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Review

Coastal forest effects on tsunami run-up heights

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ABSTRACT

An experimental study was carried out to determine the effects of a coastal forest on tsunami run-up heights. The beach was built as a natural sandy beach at laboratory scale. The coastal forest model was constructed using artificial trees (FM–I) and cylindrical timber sticks (FM–II). Artificial trees were placed on a 1:5 slope in three different layouts: rectilinear, staggered, and dense rectilinear. It was shown that in the case when the trees were placed in the dense rectilinear pattern and close to the still water level (SWL), the run-up height was reduced by approximately 45% compared with the case without trees. After evaluation of the experimental results, the parameters that affect the run-up height were determined. These parameters were written as a dimensionless group using Buckingham's Pi theorem. An extensive regression analysis was carried out and equations proposed. Furthermore, all experiments were repeated with a slope of 1:3.5 to verify the proposed equations. The experimental results were compared with the results of the proposed equations, and it was shown a good agreement between the results.

Contents

1. Introduction

Tsunamis have caused great impacts on human life and coastal environments, including massive loss of human life, devastation of coastal ecosystems and settlements, and damage to infrastructure and facilities. Minimizing the impact of tsunamis on coastal regions is an important issue in coastal engineering.

There is no doubt that tsunami damage occurs mostly in the near-shore zone and in the coastal area behind the coastline, because of the tsunami hydrodynamics during the run-up period. Run-up heights are significant parameters for the design of coastal structures. Various analytical solutions for the run-up of nonlinear waves on plane slopes were given by Pedersen and Gjevik (1983), Synolakis (1987), Synolakis and Skjelbreia (1993), Kanoglu and Synolakis (1998), Liu et al. (1991), Maiti and Sen (1999) and

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Carrier et al. (2003). Experimental data on the run-up of solitary waves were given by Pedersen and Gjevik (1983), Synolakis (1987), Teng et al. (2000), Shankar and Jayaratne (2003) and Gedik et al. (2005), among others. Tsunami run-up heights depend strongly on coastal morphology and land use configuration, including vegetation. That is why, in the last decade, there has been a growing interest in studies that attempt to understand the impact of vegetation on tsunamis. Researchers and engineers consider that vegetation may strengthen coasts against tsunami attack by increasing the resistance force. Some studies related to coastal vegetation are summarized below.

Hiraishi and Harada (2003) proposed a greenbelt barrier, instead of hard systems like breakwaters, because of its lower cost for tsunami protection. They carried out two-dimensional experiments in a tsunami channel to evaluate the tsunami reduction effect. To reproduce the coastal forest in the experimental channel, Hiraishi and Harada (2003) used a chemical porous medium. Their experimental results showed that the greenbelt had a reduction effect similar to that of coastal dikes composed of wave energy dissipating blocks. In addition, they carried out a numerical simulation with a nonlinear long wave model with drag force terms to study the applicability of a greenbelt in a natural topography, using 1998 Papua New Guinea tsunami data. Hiraishi and Harada (2003) found that the maximum tsunami run-up height on shore was smaller in the presence of a greenbelt than when there was no protection. Their numerical model results showed that a greenbelt with specified tropical trees can be used as a sustainable tsunami damage-prevention method in the South Pacific region. Struve et al. (2003) investigated the additional resistance created by mangrove model trees through physical model experiments in a hydraulic flume and with two-dimensional depth-integrated numerical modeling. Their results suggest that the drag coefficient may increase with increasing tree surface, but that more data would be required to confirm this relationship. The study by Kathiresan and Rajendran (2005) on 18 coastal hamlets along the southeast coast of India, conducted after the December 26th, 2004, tsunami, reiterates the importance of coastal mangrove vegetation and the location characteristics of human inhabitations in protecting life and property from the fury of tsunamis. According to this study, tsunami damage depends on the area occupied by coastal vegetation and on the distance and elevation of human inhabitations from the sea. Moreover, they suggested some suitable plant species to cultivate for coastal protection between human inhabitations and the sea. Hiraishi (2005) carried out a field survey after the same tsunami (Indian Earthquake Tsunami) to investigate the effect of a greenbelt on the Thailand coast. In this study, the greenbelt tsunami prevention technique was discussed, and the applicability of a greenbelt was demonstrated numerically for the model coast. It was also pointed out that the stabilization of sandy beaches was another positive impact of a greenbelt for tsunami disaster mitigation. According to the model results, the eroded volume at a beach with some vegetation was smaller than at a beach without vegetation. Kongko (2005) presented an overview of the effectiveness of mangroves in reducing tsunamis and provided evidence of the effectiveness of coastal forest against tsunamis. It was noted that mangroves and casuarina plantations attenuated tsunami-induced waves and protected shorelines against damage. The research of Danielsen et al. (2005) in the Cuddalore District, Tamil Nadu, India determined that mangroves and casuarina plantations attenuated tsunami-induced waves and protected shorelines against damage. Harada and Imamura (2005) quantitatively evaluated the hydrodynamic effects and damage-prevention functions of coastal forests against tsunamis with a view to using them as tsunami countermeasures. They also performed numerical simulations, including an evaluation of the quantitative effects of coastal forests in controlling tsunami reduction and damage. They found that an increase in forest width can reduce not only inundation depth, but also the currents and hydraulic forces behind the coastal forest. Nandasena and Tanaka (2007) analyzed two different coastal species, *Pandanus odoratissimus* and *Cocos nucifera*, which are dominant in Sri Lanka. They used numerical studies to understand the hydrodynamic behavior of these species in the case of a tsunami event. Coastal vegetation is an economically viable countermeasure, especially for developing countries, like Sri Lanka, and also has additional advantages such as enhancing the environment, minimizing local erosion by wave attack, and enhancing biodiversity. Moreover, coastal vegetation helps to develop sand dunes in front of the forest by trapping sand carried by the wind, which plays a significant role in reducing tsunami energy. Tanaka et al. (2007) studied the effects of coastal vegetation on tsunami damage based on field observations carried out after the Indian Ocean tsunami on December 26th, 2004. The study area is located on the southern coast of Sri Lanka and on the Andaman coast of Thailand. The vegetation was classified into six types according to habitat and distant tree structures. The impact of vegetation structure on drag forces was analyzed.

Vegetation effects on tsunami run-up height were not investigated in the studies mentioned earlier. In the present study, experiments were carried out in a laboratory flume to determine coastal vegetation effects on tsunami run-up heights. In these experiments, natural sand, artificial trees, and cylindrical timber sticks were used. The coastal forest model, which consisted of artificial pine trees, was called FM–I, and the model that consisted of solid cylindrical timber sticks was called FM-II. From the experimental results, the parameters that affect the run-up height were determined. The parameters were determined that affect the run-up height from the experimental results. These terms were written as a dimensionless group using Buckingham's Pi theorem. An extensive regression analysis was then carried out, and empirical equations were developed. The experimental results and the results obtained from the proposed equations were compared, and found to be in good agreement.

2. Materials and methods

2.1. Experimental design

The experiments were carried out in a glass-walled wave channel 22.5 m in length, 1.00 m in width, and 0.50 m in depth at the Hydraulics Laboratory, Faculty of Civil Engineering, Istanbul Technical University, Istanbul, Turkey. The beach was built as a natural sandy beach with a grain diameter of 0.35 mm and a specific gravity of 2.63. The slope of the beach was 1:5, as shown in Fig. 1, where R is the wave run-up height, d is the water depth, H is the wave height, and β is the angle of inclination of the plane beach. The tsunami generation mechanism consists of a piston, a PHS16B bearing, and a horizontal plate ($0.97 \times 2.00 \times 0.002$ m).

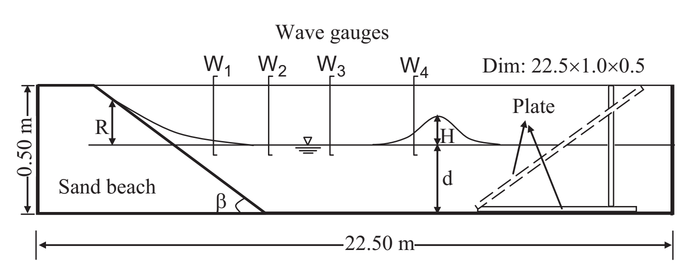

Fig. 1. Experimental set up.

The piston was a pneumatic cylinder driven by a manually controlled system. As the piston moves vertically, the plate lifts off and displaces the adjacent fluid, thereby generating long waves (Gedik et al., 2005, 2006).

The water surface elevations were measured by resistance-type wave gauges. Wave gauge W1 was installed on the sloping beach, and the other wave gauges were installed between the toe of the beach slope and the center of the wave channel. Data collection and processing were carried out using a personal computer with an A-D converter. All the wave gauges were calibrated before the experiments to ensure the accuracy of measurements. The maximum run-up height of the tsunami wave was measured both manually and using a video camera. Furthermore, all experiments were repeated at slope 1:3.5 for verification.

2.2. *Experiments*

2.2.1. *FM-I*

FM-I was built using with artificial pine trees approximately 4.6 cm in diameter and 9 cm in height (Fig. 2). Artificial trees were placed on the slope in three different layouts: rectilinear (Case I), staggered (Case II), and dense rectilinear (Case III). Plans and geometric characteristics concerning these cases are shown in Fig. 3.

In Fig. 3, c indicates the distance of the coastal forest model from the SWL, l_x is the horizontal distance between trees, l_y is the perpendicular distance between trees, e is the diameter of the trees, L_x is the width of the coastal forest model, and L_y is the length of the forest perpendicular to the coastline of the model.

2.2.2. *FM-II*

To investigate the effect of tree leaves on the run-up height, solid cylindrical timber sticks 1 cm in diameter, 9 cm in height, and equivalent to the volume of the artificial trees (Fig. 4) were used to construct a second model (FM-II). Two patterns of sticks were used rectilinear and staggered.

The models with rectilinear and staggered cylindrical timber sticks are referred to as Case IV and Case V, respectively. Plans and geometric characteristics concerning these cases are shown in Fig. 5. Table 1 summarizes the results for all cases.

Fig. 2. Artificial trees used in the model.

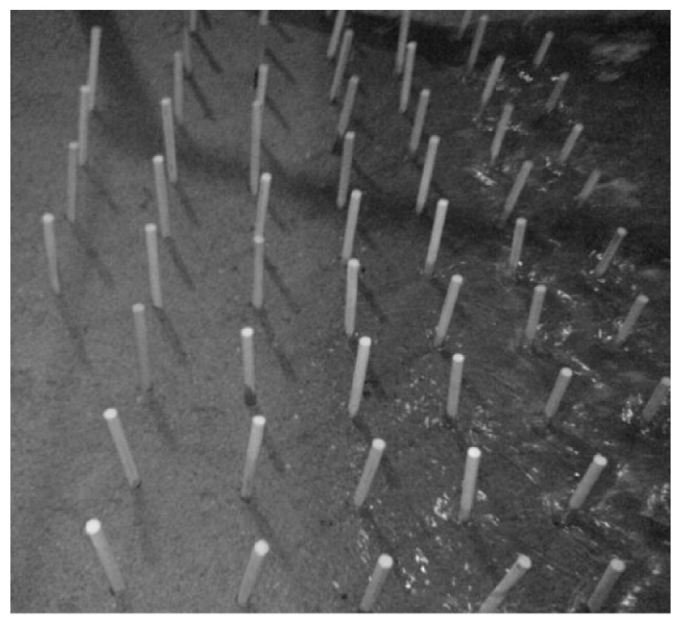

Fig. 4. Cylindrical timber sticks used in the FM–II model.

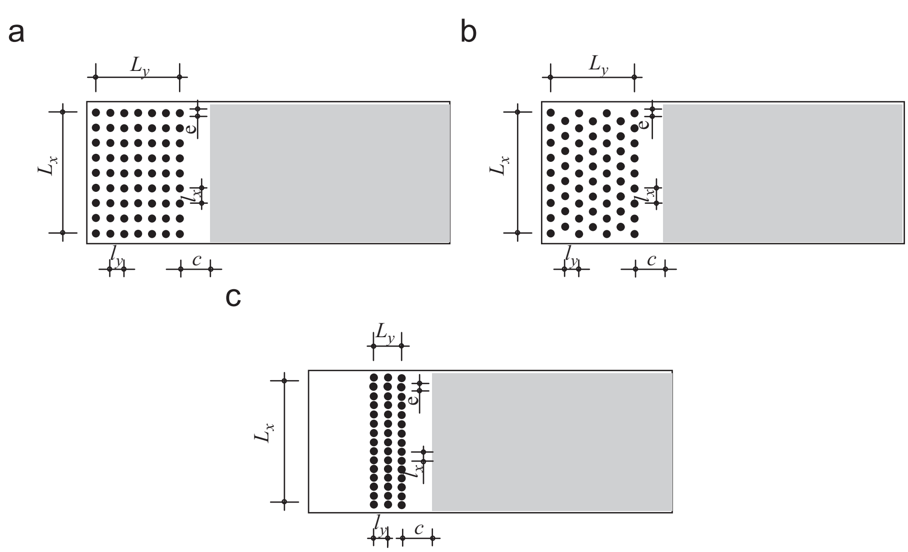

Fig. 3. Plans and geometric characteristics: (a) Case I, (b) Case II, and (c) Case III.

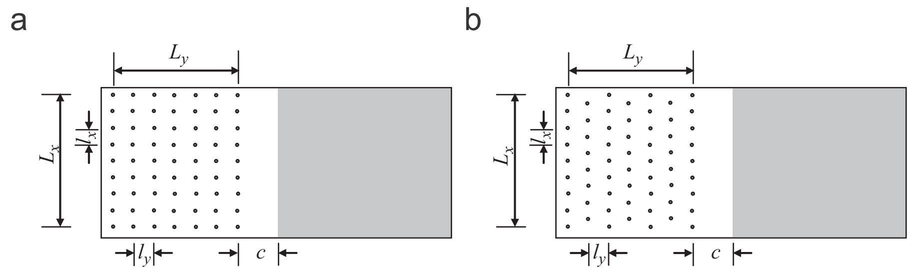

Fig. 5. Plans and geometric characteristics: (a) Case IV and (b) Case V.

Table 1
Summary of all cases for the coastal forest model.

	Layouts of artificial pine trees (FM-I)	Layouts of cylindrical timber sticks (FM-II)
Case I	Rectilinear	–
Case II	Staggered	–
Case III	Dense rectilinear	–
Case IV	–	Rectilinear
Case V	–	Staggered

3. Results and discussion

3.1. Run-up height for different cases

Variations of run-up height with wave height in FM–I and FM–II with distance from the SWL and without tree cases for slopes 1:5 and 1:3.5 are shown in Figs. 6 and 7. These figures show a variation of run-up height with wave height and in all cases R increases with increasing wave height.

Variations in the run-up height with wave height for the cylindrical timber sticks (Cases IV and V) with distance from the SWL are shown in Fig. 8. Comparisons of Cases I and IV and Cases II and V are shown in Figs. 9 and 10 to investigate the effect of leaves.

The extents of reduction of run-up height for the different cases are given in Table 2. For example, run-up height for the staggered trees (Case II, $c = 10\,\text{cm}$) was decreased by 26% compared with the case of rectilinear trees (Case I, $c = 20\,\text{cm}$).

The significant results which were obtained from Table 2 and Figs. 6–10 can be summarized as follows:

- For reducing run-up height, the most effective layout was Case III with dense rectilinear trees, in which the trees behaved as a barrier, and the trees close to SWL were more effective. The Case III model reduced the run-up height by approximately 45% compared with the case without trees (Table 2).
- Furthermore, Case II was more effective than Case I in reducing the run-up height, except for Case I ($c = 10\,\text{cm}$) compared with Case II ($c = 20\,\text{cm}$). A similar station can be observed in the comparison of Case II ($c = 10\,\text{cm}$) with Case III ($c = 20\,\text{cm}$). In these cases, distance from the SWL is more effective than the layout of the trees (Table 2).
- The run-up heights decreased in Case III, Case II, and Case I compared with the case without trees. In each case, when the FM-I was close to the SWL, the run-up height was reduced (Table 2 and Fig. 6.).
- When the cylindrical timber sticks were placed in the staggered pattern, run-up heights decreased by 9% compared with the rectilinear layout (Table 2 and Fig. 7).
- In FM-II, distance from the SWL did not affect the run-up height in the rectilinear and staggered layouts (Fig. 8). However, in FM-I, distance from the SWL reduced the run-up height (Fig. 6). The reason for these results is considered to be the porosity of the trees.
- When $c = 10\,\text{cm}$ and when Case I and Case IV were compared, the run-up height in Case I decreased by 15% compared with Case IV (Table 2 and Fig. 9b).

In summary, when the trees were placed in the dense rectilinear layout and close to the SWL, the maximum reduction in run-up heights was achieved.

3.2. Dimensionless parameters

When determining the run-up height, the following parameters were added to the parameters given in the previous sections. The sand density (γ_s) and grain diameter (D) were used to define the beach characteristics. Water density (γ_w) and gravitational acceleration (g) were used as parameters of the medium. The number of trees per unit area (ϕ) was obtained from Eq. (1)

$$\phi = \frac{N}{L_x L_y} \tag{1}$$

where N is the total number of trees, L_x is the width of the forest parallel to the beach, and L_y is the length of the forest perpendicular to the beach.

All these parameters were combined into a function as follows:

$$f(R, H, D, d, \gamma_s, \gamma_w, \beta, g, c, l_w, l_y, e, H_{veg}, \phi, V_{veg}) = 0 \tag{2}$$

The parameters of Eq. (2) were expressed in terms of dimensionless parameters using Buckingham's Pi theorem. The result is the function given in Eq. (3):

$$f(R/d, H/d, D/d, G_{sb}, \cot\beta, c/d, l_x/d, l_y/d, e/d, H_{veg}/d, d^2\phi, V_{veg}/d^3) = 0 \tag{3}$$

where, H/d is dimensionless wave height, $G_{sb} = \gamma_s/\gamma_w$ is the specific gravity of sand, $\cot\beta$ is the slope, D/d is a dimensionless grain diameter, R/d is a dimensionless run-up height parameters, c/d is a dimensionless distance from the SWL, l_x/d is a dimensionless horizontal distance between trees, l_y/d is a dimensionless perpendicular distance between trees, e/d is a dimensionless tree diameter, H_{veg}/d is a dimensionless tree height, $d^2\phi$ is a dimensionless number of trees per unit area, and V_{veg}/d^3 is a dimensionless tree volume.

3.3. Prediction of run-up height

3.3.1. Prediction of run-up height for FM-I

Considering the experimental data, observations, and previous studies, the following parameters can be identified

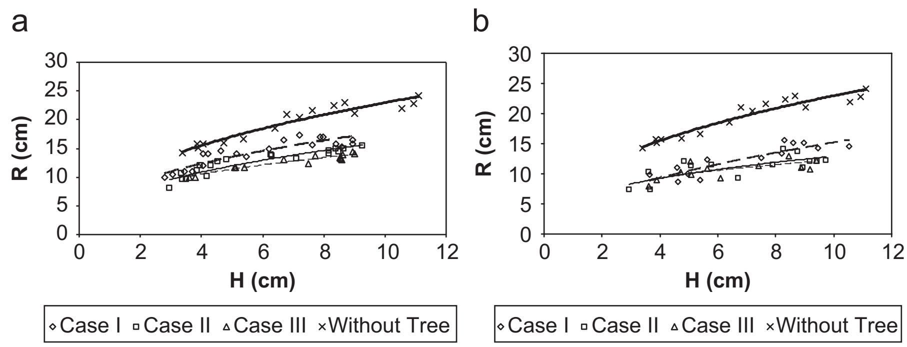

Fig. 6. Variation of R with H for FM–I: (a) $c = 20$ cm and (b) $c = 10$ cm.

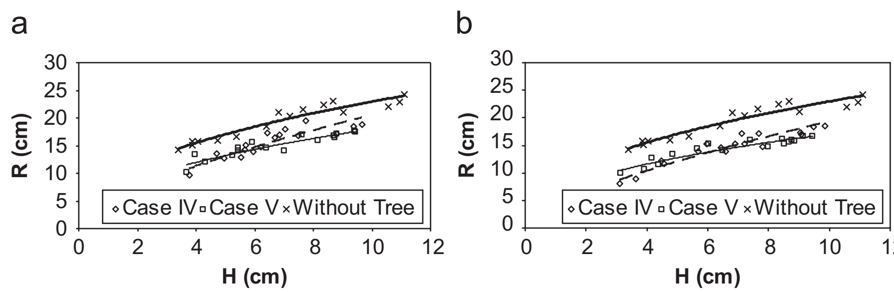

Fig. 7. Variation of R with H in FM–II: (a) $c = 20$ cm and (b) $c = 10$ cm.

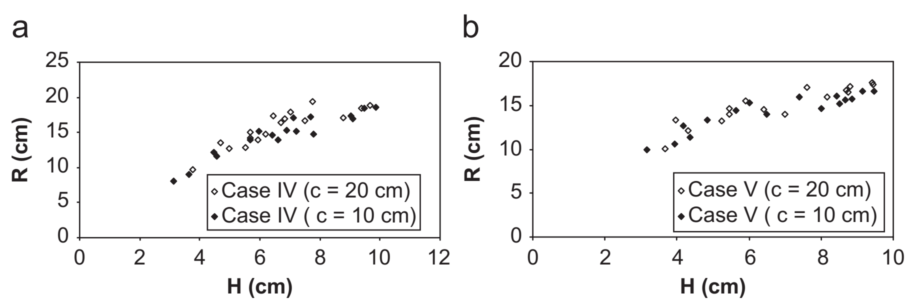

Fig. 8. Variation of R with H in FM–II: (a) Case IV and (b) Case V.

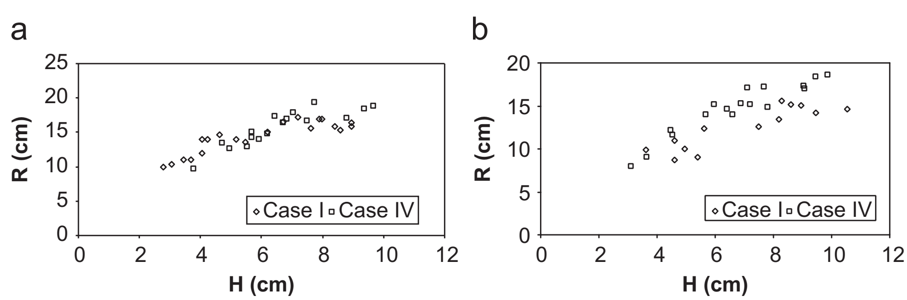

Fig. 9. Comparison of the Case I with Case IV: (a) $c = 20$ cm and (b) $c = 10$ cm.

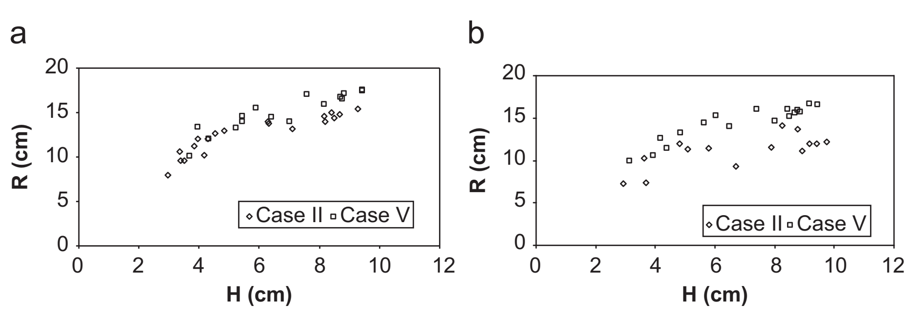

Fig. 10. Comparison of the Case II with Case V: (a) $c = 20$ cm and (b) $c = 10$ cm.

as affecting run-up height. Run-up height increases with increase in wave height. It has been noted that run-up height decreases with increase in slope, grain diameter, water depth in front of the beach, tree height, number of tree unit area, and tree volume. Furthermore, it has been observed that run-up height increase with increasing distance from SWL, horizontal distance between trees, perpendicular distance between trees, and the specific gravity of sand.

A general parameter including all dimensionless terms pertaining to FM-I was called *par*1: this parameter was given by Eq. (4):

$$par1 = \frac{HG_{sb}(\cot\beta)^{a}c(l_x - e)(l_y - e)}{H_{veg}DV_{veg}\phi d} \quad (4)$$

where

$$a = \frac{5}{\cot\beta} \quad (5)$$

For Cases I, II, and III, the variation of run-up height with *par*1 is shown in Fig. 11. In each case, as *par*1 increases, the dimensionless run-up height increases.

Table 2
Extents of reduction of run-up height for different cases.

Cases	c (cm)	Without tree	Case I		Case II		Case III		Case IV		Case V	
			c (cm)		c (cm)		c (cm)		c (cm)		c (cm)	
			10	20	10	20	10	20	10	20	10	20
Case I	10	0.37	–	–	–	0.11	–	–	0.15	0.21	0.16	0.18
	20	0.21	–	–	–	–	–	–	0.01	0.06	0.05	~0
Case II	10	0.42	0.08	0.26	–	–	–	0.11	0.23	0.27	0.22	0.25
	20	0.30	–	0.11	–	–	–	–	0.10	0.12	0.06	0.10
Case III	10	0.45	0.10	0.28	0.02	0.19	–	–	0.23	0.29	0.24	0.27
	20	0.35	0.03	0.17	–	0.07	–	–	0.15	0.18	0.13	0.16
Case IV	10	0.25	–	–	–	–	–	–	–	–	–	–
	20	0.19	–	–	–	–	–	–	–	–	–	–
Case V	10	0.25	–	–	–	–	–	–	0.06	0.09	–	–
	20	0.22	–	–	–	–	–	–	0.03	0.06	–	–

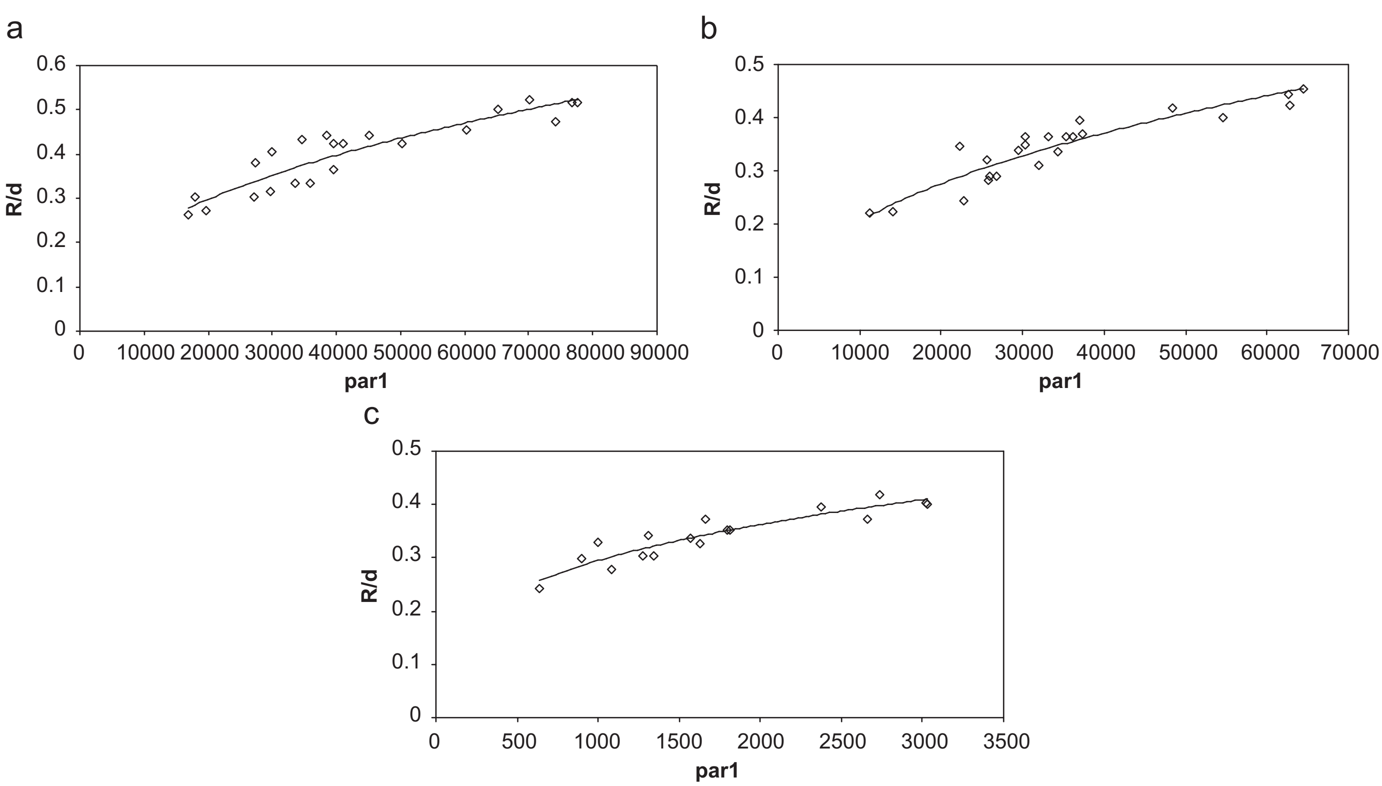

Fig. 11. Variation of R/d with *par*1 in FM–I: (a) Case I, (b) Case II, and (c) Case III.

The empirical equations, obtained by regression analyses are given as follows. Eqs. (6)–(8) were proposed to determine R/d. The correlation coefficients for these equations are 0.902, 0.920, and 0.930, respectively.

$$\frac{R}{d} = 0.0048(par1)^{0.4158} \quad \text{for case I} \tag{6}$$

$$\frac{R}{d} = 0.004(par1)^{0.4273} \quad \text{for case II} \tag{7}$$

$$\frac{R}{d} = 0.0376(par1)^{0.2984} \quad \text{for case III} \tag{8}$$

3.3.2. Prediction of run-up height for FM-II

*Par*2, which includes all dimensionless terms pertaining to FM-II, is given by Eq. (9)

$$par2 = \frac{HG_{sb}(\cot\beta)^{a}c^{0.1}(l_x - e)(l_y - e)}{H_{veg}DV_{veg}\phi d^{0.1}} \tag{9}$$

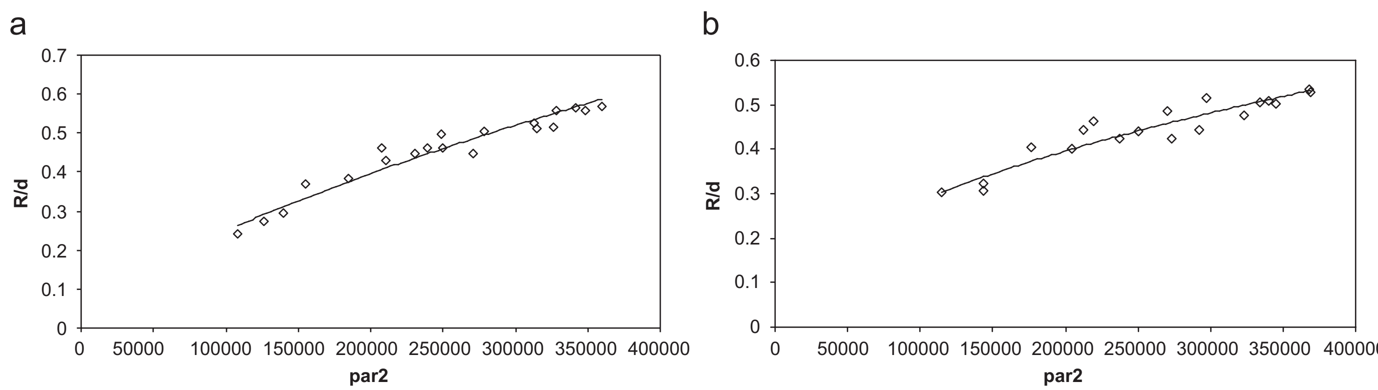

Fig. 12. Variation of R/d with *par*2 in FM–II: (a) Case IV and (b) Case V.

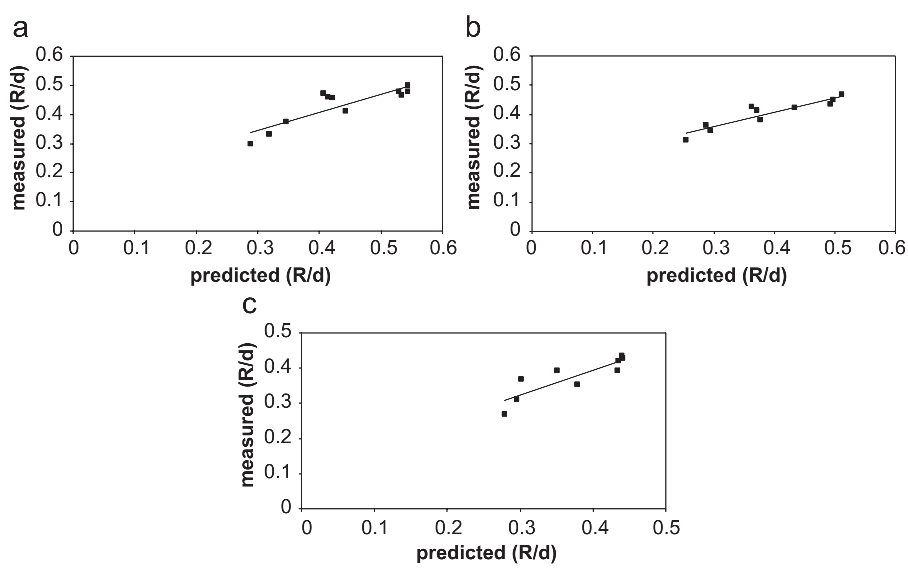

Fig. 13. Comparison of measured with predicted dimensionless run-up height in FM–I: (a) Case I, (b) Case II, and (c) Case III.

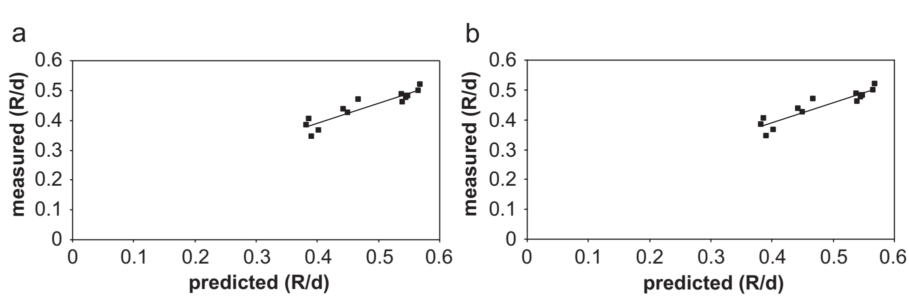

Fig. 14. Comparison of measured with predicted dimensionless run-up height in FM–II: (a) Case IV and (b) Case V.

For Cases IV and V, variations of run-up height with *par*2 are shown in Fig. 12. In both cases, when *par*2 is increased, the dimensionless run-up height increased.

For both cases, the empirical equations obtained by regression analysis are given below. Eqs. (10) and (11) were proposed to determine R/d. The correlation coefficients of the equations are 0.97 and 0.94, respectively.

$$\frac{R}{d} = 0.0001(par2)^{0.6701} \quad \text{for case IV} \tag{10}$$

$$\frac{R}{d} = 0.0011(par2)^{0.483} \quad \text{for case V} \tag{11}$$

3.4. Verification of the proposed empirical equations

The experiments were repeated at slope 1:3.5 for verification. The additional results are presented in Figs. 13 and 14. R/d values obtained using the proposed equations (Eqs. (6)–(11) with a slope of 1:5 were compared with the R/d values computed from additional experimental data (slope 1:3.5) for all cases. Good agreement was obtained between the measured (slope 1:3.5) run-up heights and the dimensionless run-up heights predicted using Eqs. (6)–(8) (Fig. 13). The correlation coefficients were 0.87, 0.92, and 0.87, respectively.

Good agreement was obtained between the measured (slope 1:3.5) run-up heights and the dimensionless run-up heights predicted using Eqs. (10) and (11) (Fig. 14). The correlation coefficients were 0.92 and 0.93, respectively.

4. Conclusions

In this study, experiments were carried out in a wave channel to determine the effects of coastal forest on tsunami run-up heights. Tsunamis are generated by a sudden vertical motion of the channel bottom under laboratory conditions. Coastal forest models were constructed using artificial trees (FM-I) and cylindrical timber sticks (FM–II). The artificial trees were placed on 1:5 slope in three different layouts: rectilinear, staggered, and dense rectilinear. To investigate the effect of tree leaves on the run-up height, solid cylindrical timber sticks with an equivalent volume to the artificial trees were placed on the beach slope in rectilinear and staggered layouts. The laboratory results were evaluated and empirical equations were proposed for FM-I and FM–II (Eqs. (6)–(8) and (10) and (11)). Furthermore, all experiments were repeated with a slope of 1:3.5 for verification of the proposed equations. The extents of reduction of run-up height for the different cases are shown in Table 2. The results for the timber sticks cases show that distance from the SWL did not affect run-up heights in the rectilinear and staggered layouts (Fig. 8). If the trees were placed near the SWL ($c = 10$ cm), and furthermore, if they were placed in the rectilinear and staggered layouts, the leaves of tree were effective, and run-up heights were reduced by approximately 15% and 22%, respectively, compared with the results for cylindrical timber sticks (Figs. 9 and 10). It can be concluded that the maximum reduction of run-up height occurred when the trees were placed in the dense rectilinear layout and close to the SWL. In this case, the trees behaved as a barrier. In the Case III model, the run-up height was reduced by approximately 45% compared with the case without trees. Case II was more effective than Case I in reducing the run-up height, except for the comparison of Case I ($c = 10$ cm) with Case II ($c = 20$ cm). Similar results were observed for the comparison of Case II ($c = 10$ cm) with Case III ($c = 20$ cm). In these cases, distance from the SWL is more effective than the layout of the trees (Table 2).

The non-dimensional run-up, R/d has been predicted from Eqs. (6)–(8) and (10) and (11) for slope 1:5 compared with the measured R/d from additional experimental data (slope 1:3.5) for all cases. Good agreement has been obtained between the measured results and the dimensionless run-up height as predicted using Eqs. (6)–(8) (Fig. 13). In future studies, coastal forest effects on tsunami run-up height could be investigated for different types of trees and for a random distribution of trees.

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