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ORIGINAL PAPER

Simplified formulae for designing coastal forest against tsunami run-up: one-dimensional approach

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Abstract In the present study, laboratory experiments were conducted to validate the applicability of a numerical model based on one-dimensional nonlinear long-wave equations. The model includes drag and inertia resistance of trees to tsunami flow and porosity between trees and a simplified forest in a wave channel. It was confirmed that the water surface elevation and flow velocity by the numerical simulations agree well with the experimental results for various forest conditions of width and tree density. Further, the numerical model was applied to prototype conditions of a coastal forest of *Pandanus odoratissimus* to investigate the effects of forest conditions (width and tree density) and incident tsunami conditions (period and height) on run-up height and potential tsunami force. The modeling results were represented in curve-fit equations with the aim of providing simplified formulae for designing coastal forest against tsunamis. The run-up height and potential tsunami forces calculated by the curve-fit formulae and the numerical model agreed within $\pm 10\%$ error.

Keywords Tsunami run-up · Coastal forest · Pandanus odoratissimus · Tsunami force

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1 Introduction

After the Indian Ocean tsunami in 2004, a number of studies have explained effects of coastal forests in reducing the tsunami run-up and the damage to humans and property based on post-tsunami surveys (for example, Danielsen et al. 2005; Kathiresan and Rajendran 2005; Tanaka et al. 2007). Nandasena et al. (2012) reported that coastal forests consisting of pine trees on the northeast coast of Japan played an important role not only to reduce in tsunami energy but also to trap solid objects like concrete slabs detached from sea walls, and boats from marinas during the 2011 Great East Japan (Tohoku-Oki) tsunami. They investigated hypothetical arrangements of coastal forests with other mitigating methods for tsunami energy reduction in advanced numerical modeling. Currently, coastal forests are increasingly considered to be an effective measure to mitigate tsunami damage from both economic and environmental points of view, despite there is still debating on its effective role due to the absence of adequate studies (Kerr and Baird 2007). In fact, several projects to plant vegetation on coasts as a bio-shield against tsunamis have been started in South and Southeast Asian countries (Tanaka et al. 2009; Tanaka 2009).

The reduction of tsunami damage behind a coastal forest depends on the vegetation species and their properties (tree height, diameter, density, and vertical configuration), extent (along-shore length and cross-shore) and arrangement of forest (uniform or staggered), local tsunami conditions (flow depth and flow velocity) and local topography (Nandasena et al. 2008; Tanaka et al. 2009). Related to the forest arrangement, Mascarenhas and Jayakumar (2008) pointed out that roads perpendicular to beaches in a coastal forest served as a passage for the tsunami to travel inland for example in many places in Tamil Nadu, India, during the of 2004 Indian Ocean tsunami. Nandasena et al. (2012) also pointed out the difference between straight and crooked roads in coastal forests, perpendicular to the beach, in terms of tsunami energy reduction in numerical modeling for the case of the 2011 Great East Japan tsunami. In their simulation, the maximum flow velocity was increased 1.37 and 1.79 times behind the straight road when the tsunami moved inland and the tsunami moved seaward, respectively, compared to that of the bare land. However, the flow velocity did not increase through the crooked road, and the maximum flow velocity behind it was roughly equal to that of the bare land (Nandasena et al. 2012).

Tanaka et al. (2007) pointed out that *Pandanus odoratissimus* is especially effective in providing protection from tsunami damage due to its density and complex aerial root structure, but its strength is not so strong above the exposed root system and hence it has a risk of breaking due to the action of high tsunamis. In previous studies by numerical simulations, however, tsunami forces acting on each tree are not discussed. The tsunami forces are directly related on the damage of the trees. Therefore, when designing a coastal forest to reduce tsunami energy, the magnitude of the tsunami force on trees becomes a key parameter to be considered. Advanced numerical models may calculate these forces, with some assumptions. However, these numerical models are not readily available for stake holders.

In this paper, therefore, we introduce simple formulae derived from advanced onedimensional numerical modeling to calculate tsunami force on forests and reduction in runup due to forests on uniform slopes for different tsunami conditions. The numerical model is based on a one-dimensional nonlinear long-wave equations (Nandasena et al. 2008). Laboratory experiments on long-period sinusoidal waves around a simplified forest model with various width and tree density were conducted in a wave channel in order to validate the applicability of the numerical model. Then, the model was applied to a coastal forest of *P. odoratissimus* with effects of forest conditions (width and tree density) and incident tsunami conditions (height and period) to discuss the tsunami force and reduction in run-up on a typical ground slope. Finally, simple equations were proposed based on the modeling results to predict tsunami run-up reduction due to coastal forest, forces on the trees and forces behind the forest. An application of these simple equations in a real case is also presented.

2 Mathematical model and numerical method

2.1 Governing equations

The governing equations are modified one-dimensional nonlinear long-wave equations that include drag and inertia forces due to interaction with trees, and porosity between trees (Nandasena et al. 2008). The continuity and the momentum equations are, respectively:

$$\theta_{\rm d} \frac{\partial \zeta}{\partial t} + \frac{\partial Q_x}{\partial x} = 0 \tag{1}$$

$$\theta_{\rm d} \frac{\partial Q_x}{\partial t} + \frac{\partial \left(\frac{Q_x^2}{d}\right)}{\partial x} + \theta_{\rm d} g d \frac{\partial d}{\partial x} + \theta_{\rm d}^{3/2} g d \frac{\partial z}{\partial x} + \theta_{\rm b} \sqrt{\theta_{\rm d}} \frac{\tau_x}{\rho} + \frac{\theta_{\rm d}^{3/2}}{\rho} \sum_{i=1}^k f_{xi} = 0$$
(2)

where Q_x is the discharge, ζ the water surface elevation measured from a datum, d the water depth, z the bed elevation measured from the datum, τ_x the bed resistance (given by Manning's equation), $\sum_{i=1}^{k} f_{xi}$ the total resistance on fluid generated by trees, g the gravitational acceleration, ρ the density of sea water, θ_d the depth-averaged porosity between trees at water depth d, θ_b the bed porosity between trees. Total resistance by trees is assumed to be equal to sum of the drag and inertia forces as follows (For more details, refer to Nandasena et al. 2008)

$$F_D = \gamma \frac{1}{2} C_{\text{D-all}} b_{\text{ref}} d \frac{Q_x^2}{d^2 \theta_{\text{d}}}$$
(3)

$$F_{I} = \gamma \rho C_{\rm M} \forall \frac{D\left(Q_{x}/d\sqrt{\theta_{\rm d}}\right)}{Dt}$$

$$\tag{4}$$

where γ is the tree density (number of trees/m²), $C_{\rm M}$ the inertia coefficient (= 2.0) (Imamura et al. 2008; Nandasena et al. 2008), and $C_{\rm D-all}$ the depth-averaged equivalent drag coefficient considering the vertical stand structure of tree, which was defined by Tanaka et al. (2007) as:

$$C_{\text{D-all}}(d) = C_{\text{D-ref}} \frac{1}{d} \int_0^d \alpha(z_{\text{G}}) \beta(z_{\text{G}}) \mathrm{d}z_{\text{G}}$$
(5)

$$\alpha(z_{\rm G}) = \frac{b(z_{\rm G})}{b_{\rm ref}} \tag{6}$$

$$\beta(z_{\rm G}) = \frac{C_{\rm D}(z_{\rm G})}{C_{\rm D-ref}} \tag{7}$$

where $b(z_G)$ and $C_D(z_G)$ are the projected width and drag coefficient of a tree at the height z_G from the ground surface, and b_{ref} and C_{D-ref} are the reference width of the trunk and the reference drag coefficient at the breast height in principle, respectively.

2.2 Definition of forest thickness B_{dNall}

Shuto (1987) defined forest thickness by combining both effects of forest width and tree density. Tanaka et al. (2009) improved it to include the resistance characteristics due to tree species ($C_{\text{D-all}}$). In the present paper, the forest thickness improved by Tanaka et al. (2009) was used with SI unit as follows:

$$B_{\rm dNall} = \gamma (1 \times B_{\rm F}) b_{\rm ref} C_{D-\rm all} = \gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-\rm all}$$
(8)

where b_{ref} can be considered as the reference width per one tree and b_{ref}^* is a logical reference width to make so that B_{dNall} has a unit of meter in the simple form. B_F is the cross-shore forest width. Note b_{ref}^* has the same value as b_{ref} but the unit of m²/tree.

2.3 Definition of non-dimensional forest thickness

In the present study, the following non-dimensional forest thickness combining forest and tsunami conditions is defined:

$$\frac{B_{\rm dNall}}{T\sqrt{gH_{\rm sl0}}} = \frac{\gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-all}}{T\sqrt{gH_{\rm sl0}}} \tag{9}$$

where $T\sqrt{gH_{sl0}}$ is considered the representative wave length at the shoreline, and T and H_{sl0} are tsunami period and height at the shore line, respectively. The range of this nondimensional parameter in the present study was 0–0.00217 excepting the additional case of $B_{\rm F} = 1000$ m.

2.4 Tsunami force

A tsunami force vector (\vec{F}^*) is defined by the following equation (Tanimoto et al. 2007; Thuy et al. 2010, 2012; Thuy et al. 2017):

$$\vec{F}^* = \frac{1}{2}\rho d\vec{V} \left| \vec{V} \right| \tag{10}$$

where V is the flow velocity. This is a potential tsunami force integrated over the inundated depth d and corresponds to the total drag force due to tsunami acting on a virtual high column with a unit width and a unit drag coefficient. For an example, the integrated drag force vector (\vec{F}_{Tree}) on a single tree with the height of H_{Tree} can be calculated by the following relation:

$$\vec{F}_{\text{Tree}} = C_{\text{D-all}} b_{\text{ref}} \vec{F}^*, \qquad H_{\text{Tree}} \ge d$$

$$= C_{\text{D-all}} b_{\text{ref}} \frac{H_{\text{Tree}}}{d} \vec{F}^*, \qquad H_{\text{Tree}} < d$$
(11)

In reality, flow bifurcation near a tree can be observed. This generates imbalance in flow. In the numerical model however the depth-averaged flow is considered through the forest.

2.5 Method of numerical simulations

Equations (1) and (2) were solved by a finite-difference method with a staggered leap-frog scheme. An upwind scheme was used for nonlinear convective terms in order to maintain numerical stability. A semi–Crank–Nicholson scheme was used for the terms of bed friction, drag, and inertia (Nandasena et al. 2008; Thuy et al. 2009a, b, 2010, 2012). The wave generation zone has a constant water depth in which governing equations are behaved as linear long waves. This method was used to generate non-reflective waves at the wave generation boundary. The incident sinusoidal tsunami was given as a time-dependent boundary condition at the wave generation zone. A number of algorithms are necessary to simulate the flow when the water surface elevation is high enough can flow to the adjacent dry cells.

3 Experiments and validation of numerical model

3.1 Experimental setup and conditions

The present experiments were similar to that of Thuy et al. (2009a, b, 2010) in which a simplified forest model of vertical cylinders with a fixed width, and tree density was investigated by a fixed condition of long waves in a wave channel with 0.4 m wide. The model scale was 1:300. However, the vertical configuration of a real Pandanus tree was scaled down to a rigid cylinder by taking breast height diameter and some contribution from Alpha function. We also kept the Froude number similarity between the model and the prototype. The effect of forest conditions (width and density) on the flow velocity and flow depth behind the forest model (Fig. 1) was mainly investigated.

The experimental setup in the wave channel where the forest model was set in the water area for the convenience of velocity measurements (Fig. 1). Trees were modeled by stiff wooden cylinders with a diameter of 0.005 m mounted in a staggered arrangement. The forest model was placed in shallow water and still water depth behind the model at x = 11.36 m was 0.037 m (Fig. 1). Three densities of trees with fixed forest width of 1.0 m were tested; 500, 1000, and 2200 trees/m². Then, the forest width was changed in cases of 0.2, 0.5, 0.7 and 1.0 m with the fixed density of 2200 trees/m². In addition to those cases, experiments for the case of no forest model were also conducted.

The flow velocity and water surface elevation were measured at the gauges (Fig. 1b). Water surface elevations were measured using capacitance type wave gauges, while flow velocities were measured using electromagnetic current meters in two perpendicular horizontal directions (along the flow and normal to the flow) at the middle of the still water depth. Wave conditions were fixed as that the incident wave height at still water depth of wave generation boundary 0.44 m was 0.02 m and the wave period was 20 s (Fig. 1a) similar to the previous experiments (Thuy et al. 2009a, b, 2010).

3.2 Model validation with experimental data

The uniform grid size of 0.005 m and time step of 0.002 s were selected for modeling of experimental data. The Manning's roughness coefficient was $0.012 \text{ s/m}^{1/3}$ for the relatively



Fig. 1 a Experimental setup with the forest model in the wave flume, and **b** plan view of the flume showing the measuring locations for water surface elevation and velocity of waves

rough wooden bottom. The drag coefficient C_{D-ref} depends on both the Reynolds number and relative spacing of vegetation (s/D), where s is the distance between cylinders and D is the diameter of cylinder (Thuy et al. 2010). However, the interaction between multiple cylinders becomes small when s/D is larger than 2, and the drag coefficient of multiple cylinders approaches to a single cylinder (Chakrabati 1991). In our experimental conditions, the drag coefficient may be assumed as a single cylinder since the s/D is considerably greater than 2. The drag coefficient $C_{\text{D-ref}}$ was determined to be 1.5 after calibration of the numerical model for the cases with the tree density of 1000 trees/m² and forest width of 0.5 m. The Reynolds number for the experiment was around 300 which is consistent with the drag coefficient of a circular cylinder in laminar flows. Figure 2 displays wave height measured at six locations (Fig. 1b) in cases of no forest model and forest model. In the figure, the two cases simulated with the incident wave height of 0.02 m were plotted for the actual channel length. The distribution of wave height along the channel length extended by 21 m which equals half a wavelength at the still water depth of 0.44 m were also shown. The simulated wave heights agreed well with measured wave heights. Figure 3 displays the temporal variation of flow velocity at the center point behind the forest model (at x = 11.37 m, Fig. 1) for the case $B_{\rm F} = 1.0$ m and $\gamma = 0.22$ trees/cm². It is confirmed that the flow velocity was almost steady in pattern and the simulated maximum value in particular agrees well with the measured maximum values as already shown in the previous study (Thuy et al. 2009a, b, 2010).



Figure 4 shows the change in wave crest (ζ_{max}), and maximum velocity at the center point behind the forest model (V_{max}) against the forest width and density, respectively. For both cases, the wave crest and velocity decreases as forest width and tree density increases. The numerical results agree fairly well with the experimental results.

4 Application of the model to prototype condition

4.1 Topography and forest

A uniform coastal topography (slope 1/500), as displayed in Fig. 5, was selected as a prototype case. The bathymetry profile consisted of three slopes 1/10, 1/100, and 1/50. The sea depth at the wave generation zone with a horizontal bottom was 100 m below the datum level of mean sea level. The tide level when the tsunami arrives was considered to be 2 m, and therefore the still water level was at 2 m above the datum level. The direction of the incident tsunami was normal to the shoreline. The coastal forest began at the starting point of the slope of 1/500 on the land (x = 5700 m; Fig. 5), where the height of the ground was 4 m above the datum level (i.e. 2 m above the tide level at tsunami attack). The forest was assumed to extend infinitely in the direction of the shoreline (y-axis) with the same arrangement.



Pandanus odoratissimus was considered the candidate tree type in the present study. They have a complex aerial root structure that provides additional stiffness and increases in the coefficient of drag (Tanaka et al. 2007). It was observed in the field surveys conducted after the 2004 Indian Ocean tsunami that a weak point of *P. odoratissimus* is just above the top of aerial roots as the root region shares the breaking moment (Tanaka et al. 2007). Figure 6b shows α , β and C_{D-all} of *P. odoratissimus* modified slightly from those proposed by Tanaka et al. (2007) to the following conditions: the tree height $H_{Tree} = 8$ m (for a mature







tree), the reference diameter $b_{\rm ref} = 0.195$ m, and the reference drag coefficient $C_{\rm D-ref} = 1.0$. The reference drag coefficient of 1.0 was adopted for the trunk with a circular section and a rough surface in the region of high Reynolds number (Nandasena et al. 2008; Thuy et al. 2009a, b, 2010, 2012). The value of $C_{\rm D-all}$ varies at different rate with the flow depth *d* (inundated depth) because the projected width *b* and the drag coefficient $C_{\rm D}$ vary differently with height from the ground surface $Z_{\rm G}$. The drag coefficient $C_{\rm D}$ varied from 1.5 to 1, according to the spacing of the aerial roots and leaf, which obtained based on the field survey (Nepf 1999; Tanaka et al. 2007). The inertia coefficient was kept as 2.0 as there was no field values in particular related to tsunami-vegetation studies.

4.2 Conditions of tsunami and forest

As already described, the tsunami propagation to attack the coast was perpendicular to the shoreline at the tide level of 2 m. Incident tsunami waves at the offshore boundary was represented by large sinusoidal waves with different wave period and height which were changed in the ranges from 600 to 3600 s and from 2 to 8 m, respectively, for selected cases. In the present paper, the run-up of a single wave was analyzed that representing the

Table 1 Summary of all simulation cases of combined	Series	B _F	(m)		γ (trees	s/m ²)	H _{sl0}	(m)	T (s)	
conditions of forest and tsunami	Change of forest conditions										
	1	0-	200, 10	00	0.226		6.94		1200		
	2 10		0	0-0.4			6.94		1200		
	Change of tsunami conditions										
	3	10	00		0.226		3.08-8.51		1200		
	4 100		0		0.226		6.94		600-3600		
	Change of tree density and tsunami conditions										
	5	10	0		0.05		4.21-7.73		1200		
	6	100			0.05		6.94		600-3600		
	7	100			0.1		4.21-7.73		1200		
	8 100		0		0.1		6.94		600-3600		
	Change of forest width and tsunami conditions										
	9	20			0.226		4.21-7.73		1200		
	10	20			0.226		6.94		600-	-3600	
	11	50			0.226		4.21-7.73		1200		
	12	12 50			0.226		6.94		600-3600		
Table 2 Tsunami height at shoreline (H_{sl0}) , run-up height (R_{H0}) and distance (R_{D0}) in case of no forest $(T = 1200 \text{ s})$	$\overline{H_{i}(m)}$		2	3	4	5	6	6.5	7	8	
	$H_{\rm sl0}({\rm m})$		3.08	4.21	5.19	6.09	6.94	7.34	7.73	8.51	
	$R_{\rm H0}({\rm m})$		2.99	4.08	5.08	5.98	6.88	7.31	7.72	8.48	
	$R_{\rm D0}/10^3$	km)	5.91	1.14	1.64	2.09	2.54	2.75	2.96	3.32	

highest wave among the wave train of a tsunami. Numerical simulations were conducted for twelve series of combined conditions of forest and tsunami as tabulated in Table 1.

5 Results and discussions

5.1 Modeling results and simple formulae

5.1.1 Tsunami height at shoreline, run-up height and distance

The incident tsunami height (H_i) at the generation boundary was random, because the generation boundary may be set at any arbitrary depth. Therefore, the tsunami height (H_{sl0}) above the ground surface at the shoreline, the final run-up height (R_{H0}) above the still water level and the final run-up distance (R_{D0}) from the shoreline in the case of no forest are tabulated in Tables 2 and 3 in order to demonstrate the incident tsunami scale more generally. This means the conditions of the local tsunami were treated as the important factor than the incident wave conditions defined at the generation boundary. In this paper, therefore, H_{sl0} was used instead of H_i and called the incident tsunami height for the simplicity. Note that the suffix 0 indicates the case of no coastal forest.

SIU ···· /									
10×60	20×60	30×60	40×60	50×60	60×60				
6.94	6.94	6.94	6.94	6.94	6.94				
6.01	6.88	7.22	7.36	7.45	7.46				
2.10	2.54	2.71	2.77	2.82	2.83				
	10 × 60 6.94 6.01 2.10	10 × 60 20 × 60 6.94 6.94 6.01 6.88 2.10 2.54	10 × 60 20 × 60 30 × 60 6.94 6.94 6.94 6.01 6.88 7.22 2.10 2.54 2.71	10×60 20×60 30×60 40×60 6.94 6.94 6.94 6.94 6.01 6.88 7.22 7.36 2.10 2.54 2.71 2.77	10×60 20×60 30×60 40×60 50×60 6.94 6.94 6.94 6.94 6.94 6.01 6.88 7.22 7.36 7.45 2.10 2.54 2.71 2.77 2.82				

Table 3 Tsunami height at shoreline (H_{sl0}), run-up height (R_{H0}) and distance (R_{D0}) in case of no forest ($H_{sl0} = 6.94$ m)



Fig. 7 Run-up height ($R_{\rm H}$) and run-up distance ($R_{\rm D}$) against incident tsunami height ($H_{\rm sl0}$)

Figure 7 shows the run-up height and run-up distance against the incident tsunami height H_{sl0} at the shoreline in case of T = 1200 s for both with and without forest condition. The forest condition in this case was width $B_F = 100$ m and density $\gamma = 0.226$ trees/m². The relationship between run-up height and incident tsunami height was almost linear and can be expressed as:

$$R_{\rm H0} = 0.968 H_{\rm sl0}, \quad R_{\rm H} = 0.802 H_{\rm sl0}$$
 (12)

But the relationship between run-up distance and the incident tsunami height was slightly nonlinear due to the change of slope from 1/50 to 1/500 in the run-up zone. The run-up distance is not further discussed.





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Figure 8 shows all simulation results of the run-up height by changing the conditions of tsunami and forest in the non-dimensional form. The run-up height was made dimensionless by $H_{\rm sl0}$, and the abscissa is the non-dimensional forest thickness defined by Eq. (9). The zero of the abscissa corresponds to the case of no forest and the non-dimensional runup height is around 1.0 and it does represent the run-up for the case without vegetation.

The best-fit equation to represent the tendency of all results is given by the following equation:

$$\frac{R_{\rm H}}{H_{\rm s10}} = 0.293 \exp\left(-1032 \frac{B_{\rm dNall}}{T \sqrt{gH_{\rm s10}}}\right) + 0.692$$
(13)

Equation (13) gives about 1.0 for the case of no forest and about 0.7 for the case of infinite non-dimensional forest thickness. The accuracy of proposed equation was not so bad although data were considerably scattered due to variety of conditions. Figure 9 shows the correlation of run-up height by numerical simulations and by the best-fit equation (Eq. 13). It can be noticed that the error is within 10%.



5.1.2 Tsunami forces

Figure 10 shows the time variations of flow depth d, flow velocity V, tsunami force F^* in front of the forest for the case of $B_F = 100$ m, $\gamma = 0.226$ trees/m², $H_{sl0} = 6.94$ m and T = 1200 s. The flow velocity and tsunami force are vectors and, for example, flow velocity can be defined by the following equation in the direction of x-axis in this study:

$$V = \operatorname{sign}(V_x) \left| \vec{V} \right| \tag{14}$$

As shown in Fig. 10, their peak appeared at different time. In particular, the maximum of V appeared early when the flow depth was low, consequently tsunami force was not at its peak. Therefore, representative flow depth and velocity are defined as values at the time of temporal maxima of tsunami force (F_{max}^*). They are denoted as $d_{F*\text{max}}$, $V_{F*\text{max}}$ for F_{max}^* . Those maximum and representative values are as follows:

$$d_{\text{max}} = 5.94 \text{ m}, V_{\text{max}} = 2.64 \text{ m/s}, F_{\text{max}}^* / 10^3 = 9.09 \text{ kN/m}$$

 $d_{F*\text{max}} = 5.80 \text{ m}, V_{F*\text{max}} = 1.76 \text{ m/s}$

The maximum tsunami force F^*_{max} was non-dimensionalized as the following relation:

$$\frac{F_{\text{max}}^*}{\rho g H_{\text{sl0}}^2} \tag{15}$$

where $\rho g H_{sl0}^2$ (unit: N/m) equals two fold of hydrostatic force acting on an imaginary high wall per unit width by flow depth of H_{sl0} . The non-dimensional tsunami forces obtained for the incident tsunami conditions of T = 1200 s and $H_{sl0} = 6.94$ m with different forest conditions of width and tree density (series 1 and 2 in Table 1) and were plotted against the nondimensional forest thickness in Fig. 11. The tree density was kept constant as 0.226 trees/ m² when change in forest width and constant forest width as 100 m when change in density of forest. Tsunami forces behind the forest (point B) and in front of the forest (point A) are simply denoted as $F_{\text{max B}}^*$ and $F_{\text{max A}}^*$, respectively. In front of the forest and behind the forest, non-dimensional tsunami force decreased as the non-dimensional forest thickness increased, with change in forest width and tree density. The best-fit equations of tsunami



Fig. 11 Non-dimensional tsunami force against non-dimensional forest thickness at B (behind the forest) and A (in front of the forest)



force at A and B are given as Eqs. (16 and 17). Those best-fit equations agreed well with the simulation results.

$$\frac{F_{\max A}^{*}}{\rho g H_{sl0}^{2}} = 0.0794 \exp\left\{31.1 \left(\frac{B_{dNall}}{T \sqrt{g H_{sl0}}}\right)^{0.492}\right\}$$
(16)

$$\frac{F_{\max B}^*}{\rho g H_{sl0}^2} = 0.0814 \exp\left\{33.4 \left(\frac{B_{dNall}}{T \sqrt{g H_{sl0}}}\right)\right\}$$
(17)

When the incident tsunami condition varied, however, the formulation was not simple against the non-dimensional forest thickness. Therefore, the curve-fit equation with dimension was considered first. Figure 12a, b shows tsunami forces at two check points (B, behind the forest and A, in front of the forest) and the tsunami force $F^*_{\max 0}$ in the case of no forest against the incident tsunami height and period. The conditions were $B_F = 100$ m, $\gamma = 0.226$ trees/m², T = 1200 s (for varying tsunami height) and $H_{sl0} = 6.94$ m (for varying tsunami period), Table 1. The tsunami force as the incident tsunami height increased. The relationship between the tsunami force and incident tsunami height is non-linear and can be expressed as:

$$F_{\max}^* = a_{\rm Hf} (H_{\rm sl0} - H_{\rm cf})^{b_{\rm Hf}}, \quad H_{\rm sl0} \ge H_{\rm cf}$$
 (18)

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where H_{cf} is the threshold incident tsunami height at which the tsunami force becomes 0 and a_{Hf} has a dimension. In the present study, b_{Hf} was fixed as 2, because it may be logical to assume that tsunami force is proportional to the second power of the inundation depth and that the inundation depth is proportional to $(H_{sl0}-H_{cf})$. H_{cf} was also fixed as 2.5 m in the present study after considering the effect on the result and simplicity. It is a function of forest condition and tsunami period. The empirical constant including the fixed values are as follows:

$$b_{\rm Hf} \equiv 2, H_{\rm cf} \equiv 2.5 \,\mathrm{m}$$

$$a_{\rm Hf} = 1.89 \times 10^3 \,\mathrm{N/m^3} \quad (\text{no forest})$$

$$= 0.592 \times 10^3 \,\mathrm{N/m^3} \quad (\text{at A})$$

$$= 0.363 \times 10^3 \,\mathrm{N/m^3} \quad (\text{at B})$$
(19)

On the other hand, the tsunami force decreased as the tsunami period increased. The relationship between the tsunami force and tsunami period can be given in the form of the following equation:

$$F_{\max}^* = a_{\mathrm{Tf}} \exp\left\{-b_{\mathrm{Tf}} \left(\frac{T}{T_{\mathrm{rep}}} - 1\right)\right\}$$
(20)

where $T_{\rm rep}$ is the representative tsunami period and was taken as 1200 s in this study, and $a_{\rm Tf}$ is a dimensional parameter. The empirical constants of $a_{\rm Tf}$ and $b_{\rm Tf}$ are given in Eq. (21). Both best-fit relations against the incident tsunami height and period agreed well with numerical results.

$$a_{\rm Tf} = 38.4 \times 10^3 \,\text{N/m}, \quad b_{\rm Tf} = 0.590 \,(\text{no forest})$$

$$a_{\rm Tf} = 12.2 \times 10^3 \,\text{N/m}, \quad = 0.526 \,(\text{at A}) \quad (21)$$

$$a_{\rm Tf} = 7.59 \times 10^3 \,\text{N/m}, \quad = 0.400 \,(\text{at B})$$

Equation (9) is rearranged with new parameters as follows.

$$\frac{B_{\rm dNall}}{T_{\rm rep}\sqrt{gH_{\rm rep}}} = \frac{\gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-all}(H_{\rm rep})}{T_{\rm rep}\sqrt{gH_{\rm rep}}}$$
(22)

where corresponds to the length of a long wave with period of T_{rep} and height of H_{rep} . It should be noted, however, that the non-dimensional forest thickness represents the forest condition only, since the tsunami condition is fixed to the representative tsunami condition in Eq. (22). The representative tsunami height H_{rep} and tsunami period T_{rep} were taken as 7 m and 1200 s, respectively, in the present study. The tsunami force F_{max}^* was made dimensionless by the following relationship in consideration of the curve-fitting Eqs. (18 and 20) as:

$$\frac{F_{\max}^{*}}{\rho g H_{sl0}^{2}} = \frac{a_{f} (H_{sl0} - H_{cf})^{b_{Hf}} \exp\left\{-b_{Tf} (T/T_{rep} - 1)\right\}}{\rho g H_{sl0}^{2}} \frac{F_{\max rep}^{*}}{a_{f} (H_{rep} - H_{cf})^{b_{Hf}}}$$
(23)
= $\alpha_{f} f_{Hf} f_{Tf}$

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 $F_{\text{max rep}}^*$ is the representative tsunami force by an incident tsunami with the representative height H_{rep} and arbitrary period *T*. α_{f} , f_{Hf} and f_{Tf} are non-dimensional and expressed as follows:

$$\alpha_{\rm f} = \frac{F_{\rm max\,rep}^*}{\rho g H_{\rm rep}^2} = \frac{F_{\rm max}^*}{f_{\rm Hf} f_{\rm Tf} \rho g H_{\rm sl0}^2} \tag{24}$$

$$f_{\rm Hf} = \left(\frac{1 - H_{\rm cf}/H_{\rm sl0}}{1 - H_{\rm cf}/H_{\rm rep}}\right)^{b_{\rm Hf}} = 2.42 \left(1 - \frac{2.5}{H_{\rm sl0}}\right)^2 \tag{25}$$

$$f_{\rm Tf} = \exp\left\{-b_{\rm Tf}\left(\frac{T}{T_{\rm rep}} - 1\right)\right\}$$
(26)

The empirical constant of b_{Tf} at B (behind the forest) and A (in front of the forest) is

$$b_{\rm Tf} = 0.526 \text{ (at A)}$$

= 0.400 (at B) (27)

All simulated results of non-dimensional value of α_f of Eq. (24) against the non-dimensional forest thickness of Eq. (22) are shown in Fig. 13. f_{Hf} and f_{Tf} are modification factors so that the non-dimensional tsunami force is normalized to the non-dimensional tsunami force due to the incident tsunami with the representative height of H_{rep} . The α_f is called the normalized tsunami force. The best-fit curves for data in Fig. 13 are given as:

$$\alpha_{\rm f} = 0.0794 \exp\left(-0.0311 \times 10^3 \left[\frac{\gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-all}(H_{\rm rep})}{T_{\rm rep} \sqrt{g H_{\rm rep}}}\right]^{0.492}\right), \text{ at A}$$

$$= 0.0139 + 0.0678 \exp\left(-4.05 \times 10^3 \frac{\gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-all}(H_{\rm rep})}{T \sqrt{g H_{\rm rep}}}\right), \text{ at B}$$
(28)



Fig. 13 Non-dimensional tsunami force against non-dimensional forest thickness at B (behind the forest) and A (in front of the forest)

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(series 1–12 in Table 1)



Equation (28) represents the average relationship of the non-dimensional tsunami force against non-dimensional forest thickness fairly well although the data are considerably scattered due to a number of variables in the problem.

Figure 14 shows the comparison between tsunami forces estimated by Eq. (28) and obtained by numerical simulations. The agreement is acceptable. The error was within 10%.

At this moment there is no data from field that can be used for validation of best-fit equations, in particular, the tsunami height and period at the shoreline, and the tsunami force. However, although the coastal tree was not *Pandanus*, the pine trees in Japan were affected by the 2011 Japanese tsunami. The trees were destroyed but mitigated the tsunami (Tanaka et al. 2014). The numerical model (Eqs. 1–7) in this study, the source for these best-fit equations, was used to simulate tsunami flow depth and inundation area (Tanaka et al. 2014). The model worked well for reproducing the tsunami flow depth and inundation and as well as damaged area of the forest (Tanaka and Onai 2016).

The curve-fitting equations developed herein may be used to calculate tsunami run-up and tsunami forces both in front of forest, this is important to determine damage to forest, and behind the forest, this is useful to determine damage to houses or infrastructures against a design tsunami condition when proposing bio-shield concept to protect from the tsunami. These calculations are simple compared to advance numerical modeling saving time and cost effective. Such first-hand information is pertinent for preliminary decision making in pilot projects of tsunami mitigation from bio-shields prior to a detailed analysis. Calculation steps for a case study are given in "Appendix".

6 Summary and conclusions

Laboratory experiments were conducted to validate a numerical model based on onedimensional nonlinear long-wave equations including resistance of trees (drag and inertia) on fluid flow and porosity between trees. The water surface elevation and flow velocity by the numerical simulations agree well with the experimental results for various forest conditions of width and tree density. Then the numerical model was applied to simulate prototype conditions of coastal vegetation against tsunamis. *P. odoratissimus* was considered as the potential tree type and numerical simulations were carried out to investigate the effects of forest characteristics (width and tree density) and incident tsunami conditions (period and height) on potential tsunami force (simply called tsunami force). As a useful information, the run-up height was also investigated. These parameters were mostly discussed in non-dimensional forms with best-fit equations. The aim of proposing these best-fit equations is to form a set of simplified formulae for designing a coastal forest against tsunamis. The curve-fit equations agree well with the modeling results for most of the cases with the error of about 10%.

In this study, uniform distribution of *P. odoratissimus* in the forest has been considered. However, this is not the case for actual forests and even for planted forests that may be changed with the growth stage. Further tree breaking was not considered. To investigate the effects of non-uniform distribution of trees at various growth stages and tree breaking on the tsunami force is an exciting subject to be considered in future. Moreover, the real conditions of tsunami wave and topography should be studied in future.

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Appendix

Calculations of run-up height and tsunami force for tsunami height at shore $H_{s10} = 6.5$ m, tsunami period T = 1800 s, forest width = 100 m, tree density $\gamma = 0.226$ trees/m².

Constant parameters:

Gravitational acceleration = 9.81 m/s^2 Density of sea water = 1029 kg/m^3 $T_{\text{rep}} = 1200 \text{ s}, H_{\text{rep}} = 7 \text{ m}, b_{\text{ref}}^* = b_{\text{ref}} = 0.195 \text{ m}, b_{\text{TF}} = 0.526 \text{ (at A)}; = 0.4 \text{ (at B)}$ $C_{\text{D-all}(\text{Hrep})} = 2.66$

(a) For run-up height

Step 1: Estimate $C_{\text{D-all}}$ from Fig. 6b based on the tsunami height H_{sl0} Step 2:

$$B_{\rm dNall} = \gamma (1 \times B_F) b_{\rm ref} C_{\rm D-all} = \gamma B_F b_{\rm ref}^* C_{\rm D-all}$$

Step 3: Run-up height

$$R_{\rm H} = H_{\rm sl0} \left[0.293 \exp\left(-1032 \frac{B_{\rm dNall}}{T \sqrt{gH_{\rm rep}}}\right) + 0.692 \right]$$

Solution

Case number	Tsunami height at shore line H _{sl0} (m)	Tsunami period T (s)	Forest width $B_{\rm F}$ (<i>m</i>)	Tree density γ (trees/m ²)	Drag coefficient $C_{\text{D-all}}(H_{\text{sl0}})$	$\frac{B_{\rm dNall}}{b_{\rm ref}} \frac{(\gamma B_{\rm F}}{C_{\rm D-all}})$	Run-up height <i>R</i> _H (m)
1	6.5	1800	100	0.226	2.56	11.3	5.3

Case number	Tsunami height at shore line H _{sl0} (m)	Tsunami period T (s)	Forest width $B_{\rm F}$ (m)	Tree density γ (trees/m ²)	Drag coefficient $C_{\text{D-all}}(H_{\text{sl0}})$	$\begin{array}{l} B_{\rm dNall} \left(\gamma B_{\rm F} \\ b_{\rm ref} \ C_{\rm D-all} \right) \end{array}$	Run-up height $R_{\rm H}$ (m)
2	6.5	1800	0 (no for- est)	0	0	0	6.4

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(b) For tsunami force

Step 1:

$$f_{\rm Hf} = 2.42 \left(1 - \frac{2.5}{H_{\rm sl0}} \right)^2; \quad f_{\rm Tf} = \exp\left\{ -b_{\rm Tf} \left(\frac{T}{T_{\rm rep}} - 1 \right) \right\}$$

Step 2:

Solution

$$\begin{aligned} \alpha_{\rm f} &= 0.0794 \exp\left(-0.0311 \times 10^3 \left[\frac{\gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-all}(H_{\rm rep})}{T_{\rm rep} \sqrt{g H_{\rm rep}}}\right]^{0.492}\right), \quad \text{at A} \\ &= 0.0139 + 0.0678 \exp\left(-4.05 \times 10^3 \frac{\gamma B_{\rm F} b_{\rm ref}^* C_{\rm D-all}(H_{\rm rep})}{T \sqrt{g H_{\rm rep}}}\right), \quad \text{at B} \end{aligned}$$

Step 3: Tsunami force at A and B

$$F^*_{\text{max}} = \alpha_{\text{fA}} f_{\text{Hf}} f_{\text{Tf}} \rho g H_{H\text{sl0}} \quad \text{at A}$$
$$= \alpha_{\text{fB}} f_{\text{Hf}} f_{\text{Tf}} \rho g H_{H\text{sl0}} \quad \text{at B}$$

Case Tsunami Tsunami Forest Tree Tsunami Tsunami $f_{\rm Tf}$ $f_{\rm Hf}$ number height at period width $B_{\rm F}$ force at A force at B density shore line T (s) (m) γ (trees/ (kN/m)(kN/m) $H_{\rm sl0}$ (m) m^2) 1 6.5 1800 100 0.226 0.92 0.77 (at 7.7 4.6 A) 0.82 (at B) 2 6.5 1800 0 (no for-0 0.92 0.82 26.1 est)

References

Chakrabati SK (1991) Wave force on offshore structures. In: Herbich JB (ed) Handbook of coastal and ocean engineering, vol 2. Gulf Publishing Company, Houston, pp 1–54

Danielsen F, Sorensen MK, Olwig MF et al (2005) The Asian tsunami: a protective role for coastal vegetation. Science 310:643

Imamura F, Goto K, Ohkubo S (2008) A numerical model of the transport of a boulder by tsunami. J Geophys Res 113:C01008

- Kathiresan K, Rajendran N (2005) Coastal mangrove forests mitigated tsunami. Estuar Coast Shelf Sci 65:601–606
- Kerr AM, Baird HB (2007) Natural barriers to natural disasters. Bioscience 57(2):102-103
- Mascarenhas A, Jayakumar S (2008) An environmental perspective of the post-tsunami scenario along the coast of Tamil Nadu, India: role of sand dunes and forests. J Environ Manag 89:24–34
- Nandasena NAK, Tanaka N, Tanimoto K (2008) Tsunami current inundation of ground with coastal vegetation effects; an initial step towards a natural solution for tsunami amelioration. J Earthq Tsunami 2(2):157–171
- Nandasena NAK, Sasaki Y, Tanaka N (2012) Modeling field observations of the 2011 Great East Japan tsunami: efficacy of artificial and natural structures on tsunami mitigation. Coast Eng 67:1–13
- Nepf HM (1999) Drag, turbulence, and diffusion in flow through emergent vegetation. Water Resour Res 35(2):479–489
- Shuto N (1987) The effectiveness and limit of tsunami control forests. Coast Eng Jpn 30(1):143-153
- Tanaka N (2009) Vegetation bioshields for tsunami mitigation: review of the effectiveness, limitations, construction, and sustainable management. Landsc Ecol Eng 5:71–79
- Tanaka N, Onai A (2016) Mitigation of destructive fluid force on buildings due to trapping of floating debris by coastal forest during the Great East Japan tsunami. Landsc Ecol Eng 13:131–144
- Tanaka N, Sasaki Y, Mowjood MIM, Jinadasa KBSN (2007) Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. Landsc Ecol Eng 3:33–45
- Tanaka N, Nandasena NAK, Jinadasa KSBN, Sasaki Y, Tanimoto K, Mowjood MIM (2009) Developing effective vegetation bioshield for tsunami protection. J Civ Environ Eng Syst 26:163–180
- Tanaka N, Yasuda S, Iimura K, Yagisawa J (2014) Combined effects of coastal forest and sea embankment on reducing the washout region of houses in the Great East Japan tsunami. J Hydro-Environ Res 8:270–280
- Tanimoto K, Tanaka N, Nandasena NAK, Iimura K, Shimizu T (2007) Numerical simulation of tsunami prevention by coastal forest with several species of tropical tree. Annu J Coast Eng 54(2):1381–1385 (in Japanese)
- Thuy NB, Tanimoto K, Tanaka N, Harada K, Iimura K (2009a) Effect of open gap in coastal forest on tsunami run-up—investigations by experiment and numerical simulation. Ocean Eng 36:1258–1269
- Thuy NB, Tanaka N, Tanimoto K, Harada K, Iimura K (2009b) Tsunami flow behind the coastal forest with an open gap-effects of tsunami and tree condition. In: Proceedings of the 6th international conference on coastal dynamic, Tokyo-Japan (CD-Rom). https://doi.org/10.1142/9789814282475_0050
- Thuy NB, Tanimoto K, Tanaka N (2010) Flow and potential force due to runup tsunami around a coastal forest with a gap—experiments and numerical simulations. Int J Sci Tsunami Hazards 29:43–69
- Thuy NB, Tanaka N, Tanimoto K (2012) Tsunami mitigation by coastal vegetation considering the effect of tree breaking. J Coast Conserv 16:111–121. https://doi.org/10.1007/s11852-011-0179-7
- Thuy NB, Nandasena NAK, Dang VH, Kim S, Hien NX, Hole LR, Thai TH (2017) Effect of river vegetation with timber piling on ship wave attenuation: investigation by field survey and numerical modeling. Ocean Eng 129:37–45