Fusion Journal of Engineering and Sciences

Article

Computational Investigation of Staggered Vegetation Barriers for Coastal Defense Systems using VOF

Talha Jami [1*], Naveed Anjum [1], Abdur Rauf Khan [1], Abdul Rafay [1], Zaheer Ahmad [1]

[1] Khwaja Fareed University of Engineering and Information Technology, Pakistan
engr.talhajamiii@gmail.com, naveed.anjum@kfueit.edu.pk, engr.raufkhann@gmail.com, cengr.abdulrafay@gmail.com, dr.zaheer@kfueit.edu.pk
* engr.talhajamiii@gmail.com

Abstract

In coastal areas, the threat of tsunamis always remains, and these areas are highly affected by tsunamis. After the 2011 earthquake and tsunami in Japan, researchers were prompted to recognize that engineered hard elements like embankments alone are not sufficient, so they shifted their focus to using vegetation as a natural protection system with engineered elements to reduce tsunami energy. Trees not only reduce energy but also help in reducing the depth of flowing water, and they are economically feasible and environmentally friendly. In this study, we placed vegetation in a numerical model in a staggered arrangement. We performed simulations in ANSYS FLUENT using the VOF model, and after the water passed through the vegetative zone, the percentage of energy reduction and the changes in velocity were observed. We set the domain under subcritical conditions (Fr=0.66), which represents a small-scale tsunami flow. From the model, we observed a noticeable 25% reduction in energy as the flow passed through the vegetative region. When flowing water struck the stem, there was a sudden loss of velocity, and at that point, the velocity became approximately equal to 0. After passing through the vegetation, the depth also reduced by 55.2%. These results show that even small vegetation can affect the flow behavior of water. This study adds support for including vegetation in hybrid coastal protection strategies and may help guide future improvements.

Keywords: Tsunami mitigation, Coastal protection, Vegetation modeling, ANSYS FLUENT, Numerical investigation, Flow energy reduction

1. Introduction

Understanding flow evolution within vegetated channels is essential for hydraulic engineers. Vegetation plays a crucial role in shaping hydrodynamics of rivers, streams, and man-made channels. The combined presence of tall and short vegetation patches has been shown to optimize energy dissipation in open channels. Coastal vegetation also mitigates the impact of tsunamis and flood currents by reducing flow velocity and dissipating energy. The type of vegetation and its installation position downstream of embankments significantly influence flow characteristics and fluid forces. Historical studies have highlighted the importance of greenbelt and vegetative barriers in tsunami-prone regions, particularly in the South Pacific.

The effectiveness and limitations of tsunami control forests were first systematically examined by Shuto. Mangrove forests in Banda Aceh, Indonesia, were observed to reduce tsunami damage through energy dissipation and localized flow control. Review studies emphasize that vegetation bio shields provide sustainable mitigation solutions, although their efficiency depends on density, species, and maintenance. Mangrove forests also offer ecological benefits, contributing resilience against global climate change while protecting coastal regions.

Experimental investigations of discontinuous vertically layered vegetation have shown that such configurations significantly alter turbulent flow patterns in channels. Vegetation played a protective role during the 2004 Asian tsunami by reducing flow energy and protecting infrastructure. Laboratory studies with synthetic canopies confirmed that vegetation density directly affects wave attenuation. Emergent vegetation of varying thickness generates undular hydraulic jumps, enhancing energy loss in flow. Flow structures around colony-type emergent roughness elements demonstrate that vegetation geometry influences drag characteristics and turbulence generation. Finally, mangrove forests have been widely recognized for their ability to reduce wave heights and dissipate energy in coastal regions.

2. Materials and Methods

2.1 Hydraulic Conditions

This study is based on numerically modeled channel developed in ANSYS Design Modeler. To represent coastal defense system, cylindrical elements were introduced inside channel in a staggered configuration to represent vegetation trees. The flow conditions were maintained in subcritical regime, Froude number kept <1. To capture interaction between water-air, the region above water surface was modeled as air-phase in numerically designed model, and a two-phase flow simulation was carried out by using Volume of Fluid techniques. Flow velocity was evaluated by using Froude No. relationship [Fr= U/(g*Z)0.5] by considering the gravity and water depth Z(m). This numerical setup allowed effective way for analysis of flow behavior and associated energy variations under subcritical flow conditions.

2.2 Numerical Model (Details)

Numerical modeling was carried out using ANSYS FLUENT, where three-dimensional model was developed. The 1/100 scale was set to represent better real field conditions. Vegetation was modeled with an average diameter of 40 cm. In model, height of vegetative cylinders was defined as HT, and total vegetation width (Wv) was maintained at 21.1 cm. According to 1/100 Scale, each cylinder had a diameter of 0.4 cm (R=0.2cm) and was modeled as part of the Vegetative region. A total of 115 cylinders were arranged in 10 rows, with a center-to-center spacing D. This arrangement was intended to represent a realistic coastal forest configuration. The detailed geometry and layout of model are illustrated in Figure 1 (A, B, C). Using the model, a complete analysis of velocity distribution, water depth variations, and energy dissipation was performed. The vegetation conditions and parameters are shown in Table 1. Entire setup was based on channel with dimensions of 120 cm = length, 30 cm = width, and 15 cm = depth, and this modeling approach proved effective for understanding of hydraulic effects of vegetation trees.

Table 1.

Sr. No.	Arrange-ment	Channel Length [cm]	Channel Width [cm]	Channel Height [cm]	D [cm]	d [cm]	Fr	Wv [cm]	Flow Depth [cm]
1	Staggered	120	30	15	2.3	0.4	0.66	21.1	6

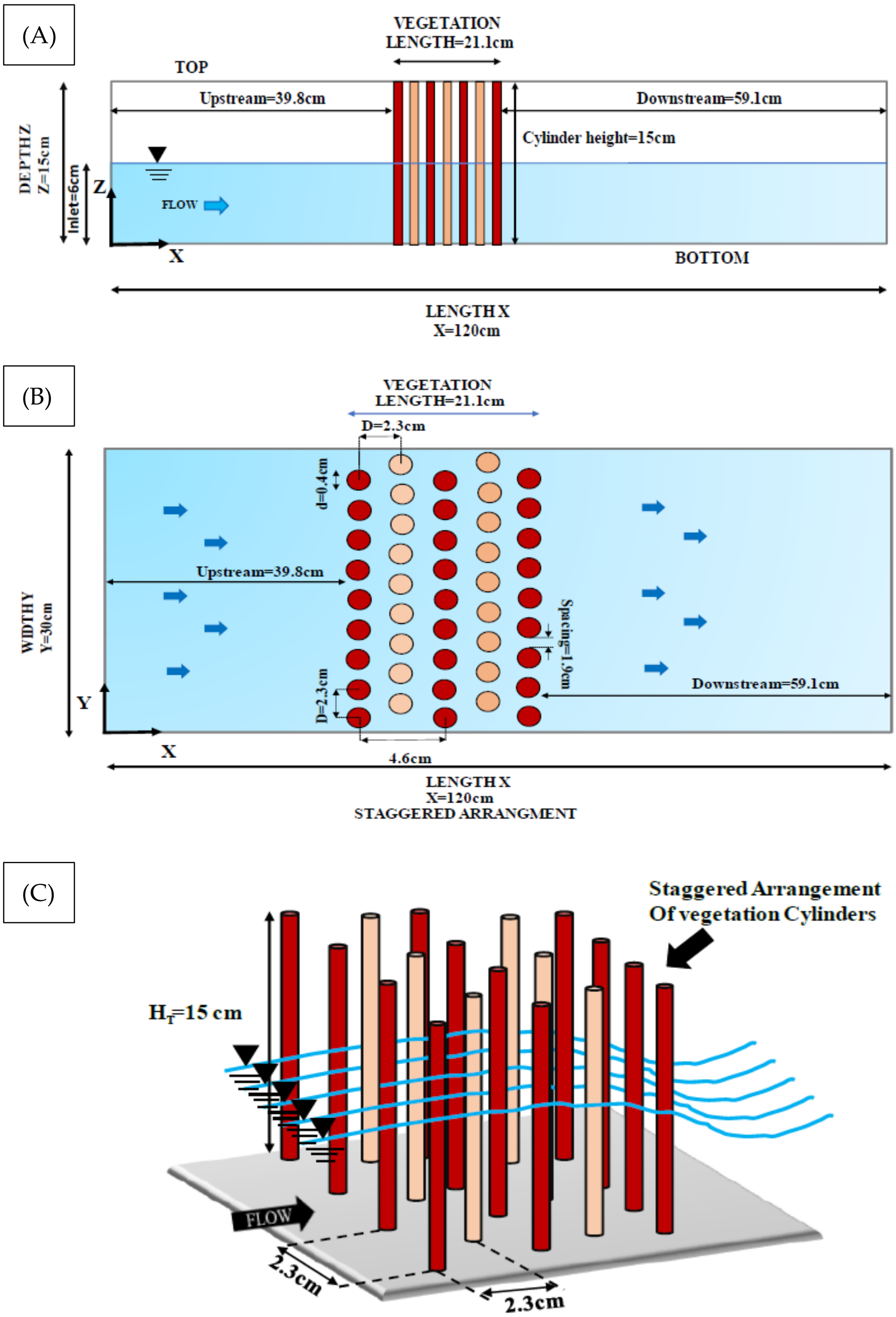


Figure 1. Details of Setup: (A) Sketch , (A)staggered Arrangement of Vegetation Cylinders, (C) model of Vegetative Cylinders(3-dimensional)

2.3 Numerical Model Setup:

For numerical model setup of this study, ANSYS Fluent was used, where a refined mesh containing 0.35 million nodes was generated. A finer triangular mesh was applied around vegetation cylinders to represent channel geometry more accurately and to better capture flow details. Mesh quality was carefully checked to ensure numerical stability and solution reliability. Boundary setup of channel is illustrated in Figure 2, where inlet was defined as a velocity inlet and outlet was specified as a pressure outlet. The boundary above water surface was also set as pressure outlet to allow free surface movement. The channel side walls and bed were assigned wall conditions, while vegetation cylinders were modeled as solid walls. After process of mesh generation, VOF was applied to track water surface. To ensure result accuracy, absolute convergence criterion 1e-10-6 was adopted. This numerical setup realistically simulates flow behavior and provides a stable and reliable analysis of hydraulic effects of vegetation trees in a coastal defense system.

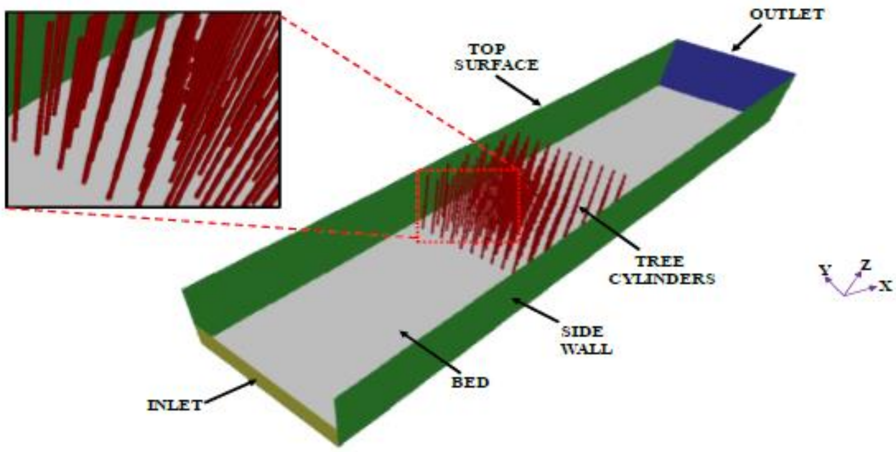


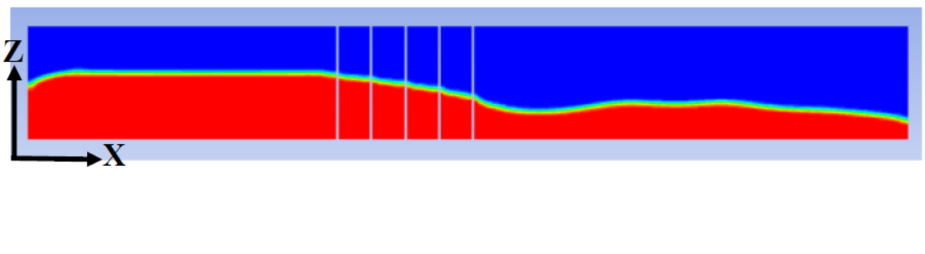
Figure 2. Boundaries setup of CFD Channel

3. Results

3.1 Depth-Averaged Velocity Distribution

In this study, a detailed analysis of depth-averaged velocity along the channel was carried out, considering two different regions. The first region was the free-flow region located before and after vegetation, while the second region consisted of the vegetative region. At location $X_1 = 39.8$ cm, before vegetation, the velocity distribution was observed to be nearly uniform, showing stable flow conditions. As water enters the vegetative region after X_1, water directly interacts with the stems of vegetation cylinders. As a result of this interaction, the velocity decreases significantly and, at some points, approaches approximately zero. Within the vegetative region, increased flow resistance and turbulence lead to momentum loss. When water passes the end of the vegetative region at $X_2 = 60.9$ cm, the flow starts to recover. After this point, a gradual increase in velocity is observed. These trends are clearly shown as a graphical representation in Figure 3(c), while velocity contours are shown in Figure 3(b).

(a)



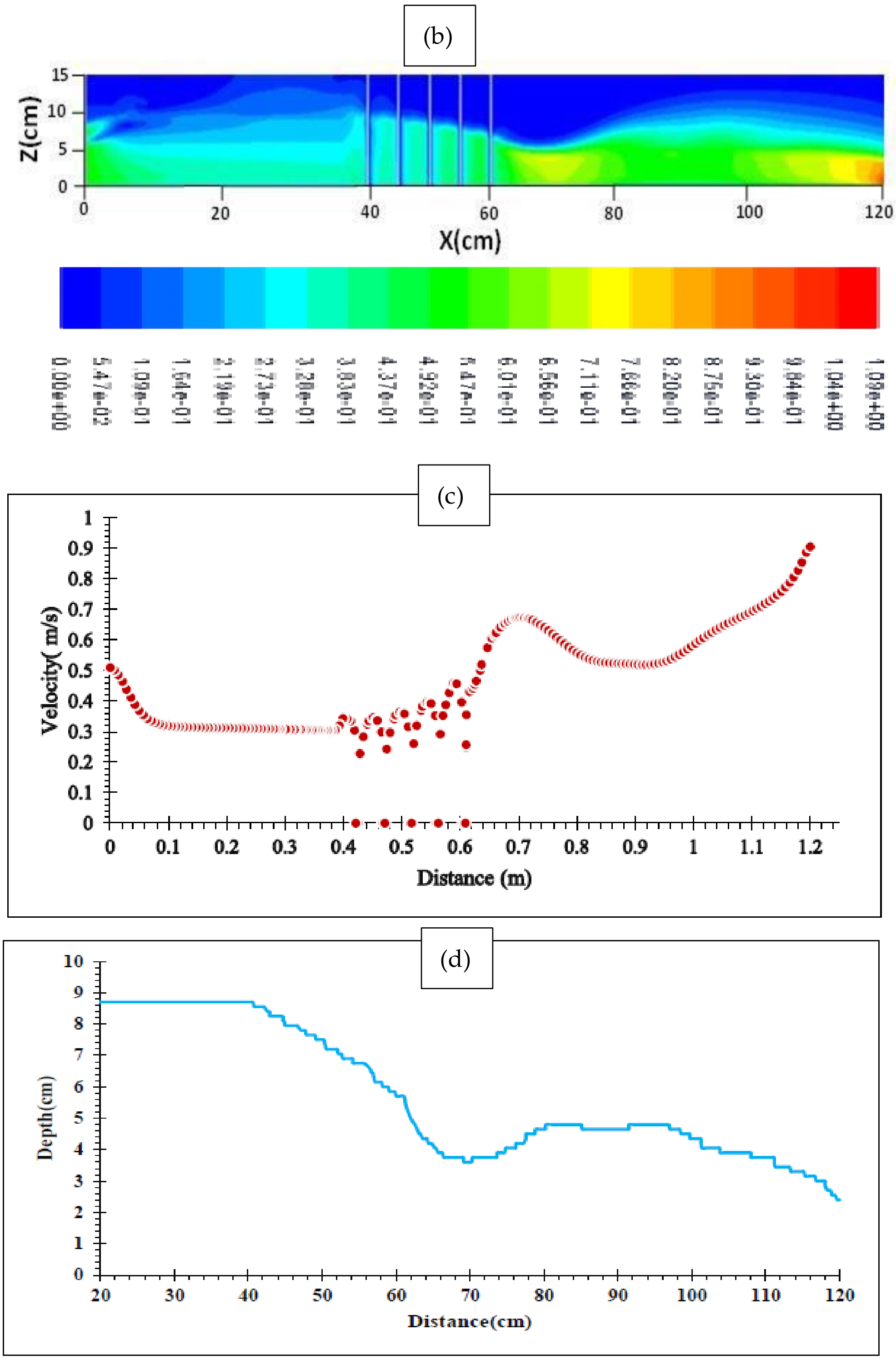


Figure 3. Volume Fraction Distribution (Contour)(a), Velocity Contours(b), Graphical Representation of Depth-averaged velocity in Channel (c), Graph: Depth vs distance X (d)

3.2 Loss of Energy

The analysis of energy dissipation was carried out at two different sections where the flow was stable before and after the vegetative region, as shown in Figure 4. The reduction in energy (%) was calculated using

$\Delta E = (E_1 - E_2) / E_1 \times 100$, where E_1 represents the total energy at the upstream section consisting of Z_1 and the velocity head $\alpha V_1^2/2g$.

E_2 at the downstream section is composed of Z_2 and $\alpha V_2^2/2g$, showing the flow condition after passing through the vegetative zone. As water passed through the vegetative zone, it encountered significant resistance and turbulence, which led to a noticeable reduction in kinetic energy.

Numerical results indicated that the total energy was dissipated by approximately 25 percent, which shows the effectiveness of vegetation. In addition, a clear change in water depth was noticed, with a reduction of about 55.2 percent, as shown in Figure 3(d). These observations indicate that vegetative barriers not only reduce flow velocity but also effectively control flow depth and overall energy.

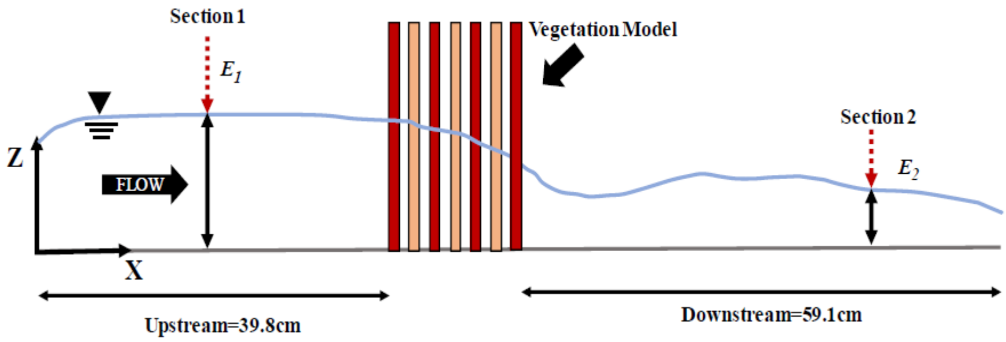


Figure 4. Schematic diagram of the CFD Channel

4. Discussion

Numerical results of the study clearly indicate that staggered vegetation significantly modifies flow behavior under tsunami-like flow conditions. A noticeable reduction in velocity was observed within the vegetative region, primarily due to increased drag and turbulence. As the flow repeatedly interacts with vegetation stems, its momentum decreases, making the staggered arrangement more effective. The observed reduction in energy suggests that vegetation has the ability to absorb and redistribute kinetic energy. The reduction in water depth downstream further contributes to flow attenuation and helps reduce flood-related risks. These results also demonstrate that vegetation layout plays a vital role in hydraulic performance. The VOF model effectively captured free-surface variations and flow–vegetation interactions. Overall trends are consistent with observations reported in earlier studies. In this research, vegetation was assumed to be rigid, which represents a simplified condition. Future studies should consider flexible vegetation and more complex flow scenarios for improved realism.

5. Conclusions

This research evaluates the performance of a coastal defense system based on staggered vegetation under tsunami-like flow conditions. A CFD-based approach was employed using ANSYS FLUENT with the VOF model to simulate free-surface flow. The analysis focused on velocity distribution, energy dissipation, and variations in water depth. Results showed a clear reduction in flow velocity within the vegetative region. Total flow energy was reduced by approximately 25%, indicating effective energy dissipation. In addition, a significant reduction of about 55.2% in water depth was observed downstream of the vegetation zone. These findings confirm that staggered vegetation has a strong hydraulic influence on flow behavior. Vegetation arrangement was identified as a key factor in controlling flow dynamics. The study highlights the effectiveness of nature-based solutions for coastal protection. The results provide valuable guidance for the development of sustainable and hybrid coastal defense strategies.

Funding

This research did not receive any external funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

D	Center-to-center gap between two cylinders
D	Diameter of vegetative cylinder
Z	Water depth
Wv	Width of Vegetation
Fr	Froude Number
HT	Tree Height
R	Radius of Cylinder
K.E	Kinetic Energy

References

[1] Anjum, N.; Iqbal, S.; Pasha, G.; Tanaka, N.; Ghani, U. Optimizing Coastal Forest Arrangements for Tsunami Flow Dynamics Using a Three-Dimensional Approach. Phys. Fluids 2025, 37.

[2] Anjum, N.; Iqbal, S.; Ali, M.; Pasha, G.; Ghumman, A.R. Investigation of Flow Behavior within Staggered Vegetation Patches of Various Shapes in an Open Channel. J. Ecohydraul. 2025, 10, 1–19.

[3] Anwar, S.; Anjum, N.; Ali, A.; Shah, S.; Ahmed, I.; Ahmad, Z.; Sidiqy, J.A. Investigating the Combined Effect of Tall and Short Vegetation Patches in Open Channel Flow. Fusion J. Eng. Sci. Special Issue, 2025, Article 48 (Preprint).

[4] Ahmad, S.; Anjum, N.; Abbas, M.S.; Shahid, A.; Bukhari, A.; Sohail, A.; Ahmad, Z.; Aslam, H. Modeling the Effects of Coastal Vegetation in Mitigating Tsunami and Flood Current. Constr. Technol. Archit. 2025, 17, 181–189.

[5] Rashedunnabi, A.H.M.; Tanaka, N.; Rahman, M.A. Transformations in Flow Characteristics and Fluid Force Reduction with Respect to the Vegetation Type and Its Installation Position Downstream of an Embankment. Fluids 2025, 10, 16.

[6] Hiraishi, T.; Harada, K. Greenbelt Tsunami Prevention in the South Pacific Region. Rep. Port Airpt. Res. Inst. 2003, 42(2), 1–23.

[7] Shuto, N. The Effectiveness and Limit of Tsunami Control Forests. Coast. Eng. Jpn. 1987, 30(1), 143–153.

[8] Yanagisawa, H.; Koshimura, S.; Miyagi, T.; Imamura, F. Tsunami Damage Reduction Performance of a Mangrove Forest in Banda Aceh, Indonesia Inferred from Field Data and a Numerical Model. J. Geophys. Res. 2010, 115, C06032.

[9] Tanaka, N. Vegetation Bioshields for Tsunami Mitigation: Review of the Effectiveness, Limitations, Construction and Sustainable Management. Landsc. Ecol. Eng. 2009, 5, 71–79.

[10]Alongi, D.M. Mangrove Forests: Resilience, Protection from Tsunamis, and Responses to Global Climate Change. Estuar. Coast. Shelf Sci. 2008, 76(1), 1–13.

[11]Anjum, N.; Tanaka, N. Experimental Study on Flow Analysis and Energy Loss around Discontinued Vertically Layered Vegetation. Environ. Fluid Mech. 2020, 20, 791–817.

[12]Danielsen, F.; Sørensen, M.K.; Olwig, M.F.; Selvam, V.; Parish, F.; Burgess, N.D.; Quarto, A. The Asian Tsunami: A Protective Role for Coastal Vegetation. Science 2005, 310(5748), 643.

[13]Maza, M.; Lara, J.L.; Losada, I.J.; Ondiviela, B. Role of Vegetation Density on Wave Attenuation: A Laboratory Study with Synthetic Canopies. Coast. Eng. 2015, 98, 1–16.

[14]Pasha, G.A.; Tanaka, N. Undular Hydraulic Jump Formation and Energy Loss in a Flow through Emergent Vegetation of Varying Thickness and Density. Ocean Eng. 2017, 141, 308–325.

[15]Takemura, T.; Tanaka, N. Flow Structures and Drag Characteristics of a Colony-Type Emergent Roughness Model Mounted on a Flat Plate in Uniform Flow. Fluid Dyn. Res. 2007, 39, 694–710.

[16]Mazda, Y.; Magi, M.; Kogo, M.; Hong, P.N. Wave Reduction in Mangrove Forests. J. Oceanogr. 2006, 62(4), 517–528.