunami height.
The plotted values of $C_{D\text{-all}}$ were calculated according to the following equations \cite{Tanaka et al., 2007}.

\begin{align}
C_{D\text{-all}} &= \alpha \beta \times C_D \\
\frac{dN_{\text{all}}}{W} &= C_{D\text{-all}} \times \frac{dn}{W} \\
n / W &= 1 / \ell^2 \\
\frac{dN_u}{W} &= \frac{dN_{\text{all}}}{W} / W = \frac{dN_{\text{all}}}{W} / \ell \times n = \alpha \beta d / \ell \\
\alpha \beta &= \sum_{i=1}^{n} \alpha_i(\ell) \beta(\ell) = \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 \\
\frac{dA_1}{dA_{1.2}} &= \frac{dA_1}{dA_{1.2}} \\
\end{align}

In Equation 4 to 9, $W(m)$ is the width of a coastal vegetation belt in the direction of tsunami flow, $n(\text{trunk/m}^2)$ 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, $dn(\text{cm/vegetation belt width-m}^2)$ is the cumulative tree diameter of the vegetation belt in the tsunami direction, called "vegetation thickness", $\alpha$ is the branch effect on $C_D$, $\beta$ is the leaf effect on $C_D$, $dA(m^2)$ is the area the tree parts cover, $dA_1(\text{m}^2)$ 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, $dN_{\text{all}}(\text{cm/vegetation belt width-m}^2)$ is the effective vegetation thickness in the $W(m) \times 1\text{m}$ area of the vegetation belt, $dN_u(\text{cm/unit area-m}^2)$ 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 vegetables are shown in Figure-5(b).

Making use of the above calculation approach, Tanaka & Iimura \cite{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, $dN_{\text{all}}$ 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, Rhizophora apiculata and Anacardium occidentale under the conditions shown in Table 2.

Harada & Kawata \cite{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/100m².

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

<table>
<thead>
<tr>
<th>Vegetation-species</th>
<th>Tree height (m)</th>
<th>DBH (cm)</th>
<th>Average spacing (m)</th>
<th>Vegetation belt density (trees/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pandanus odoratissimus</em></td>
<td>6</td>
<td>15.5</td>
<td>1.692</td>
<td>0.403</td>
</tr>
<tr>
<td><em>Anacardium occidentale</em></td>
<td>5</td>
<td>29.7</td>
<td>7.100</td>
<td>0.023</td>
</tr>
<tr>
<td><em>Casuarina equisetifolia</em></td>
<td>10</td>
<td>12.4</td>
<td>2.160</td>
<td>0.247</td>
</tr>
<tr>
<td><em>Rhizophora apiculata</em></td>
<td>8</td>
<td>17.7</td>
<td>3.336</td>
<td>0.104</td>
</tr>
</tbody>
</table>

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

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 indispensable.

(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>
<thead>
<tr>
<th>Item</th>
<th>Description of survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation front</td>
<td>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)</td>
</tr>
<tr>
<td>Tree species</td>
<td>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.</td>
</tr>
<tr>
<td>Tree density</td>
<td>To estimate the tree density in a plan, the number of growing trees in an area of 10 x 10 m² is counted according to species.</td>
</tr>
<tr>
<td>Tree height</td>
<td>To estimate each tree species’ tolerance to tsunami wave height in a plan, the average tree height is measured according to tree species.</td>
</tr>
<tr>
<td>Vegetation belt width</td>
<td>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.</td>
</tr>
<tr>
<td>Soil material</td>
<td>Check the soil material in the investigated area.</td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Tsunami strength</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsunami height (m)</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Tsunami form</td>
<td>Gentle slope</td>
<td>Rising on the shore</td>
<td>Water wave at offshore</td>
<td>Second breaking wave</td>
<td>Increase wave which is breaking at the tip of</td>
<td>Even first wave causes a surging wave breaking</td>
</tr>
<tr>
<td></td>
<td>Steep slope</td>
<td>Fast current speed</td>
<td>Fast current speed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sound</td>
<td>Continuous sound by front wave breaking</td>
<td></td>
<td></td>
<td></td>
<td>Big blare by surging wave breaking at shore</td>
<td>Thunder blare, not recognized in distant place</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Big blare conflicting in a cliff</td>
<td>distant thunder, heard to the far places</td>
</tr>
<tr>
<td>Wooden house</td>
<td>Partial destruction</td>
<td>Full destruction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone house</td>
<td>Holding</td>
<td>Full destruction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforced concrete building</td>
<td>Holding</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fishing boat</td>
<td>Damage</td>
<td>Damage ratio 50%</td>
<td>Damage ratio 100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage of forest</td>
<td>Damage reduction</td>
<td>Partially damage</td>
<td>Full destruction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effect of forest</td>
<td>Tsunami reduction</td>
<td>Draft prevention</td>
<td>Draft prevention</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultured raft</td>
<td>Damage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coast village</td>
<td>Damage</td>
<td>Damage ratio 50%</td>
<td>Damage ratio 100%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run-up (m)</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>32</td>
</tr>
</tbody>
</table>

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](image)

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.
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/100m², 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]

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

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

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]).](image-url)
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.

\[ M_d = 0.5 F (h-H_b) \]  \hspace{1cm} (10)

\[ F = 0.5 C_D \rho A_0 u^2 \]  \hspace{1cm} (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, \( \rho \) 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. \( H_b \) 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).

\[ C_D = \begin{cases} \frac{1.2}{0.7} & \text{for } R_e \leq 2 \times 10^6 \\ 1.2 - 0.5 \left( \frac{R_e}{2 \times 10^6} - \frac{1}{2} \right) & \text{for } 2 \times 10^6 \leq R_e \leq 5 \times 10^6 \\ 0.7 & \text{for } R_e \geq 5 \times 10^6 \end{cases} \]  \hspace{1cm} (12)

\[ R_e = \frac{\rho u^2}{\mu} \]  \hspace{1cm} (13)

\[ u = \sqrt{g/h} \]  \hspace{1cm} (14)

where \( R_e \) is the Reynolds number, \( v \) 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 \( \text{dbh} \)).

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:

\[ C_{D, \text{all}} = \alpha \beta \times C_D \]  \hspace{1cm} (15)

\[ \alpha \beta = \alpha \beta \left[ \frac{d}{d_{\text{leaves}}} \right] \]  \hspace{1cm} (16)

\[ d_{\text{leaves}} = \sum_{i=1}^{n} d_{\text{leaves}} \]  \hspace{1cm} (17)

\[ d_{\text{leaves}} = \frac{d}{100} \times \pi \]  \hspace{1cm} (18)
where $h$ (m) is the tsunami inundation depth, $\alpha$ is the branch effect on $C_D$, $\beta$ 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 $i$, $dA_{1.2}$ ($m^2$) is the vertical projection area of the trunk at 1.2m abve 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 were 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 *Avicenma 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,

$$M_{GP1} = 4.45 x \frac{dbh^2}{h^{2.62}} \quad (19)$$

$$M_{GP2} = 20.52 x \frac{dbh^2}{h^{2.83}} \quad (20)$$

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

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)]](image)

### 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.

![Graph](image-url)

**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 100\(m^2\), 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 withing 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 \(dn\).

Examination of summed diameter \((dn = dxn)\)

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>
<thead>
<tr>
<th>Inundation depth ((h)) in meter</th>
<th>Summed diameter ((dn)) in cm</th>
<th>Vegetation belt response to tsunami</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Damage Stop floatage Reduce velocity Ground soil damage</td>
</tr>
<tr>
<td>(h &lt; 3)</td>
<td></td>
<td>No Yes No Possible</td>
</tr>
<tr>
<td>30 (\leq) (dn &lt; 100)</td>
<td>No Yes Expected No</td>
<td></td>
</tr>
<tr>
<td>100 (\leq) (dn &lt; 300)</td>
<td>No Yes Yes No</td>
<td></td>
</tr>
<tr>
<td>(3 \leq h &lt; 5)</td>
<td></td>
<td>Partial Yes No Possible</td>
</tr>
<tr>
<td>30 (\leq) (dn &lt; 100)</td>
<td>Partial Yes No Possible</td>
<td></td>
</tr>
<tr>
<td>100 (\leq) (dn &lt; 300)</td>
<td>Partial Yes Much Possible</td>
<td></td>
</tr>
</tbody>
</table>

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 100\(m^2\) of the vegetation belt. Returning to the previous example that gave \(n = 15/100m^2\) for \(d = 24\)cm, the value of summed diameter \(dn\) is obtained to be 15x24 = 360nr.cm within 100\(m^2\), 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 (Isumura 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](image-url)
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**

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Function and vegetation-type</th>
<th>Forest position and dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Residential housing occupies most of the nearby coastline; • Very limited space for a vegetation belt</td>
<td>• The least function of float trapping and escaping means; • Combination of hard-trunk and flexible vegetation</td>
<td>• Coastline; around houses; between blocks; 20m-width; $d_m=30$; $dbh=13cm$</td>
</tr>
<tr>
<td>• Limited space are available (100m) • Partially are used for infra-road</td>
<td>• Float trapping and flow reduction • Combination of hard-trunk and flexible vegetation • Road as a flow breaker</td>
<td>• Between coastline and the road width $\leq 50m$; $dn &gt;200$</td>
</tr>
<tr>
<td>• River mouth and flood plain along river</td>
<td>• Floatage trapping and flow reduction • Mangrove</td>
<td>• Marsh and tidal area; flood plain area width $\leq 50m$; $dn &gt;200$</td>
</tr>
</tbody>
</table>
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.

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.
Setting of protection level and space availability for vegetation belts

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 100 m. Since the original width of an open space for a coastal vegetation belt is only about 20 to 30 m, 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 700 m, which is considered to protect the coast including the relocated dwelling sections. In this plan, a tsunami inundation depth of 4.7 m is assumed to be applied to all points along the 700 m-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 4.7 m, the graph suggests that the minimally required trunk diameter of *Casuarina* is 12 cm. 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 17 cm.

Based on the above results, a trunk diameter between 15 and 20 cm 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.

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 representative trees [Source: Tanaka et al., 2005].
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 100m². The left one is for pine trees and the right for other trees.

![Figure-23](image-url)

**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 100m² 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”**:
  
  \[
  \text{Casuarina, 12m-height, (tree/m}^2\text{)} = \frac{1.000}{(\text{average spacing})^2} = \frac{1.000}{(2.6)^2} = 0.148 \\
  \text{(tree/100m}^2\text{)} = 100 \times 0.148 = 14.8 \\
  \text{Casuarina, 14m-height, (tree/m}^2\text{)} = \frac{1.000}{(3.0)^2} = \frac{1.000}{(3.0)^2} = 0.111 \\
  \text{(tree/100m}^2\text{)} = 100 \times 0.111 = 11.1 \\
  \text{Pandanus, 6m-height, (tree/m}^2\text{)} = \frac{1.000}{(1.7)^2} = \frac{1.000}{(1.7)^2} = 0.346 \\
  \text{(tree/100m}^2\text{)} = 100 \times 0.346 = 34.6
  \]

- **For “equilateral triangle arrangement”**:
  
  \[
  \text{Casuarina, 12m-height, (tree/m}^2\text{)} = \frac{1.155}{(2.6)^2} = \frac{1.155}{(3.0)^2} = \frac{1.155}{(3.0)^2} = 0.171 \\
  \text{(tree/100m}^2\text{)} = 100 \times 0.171 = 17.1 \\
  \text{Casuarina, 14m-height, (tree/m}^2\text{)} = \frac{1.155}{(3.0)^2} = \frac{1.155}{(3.0)^2} = 0.128 \\
  \text{(tree/100m}^2\text{)} = 100 \times 0.128 = 12.8 \\
  \text{Pandanus, 6m-height, (tree/m}^2\text{)} = \frac{1.155}{(1.7)^2} = \frac{1.155}{(1.7)^2} = 0.40 \\
  \text{(tree/100m}^2\text{)} = 100 \times 0.40 = 40
  \]

As a comparison, by using Figure-23 (bottom), we found that tree numbers per 100m² for 15cm *Pandanus* (6m-height) 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 100m².

Based on the above calculation results, a plot of tree arrangement within a 100m² coastal vegetation belt is illustrated in Figure-24. For example, 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:

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

(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:

$$dn = 1m \times (\text{forest width in the flow direction}) \times \{ (n_P \times d_P) + (n_C \times d_C) \}$$

(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: $dn = 1m \times 50m \times \{ (0.36 \times 15) + (0.25 \times 15) \} = 457.5$ cm and

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

In reference to Table 6 (Chapter 4), a summed diameter between 100 and 300cm ($100 < dn < 300$) will be partially damaged but capable of stopping floatage and reducing the velocity of tsunami inundation as deep as 3-5m ($3 < h < 5$). 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]).

$$dN_{all} = \gamma' \times C_{D-all} \times b_{ref}$$

(24)

where $\gamma'$ 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 $C_{D-all}$ is the whole-single tree drag coefficient. $C_{D-all}$ 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

![Figure-25](image-url)
4.7m, Figure-25 gives $C_{D\text{-all}}$ values of 2.8 and 1.3 to Pandanus and Casuarina, respectively.

Tree numbers, $\gamma'$, is calculated as follows:

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

<table>
<thead>
<tr>
<th></th>
<th>Pandanus</th>
<th>Casuarina</th>
</tr>
</thead>
<tbody>
<tr>
<td>50m-width forest</td>
<td>$\gamma' = 1m \times 50m \times (0.36/m^2) = 18$</td>
<td>$\gamma' = 1m \times 50m \times (0.25/m^2) = 12.5$</td>
</tr>
<tr>
<td>100m-width forest</td>
<td>$\gamma' = 1m \times 100m \times (0.36/m^2) = 36$</td>
<td>$\gamma' = 1m \times 100m \times (0.25/m^2) = 25$</td>
</tr>
</tbody>
</table>

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:  

$$dN_{all} = (\gamma' \times C_{D\text{-all}} \times b_{ref})_{\text{Pandanus}} + (\gamma' \times C_{D\text{-all}} \times b_{ref})_{\text{Casuarina}}$$

$$dN_{all} = (18 \times 2.8 \times 15) + (12.5 \times 1.3 \times 15) = 999.75$$

For 100m-width forest:  

$$dN_{all} = (\gamma' \times C_{D\text{-all}} \times b_{ref})_{\text{Pandanus}} + (\gamma' \times C_{D\text{-all}} \times b_{ref})_{\text{Casuarina}}$$

$$dN_{all} = (36 \times 2.8 \times 15) + (25 \times 1.3 \times 15) = 1999.5$$

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:  

$$dN_{all} = 999.75 \rightarrow \frac{R}{R_0} = 0.78; \frac{F}{F_0} = 0.45; T_d = 33 \text{ sec.}$$

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, $R/R_0 = 0.78-0.15 = 0.63$. 

---

**RUN-UP REDUCTION RATE**

**FLOW FORCE REDUCTION RATE**

**PROPAGATION TIME DELAY**

---

43
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:

\[ R_{50} = 0.78 \times 5.2m = 4.056m \]
\[ R_{100} = 0.63 \times 5.2m = 3.276m \]

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 MHWL 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.
This “Guideline: Planning and Design of Coastal Vegetation Belts for Tsunami Disaster Mitigation” is developed by the International Centre for Water Hazard and Risk Management (ICHARM) within the frame of research on sustainable tsunami disaster mitigation funded by the Public Works Research Institute (PWRI).

We would like to sincerely express deep gratitude towards Prof. Norio Tanaka of Saitama University for his thorough supervision on this manuscript as well as contribution to numerical calculation results by which this Guideline was significantly enhanced.
Bibliography


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

<table>
<thead>
<tr>
<th>Species</th>
<th>Form</th>
<th>Characteristics</th>
<th>Protection function related to past tsunami disaster events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casuarina equisetifolia</td>
<td>Typical coast woods on sand dunes in the subtropics; equivalent to</td>
<td>Growing environment</td>
<td>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 on the forefront side.</td>
</tr>
<tr>
<td></td>
<td>black pine woods in Japan; found a lot in Thailand where they often</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>grow 20-40m tall and 160 cm in trunk diameter.</td>
<td>Maximum tree height</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20-40</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saltwater tolerance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>possible</td>
<td></td>
</tr>
<tr>
<td>Pandanus odoratissimus</td>
<td>Evergreen tall trees of a screw pine family; Growing up to 10m tall</td>
<td>Growing environment</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>in mixture with mangrove; the aerial roots around a trunk</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>characteristically serve as props, which prevent the trees from</td>
<td>Maximum tree height</td>
<td></td>
</tr>
<tr>
<td></td>
<td>falling down by wind force.</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saltwater tolerance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>good</td>
<td></td>
</tr>
<tr>
<td>Cocos nucifera</td>
<td>Cocos nucifera typically grow up to about 30m tall with 5m-long</td>
<td>Growing environment</td>
<td>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;</td>
</tr>
<tr>
<td></td>
<td>leaves; each leaf has a slender lobule on both sides from the bottom</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to the tip by a pinnately compound leaf. The leaves are collected</td>
<td>Maximum tree height</td>
<td></td>
</tr>
<tr>
<td></td>
<td>at the upper tip part of a stem in crowd with the fiber.</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saltwater tolerance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>possible</td>
<td></td>
</tr>
<tr>
<td>Arenga pinnata Meer</td>
<td>Native to tropical Asia, from eastern India toward east to Malaysia,</td>
<td>Growing environment</td>
<td>The effect is on par with coconut trees and weak in salt water.</td>
</tr>
<tr>
<td></td>
<td>Indonesia, and the Philippines. This type of tree can grow up to</td>
<td>Sand</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12m to 20m tall with the maximum diameter of about 30 cm. They have</td>
<td>Maximum tree height</td>
<td></td>
</tr>
<tr>
<td></td>
<td>about 7m pinnate leaves with dark green lobules, which stick and</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>take on yellowness densely.</td>
<td>Saltwater tolerance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>poor</td>
<td></td>
</tr>
</tbody>
</table>

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

51 Planning and Design of Tsunami-mitigative Coastal Vegetation Belts
Appendix-1. Characteristics of several coastal trees and its protection function related to past tsunami disaster events (continuation)

<table>
<thead>
<tr>
<th>Species</th>
<th>Form</th>
<th>Characteristics</th>
<th>Growing environment</th>
<th>The protection function related to a past tsunami disaster event</th>
<th>Saltwater tolnc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminalia catappa L.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sand</td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max. tree height</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pongamia pinnata</td>
<td></td>
<td></td>
<td>Sand</td>
<td>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.</td>
<td>poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max. tree height</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anacardium occidentale</td>
<td></td>
<td></td>
<td>Sand</td>
<td>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.</td>
<td>good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max. tree height</td>
<td></td>
<td>10-12</td>
</tr>
<tr>
<td>Scaevola frutescens</td>
<td></td>
<td></td>
<td>Sand</td>
<td>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.</td>
<td>good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max. tree height</td>
<td></td>
<td>1-2</td>
</tr>
<tr>
<td>Hibiscus Tiliaceus</td>
<td></td>
<td></td>
<td>Sand</td>
<td>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].</td>
<td>good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max. tree height</td>
<td></td>
<td>6.9</td>
</tr>
</tbody>
</table>

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
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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)

<table>
<thead>
<tr>
<th>Species</th>
<th>Form</th>
<th>Characteristics</th>
<th>The protection function related to a past tsunami disaster event</th>
</tr>
</thead>
</table>
| *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. | Growing environment
|                        |                                           | Sand
|                        |                                           | Max. tree height
|                        |                                           | 12
|                        |                                           | Saltwater tolrc.
|                        |                                           | good                                               | No data are available related to a past tsunami disaster event. However, the results of a breaking-test field measurement show that their breaking moment capacity is similar to that of *Casuarina equisetifolia* trees. |
| *Borassus flabellifer*  | *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 | Growing environment
|                        |                                           | Sand
|                        |                                           | Max. tree height
|                        |                                           | 30
|                        |                                           | Saltwater tolrc.                                  | 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. |

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### Appendix 2:

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Tree</th>
<th>Trunk diameter</th>
<th>Elevation of breaking point</th>
<th>Length of breaking point</th>
<th>Elevation of node</th>
<th>Deflection of</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: (Location, Break etc.)

Breaking Moment Test Data Form

- **Observer Name:**
- **Name of Tree Species:**
- **Tree Code:**
- **Root height from the ground (1m from the ground):**
- **DBH (for the tree which have aribolia):**
- **Elevation of node (ground):**
- **Deflection of node:**
# TABLE FORM OF COASTAL VEGETATION FACULTIES MEASUREMENTS

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

<table>
<thead>
<tr>
<th>Nr.</th>
<th>TD (cm)</th>
<th>TD30 (cm)</th>
<th>LCL (m)</th>
<th>TH (m)</th>
<th>HR30 (cm)</th>
<th>HR (cm)</th>
<th>Distance to the next nearest tree of same species (m)</th>
<th>Average distance to the nearest trees (m)</th>
<th>CS (m)</th>
<th>Shape of canopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
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<tr>
<td>3</td>
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<td></td>
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</tr>
</tbody>
</table>

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