EFFECTIVENESS OF COASTAL FORESTS IN MITIGATING TSUNAMI DAMAGE AT EASTERN COAST OF SRI LANKA

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Abstract: This study investigates the effectiveness of coastal forests in mitigating the tsunami damage using the field data of forests. A filed survey was conducted on *Casuarina equisetifolia* forests that established after the Indian Ocean tsunami on 26 December 2004, at eastern coast of Sri Lanka. Tree and forest characteristics were measured in order to analyze the effectiveness of the forests in mitigating the tsunami damage. In addition, a numerical simulation was carried out to find out the optimum conditions of the *C. equisetifolia* forests. Results revealed that the spacing between the trees had a positive correlation with trunk diameter where larger diameter trees required greater spacing. Moreover, drag coefficient was varied along the tree height and it was affected considerably by the branches and the leaves. A numerical simulation was performed for evaluating the quantitative effect for tsunami reduction and damage. It found that the tsunami force was reduced largely and the tsunami velocity and depth were reduced slightly subsequent to the forest. The most appropriate tree density was found as 0.3 trees/m^2.

Keywords: Coastal forests, tsunami damage, drag force

1 Introduction

The tsunami on 26 December 2004 caused due to a massive undersea earthquake, measured at 9.3 on the Richter scale, the world's largest earthquake after the Alaskan event of l964. It has caused economic and ecological disaster in 13 Asian and African countries (Kandasamy and Narayanasamy 2005). About two-thirds of Sri Lanka was severely damaged on a scale this country has never experienced before (Tanaka et al. 2007). These damages give emphasis to develop methodologies to prevent or minimize the damages of future tsunamis. Goto and Shuto (1983) found that the energy associated with the tsunami was dissipated as for a tsunami passing through an obstacle. This means that the establishment of obstacles such as sea walls, wave dissipating concrete blocks, or rock breakwater structures would help to mitigate the adverse effects of tsunami. However, the developing countries cannot bear the high capital cost associated with them. In addition, these structures would adversely affect the ecology and aesthetic of the coastal environment. Coastal vegetation can significantly use in reducing the severity of tsunami waves and dissipating the amount of energy associated with them (Harada et al. 2002; Kandasamy and Narayanasamy 2005; Tanaka et al. 2007). Moreover, coastal vegetation would positively affect the ecology and aesthetic of the coastal environment.

Many researchers have experimentally and numerically investigated the effectiveness of coastal vegetation in mitigating the tsunami damage. Harada et al. (2000) proposed the tsunami numerical simulation including the effect of costal forest resistances. Harada and Imamura (2001) proposed the resistance coefficients due to mangrove under the unsteady flow from the hydraulic experiment analysis. The effectiveness of coastal forests against tsunami was analyzed statistically by considering the physical damage on pine trees in Japan (Shuto 1987). In addition, Tanaka et al. (2007) demonstrated the effectiveness of different coastal tree species in mitigating the tsunami damage in Sri Lanka and Thailand after the tsunami on 26 December 2004. However, any of the above studies have not investigated the effectiveness of established *Casuarina equisetifolia* forests in mitigating tsunami damage. In addition, they did not consider the risks associated with the coastal forest during the tsunami.

Thus, the objectives of this study are to investigate, (1) the effectiveness and (2) the optimum conditions of *C. equisetifolia* forests in mitigating the tsunami damage.

2 Materials and methods

2.1 Site description

A field survey was conducted from 24-27 May 2010 at eastern coast of Sri Lanka (Figure 1). The area investigated covered about 72 km (11 locations) from Passekudah to Kalmunai. The areas were mainly covered with *C. equisetifolia* forests that established under the various projects intended to protect people, the infrastructure and the environment from future tsunami hazards. The tree and forests characteristics, such as tree height (H), trunk diameter at breast height, tree density, forests length (L), forests width (W), the spacing between the trees in the shore and cross-shore directions (l_1 and l_2, respectively) (Figure 2), and the distance from the forest to the sea were measured during the field survey. In addition, the tsunami water depth and flow velocity were obtained from the available data.

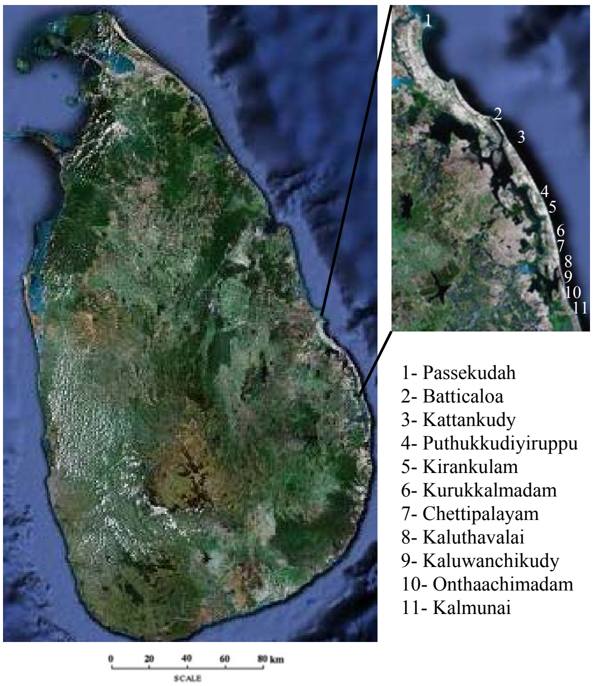


Figure 1: The locations of the investigation sites

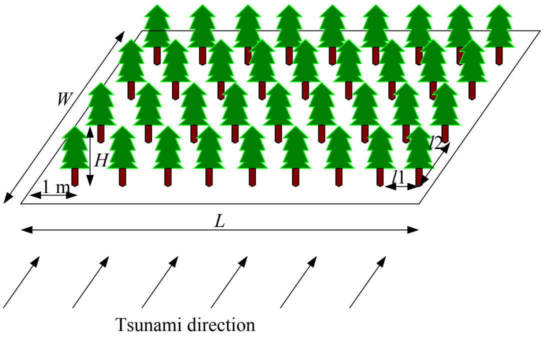


Figure 2: Definitions of the tree and the forest characteristics

2.2 Estimation of drag force coefficient using field data

The physical characteristics of coastal vegetation were considered by means of drag force of trees along a width of W (m) and a length of vegetation of 1 (m) (Figure 2). The following equation shows the cumulative drag force acting on the forest (Tanaka et al. 2007).

$$D_{\mathrm{cum}} = n * (\text{drag force on one tree}) = n * \int \frac{1}{2} C_{di} \rho u_i^2 dA_i$$

$$= \frac{n}{2}(\alpha\beta C_d)\rho U^2 (h\frac{d}{100})$$

$$D_{\mathrm{cum}} = \frac{1}{2}(\frac{dn\alpha\beta}{100}) C_d \rho U^2 h \qquad (1)$$

where D_{cum} is the cumulative drag force of trees a width of W (m) and a length of 1 (m), n is the number of trees in a vegetation width of W (m) and length of 1 (m), d is the reference tree trunk diameter at 1.2 m above the ground (cm), α and β are additional coefficients representing the effects of branches and leaves on the drag force, respectively, C_d is the drag coefficient, ρ is the density of salt water (kg/m^3), U is the depth-average velocity (m/s), and h is the tsunami depth (m). Coefficients α and β were chosen according to the average tree height.

Equations 2, 3, and 4 define the vertical vegetation structure, C_{d-all}, the effective vegetation thickness, dN_{all} (cm/ (vegetation width x 1 m^2)), and the vegetation thickness per unit area, dN_u (cm/unit vegetation area m^2), as follows.

$$C_{d-all} = \alpha\beta * C_d \tag{2}$$

$$dN_{all} = \alpha\beta * dn \tag{3}$$

$$dN_u = \frac{dN_{all}}{l^2 n} = \frac{\alpha\beta d}{l^2} \tag{4}$$

where l is the average spacing of the trees (m). Eqs. 2, 3, and 4 are related to the drag force in Eq. 1. C_{d-all} describes the characteristics of the tree itself, dN_{all} describes the characteristics including the effects of the tree structure $\alpha\beta$ in the W (m) x 1 (m) vegetation, and dN_u describes the characteristics of a unit vegetation area.

2.3 Numerical simulation including coastal forests

In order to evaluate the effect of tsunami reduction quantitatively, the tsunami numerical simulation of run up including the resistance of the control forest was carried out and the change of hydraulic parameters (velocity and tsunami depth) and the tsunami force on the land were examined. A coastal forest at Batticaloa site (length = 410 m and width = 100 m) was selected as an example to carry out numerical simulation. To evaluate the tsunami reduction effects by coastal forest, the variation of tsunami height, velocity, and tsunami force subsequent to the forest were examined with input data, including the topography, tsunami conditions, and different tree densities. Four tree density values (0.1, 0.2, 0.3, and 0.4 trees/m^2) were used in numerical simulation. The conditions for tsunami numerical simulation are shown in Figure 3.

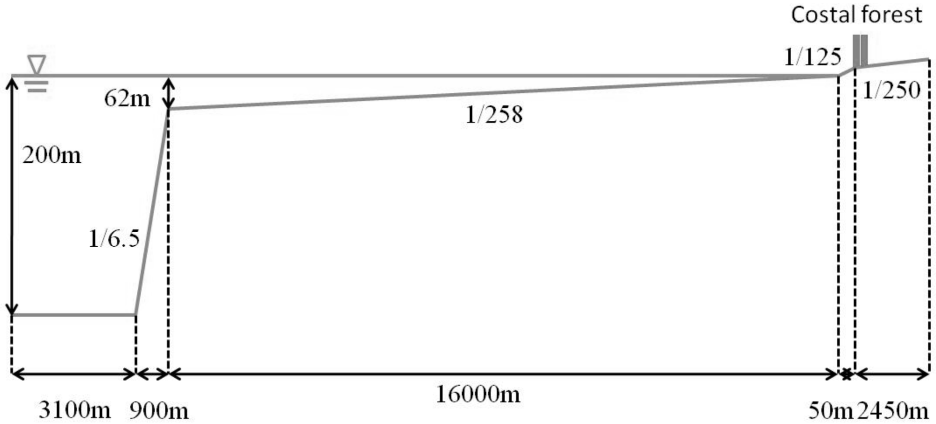


Figure 3: The section of coastal topography used in numerical simulation

The governing equations used for the numerical simulation were the continuity equation (5), the momentum equation in X and Y directions (6) and (7), and the equation for drag force (8).

$$\frac{\partial\zeta}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0 \tag{5}$$

$$\frac{\partial Q_x}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q_x{}^2}{d}\right)+\frac{\partial}{\partial y}\left(\frac{Q_xQ_y}{d}\right)+gd\frac{\partial\zeta}{\partial x}+\frac{\tau_{bx}}{\rho}+\frac{F_x}{\rho}-E_{vx}=0 \qquad (6)$$

$$\frac{\partial Q_y}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q_xQ_y}{d}\right)+\frac{\partial}{\partial y}\left(\frac{Q_y{}^2}{d}\right)+gd\frac{\partial\zeta}{\partial y}+\frac{\tau_{by}}{\rho}+\frac{F_y}{\rho}-E_{vy}=0 \qquad (7)$$

$$F=\frac{1}{2}\rho C_{d-all}AU^2 \qquad (8)$$

where, x and y are coordinates, t is time, ζ is water level, Q_x is discharge (x-direction), Q_y is discharge (y-direction), d is water depth, h is static water depth, g is acceleration due to gravity, ρ is density of water, τ_{bx} is bottom shear force (x-direction), τ_{by} is bottom shear force (y-direction), F_x is drag force of trees (x-direction), F_y is drag force of trees (y-direction), E_{vx} is eddy viscosity force(x-direction), E_{vy} is eddy viscosity force(y-direction), F is drag force on tress, and A is projected area of trees facing to the tsunami.

3 Results and discussions

3.1 Variation of drag coefficient

Figure 4(a), (b), and (c), show the relationship between the trunk diameter and the average apace between each tree, the vertical distribution of $\alpha\beta$, and the relationship between dN_u and the tsunami height, respectively. Figure 4(a) shows that the average spacing becomes larger with increasing trunk diameter. This demonstrates that a lager tree requires a larger spacing (lower tree density) and vice versa. Tanaka et al. (2007) obtained similar type of results for correlation between trunk diameter and the average space between the trees. In addition, Harada and Kawata (2004) obtained a positive and significant correlation between forest density and diameter of trunk for the coastal forest conditions in the actual field.

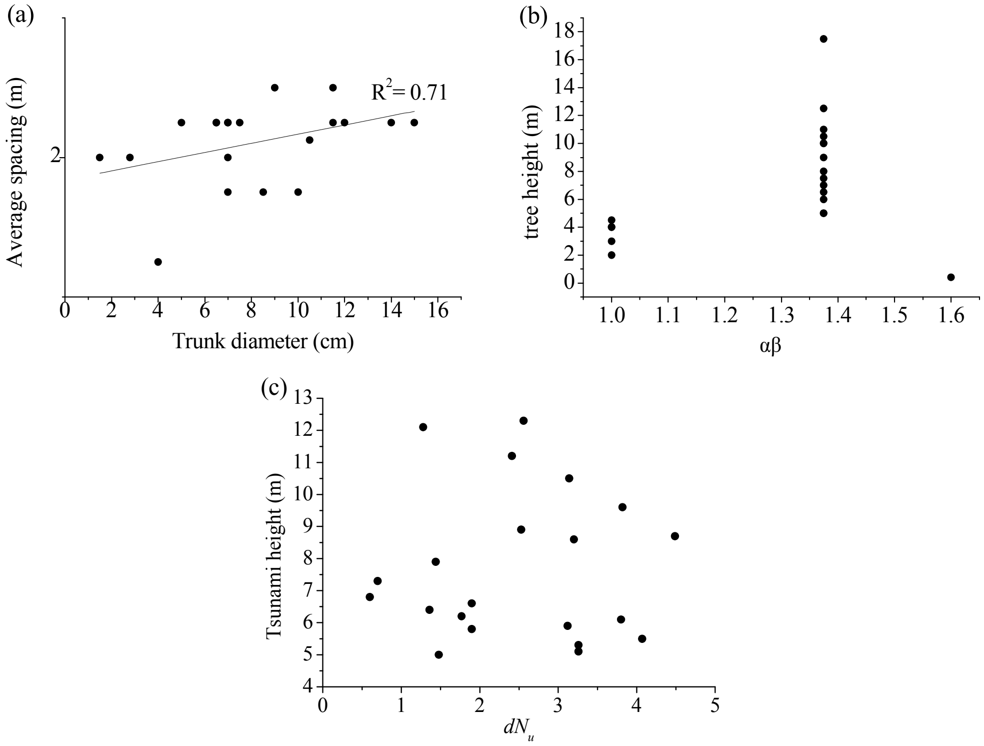


Figure 4: Characteristics of *C. equisetifolia* forests at the investigated sites with the tsunami water depth at 2004 Indian Ocean tsunami

Coefficients $\alpha\beta$ was increased (Figure 4(b)) with increasing the tree height due to large amount of branches and larger leaf area density. Figure shows that $\alpha\beta$ of the trunk was about 1 and it was nearly 1.4 for the upper part of the tree. Similar types of results were obtained by Tanaka et al. (2006) and (2007) during the field investigations in Sri Lanka and Thailand. The correlation between dN_u and the tsunami height was not clear. However, Tanaka et al. (2007) found that young *C. equisetifolia* (d=0.15 m) was effective especially in protecting tsunami higher than 10 m because it grew densely and was not broken by the tsunami. Further they found that the value of dN_u for large-diameter *C. equisetifolia* was quite small.

3.2 Results of numerical simulation

Figure 5 (a), (b), and (c) show the variation of maximum velocity, tsunami depth and tsunami force in unit width, respectively for the tree density value of 0.3 trees/m^2.

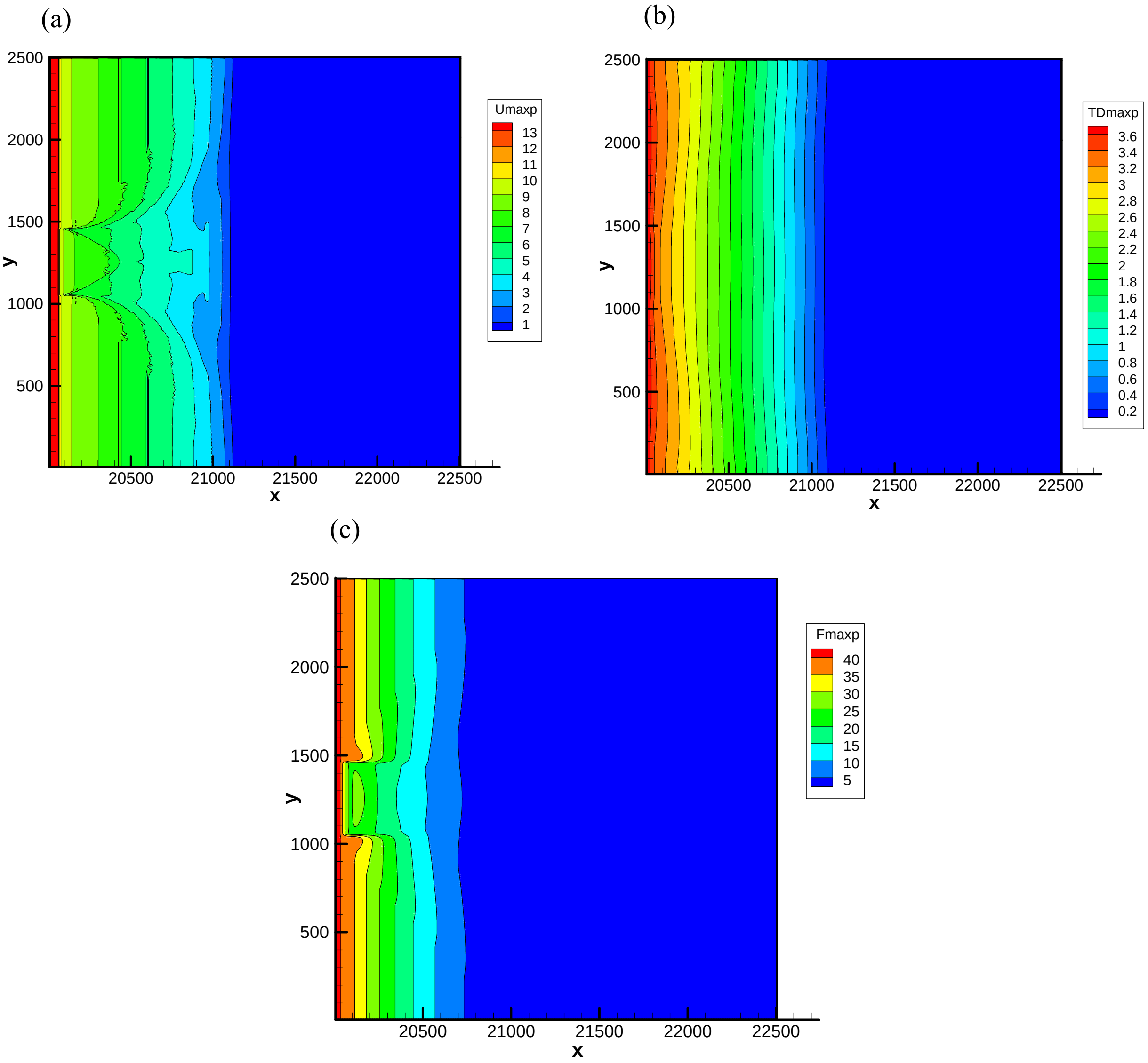


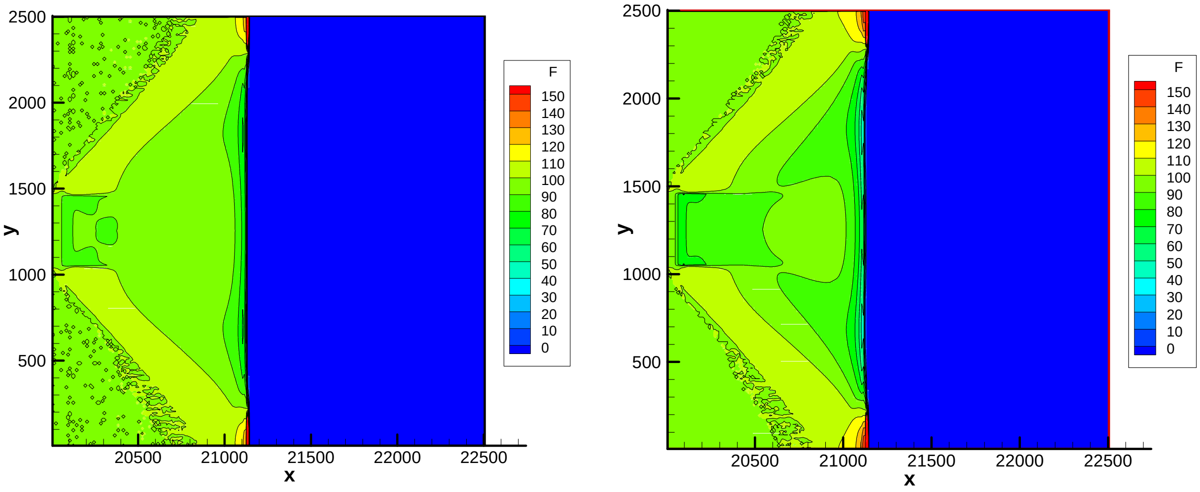
Figure 5: Variation of (a) maximum velocity (m/s), (b) tsunami depth (m), and (c) tsunami force in unit width (kN/m) in X and Y directions

The velocity of tsunami flow was reduced subsequent to the forest. The flow velocity at both ends of the forest was decreased considerably in comparison with the middle section. Consequently, people living near the middle section of the forest would suffer highly due to the tsunami. The tsunami depth shows (Figure 5(b)) comparatively slighter reduction subsequent to the forest. The depth was reduced gradually because trees were planted in rows at equal distances. The tsunami depth was comparatively greater even after the forest. The tsunami force (Figure 5(c)) was decreased significantly after the coastal vegetation. The force became almost half of its initial value just behind the forest. The main cause of force reduction was the drag force exerted by the trunks and the branches of the trees. The tsunami force near the middle section of the forest was comparatively greater as observed in the tsunami velocity. Thus, it can be observed that a dangerous zone was created near the middle section behind the forest. Since the tsunami force exhibited greater reduction subsequent to the forest in comparison with the tsunami velocity and depth, the role of the coastal forests in mitigating the tsunami damage can be described mainly by the tsunami force.

3.3 Effect of forest density to tsunami reduction

Figure 6(a), (b), (c), and (d) show the variation of percentage remaining of the tsunami force for the tree densities 0.1, 0.2, 0.3, and 0.4 trees/m^2, respectively.

(a) 0.1 trees/m^2 (b) 0.2 trees/m^2



(c) 0.3 trees/m^2 (d) 0.4 trees/m^2

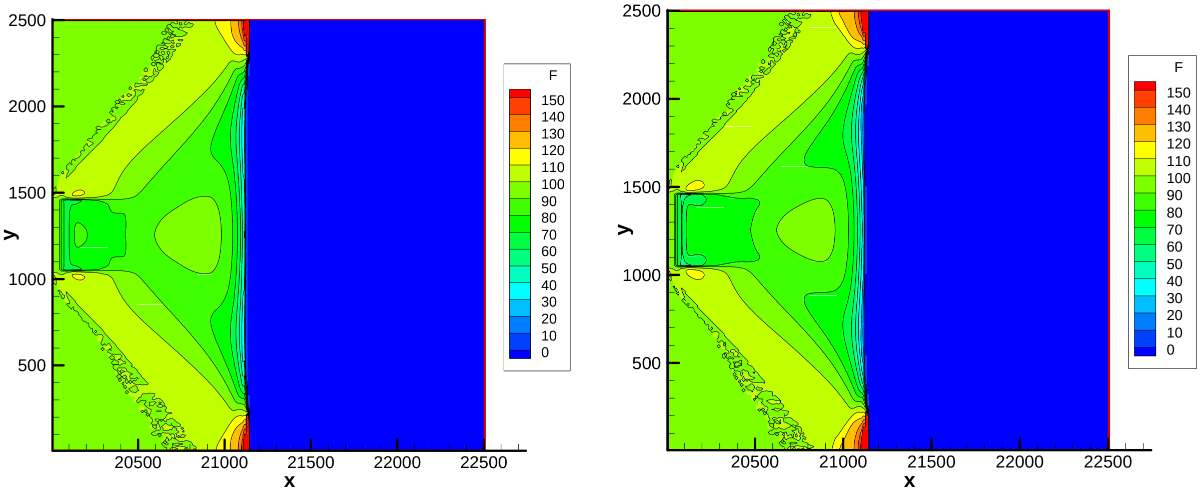


Figure 6: Percentages remaining of the tsunami force

The percentage remaining of the tsunami force was nearly 100% behind the forest in the case of tree density 0.1 (trees/m^2). The force was reduced about 30% in a small area just behind the forest. The percentage reduction of force was about 30-40% in a considerable area subsequent to the forest in the case of tree density 0.2 (trees/m^2). However, still there was a large area where the force reduction was about 0%. When compare Figure 6(c) and (d), both conditions provided better reduction of the tsunami force. About 30-40% of the force was reduced in a large area behind the forest in the case of tree density 0.4 (trees/m^2) in comparison with that of 0.3 (trees/m^2). Further, the area of the dangerous zone was relatively small. Thus, it seems that 0.4 (trees/m^2) would be the optimum tree density has to be selected when designing the coastal forests in mitigating the tsunami damage. However, the value of 0.4 (trees/m^2) is assumed to be too thick and it will create some problems, such as social, environmental, and aesthetic. Hence, 0.3 (trees/m^2) was the most appropriate tree density that should be selected when designing the coastal forests in mitigating the tsunami. Harada and Kawata (2004) carried out a numerical simulation with forest model to evaluate the quantitative effect of tsunami reduction, and the results revealed that the inundation depth, the current and the hydraulic force just behind the forest was decreased with the increase of forest density. However, they did not find an optimum tree density value. Harada and Imamura (2005) found that tree density 10 trees/100 m^2 provided the highest reduction rate of maximum current and maximum hydraulic force against the tsunami. They used the tsunami height as 3 m. The difference of the optimum tree density value in comparison with our study may be due to lesser tsunami height.

4 Conclusions

The coastal forest conditions in the actual field were complied to obtain the relationships between the forest and the tree characteristics. The average space between the trees was increased linearly with increasing the trunk diameter. This revealed that the larger diameter trees required larger spacing. Thus, these characteristics of vegetation need to be discussed as a combined effect. In addition, coefficient $\alpha\beta$ was increased with tree height due to the branches and the leaves. The value $\alpha\beta$ was equal to 1 at the trunk and 1.4 at the upper part of the tree. The results of the numerical simulation revealed that the tsunami flow velocity and depth were reduced considerably and the tsunami force was reduced largely due to the coastal forest. The tsunami force was the key parameter that should be used to describe the effectiveness of the coastal forests. The most appropriate tree density was selected as 0.3 (trees/m^2) by analyzing the percentage remaining of the tsunami force subsequent to the forest. In addition, a risky zone by the collision of repelling flow was observed behind the forest in the cases of tree density 0.3 and 0.4 (trees/m^2), but the tsunami force is less than the value without forest. The value has possibility to change tsunami condition, forest condition and slope condition. More study is needed on that point.

References

1. Goto, C., Shuto, N. (1983), “Effect o f large obstacles on tsunami inundation”, *Tsunamis Their Science and Engineering*, ed. by K. Iida and T. Iwasaki, Terra Sc. Publs. Comp., Tokyo, 511-525.
2. Harada, K., Aburaya, T., Hamzah, L., Imamura, F. (2000), “Examination on the effect of control forest to reduce a tsunami energy” (In Japanese), Proceedings of Coastal Engineering, JSCE, 47: 366-370.
3. Harada, K., Imamura, F. (2001), “Experimental study on the resistance by mangrove under the unsteady flow”, Proceedings of the first Asian and Pacific Coastal Engineering Conference, Dalian, China, 2: 975-984.
4. Harada, K., Imamura, F. (2005), “Effects of coastal forest on tsunami hazard mitigation- A preliminary investigation”, *Advances in natural and technological hazards research*, 23: 279-292.
5. Harada, K., Imamura, F., Hiraishi, T. (2002), Experimental study on the effect in reducing tsunami by the coastal permeable structures”, Proceedings of The Twelfth International Offshore and Polar Engineering Conference Kitakyushu, Japan.
6. Harada, K., Kawata, Y. (2004), “Study on the effect of coastal forest to tsunami reduction”, Annuals of Disas. Prev. Res. Inst., Kyoto University.
7. Kandasamy, K., Narayanasamy, R. (2005), “Coastal mangrove forests mitigated tsunami”, *Estuarine, Coastal and Shelf Science*, 65: 601-606.
8. Shuto, N. (1987), “The effectiveness and limit of tsunami control forests*”, Coastal Engineering in Japan*, 30: 143-153.
9. Tanaka, N., Sasaki, Y., Mowjood, M.I.M. (2006), “Effects of sand dune and vegetation in the coastal area of Sri Lanka at the Indian Ocean tsunami”, *Advances in Geosciences*, 6: 149-159.
10. Tanaka, N., Sasaki, Y., Mowjood, M.I.M., Jinadasa, K.B.S.N., Homchuen, S. (2007), “Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami”, *Landscape and Ecological Engineering*, 3: 33-45.

Acknowledgements

The authors would like to acknowledge the Department of Civil Engineering of University of Peradeniya for their assistance in the field investigations. This work was supported in part by JSPS AA Science Platform Program.

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