The Effectiveness of Tsunami Bore Reduction by Hibiscus Tiliaceus Coastal Vegetation: An Experimental Study

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ABSTRACT

Tsunamis pose a serious threat to coastal areas, where rapid development increases the potential for damage and loss of life. Effective mitigation measures are needed, including nature-based solutions involving coastal vegetation. This study experimentally investigated the effectiveness of Hibiscus Tiliaceus coastal vegetation in reducing tsunami bores generated by the dam-break method. Records of tsunami bore characteristics are presented, along with reductions in tsunami bore height for various vegetation widths and tsunami bore characteristics. The results show that H. tiliaceus vegetation effectively reduces tsunami bore height through mechanisms of hydraulic resistance and energy dissipation. An increase in the vegetation width ratio (W_v/h_b) correlates with higher tsunami bore reduction coefficients and a greater percentage of tsunami bore reduction. At a vegetation width (W_v) of 6 m and h_0 of 0.1 m, a 34.14% reduction compared to the "no-vegetation" conditions was observed. The R^2 values for the dimensionless parameters of the tsunami bore reduction coefficient were $R^2 = 0.4005$ at $h_0 = 0.08$ m and $R^2 = 0.6498$ at $h_0 = 0.1$ m, indicating instability and the potential for overtopping of coastal vegetation, but a positive trend was observed. These findings indicate that vegetation width, initial water depth, and tsunami bore characteristics are crucial for planning ecosystem-based disaster risk reduction strategies in vulnerable coastal areas.

Keywords-tsunami mitigation; dambreak method; coastal vegetation

I. INTRODUCTION

Tsunamis are ocean waves that can cause significant damage to coastal areas, particularly when triggered by earthquakes or volcanic activity [1]. The strength of a tsunami approaching land is characterized by its kinetic energy and hydrodynamic forces, which can have a significant impact, including the potential for severe damage to coastal morphology, coastal forests, and infrastructure in coastal and inland areas [2]. Conversely, coastal areas are experiencing rapid development due to their aesthetic appeal, which makes them potential tourist destinations. A large tsunami can inundate a substantial expanse of coastal terrain, thereby engendering profound devastation to human life and property. Therefore, it is significant to implement effective mitigation measures to reduce the impact of this disaster. One such measure is the use of coastal vegetation, the efficacy of which depends on the tsunami's height at the coast, the arrangement of the vegetation, and its inherent resilience. Coastal vegetation is an effective natural solution for catching debris generated by tsunamis [3-5], providing buffer zones and escape routes for people caught in a tsunami, and offering a natural ecosystem in the coastal environment [6]. However, it does not entirely reduce the energy of a tsunami. Previous studies on the effectiveness of natural protection systems have shown that vegetation with sufficient width and density can effectively dampen wave energy and adapt to rising water levels [7].

Research has demonstrated the significant role of the tree Hibiscus Tiliaceus in tsunami mitigation, comparable to other coastal vegetation such as Casuarina Equisetifolia and Terminalia Catappa [8]. Similar findings were obtained through simulations at Sissano Lagoon in Papua New Guinea, which showed that the presence of H. tiliaceus can reduce the tsunami hydraulic force by approximately 67%, with a scenario of four large trees per 100 m^2 proving very effective at reducing wave energy [9, 10]. Furthermore, the collection of coastal vegetation data in Purworejo, Central Java, also documented H. tiliaceus as one of the species capable of providing natural protection from extreme waves [11]. Studies on coastal ecology have shown that H. tiliaceus, as non-mangrove vegetation, is highly effective at complementing coastal vegetation, not only for protection against tsunamis but also against storms and other extreme wave events [12, 13]. The results of additional experimental studies corroborate the finding that vegetation density is substantial [14, 15]. An increase in density attenuates wave transmission, underscoring that H. tiliaceus is an integral element of vegetation-based mitigation strategies to confront coastal disaster threats.

Besides the literature on coastal vegetation for tsunami mitigation, there are several important limitations. Previous experimental studies have mainly focused on a narrow range of hydrodynamic conditions and limited spatial extents, often conducted at prototype or near-prototype scales [16]. This focus creates significant knowledge gaps in applying results to real-world scenarios and to larger spatial scales. Furthermore, much of the existing research is concentrated on exotic species such as Casuarina equisetifolia and Pandanus odoratissimus [17, 18]. Despite their use, the specific mechanisms of tsunami attenuation remain insufficiently understood, and the Manning roughness coefficients exhibit substantial variation across different studies and vegetation types [19].

The ecological implications of relying on these exotic species raise serious concerns. For instance, Casuarina plantations have been shown to accelerate dune fixation, suppress native psammophilous species, and destroy sea turtle nesting habitats, ultimately reducing overall coastal biodiversity [20-22]. These findings underscore the need for native alternatives that can provide effective tsunami mitigation without compromising long-term ecological sustainability. In this context, H. tiliaceus represents a promising native species that has received limited scientific attention. Unlike mangroves, which are restricted to intertidal mudflats, H. tiliaceus is a versatile species documented for its ability to fortify natural protection across diverse tropical coastal regions while supporting local biodiversity [20, 23]. Quantitative data on the species-specific attenuation capacity of H. tiliaceus, particularly regarding the influence of its unique stem structure, canopy density, and vegetation width, remain scarce [16]. This lack of detailed physical data aligns with [24], which emphasized that the effectiveness of nature-based solutions is primarily dependent on the precision of environmental parameter mapping. Without metrics such as stem structure and canopy density, which serve as crucial indicators for risk management rather than mere additional variables, effective protection strategies in coastal zones are challenging [25]. The present study addresses these knowledge gaps through an experimental investigation of the efficacy of H. tiliaceus in mitigating tsunami bores.

II. MATERIALS AND METHODS

A. Experimental Setup

The laboratory studies were conducted at the Hydraulics Laboratory of the Department of Civil Engineering, Hasanuddin University, Indonesia. The experiments were carried out in a flume measuring 15 m in length, 0.3 m in width, and 0.45 m in height. Vegetation models were placed after a 1:10 beach slope in the coastal land area. Tsunami waves were generated in the flume using the dam-break mechanism. This method is based on the ratio of the water level in the reservoir (h_1) to the initial water level (h_0), between which a dam-break gate is placed. The water height ratio (h_1/h_0) is indicative of the strength/magnitude of the tsunami bore, with a fully developed bore (strong bore) characterized by $h_1/h_0 > 2$ and an undular bore by $h_1/h_0 < 2$. The dam-break gate was raised quickly using an 8 kPa pressurized pneumatic system. As the dam-break gate began to elevate, water from the reservoir (upstream) flowed behind it, forming a tsunami bore directed toward the coast. The resulting tsunami bore persisted until the bore length (L_b) of 9.81 m was a non-decaying bore [26, 27]. Table I shows the experimental conditions. The Froude number, F, was determined as:

$$F = \frac{u_b}{c_0} \tag{1}$$

where $c_0 = \sqrt{gh_0}$ is the long wave velocity in front of the bore, and $F > 1$ is a positive bore surging. Using the conservation of mass and momentum around the bore, the bore strength can be related to u_b, h_b, and h_0 as [27]:

$$\frac{u_b}{c_0} = F\frac{\sqrt{1+8F^2}-3}{\sqrt{1+8F^2}-1} \tag{2}$$

$$\frac{h_b}{h_0} = \left(\frac{c_b}{c_0}\right)^2 = \frac{1}{2}\left(\sqrt{1+8F^2}-1\right) \tag{3}$$

where $c_b = \sqrt{gh_b}$ is the bore celerity. The ratio between the water depths on both sides of the gate can be calculated as a function of bore strength:

$$\frac{c_1}{c_0} = \frac{1}{2}\frac{u_b}{c_0} + \frac{c_b}{c_0}, \tag{4}$$

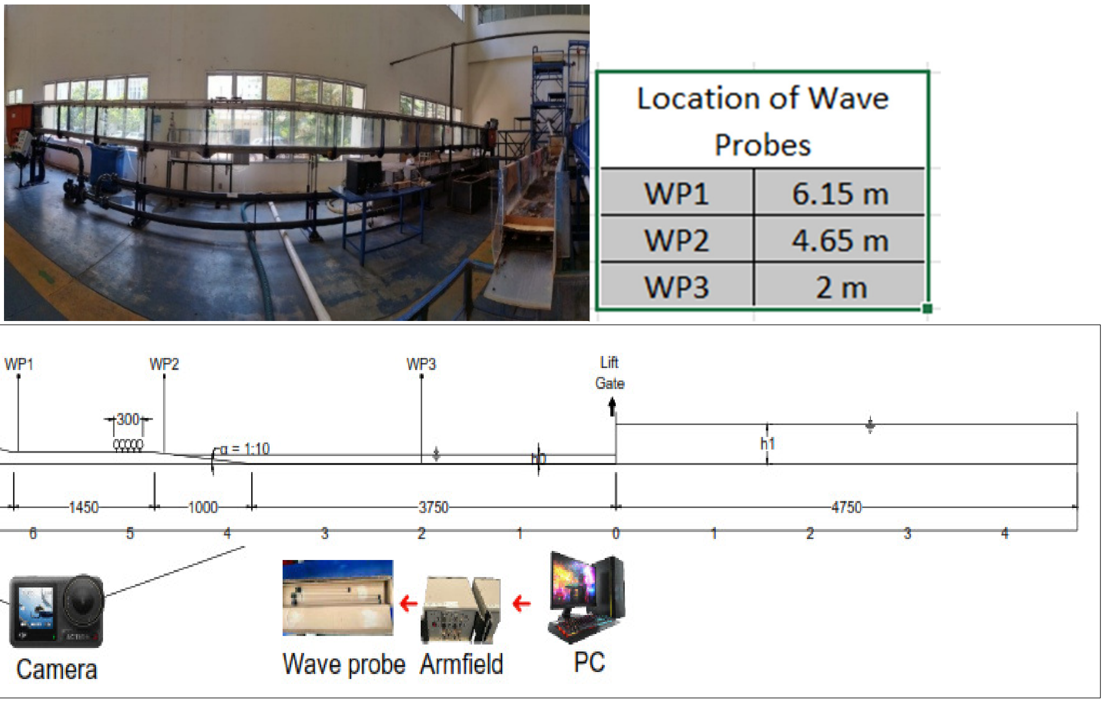
In the present study, the water level was measured using a wave probe connected to a computer running Eagle WVFW software. The measurements were collected for 10.9 s at 100 Hz. The video camera used for recording was a DJI Osmo Action 4, which recorded at 4 K. The dimensions of the recording area were 0.45 m high and 4 m long. The research facilities and equipment used are displayed schematically in Figure 1.

TABLE I. EXPERIMENTAL CONDITIONS AND VEGETATION CONFIGURATION

W_v (m)	h_0 (m)	F	h_1 (m)	L_x=L_y
0	0.1, 0.08	1.74, 1.66, 1.58, 1.50, 1.41, 1.96, 1.86, 1.77, 1.65, 1.57	0.34, 0.31, 0.28, 0.25, 0.22	6
0.3				
0.6				

B. *Vegetation Model*

The vegetation model employed in the present study was developed to emulate the characteristics of the Waru tree (H. tiliaceus), which is widely encountered in coastal ecosystems. Its trunk height and diameter can range from 5–15 m and 0.5 m, respectively. The H. tiliaceus trunk is characterized by its hardwood, round shape, numerous branches, and brown color. The trunk of H. tiliaceus depends on soil conditions, with a strong correlation between soil fertility and trunk straightness. To accommodate the limitations of the experimental flume, the H. tiliaceus tree was replicated as a physical model at a 1:100 scale, with its morphological features maintained. The original H. tiliaceus tree and corresponding model are depicted in Figure 2.



Location of Wave Probes	
WP1	6.15 m
WP2	4.65 m
WP3	2 m

Fig. 1. Flume and experimental setup.

Fig. 2. Hibiscus tiliaceus and the respective model used in the study.

The tree model, fabricated from synthetic materials, had the following dimensions: 0.13 m tall, with a crown width of approximately 0.05 m and a crown height of 0.08 m. The trunk diameter of the model was 0.005 m. The parameters were selected to ensure that the interaction between the tsunami bores and the vegetation model could accurately describe the relevant hydrodynamic phenomena at the field scale. To test this, vegetation widths of 0.3 m and 0.6 m were used in the model. The parameters and placement configuration of the H. tiliaceus coastal vegetation are illustrated in Table I and Figure 3.

III. RESULTS AND DISCUSSION

A. *Characteristics of Tsunami Bores and Water Level Fluctuations*

In the context of their interaction with coastal vegetation, tsunami bores alter water-level fluctuations behind the vegetation. As demonstrated in Figure 4, the water level of the tsunami bores decreased after passing through H. tiliaceus.

The water levels at vegetation widths of W_v = 0.3 m and W_v = 0.6 m were lower than those in the condition without vegetation. This phenomenon can be attributed to vegetation as a natural barrier that increases hydraulic resistance to the incoming tsunami bore, and to its structure, which provides a larger contact area that inhibits flow and dissipates the tsunami bore's energy.

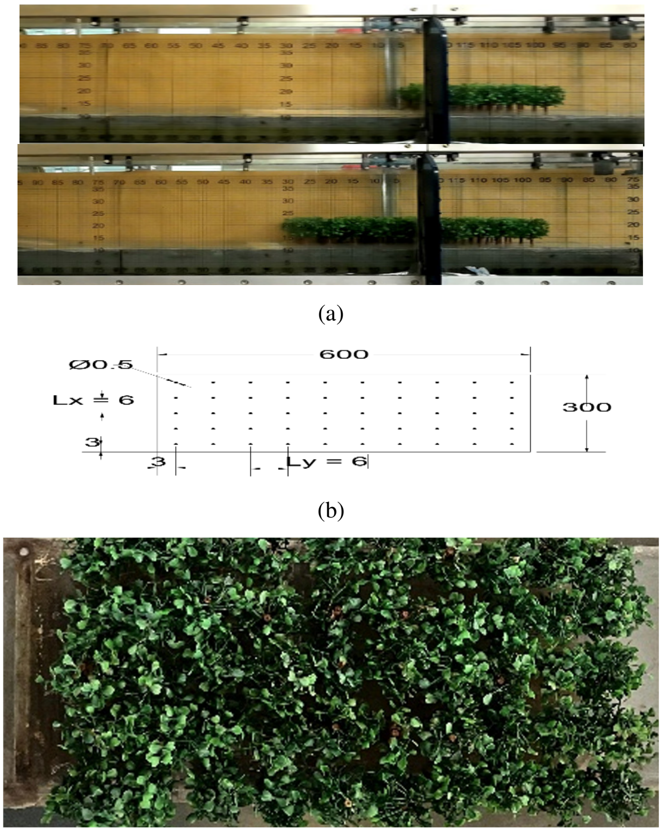


Fig. 3. Placement of coastal vegetation on the flume: (a) vegetation width (W_v) = 0.3 m, (b) vegetation thickness (W_v) = 0.6 m, and (c) coastal vegetation placement parameters for W_v = 0.6 m.

As presented in Figures 4(b) and 4(c), the maximum water level of the tsunami bore for the tsunami bore height ratio (h_b/h_0) = 2 exhibits a relatively steep incline prior to reaching the vegetation, in contrast to the h_b/h_0= 2.25 scenario, where the maximum water level of the tsunami bore presents a relatively gentle incline and is located somewhat further away before reaching the vegetation.

B. Reduction of Tsunami Bores

The reduction of tsunami bores was analyzed using the reduction coefficient:

$$C_r = \frac{(\eta_{average}\,WP_3 - \eta_{average}WP_1)}{\eta_{average}\,WP_3} \tag{5}$$

where C_r is the tsunami wave reduction coefficient, $\eta_{average}WP_3$ is the water level height at WP_3 before vegetation or the tsunami wave height (h_b), and $\eta_{average}\mathrm{WP}_1$ is the water level height at WP_1 as it propagates toward the land; if vegetation is present, it represents the measured water level height after vegetation.

1) The Effect of Vegetation Width (W_v/h_b) on Tsunami Bore Reduction

Figure 5 shows the relationship between the vegetation width ratio (W_v/h_b) and the reduction coefficient (C_r) under various conditions of tsunami bore height and initial water level height ratio (h_b/h_0). In general, both graphs show that an increase in W_v/h_b is typically followed by an increase in C_r values, indicating that wider coastal vegetation is better at reducing tsunami bores. This phenomenon is related to increased flow resistance and energy dissipation due to the interaction between the tsunami bore and vegetation components (trunks and canopy). Figure 5(a) exhibits a consistent trend in C_r across all widths, with some values showing minimal disparity, regardless of the thickness. Compared with Figure 5(b) at $W_v/h_b = 3$, the C_r value increases relative to W_v/h_b = 1.5.

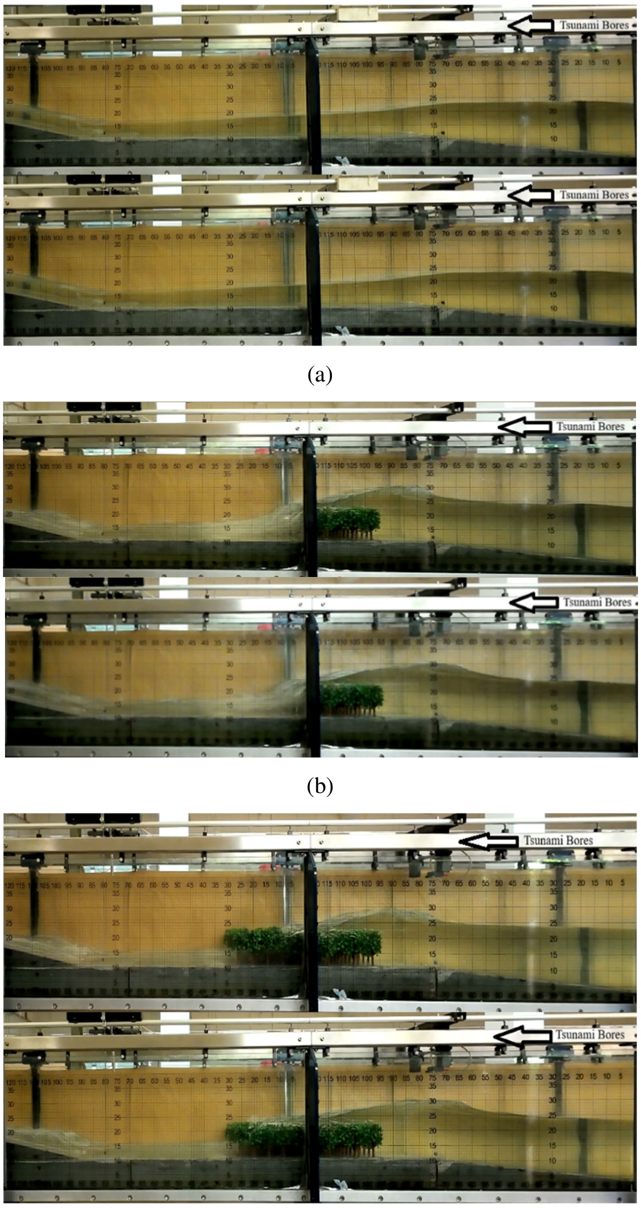


Fig. 4. Tsunami bore characteristics at a time interval of 4.1 s with h_b/h_0 to be 2 and 2.25 when (a) W_v = 0 m, (b) W_v = 0.3 m, and (c) W_v = 0.6 m.

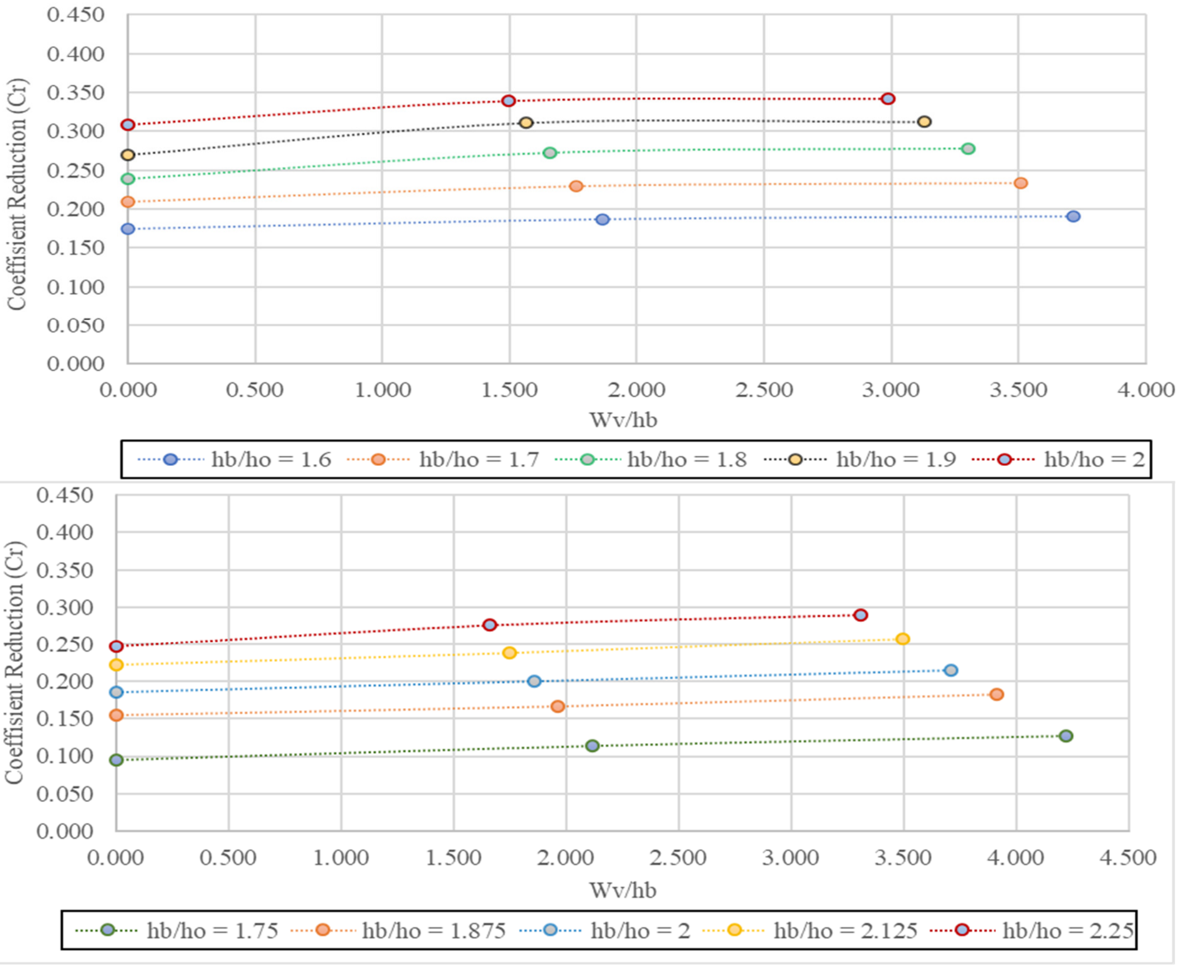


Fig. 5. Effects of vegetation width ratio and (W_v/h_0) on the reduction coefficient (C_r) and the tsunami bore height ratio (h_b/h_0): (a) h_b/h_0= 1.6, 1.7, 1.8, 1.9, 2.0, and (b) h_b/h_0= 1.75, 1.875, 2.0, 2.125, 2.25.

The impact of the tsunami bore height ratio (h_b/h_0) shown in Figures 5(a) and 5(b) on the C_r indicates that the relative differences in C_r values across all variations are linearly correlated. This finding aligns with previous studies that assert the influence of tsunami bore characteristics on vegetation effectiveness. Specifically, these studies indicate that in cases of substantial tsunami bore conditions, the initial water-level characteristics persist as significant factors, even in the presence of dense coastal vegetation [7, 17, 28, 29].

2) *The Effect of Vegetation Width on the Dimensionless Parameter of the Tsunami Bore Reduction Coefficient* ($C_r{}^{0.5}/(h_b/h_0)^{1.5}$)

The relationship between vegetation width and the dimensionless tsunami bore reduction coefficient ($C_r{}^{0.5}/(h_b/h_0)^{1.5}$) is presented in Figure 6, which shows that H. tiliaceus can attenuate tsunami bores with an attenuation coefficient ranging from 0.11 to 0.34. This analysis revealed a linear correlation among C_r, vegetation width ratio, and initial water depth, consistent with the theory that energy dissipation increases with coastal vegetation width [7, 30]. However, this effectiveness is highly influenced by the hydrodynamic conditions. At h_0 = 0.08 m, the gentle slope of the graph and lower correlation value (R^2 = 0.4005) indicate that higher tsunami energy can overcome the vegetation's hydraulic resistance. This phenomenon of reduced effectiveness at high energy levels aligns with the performance of nature-based solutions [28, 29]. Conversely, the stronger performance at h_0 = 0.1 m (R^2 = 0.6498) confirms that while H. tiliaceus is a natural mitigation measure capable of attenuating bore tsunamis; the plant's mitigation efficiency is highly dependent on the energy flux and height of the incoming tsunami bore, thus requiring precise calculations of hydrodynamic parameters in coastal protection planning.

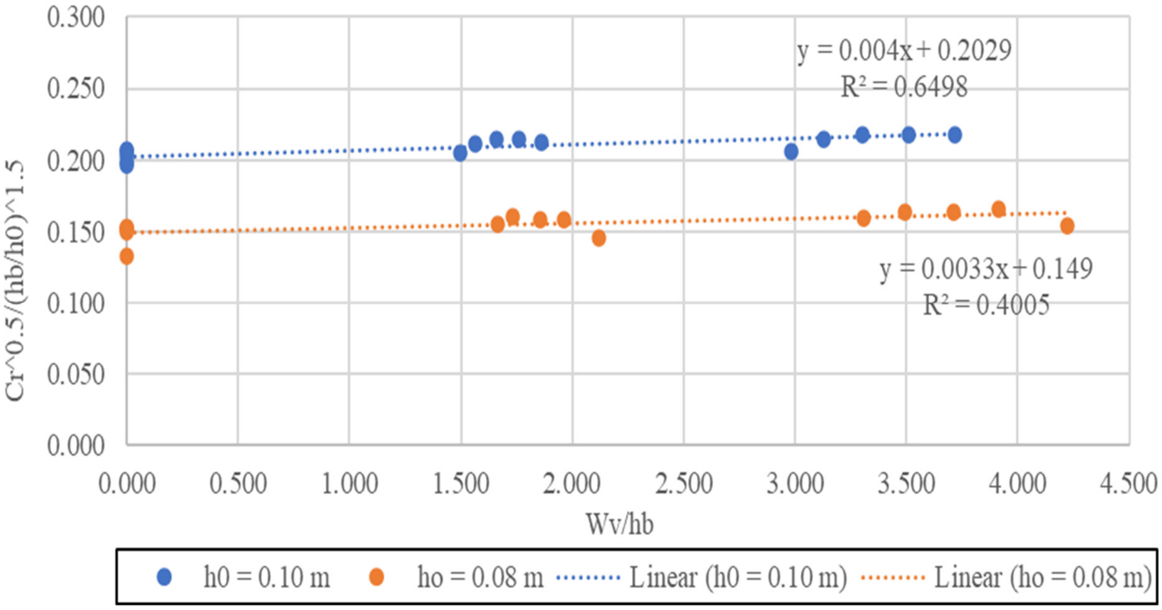


Fig. 6. Dimensionless reduction coefficient $\left(C_r{}^{0.5}/_{(h_b/h_0)^{1.5}}\right)$ in terms of the width of vegetation at the bore tsunami height (W_v/h_b), and initial water level height (h_0).

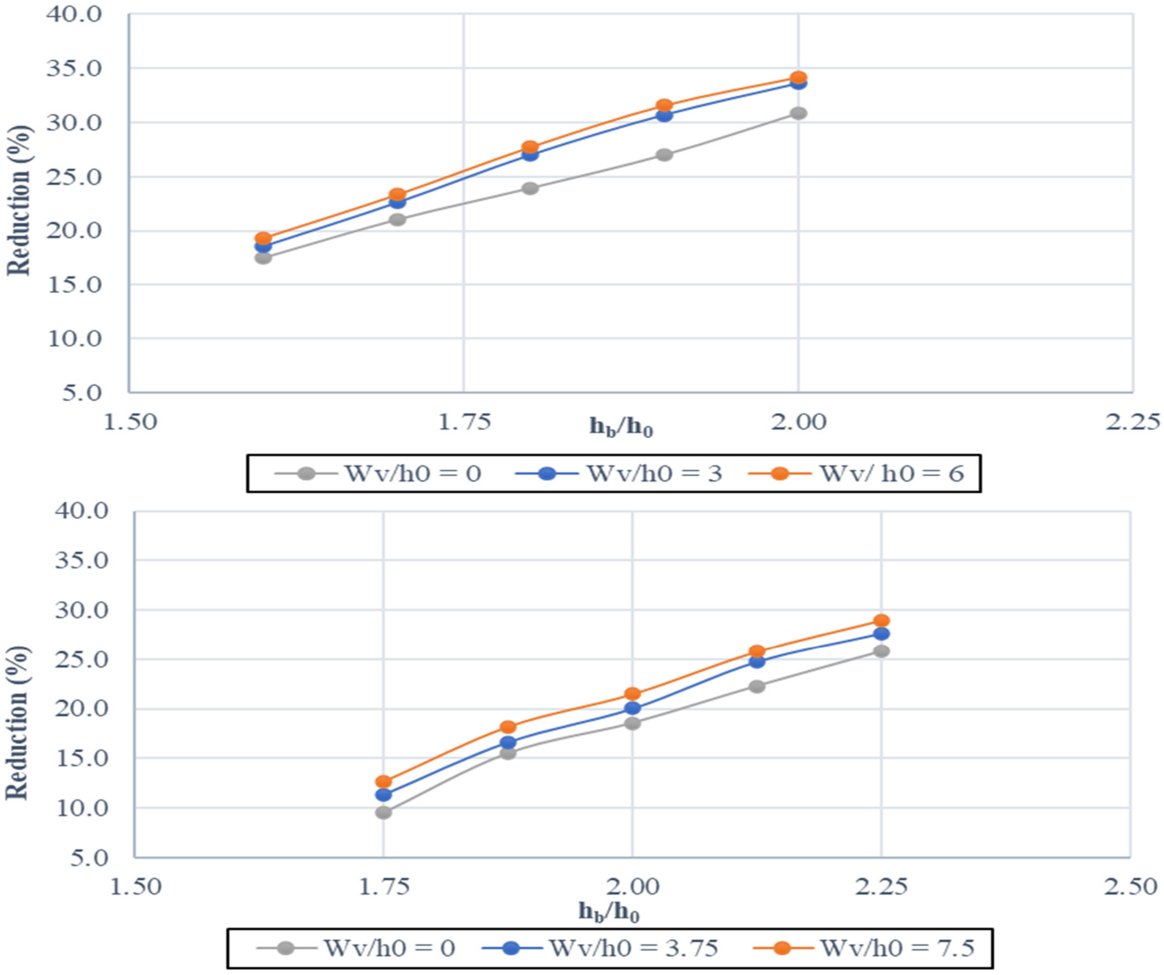


Fig. 7. Percent reduction of tsunami bores versus the ratio h_b/h_0.

3) Percentage of Tsunami Bore Reduction

Figure 7 shows that variations in coastal vegetation width (W_v/h_0) and the ratio of tsunami bore height to the initial water level (h_b/h_0) affect the percentage reduction in the tsunami bore height. As demonstrated in Figure 7(a), for the first condition (h_b/h_0 ranging from 1.6 to 2.0), the vegetation width of W_v/h_0= 6 resulted in the highest reduction, ranging from 19.36% to 34.14%. This is followed by W_v/h_0 = 3 with lower values ranging between 18.53% and 33.56%. In the second series, h_b/h_0 ranges from 1.75 to 2.25, as portrayed in Figure 7(b), W_v/h_0 = 7.5 resulted in a reduction to 12.68% and 28.97%, while W_v/h_0 = 3.75 decreased from 11.36% to 27.61%. The "no vegetation" case (W_v/h_0= 0) serves as a reference for natural attenuation due to bed friction and distance, which reaches up to 30.8% at h_b/h_0 = 2.0 for the maximum tsunami bore height. The additional reduction from vegetation, although shown as a small slope in the linear regression, indicates a positive trend: as vegetation width increases, energy dissipation increases. This result is in line with [7, 30-33] stating that greater vegetation width is more effective at dissipating wave energy [7, 30-33].

IV. CONCLUSIONS

This experimental study demonstrates that the coastal vegetation Hibiscus tiliaceus can reduce the force of tsunami bore waves through energy dissipation mechanisms, while also filling a knowledge gap by providing experimental data on the hydrodynamic attenuation of the tropical species H. tiliaceus, which has previously been understudied compared to other species such as Casuarina equisetifolia. The analysis shows that an increase in the relative width of vegetation linearly increases the reduction coefficient (C_r) and the percentage of height reduction because a wider coastal vegetation generates higher drag forces and reduces flow velocity. Attenuation is also evident at an initial water depth (h_0) = 0.1 m and under maximum tsunami bore height conditions. A relative vegetation width (W_v/h_0) = 6 results in a reduction of 34.14%, a higher attenuation compared to the "no vegetation" condition. As the vegetation width increases, the tsunami bore energy dissipation increases. Furthermore, this study highlights the importance of evaluating effectiveness using a nondimensional parameter based on the tsunami bore energy flux scaled by $h_b^{1.5}$, thereby further supporting previous theories that the initial characteristics of the tsunami bore significantly impact mitigation effectiveness, even in dense coastal forests. Despite data variability, as indicated by R^2 values ranging from 0.4005 to 0.6498, reflecting turbulence and the potential for tsunami bores to overtop coastal vegetation, the positive trend confirms that H. tiliaceus can serve as a natural tsunami mitigation measure. Optimizing vegetation width and understanding the characteristics of incoming tsunami bore waves are crucial for the success of ecosystem-based tsunami mitigation strategies in vulnerable coastal areas.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

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DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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