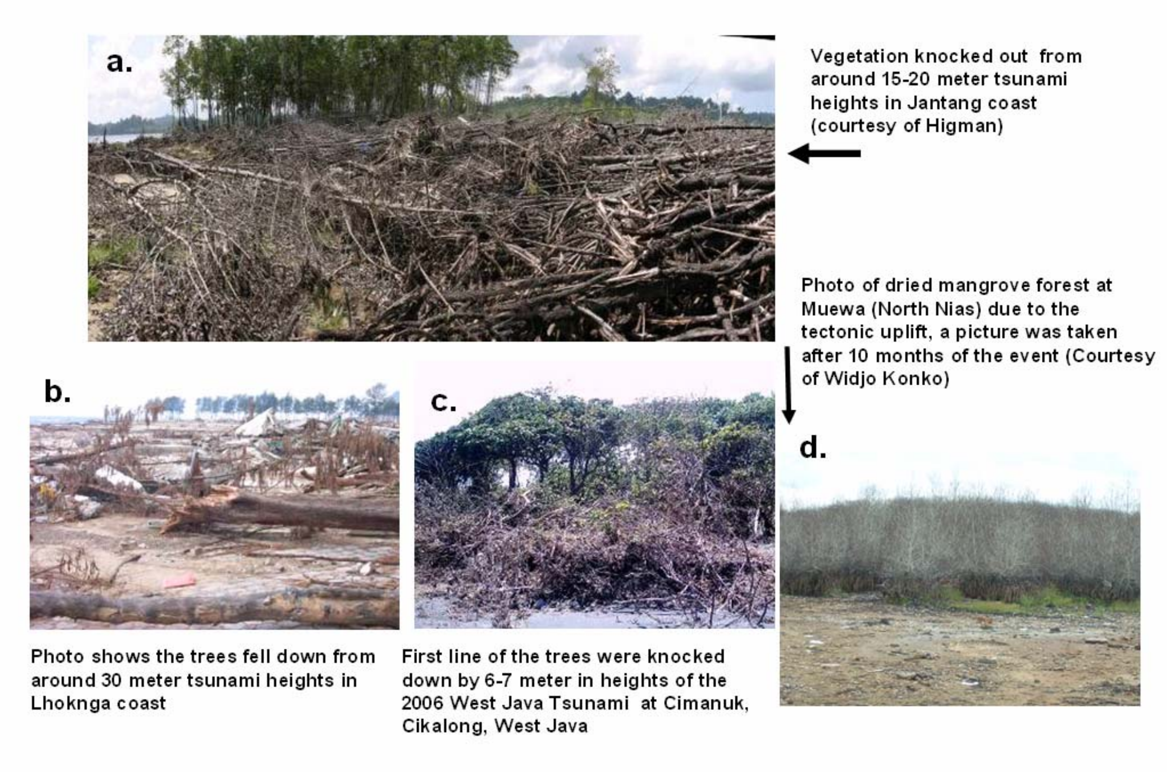
**Plate 1.6 Trees were uprooted by a huge tsunami and became floating debris that destroyed houses**

## 2.4 Tsunami Impact on vegetation

The impacts of the 2004 tsunami on natural vegetation were reported by several agencies and institutes, including the European Commission Joint Research Centre (ECJRC, 2005). ECJRC analysed satellite imagery of 11 000 kilometers along the affected coastal areas in the Indian Ocean before and after the event. Roughly, 80 795 hectares were mapped as severely damaged. Changes included the destruction of standing crops, removal of topsoil, uprooting and snapping of trees and complete levelling of the land. Preliminary estimates indicated that 10 960 hectares of forest and woodland (palm trees, broadleaf evergreen species and mangrove), 4 393 hectares of beach, 56 249 hectares of mixed agriculture and villages, and 9 193 hectares of urban land had been severely damaged. Long-term damage to mangrove forest because of silting may become apparent only later. The loss of mangrove forest and other coastal vegetation will have important implications regarding protection from future tsunamis, as evidence from 2004 tsunami showed that regions which once had extensive mangroves were relatively more damaged than regions where they remain intact (ECJRC, 2005).

The photographs (a–d) in Plate 1.7 concur with the ECJRC (2005) reports. Plate 1.7a shows mangrove flattened by a 15–20 metermetre tsunami at Jantang, Aceh. Large trees of 50 centimetres in diameter were uprooted or snapped by a 30-metre tsunami along Lhoknga coast, Aceh (Plate 1.7b). The implication is that the coastal vegetation, which had an average height of 8–12 metermetres, was unable to withstand a tsunami exceeding 10 metermetres, the maximum as suggested by Mani and Parthasarathy (2006). Some literature, however, suggests that the maximum tsunami height vegetation can withstand and still be effective in mitigating a tsunami is much less at 6 metermetres, depending on the tree type, forest density and width (J.B. Hinwood, pers. comm.). On the other hand, a field survey in West Java found that the forest did indeed resist a 6–7 metermetre tsunami, with only the first line of trees collapsing, as shown in Plate 1.7c. The final image, Plate 1.7d, documents the damage to mangroves by wave forces, deposition excessive sediment, and impact of tectonic uplift that can occur near the earthquake epicenter. Here a rise of two metermetres deprives the mangrove of daily tides, with the result vegetation is beginning to dieback.



Vegetation knocked out from around 15-20 meter tsunami heights in Jantang coast (courtesy of Higman)

Photo of dried mangrove forest at Muewa (North Nias) due to the tectonic uplift, a picture was taken after 10 months of the event (Courtesy of Widjo Konko)

Photo shows the trees fell down from around 30 meter tsunami heights in Lhoknga coast

First line of the trees were knocked down by 6-7 meter in heights of the 2006 West Java Tsunami at Cimanuk, Cikalong, West Java

**Plate 1.7a–d.Tsunami and earthquake impact on coastal vegetation**

## 2.5 Protective role of pine forests: Case of Japan

Documenting the impacts of five large tsunamis in Japan, Shuto (1987) produced empirical evidence of resistance by coastal forests to tsunamis. Plotting observations of the degree of damage relative to wave height, the protective role is inferred for increasing tsunami intensity until waves become too large and the forest is destroyed.[3] Figure 1.7 shows that a pine forest of trees with diameters of 10 centimetres can resist a tsunami up to 4.65 metermetres. A larger wave would destroy the forest, unless tree diameter, d, increases with the relation of $d = 0.1H^3$, where H is inundation height above ground in metermetres. Figure 1.8 shows the effect of the tsunami on coastal forests of varying widths. Forest widths less than 20 metermetres survived tsunamis up to 3 metermetres (Region a), yet Shuto (1987) suggests that because of the narrow width there would be no energy reduction, though it would still capture floating debris. Slightly larger waves would partially damage the forest, though debris still would be caught. However, waves greater than 4.65 metermetres would destroy the forest, and there would be no reduction in tsunami energy or debris catch (Regions b-1 and b-2, respectively). At widths greater than 20 metermetres (Region c) forests would start to reduce tsunami energy, in addition to catching debris. But for waves over 3 metermetres, the width would need to significantly increase. Figure 1.9 combines width and diameter to give an indication of the projected area of resistance to a wave. This new parameter, termed summed tree diameter, is defined as the “product of the diameter at breast high and the number of trees in a rectangle with a frontage of unit length along the shoreline and a depth equal to the width of the forest” (Shuto, 1987). The figure depicts similar threshold values. Forests in Region A would stop boats and debris, but the width is not large enough to reduce tsunami energy. Region B-2 indicates that tsunamis greater than 4.65 metermetres would cut down trees, but no

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[3] In figures 1.7 to 1.9, the degree of damage is indicated by various shapes and shadings: ○-no damage to the tree with the effect of stopping floatages; ●-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

energy reduction effect is expected; however,. Tthere might be some debris protection for slightly smaller waves (Region B-1), however. For summed diameters, dn, greater than 30, energy reduction is expected for tsunamis up to 3 metermetres, but there needs to be dense vegetation growing under the trees (Region C). If there is no undergrowth, then the summed diameter must be in excess of 100 (Region D-1). Tsunamis up to 4 metermetres can be resisted, but with larger waves the summed diameter must increase significantly (Region D-1).

The diagrams below are useful for quick and quantitative judgment on of the capacity of trees and forest to attenuate tsunamis. Shuto (1987) suggested the following diameters (measured at breast height) to mitigate tsunamis based on these diagrams: diameters of 10 centimeters for 4.65 metermetre high waves, 34.3 centimeters centimetres for seven metermetre waves, 100 centimeters centimetres for ten metermetre waves. For a tsunami wave of three metermetres, the effective forest width is 20 metermetres, and for six metermetres the effective width is 100 metermetres. For a more detailed evaluation, numerical calculations are necessary, including the determination of hydraulic resistance of trees and undergrowth through hydraulics experiments.

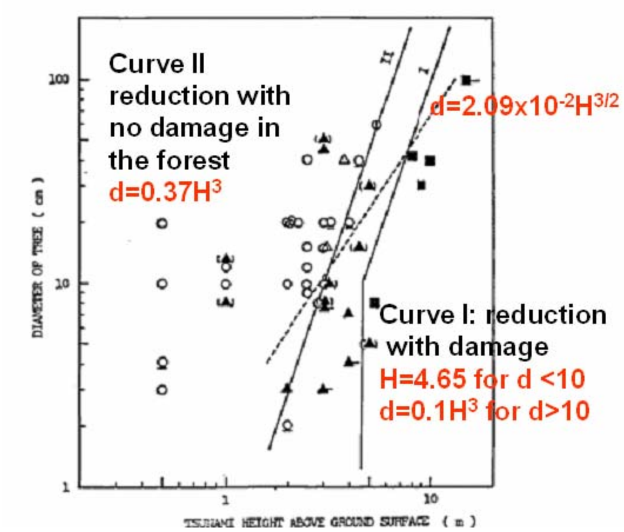


Figure 1.7 Degree of damage to trees (after Shuto, 1987)

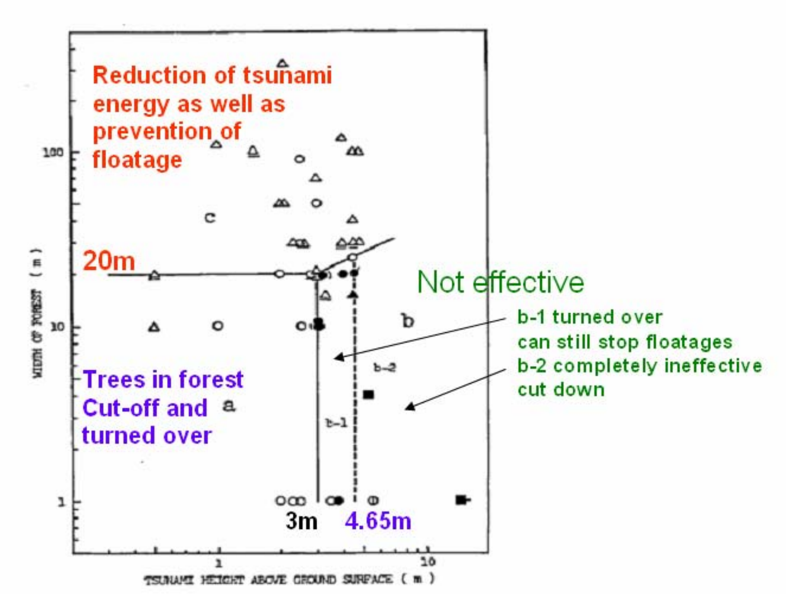
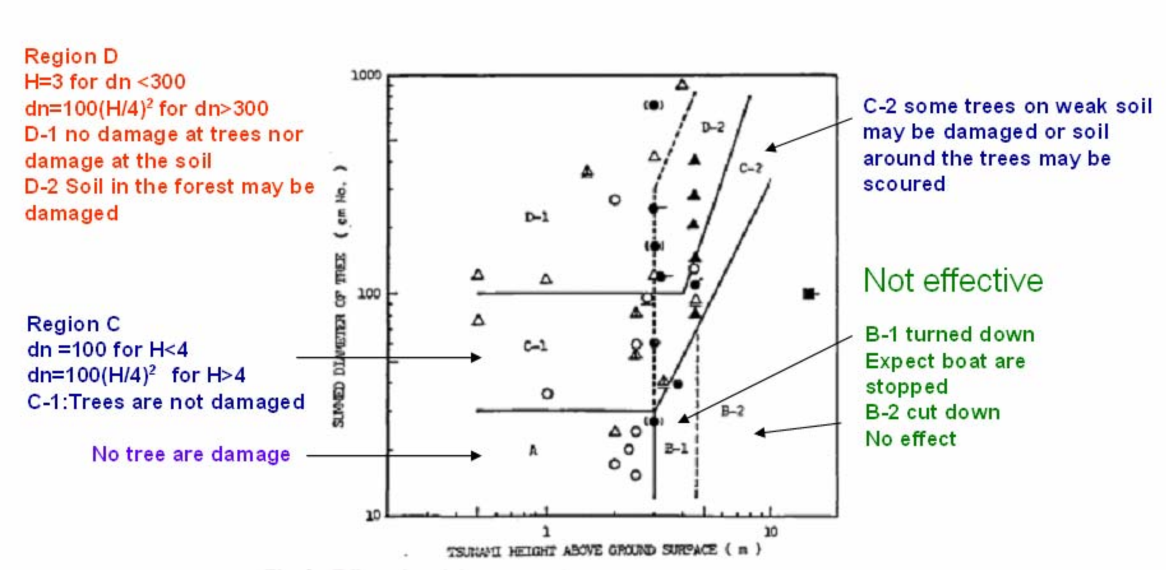


Figure 1.8 Effect of the tsunami control forest in terms of forest width (after Shuto, 1987)



Region D
H=3 for dn <300
$dn=100(H/4)^2$ for dn>300
D-1 no damage at trees nor damage at the soil
D-2 Soil in the forest may be damaged

Region C
dn =100 for H<4
$dn=100(H/4)^2$ for H>4
C-1:Trees are not damaged

No tree are damage

C-2 some trees on weak soil may be damaged or soil around the trees may be scoured

Not effective

B-1 turned down
Expect boat are stopped
B-2 cut down
No effect

**Figure 1.9 Effect of, and damage to, the tsunami control forest in terms of the summed tree diameter (after Shuto, 1987)**

# 3 Modeling coastal forest mitigation effects on tsunamis

## 3.1 Fluid dynamics

The capacity of forests to mitigate the impacts of a tsunami can be estimated by fluid dynamics models. These models, that examine the hydrodynamic relationship of a fluid moving through vegetation, require various parameters and associated coefficients to estimate forest resistance to tsunamis of different heights and pressures. The most important numbers to obtain are volumetric occupancy, drag coefficient, inertia coefficient and Manning's coefficient of roughness. These are estimated from measurements of the diameter and height of tree trunks, height and density of the canopy, and tree density. If the effective projection area is known, one can convert this to volumetric occupancy, and then the Manning coefficient, drag coefficient and inertia coefficient can be determined (Latief, 2000; Latief and Imamura, 2000; Harada *et al.*, 2000; Harada *et al.*, 2002). Figure 1.10 illustrates some of the key concepts related to the hydraulic model. It shows that volumetric occupancy is a function of the volume of water relative to the volume of submerged trees. A stream of water striking a tree trunk and imparting impact and frictional forces, along with the associated coefficients of inertia, $C_m$, and drag, $C_d$, is also portrayed in the figure. A full description of the technical aspects of modeling as applied to the Pancer Bay, East Java, case study is provided in Appendix A.

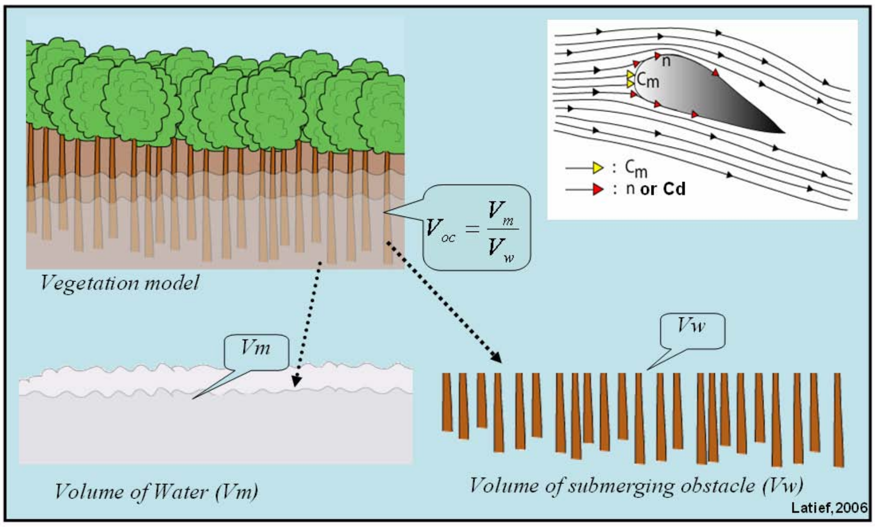


**Figure 1.10 Vegetation model: Volume of submerged obstacles, volume of water and volumetric occupancy**

### 3.2 Case of Pancer Bay, Indonesia

Located on the southern coast of East Java, Pancer Bay suffered considerable damage from the 1994 East Java tsunami. It claimed more than 121 lives or 3.8 percent of population, and destroyed seventy percent of the houses. Approximately 250 houses were heavily damaged and 450 houses were completely swept away. In order to gauge the mitigation effects of a coastal forest to protect the people of Pancer village from future tsunami hazards, a simulation model was developed. The study provides an example of application of the fluid dynamics model discussed in section 3.1 (also see Appendix A). A numerical simulation of the extent of inundation on land gives an indication of damage reduction by coastal forest in the context of actual coastal landform and topography of Pancer Bay.

Pancer Bay is a typical narrow bay facing directly offshore (see Figure 1.11). The bay mouth is around 3.8 kilometres wide and there are several small islands at the front of the bay. The lowland stretch, approximately 4.5 kilometres in length and 500 to 700 metermetres in width, is surrounded by hills. The sand covered beach, with numerous sand dunes, has a topographical elevation of two to eight metermetres and slopes range from five to eight percent. There is a small river behind the village, the mouth of which is located at the western part of the bay. Daily activities are mostly concentrated at and near the river mouth due to the presence of a fishing port and market.

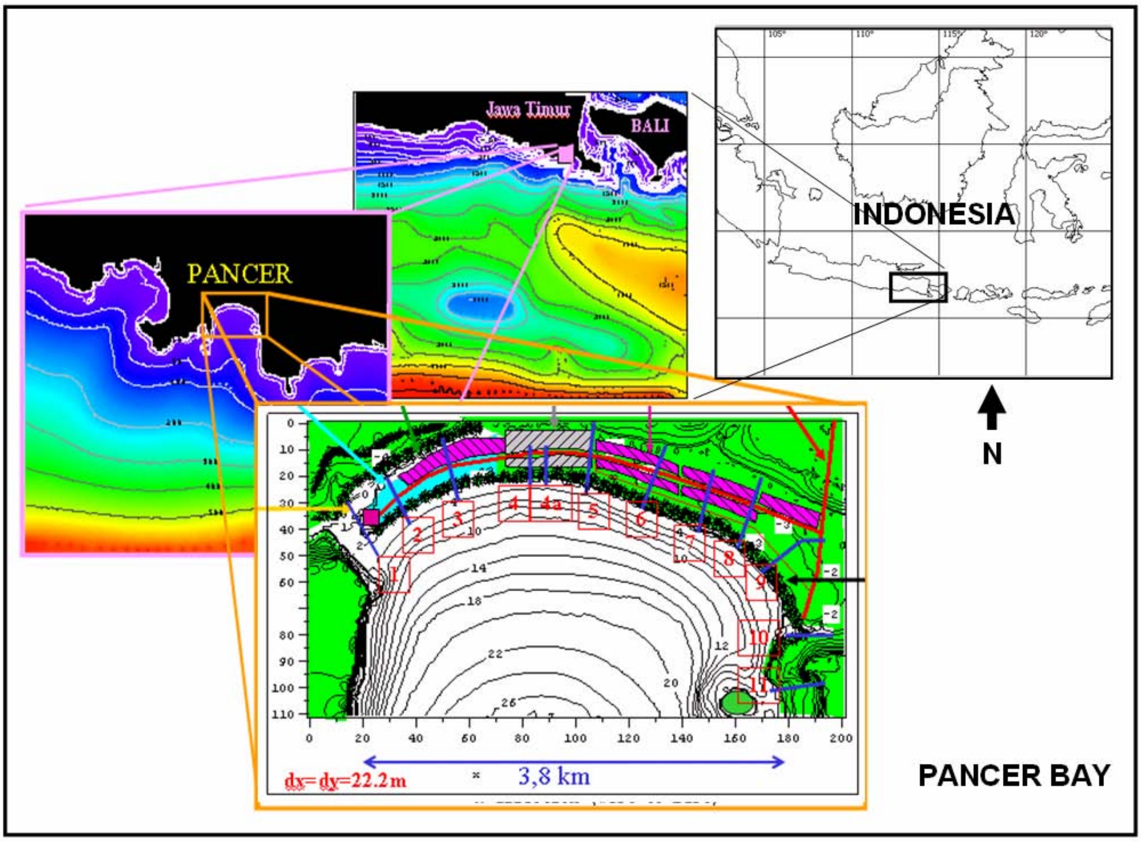


**Figure 1.11 Map of Pancer Bay (Latief, 2000)**

After the 1994 East Java tsunami, various surveys were conducted to access the magnitude of the tsunami. Some reported that the tsunami heights ranged from 5.7 to 9.4 metermetres (Tsuji *et al.*, 1995b), while others found the tsunami height above mean sea level (MSL) to be approximately 4.0 to 5.0 metermetres (Najoan *et al.*, 1997). The ground elevation of the residential area is about 4.0 metermetres. Distinct watermarks on some house walls were found, indicating a tsunami height 4.7 metermetres above ground. Three large waves were observed by local people, the second being the biggest with an average penetration of about 300 metermetres, and up to 500 metermetres in lowland areas. Much of this information was used to derive cross-sectional charts of tsunami run-up (Najoan *et al.* (1997). Figure 1.11 identifies the location of these cross-sections running parallel to the water as it flowed across the land. (These numbers correspond to the individual cross-section in Figure 1.15). The maximum wave height at the bay mouth was around two metermetres and the wave period was around 20 minutes.

Maramai and Tinti (1997) reported that the part of the village between the sea and the main road was completely destroyed and only house foundations remained. About 20 lines of *mustika* (big, robust trees) and coconut trees were located in front of the village. The trees probably had played some role as natural barriers against the waves, inducing wave break and energy dissipation. According to witnesses, the wave broke around the last tree line on the beach and the wave direction was perpendicular to the beach in the central part of the bay. So in this case, the control forest is placed before the breaking wave in the simulation model. In Figure 1.11, there is a small river behind the village, which the tsunami penetrated. The river was sufficiently wide for the wave to penetrate to the back of the village. The seawater flooded the village not only by frontal attack, but also laterally through the river, rising up behind the village.

The model simulation included three scenarios:

- Scenario-1: without vegetation
- Scenario-2: with forest along the coast and the river, including only drag forces
- Scenario-3: with same forest as Scenario-2, including both drag and impact forces

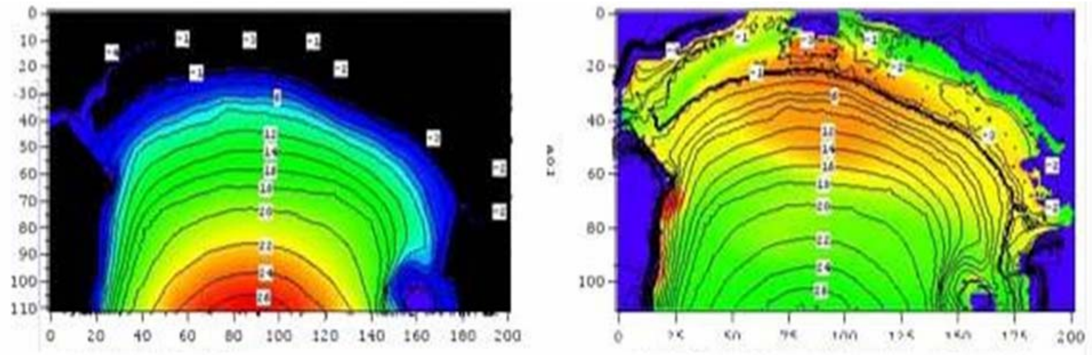
In each scenario, tsunami height, flow depth and inundation area are measured to show the relative mitigation effects of the scenario. Scenario-1, without vegetation, is the control simulation. The incremental benefit of the coastal forest is measured against it. Scenario-2 evaluates the effect of friction and the Manning coefficient to reduce tsunami height, inundation depth and area. Scenario-3 adds the impact force coefficient $C_M V_{oc}$, such that additional reductions are attributable to impact force.

Based on the volumetric occupancy measure of vegetation density, set at 16 percent for this simulated forest, the appropriate coefficients are calculated using equations (4) and (5) in Appendix A. The values used in the simulations are summarized in Table 1.3. The simulations were run using tsunami time series data for offshore tsunami elevations taken from the 1994 East Java Tsunami simulations (Latief and Imamura, 1998).

**Table 1.3 Simulation scenarios and their conditions**

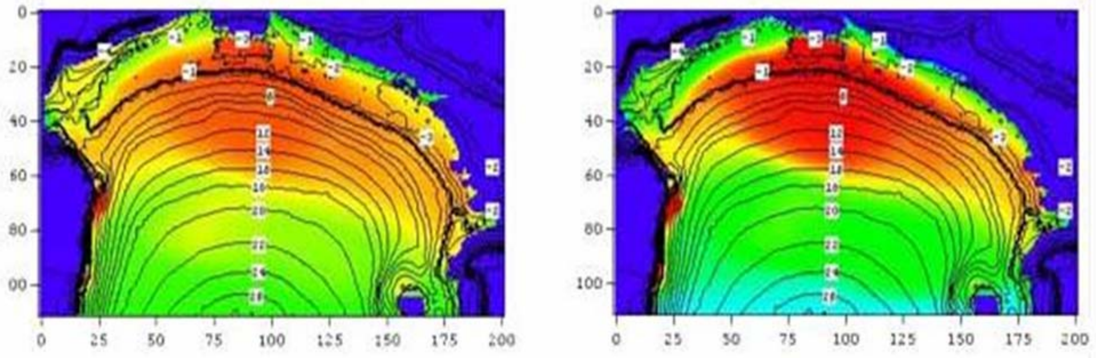
| **Scenarios** | **Manning coeff., *n*** | | **Impact force coefficient, $C_M V_{oc}$** | **Remarks** |
|---|---|---|---|---|
| | **Water/land** | **Vegetation** | | |
| Scenario-1 | 0.025 | 0.0 | 0.0 | No vegetation |
| Scenario-2 | 0.025 | 0.048 | 0.0 | Only considers friction by vegetation with 16% of the volumetric occupancy being relatively dense vegetation |
| Scenario-3 | 0.025 | 0.048 | 2.8 | Considers friction and impact force by vegetation; volumetric occupancy also 16% |

The results of the simulation show that the coastal forest would have mitigated the impact of the 1994 East Java tsunami. Tsunami heights, flow depth and inundation area were all reduced. The overlay of simulation results of the inundated area on the bathymetric map of Pancer Bay is shown in Figure 1.14 (a-d). These figures show that when vegetation is present, the area inundated would be diminished mostly by the effect of frictional drag (Figure 1.14c) and further diminished if impact force is also included in the model (Figure 1.14d). The cross-sectional profiles of the inundation depth and extent for the three scenarios are shown in Figure 1.15 — corresponding to positions in Figure 1.11 — also portray these mitigation effects. The figures show that the reduction in tsunami height and inundated area are in Sections 6 to 10 on the eastern side of the bay. Though the coastal forest is present on the western side of the bay, the river mouth allowed the channeling of the tsunami up the river and behind the forest, flooding the village. The area inundated by the tsunami would decrease if the density of the coastal forest increased.



a. Bathymetry-topography map

b. Inundated area before planting trees (sce-1)



c. Inundated area after planted trees (sce-2)

d. Inundated area after planted trees (sce-3)

**Figure 1.14** (a) Bathymetric and topography map (b) tsunami-inundated area without vegetation (c) with vegetation only, considering Manning's coefficient (d) with vegetation considering Manning's roughness and impact force coefficients (Latief, 2000)

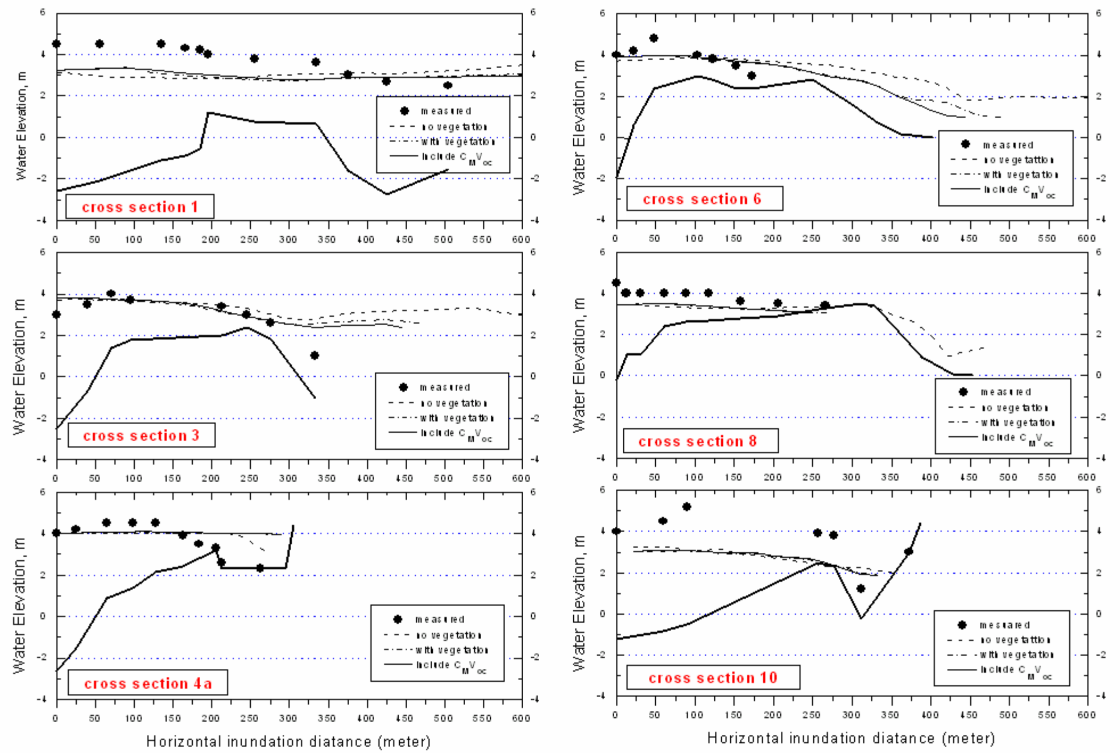


**Figure 1.15** Comparison between computed inundation heights and measured runup (the locations of each cross-section can be seen in Figure 1.11) (Latief, 2000)

## 4 Conclusions

The Indonesian and Philippine archipelagoes are vulnerable to tsunami threats because they are located near active earthquake faults and arrival times for a tsunami can be as little as a few minutes. In the case of the 2004 Sumatra tsunami, countries such as Thailand, Malaysia, Bangladesh, India and Sri Lanka were further away from the epicenter and arrival time varied from one to ten hours, allowing time for evacuation. Historical patterns of tsunami events indicate that sooner or later a major earthquake and tsunami are likely to strike again in the Indian Ocean region.

Though tsunami height on shore depends on the tsunami source (earthquake magnitude, distance to source), bathymetry and coastal morphology, coastal forests have a role in mitigating the impacts of a tsunami, within limits. The effectiveness of a forest depends on the width, density and structure of the forest and the tree characteristics (height and diametermeter at breast height). Shuto (1987) suggested the following diameters (measured at breast height) to mitigate tsunamis: ten centimeters centimetres for 4.65 metermetre high waves, 34.3 centimetreres for seven meter waves, 100 centimetres centimetres for ten metermetre waves. For a tsunami wave of three metermetres, the effective forest width is 20 metermetres and for six-metermetre high tsunami waveseight the, effective width is 100 metermetres. These numbers apply to Japanese coastal forests, but may give an indication of mitigation for similar forests.

For other forests, such as mangroves, the effectiveness of vegetation in mitigating the effect of tsunamis can be estimated from numerical simulations utilizing resistance coefficients such as Manning’s roughness, drag force and inertia. In the case study reported in this paper, the authors proposed that these coefficients can be derived from the function of the volumetric occupancy of vegetation, $V_{oc}$, which can be estimated by measuring the diametermeters of roots and trunks, tree height and foliage via ribbon measures or digital cameras. The simulation results of the inundated area show that vegetation can reduce tsunami wave height and current pressures up to a certain degree. The inundated area and tsunami run-up will be decreased when the density of the coastal forest increases.

### Acknowledgements

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# Appendix A Technical notes on modeling coastal forest mitigation effects on tsunamis

The following is a technical presentation on the modeling of mitigation effect by coastal forests on tsunamis. Part A.1 outlines the necessary coefficients for the numerical simulation of the hydrodynamic impact of vegetative barrier to flow of tsunami wave. Typically, these coefficients are difficult to determine in the field, so that the hydraulics experiments are conducted in laboratory wave tanks to estimate the coefficient values. Part A.2 chronicles the current research in this area, and presents a new approach based on the concept of volumetric occupancy. The final part, A.3, presents the derivation of momentum used to simulate the tsunami inundation on land and through vegetation. The set up for the numerical simulation in the Pancer Bay case study is also presented.

## A.1 Estimation of model coefficients

### Manning's coefficients of roughness *(n)*

Various Manning's coefficients of roughness have been estimated through experiments over the years. Table A.1 provides a select list of Manning coefficients typically used for calculating water flow through different types of vegetation and residential areas.

**Table A.1 Manning's coefficient of roughness for forest and housing**

| **Aida (1977)** | | **Kotani *et al.* (1998)** | |
|---|---|---|---|
| **Categories** | **Roughness** | **Categories** | **Estimated coefficients** |
| Dense vegetation | 0.07 | High density residential area | 0.08 |
| Relatively dense vegetation | 0.05 | Middle density residential area | 0.06 |
| Nearshore, including trees | 0.04 | Low density residential area | 0.04 |
| Others | 0.02 | Forest | 0.03 |
| | | Rice field | 0.02 |
| | | Water area, rivers and trees | 0.025 |

### Drag coefficient ($C_D$)

Petryk and Bosmajian (1975) introduced a method of hydraulic force balance to estimate Manning's coefficient due to vegetation and boundary roughness. They suggested that a flow is resisted mainly due to the drag force exerted by vegetation. Because a stand of trees projects an area of resistance to the flow of water through it, vegetation density can be inferred from the ratio between the projection area and water flow through the vegetation. They also proposed a relationship between Manning's coefficients of roughness, $n$, and drag coefficient, $C_D$ as follows:

$$n^2 = \frac{R^{4/3}}{2g}\left(\frac{C_D \sum A_i}{AL}\right) \quad (1)$$

where $\sum A_i/(AL)$ is vegetation density in the channel, $R$ is the hydraulics radius, $A$ is the cross-section area of flow, $L$ is the length of channel reach being considered, $C_D$ is the drag coefficient for vegetation, $A_i$ is the projected area of $i^{th}$ plant and $g$ is the gravitational acceleration.

To estimate the drag coefficient, $C_D$ , Mazda *et al.* (1997a) introduced vegetation length, $L_E$ as a parameter related to the projected area of the vegetation, $A$, and the volume of the submerged vegetation, $V_M$. The vegetation value length depends on mangrove species and water depth. They proposed for tidal and wind-induced waves,

$$C_D = \frac{2gI}{u^2} L_E \qquad (2)$$

where $I$ is water surface slope, $u$ is flow velocity and $g$ is gravity acceleration. $C_D$ can be calculated if $L_E$, $I$ and $u$ are measured. For a tsunami equation (2) can be re-written as follows:

$$C_D = \frac{2}{u^2} L_E \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{dx} + gI \right) \qquad (3)$$

### Inertia coefficient ($C_M$)

As a tsunami has transient waves, the inertia coefficient should be considered. Noji *et al.* (1993) carried out experiments and numerical analyseis on the movement of rocks by tsunamis. They disaggregated them into the drag force and the impact force, of which the impact force is inertia force due to a tsunami wave striking. The drag coefficient, $C_{D,}$ was evaluated to be in the order of 2 to 6 and the inertia coefficient, $C_M$, in the order of 2 (when the rock model was completely submerged). Latief (2000) proposed $C_M$ as a function of volumetric occupancy of vegetation (see equation 5) and Hiraishi and Harada (2003) proposed an inertia coefficient $C_M$ of about 1.7 for flow through vegetation.

## A.2 Hydraulics experiments

Hydraulic experiments are designed to understand the dynamics and unsteady behaviour of a tsunami passing through a mangrove forest and the effectiveness of the forest in reducing tsunami impact. The mangrove model consists of three components: leaves, trunks and roots. Hydraulic resistances due to both boundary and vegetation roughness (Manning's roughness coefficient, *n*, and drag coefficient, $C_D$, and the inertia coefficient, $C_M$) have been evaluated by Latief and Harada at the Tsunami Engineering Laboratory, DCRC Tohoku University. A similar experiment was also conducted by Harada and Hiraishi in the Port and Airport Research Institute, Japan. The results of the hydraulic experiment on the effect of mangrove forest in mitigating tsunami force are described by Latief *et al.* (1998), while Latief *et al.* (1999) elaborate on experimental and numerical studies on the effect of mangrove forest in mitigating tsunami force. Other notable hydraulic experiments of a similar nature include:

- Latief and Imamura (2000) studied tsunami mitigation via green belts in a case study of Pancer Bay, East Java, Indonesia.
- Latief (2000) studied tsunamis and their mitigation by a green belt in Indonesia.
- Harada *et al.* (2000) and Harada and Imamura (2001) studied a mangrove control forest to reduce tsunami impact and conducted an experimental study on mangrove resistance under unsteady flow.
- Harada ***et al.*** (2002) described tsunami force mitigation by green belts and permeable coastal structures.
- Hiraishi and Harada (2003) described green belts for tsunami attenuation in the South Pacific.

All these experiments were conducted to determine the hydraulic resistance due to boundary roughness and vegetation. Common to each is the measurement of water elevation and velocity, which are measured at points before, at and behind model forest. Measurements are captured as a time series as the wave is generated and first strikes, and passes through the vegetation. Figure A.1

shows ratio of water elevations before and behind the model versus the volumetric occupancy in the vegetation model. It clearly indicates the forest reduces water elevation as it passes through the forest, and this reduction effect increases with greater volumetric occupancy (i.e. increases in vegetation density).

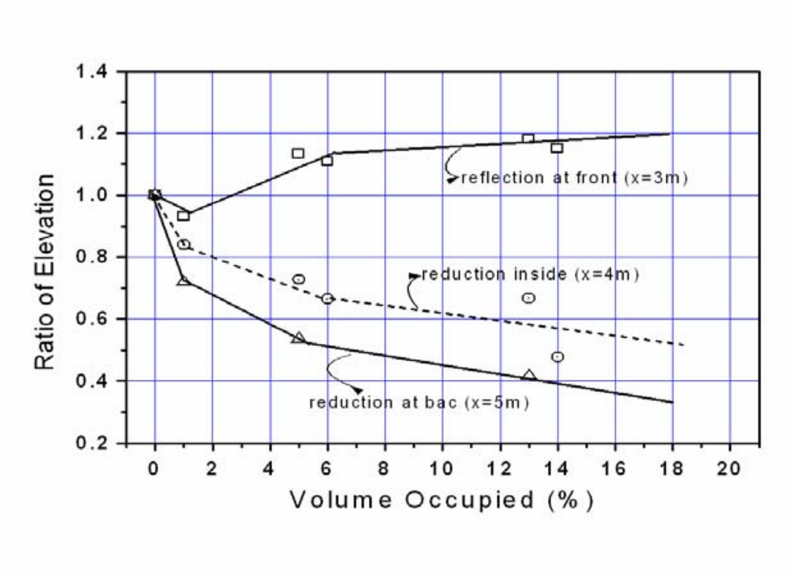

**Figure A.1 Ratio elevations with volumetric occupancy in the vegetation model (Latief, 2000)**

FromBy the measures ofmeasuring the water level and velocity, the Manning's roughness coefficient, $n$, drag coefficient, $C_D$, and inertia coefficient, $C_M$, are estimated as a function of occupancy volume. Latief (2000) and Harada *et al.* (2000) proposed an empirical formula of Manning's coefficient, $n$, and an impact force parameter, $C_M V_{oc}$,, as functions of the volumetric occupancy, $V_{oc}$. This is shown in equations (4) and (5), respectively.

| | | |
|---|---|---|
| $n = \begin{cases} 0.16 + 0.17\,V_{oc} \\ 0.03 \end{cases}$ | if $V_{oc} \geq 0.07$ | (4) |
| | if $V_{oc} < 0.07$ | |

For volumetric occupancy of less than 7 percent, $n$ is 0.03. This value is mainly attributable to the mangrove roots in the model. For occupancy larger than 7 percent, the effects of trunks, branches and leaves are dominant, and the relation between $n$ to $V_{oc}$ becomes relevant. Impact force is represented by the product of the inertia coefficient and volumetric occupancy, as follows:

| | | |
|---|---|---|
| $C_M V_{oc} = \begin{cases} 0.67 + 6.65\,V_{oc} \\ 1 \end{cases}$ | if $V_{oc} \geq 0.06$ | (5) |
| | if $V_{oc} < 0.06$ | |

For occupancies less than 6 percent $C_M V_{oc}$ equals unity, meaning the impact force can be ignored. For dense vegetation greater than 6 percent, volumetric occupancy the upper relationship is relevant. The other important parameters are provided by Hiraishi and Harada (2003), who proposed the drag coefficient to be $C_D = 8.4 Vo/V + 0.66$ and the inertia coefficient, $C_M$, to equal 1.7 for any kind vegetation.

### A.3 Derivation of momentum and governing model equations

The final aspect of modeling tsunami mitigation effects is to determine the momentum that carries the wave energy on land. The amount of momentum diminishes from frictional forces of seabed, beach, vegetation and dry ground as the tsunami runs up on land. Calculation of momentum is based on the coefficients estimated in the hydraulic experiments, described above. The momentum equation is as follows:

$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+gD\frac{\partial \eta}{\partial x}+C_M\frac{V_m}{V_w}\frac{\partial M}{\partial t}+\frac{gn^2M/M/}{D^{7/3}}+\frac{C_D}{2}\frac{A_o}{\Delta x\Delta y}\frac{M|M|}{D^2}=0 \tag{6}$$

where $M$ and $N$ are water discharges in $x$- and $y$-directions (cross-shore and long-shore), respectively; $D=h+\eta$ is the total water depth; $h$ is water depth; $\eta$ is wave height; $g$ is gravitational acceleration; $n$ represents Manning's roughness coefficient on the seabed and land; $C_D$ is the drag coefficient due to vegetation (submerged obstacles); $C_M$ is the inertia coefficient; and $A_0$ is the effective projection area of vegetation. As in the hydraulic experiment, $V_M$ is submerged volume of forest, and $V_W$ is control volume of water.

To simulate tsunami propagation and run-up, the shallow water theory including the effects of inertia coefficient ($C_M$) and Manning coefficient ($n$) in a two-dimensional problem is used. The following equations are the required continuity and momentum equations:

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \tag{7}$$

$$(1+C_MV_{oc})\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}=0 \tag{8}$$

$$(1+C_MV_{oc})\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}=0 \tag{9}$$

where $V_{oc}=V_m/V_w$ and all other variables are defined as above. The depth-integrated continuity and momentum equations are solved by the finite difference method with the staggered leap-frog scheme (Goto and Ogawa, 1992; Imamura, 1995).

For the Pancer Bay study, the grid size is 202 x 112 cells with a square mesh cell size of 22.22 metermetres, representing the bay area of 4.5 by 2.5 kilometers. The time-step for the simulation is 0.5 seconds. The tsunami input data were taken from the JAVA32 model with the CPX4 initial tsunami source (Latief and Imamura, 1998) by storing the time series of the computed tsunami height at the points at the bay mouth and the computed waveform at each point. Maximum wave height at the bay mouth was around two metermetres and the wave period was around 20 minutes. Results of the simulation are presented in Section 3.2.

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# Appendix B Glossary of Technical Terms

## Tsunami

**Arrival time:** Time of arrival, usually of the first wave, of the first wave of the tsunami at a particular location.

**Crust:** The outer layer of the earth's surface.

**Earthquake:** Shaking of the earth caused by a sudden movement of rock beneath its surface.

**Epicenter:** That point on the earth's surface directly above the hypocenter of an earthquake.

**Fault:** A weak point in the earth's crust where the rock layers have ruptured and slipped.

**Horizontal inundation distance:** The distance that a tsunami wave penetrates onto the shore, measured horizontally from the mean sea-level position of the water's edge. Usually measured as the maximum distance for a particular segment of the coast.

**Intensity:** A measure of the effects of an earthquake at a particular place on humans and/or structures. The intensity at a point depends not only upon the strength of the earthquake (magnitude), but also upon the distance from the earthquake to the epicenter and the local geology at that point.

**Inundation:** The depth, relative to a stated reference level, to which a particular location is covered by water.

**Inundation area:** An area that is flooded with water.

**Inundation line (limit):** The inland limit of wetting measured horizontally from the edge of the coast defined by mean sea level.

**Local/regional tsunami:** Source of the tsunami within 1 000 kilometres of the area of interest. Local or near-field tsunami waves have a very short travel time (30 minutes or less), mid-field or regional tsunami waves have travel times on the order of 30 minutes to two hours. Note: " Local" tsunami is sometimes used to refer to a tsunami of landslide origin.

**Ms (Surface Wave Magnitude):** Magnitude of an earthquake as measured from the amplitude of seismic surface waves. Often referred to by the media as "Richter" magnitude.

**Mw (Moment Magnitude):** Magnitude based on the size and characteristics of the fault rupture, and determined from long-period seismic waves. It is a better measure of earthquake size than surface wave magnitude.

**Magnitude:** A quantitative measure of the strength of an earthquake.

**Major earthquake:** An earthquake having a magnitude of 7 or greater on the Richter scale.

**Period:** The length of time between two successive peaks or troughs. May vary due to complex interference of waves. Tsunami periods generally range from five to 60 minutes.

**Plate:** Pieces of crust and brittle uppermost mantle, perhaps 100 kilometres thick and hundreds or thousands of kilometres wide, that cover the earth's surface. The plates move very slowly over, or possibly with, a viscous layer in the mantle at rates of a few centimetres per year.

**Plate tectonics:** A widely accepted theory that relates most of the geologic features near the earth's surface to the movement and interaction of relatively thin rock plates. The theory predicts that most earthquakes occur when plates move past each other.

**Recurrence interval:** The approximate average length of time between earthquakes in a specific seismically active area.

**Richter magnitude scale:** The system used to measure the strength or magnitude of an earthquake. The Richter magnitude scale was developed in 1935 by Charles F. Richter of the California Institute of Technology.

**Runup:** Maximum height of the water onshore observed above a reference sea level. Usually measured at the horizontal inundation limit.

**Rupture zone:** The area of the earth through which faulting occurred during an earthquake. For very small earthquakes, this zone could be the size of a pinhead, but in the case of a great earthquake, the rupture zone may extend several hundred kilometres in length and tens of kilometres in width.

**Seismic:** Pertaining to earthquakes.

**Seismicity:** Earthquake activity.

**Seismic zone:** A region in which earthquakes are known to occur.

**Subduction:** The process in which one lithospheric plate collides with and is forced down under another plate and is drawn back into the earth's mantle.

**Subduction zone:** The zone of convergence of two tectonic plates, one of which is subducted beneath the other. An elongated region along which a plate descends relative to another plate.

**Tectonic:** Pertaining to the forces involved in the deformation of the earth's crust, or the structures or features produced by such deformation.

**Teletsunami:** Source of the tsunami more than 1 000 kilometres away from the area of interest. Also called a distant-source or far-field tsunami.

**Tidal wave:** Common term for tsunami used in older literature, historical descriptions and popular accounts. Tides, caused by the gravitational attractions of the sun and moon, may increase or decrease the impact of a tsunami, but have nothing to do with their generation or propagation.

**Travel time:** Time (usually measured in hours and tenths of hours) that it took the tsunami to travel from the source to a particular location.

**Tsunami:** A Japanese term derived from the characters "tsu" meaning harbour and "nami" meaning wave. Now generally accepted by the international scientific community to describe a series of traveling waves in water produced by the displacement of the sea floor associated with submarine earthquakes, volcanic eruptions, or landslides.

**Tsunami height:** The vertical distance between a tsunami crest and mean sea level (MSL) at the shoreline.

**Tsunami magnitude:** A number which characterizes the strength of a tsunami based on the tsunami wave amplitudes. Several different tsunami magnitude determination methods have been proposed.

## Hydraulics

**Drag force:** resistance to the movement of a solid object through a fluid. Drag is made up of friction forces, which act in a direction parallel to the object's surface, plus pressure forces, which act in a direction perpendicular to the object's surface.

**Drag coefficient ($C_D$):** A dimensionless quantity that describes a characteristic amount of aerodynamic drag caused by fluid flow, used in the drag equation. Two objects of the same frontal area moving at the same speed through a fluid will experience a drag force proportional to their $C_d$ numbers.

**Friction**: The force that resists the (sliding) motion of two surfaces in contact. The force of friction is present everywhere two objects are in contact. It is easily observed when one attempts to displace a block sitting atop a table.

**Friction coefficient:** A *material property*, defined as the ratio of the *Friction* force (**F**) to the *Normal* (**N**) force.

**Friction force:** The product of the coefficient of friction and the *Normal* force. The coefficient of friction can be static or kinetic, and varies according to the material properties; its value is determined experimentally.

**Green belt:** Land use designation used in land-use planning to retain areas of largely undeveloped, wild, or agricultural land surrounding or neighbouring urban areas.

**Inertia** (physics): The tendency of a body to maintain its state of rest or uniform motion unless acted upon by an external force.

**Inertia coefficient:** A dimensionless quantity that describes a characteristic of a body to maintain its state of rest upon contact with an external force, i.e. a high velocity collision (an impact).

**Inertia force:** In simple terms "In an isolated system, a body at rest will remain at rest and a body moving with constant velocity will continue to do so, unless disturbed by an unbalanced force".

**Impact force:** A high velocity collision (an impact) does not provide sufficient time for these deformations and vibrations to occur.

**Roughness** or **rugosity:** A measurement of the small-scale variations in the height of a physical surface as it causes friction, wear, drag and fatigue**.**

**Volumetric occupancy:** A volume of water passing through trees or forest occupied by submerged roots and tree trunks.

## Field study presentation: The role of coastal vegetation in protecting the Thai coast against the 2004 tsunami

### Absornsuda Siripong, Chulalongkorn University, Thailand

*The main impacts of the tsunami on coastal wetlands included loss or degradation of mangrove and seagrass beds, siltation of the coastal ecosystem and major changes to coastal features and land productivity. The mangroves diminished wave energy and so afforded some measure of protection to the infrastructure behind them. Damage from the tsunami could have been mitigated if more coastal areas had maintained their protective shields of mangrove swamps, beach forest and coral reefs. Erosion and sedimentation properties from the tsunami's runup and rundown were analysed for implementing coastal rehabilitation activities. There was less damage to the mangrove coast compared to the sandy beach at Prathong Island. Erosion and sediment transport from tsunami wave and wind wave action were studied at Ban Thao Bay, Phuket. Rehabilitation for coastal protection was recommended.*

*Green belt effects vary according to coastal topography. In some areas, mangroves can prevent people or properties from being washed out to sea by a powerful tsunami wave. They form a protective buffer, stabilize sediments, reduce shoreline and riverbank erosion, regulate flooding and recycle nutrients.*

*It can be concluded that coastal forests provided significant protection where there was sufficient density of intact forest. Degraded forest or widely spaced trees afforded little protection. The situation varied significantly between sites and was influenced by different factors. There is strong justification for protection of remaining coastal forests and for immediate support for rehabilitation. In-depth experience must be available in the region for rehabilitation techniques — but information is scattered and not available to many of the affected communities.*

## Field study presentation: Outcomes of the project "In-depth assessment of mangroves and other coastal forests affected by the tsunami in Southern Thailand"

### Chongrak Wachrinrat, Kasetsart University, Thailand

*The study assessed the impact of the 2004 Indian Ocean tsunami on mangroves and other coastal forests in Thailand. Large trees of* Casuarina equisetifolia *were uprooted and some mangrove trees (for example* Avicennia alba *and* Xylocarpus *sp.) were damaged. Conversely, trees of* Rhizophora *sp. were left undamaged, presumably due to their sizeable and stable stilt roots and the high tree density in the forest.*

*The study revealed that the dominant species of beach forests were* Casuarina equisetifolia, Barringtonia asiatica, Terminalia catappa, Syzygium *sp.,* Pouteria obovata, Derris indica *and* Callophyllum inophyllum*. Dominant species of mangroves were* Rhizophora apiculata, R. mucronata, Avicennia alba *and* Sonneratia ovata*. The regeneration of the beach forest after the tsunami was low, particularly for the dominant species.* Casuarina *sp. and* Derris indica *succeeded in competing with other pioneer species, while remaining pioneer species (including* Gloriosa superba, Ipomoea pescaprae *and* Chromolaena odoratum*) rapidly occupied the gaps left in the area. With regard to mangroves, few seedlings were found in the sample plots and regeneration was very difficult owing to accumulated sand from the tsunami runup and rundown and the high percentage of mud on the forest soil. The sole exception was* Rhizophora apiculata*, the seedlings of which were found in relatively high numbers.*

## Field study presentation: Understanding tsunami impacts from reef island perspectives — experience from the Maldives

**Mohamed Ali, Ministry of Environment, Energy and Water, the Maldives**

*The Maldives comprise various types of islands and atolls and host six main ecosystems, i.e. coastal vegetation, evergreen moist forests, mangroves, "pond" ecosystems, coral reefs and seagrass beds. The evergreen moist forests house more that 490 different species, some of which are endemic, rare, threatened, or endangered. Mangroves grow along the coast of 150 islands; the 13 mangrove species are often associated with enclosed or semi-enclosed brackish waterbodies (*kulhi*), or with marshes (*chasbin*), but no estuarine mangroves exist in the country. Coastal erosion and other damage induced by the impact of the Indian Ocean tsunami in 2004 were studied in different islands; the degree of damage generated by the hazard was related to the size, orientation and location of the islands.*

*Results indicated that the following factors had a relevant importance in affecting the impact of the tsunami on the islands: (1) proportion of passages (open/closed); (2) orientation (east–west, north–south); (3) reef type (*faro*, patch); (4) island form (ridge, bowl-shaped); (5) island shape (circular, elongated); (6) size (small, medium, large); and (7) modifications (harbour, reclamation). The shape of coral reefs, the height of the island and the development of beach ridges were significant factors for reducing damage.*

## Key points and observations emphasized in the discussions

The technical paper, field study presentations and discussions undertaken during this session highlighted that mangroves and other coastal forests may afford protection to lives and resources against a tsunami strike, but several factors influence the severity of tsunami damage; these include *inter alia* the steepness of the beach, the configuration of the coastline, topography, geomorphology, direction of the tsunami and the properties of the existing coastal vegetation.

The following factors were identified:

1. Tsunami characteristics are very different from normal waves; they are, in effect, "walls of water" of great width and with sustained force and velocity that cannot easily be reduced.
2. Trees and coastal forests can help in mitigating the impacts of tsunamis; however, whether they are effective and the degree of their effectiveness depend on many variables. Coastal forests and trees will not help in the case of very large tsunamis.
3. The effectiveness of trees and forests in reducing tsunami impacts depends on the width, density and structure of the vegetation (e.g. the threshold of effective hydraulic resistance for a tsunami of 4.65-metre height appears to be approximately 10 centimetres in diametre.
4. Narrow strips of coastal trees can exacerbate the damage if trees collapse and add to the floating debris carried inland by the tsunami.
5. According to the numerical models described, coconuts provide little or no protection against tsunamis owing to their tall and slender profile and superficial rooting system. Similarly, mangrove forests, if not dense, wide and healthy, can provide only little protection.
6. Most human mortality from the 2004 tsunami occurred in areas where the original natural vegetation was beach forest, often modified by human development, rather than areas where the original vegetation was mangrove forests; this was probably because beach forest areas provide more attractive areas for human habitation and tourist development.
7. The impacts of tsunamis on reef islands are very different than in other areas and coastal vegetation may have very little influence on these islands relative to other factors such as reef type, island form and size, orientation, coastal slope and human modifications.

During the session, the experts emphasized and recommended that:

1. Communication between research modellers, biologists, botanists and foresters should be initiated or strengthened; this collaboration is urgent to ensure that realistic biophysical characteristics and parametres are incorporated into models.
2. Studies of tsunami impacts need to consider both the runup and rundown effects of waves (both of which are important and may have differing impacts).
3. There is a need for greater clarity and definition of the terms that are used in describing tsunami characteristics and their impacts in research and literature.
4. Studies of tsunami impacts and mitigation need to assess the numerous factors and complexities that influence tsunami damage rather than individual factors in isolation.
5. Effective early warning systems and evacuation plans are essential for saving lives from the impact of a tsunami.
6. The value of peatlands and wetlands in mitigating the impacts of tsunamis should receive greater recognition.