

Behavior Propagation of Surge Tsunami in Casuarina Equisetifolia Forest

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Abstract—Indonesia is highly vulnerable to tsunami hazards due to its tectonic setting within the Pacific Ring of Fire. Coastal vegetation such as Casuarina equisetifolia forests has been widely considered a natural mitigation measure capable of reducing tsunami wave energy. This study aims to analyze the propagation behavior of surge tsunamis and evaluate the effectiveness of Casuarina equisetifolia coastal forests in reducing tsunami flow velocity. This research was conducted using a physical model simulation approach in the laboratory, using a dam break-based tsunami wave generation method by making a simulation of the flume used measuring 16.80 m x 1.0 m x 0.8 m equipped with a dam break gate. Making a model of a casuarina forest is done by observing and measuring tree dimensions, plant spacing and density. The research results show that there was a decrease in water velocity for the tsunami model $d_0 = 60$ cm for the model without canopy 1 m is 21.09%, 2 m is 29.36%, and 3 m is 36.50%. The decrease surge velocity due to the model with canopy 1 m is 21.71 %, 2 m is 29.67 %, and for 3 m is 40.40 %. For the velocity function to be changed to $f V$ (m, L, n, ξ). The tree canopy effect is quite effective for high tsunamis but for low tsunami it is not effective, because the tsunami surge will propagate through the tree trunks below canopy.

Keywords— Surge Tsunami, Greenbelt, Casuarina Equisetifolia.

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I. INTRODUCTION

Tsunamis are among the most destructive natural hazards affecting coastal regions, often resulting in significant loss of life and severe damage to infrastructure. One of the most devastating events was the Indian Ocean tsunami on 26 December 2004, which caused more than 300,000 fatalities worldwide and led to catastrophic destruction in many coastal areas. A tsunami is a series of large ocean waves generated by disturbances such as undersea earthquakes, submarine volcanic eruptions, or large objects falling into the sea [1].

Indonesia is highly vulnerable to tsunami hazards because it is located at the convergence of major tectonic plates, particularly the Eurasian Plate and the Indo-Australian Plate. The interaction and collision of these plates frequently generate strong earthquakes that can trigger tsunami events [2]. In addition, Indonesia lies within the Pacific Ring of Fire, a region characterized by intense seismic and volcanic activity surrounding the Pacific Ocean basin. This area contains numerous active volcanoes and experiences frequent earthquakes, making it one of the most geologically active regions in the world.

Disaster management aims to minimize the risks and impacts caused by natural hazards. Tsunami mitigation can be implemented through structural (*hard engineering*) and non-structural (*soft engineering*)

approaches [3]. Structural mitigation commonly involves the construction of coastal protection structures such as breakwaters and seawalls. In contrast, non-structural mitigation emphasizes natural protection systems, including the use of coastal forests as biological barriers [4]. According to the Coastal Development Institute of Technology (CDIT) Japan (2009), many villages affected by the 2004 Aceh tsunami experienced severe damage in open coastal areas that lacked vegetation such as mangroves, casuarina trees, or other coastal plants. In contrast, villages protected by coastal forests suffered significantly less damage, and some areas remained relatively unaffected. These observations suggest that coastal forests can reduce tsunami impacts and minimize the extent of damage in coastal communities. In addition to attenuating wave energy, coastal forests can also contribute to saving human lives during tsunami events, as tree trunks and branches may provide support for people to hold onto or climb to safer elevations above the water level [5].

The height and velocity of tsunami waves change significantly as they propagate from the deep ocean toward coastal areas. This transformation occurs primarily due to variations in water depth. As the wave approaches shallower waters, the shoaling effect causes an increase in wave height while the wave velocity decreases due to bottom friction. When the tsunami reaches the shoreline, the wave often transforms into a surge-like flow similar to the wave generated by a dam-break phenomenon [6].

Research on tsunami mitigation based on coastal vegetation has developed rapidly over the past decade. Numerous studies have shown that coastal vegetation such as mangroves and coastal forests can function as bio-shields capable of dissipating wave energy, reducing wave height, and decreasing flow velocity before the waves reach inland areas. Experimental research conducted by Chen *et al.* demonstrated that the presence

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of mangrove forests can significantly reduce the height of tsunami bores, particularly when vegetation density increases. The interaction between tree trunks and vegetation structures generates hydrodynamic resistance to the incoming wave flow [7]. Other studies have also confirmed that vegetation morphology, including trunk density and canopy structure, strongly influences the process of wave energy dissipation and alters hydrodynamic characteristics within vegetated areas [8]. Furthermore, recent research indicates that mangrove forests can significantly contribute to reducing coastal flood risk and wave energy through mechanisms of wave attenuation and increased flow friction within vegetation zones [9]. Recent literature reviews also emphasize that coastal vegetation represents an effective nature-based solution for tsunami mitigation when designed with appropriate consideration of vegetation type, density, and planting configuration [10]. However, most studies still focus primarily on mangrove ecosystems, and experimental investigations that specifically evaluate tsunami propagation interactions with other coastal vegetation species, such as *Casuarina equisetifolia*, remain relatively limited.

The novelty of this study lies in the use of *Casuarina equisetifolia* vegetation as a coastal greenbelt in tsunami mitigation studies, which has been relatively less explored compared to mangrove vegetation. This research evaluates the role of coastal pine forest structures in reducing tsunami propagation velocity through a laboratory-based physical modeling approach.

Therefore, this study aims to analyze the propagation behavior of surge tsunamis and evaluate the effectiveness of *Casuarina equisetifolia* coastal forests in reducing tsunami flow velocity through laboratory-based physical modeling using a dam-break tsunami generation method. The findings contribute to a better understanding of the role of coastal vegetation structure in tsunami energy dissipation and provide practical insights for the design of coastal greenbelt systems for tsunami mitigation.

Literature Review

Tsunamis are long-period ocean waves that are generally caused by major disturbances on the seabed, such as tectonic earthquakes, submarine volcanic eruptions, or underwater landslides. Tsunami waves have very long wavelengths, allowing them to propagate at high speeds in deep ocean waters. As a tsunami moves toward coastal areas, its wave characteristics change due to variations in water depth and bottom friction. In shallow water, a shoaling process occurs in which the wave height increases while the propagation velocity decreases [11]. When the wave reaches the shoreline, it often transforms into a rapidly moving surge or bore that can propagate inland. This phenomenon has hydrodynamic characteristics similar to flows generated by a dam-break event, which involves the sudden release of a large mass of water producing a steep and fast-moving wave front. Therefore, the dam-break modeling approach is frequently used in laboratory studies to simulate tsunami propagation in coastal areas [12].

In the hydrodynamic analysis of tsunamis, several important parameters influence wave behavior, including water depth, seabed slope, surface roughness, and the presence of obstacles along the wave propagation path. These obstacles may consist of artificial structures or natural elements such as coastal vegetation. Vegetation growing in coastal areas can significantly influence tsunami flow characteristics because plant stems, roots, and canopies increase resistance to water flow. This resistance generates drag forces that enhance friction and turbulence in the flow, gradually reducing wave energy. Studies on the interaction between waves and vegetation have been widely conducted using laboratory experiments and numerical simulations. Several studies have shown that coastal vegetation can reduce wave height, decrease flow velocity, and lower hydrodynamic forces acting on structures in coastal areas [13], [14].

The concept of a coastal greenbelt is one disaster mitigation approach that utilizes vegetation as a natural protective barrier for coastal areas. This vegetation belt functions as a buffer zone that dissipates wave energy before waves reach settlements or infrastructure. Various types of vegetation have been studied in the context of tsunami mitigation, particularly mangroves, which are known for their complex root systems and high vegetation density. Experimental studies have shown that mangrove forests can effectively reduce wave energy through the resistance generated by their stems and roots, which increases flow resistance. In addition, hydrodynamic studies indicate that the width of vegetation belts, plant density, and planting configuration strongly influence the effectiveness of wave attenuation [15], [16], [17].

In addition to mangroves, several other coastal plant species are used as protective coastal belts, one of which is *Casuarina equisetifolia*, commonly known as the beach she-oak or coastal pine. This tree species is widely found in tropical and subtropical coastal areas and is known for its strong adaptability to coastal environments. *Casuarina equisetifolia* can grow in sandy soils with high salinity levels and possesses a relatively strong root system capable of stabilizing soil and reducing erosion. Its slender trunk structure combined with dense branches and canopy makes this plant potentially effective in providing resistance to incoming wave flows. For this reason, coastal pine trees are often planted as coastal forest belts to protect coastal regions from sea winds, coastal erosion, and extreme waves [18].

Several previous studies have examined the growth characteristics and vegetation structure of *Casuarina equisetifolia* in coastal areas. The results indicate that planting patterns, tree density, and root system development can influence soil stability and vegetation resilience under coastal environmental conditions [19]. Furthermore, research on the interaction between coastal vegetation and wave dynamics shows that the presence of tree trunks and canopy structures can increase flow resistance, resulting in a reduction in flow velocity and changes in energy distribution within the water column [14]. In open-channel hydrodynamic studies, this increase in resistance can be explained through the

concept of hydraulic roughness, which affects energy distribution and flow velocity in a channel [10].

Physical modeling in laboratories is one of the methods commonly used to study the interaction between tsunami waves and coastal vegetation. Through simulations in a wave flume, researchers can observe changes in flow characteristics such as wave height, flow velocity, and energy distribution before and after passing through vegetation zones. The dam-break wave generation method is widely used in tsunami studies because it can produce surge-type waves with characteristics similar to tsunamis when they reach coastal areas. Using this approach, the effects of vegetation parameters such as forest belt length, plant density, and canopy structure can be analyzed in a controlled environment to better understand the interaction mechanisms between tsunami flows and coastal vegetation [20].

In general, studies on coastal vegetation show that the presence of coastal forests can play an important role in reducing wave energy and slowing the propagation of tsunami flows toward inland areas. Vegetation functions as a natural element that increases flow resistance through interactions between plant stems, roots, and canopy structures with the water flow. These interactions generate increased turbulence and energy dissipation, resulting in reduced flow velocity and altered wave characteristics. Therefore, understanding the relationship between coastal vegetation characteristics and tsunami hydrodynamic behavior is essential for developing ecosystem-based disaster mitigation strategies in coastal regions.

Dam Break-based Tsunami Generation

This study was conducted using a laboratory-based physical model with a dam-break tsunami generation method to analyze the effect of *Casuarina equisetifolia* forests as a reducing factor in tsunami propagation under different forest lengths and densities. The dam-break method developed by [10] was used to generate tsunami waves in the laboratory. This study focuses on the reduction factor caused by tsunami run-up and does not consider the run-down effect. The analysis aims to obtain parameters that can be applied in the design of coastal areas for tsunami disaster mitigation. Equation (1) proposed by Chanson is used to calculate flow velocity and flow depth. The research flowchart is presented in Figure 1.

The physical model simulation was carried out in a wave flume measuring 16.80 m × 1.0 m × 0.8 m, equipped with a dam-break wave generation gate (Figure 2). The dam-break gate was constructed from multiplex boards and supported by a steel frame structure designed to lift a concrete load and release it rapidly, allowing the gate to open quickly. The gate-opening mechanism uses a quick-release system in which a 280 kg concrete load is attached to the gate and dropped from a height of 1 m to initiate the opening process (Figure 3). Figure 4 illustrates the tsunami generation mechanism when the gate is closed and after it is opened.

The initial water levels in the reservoir were varied at 0.2 m, 0.4 m, and 0.6 m to generate different wave heights. The dam-break gate was used as the reference point for the horizontal coordinate ($x = 0$), where the downstream direction is defined as positive (+) and the upstream direction as negative (-). The results of this simulation are used to evaluate the reduction in tsunami surge velocity as a function of the forest length, density, and layout of the *Casuarina equisetifolia* forest model.

II. METHOD

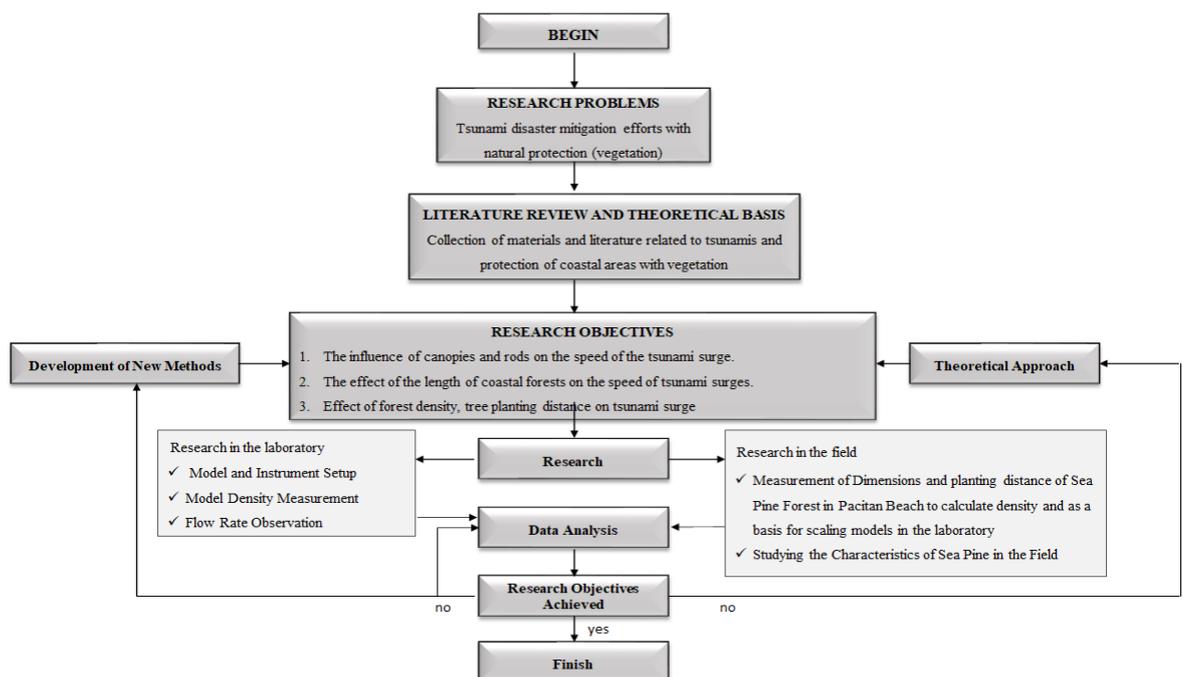


Figure 1. Flowchart Research



Figure 2. Channels used in Reasearch



Figure 3. Dam Break gate , load concrete , and cranes for tsunami model simulation

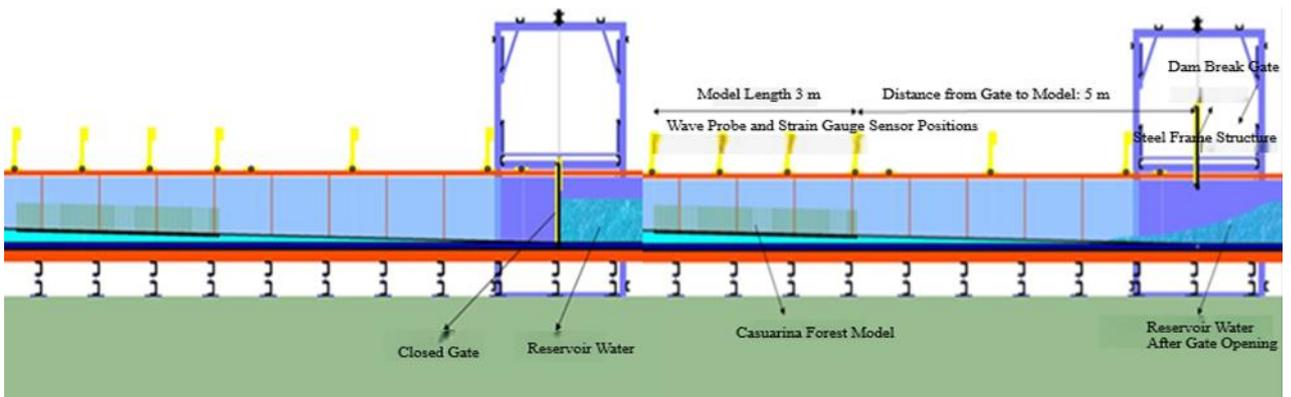


Figure 4. Mechanism current tsunami generation gate closed and open

The tsunami generation method in the channel is carried out by rapidly opening the separator gate between the upstream and downstream sections by dropping a 280 kg load. The gate-opening time is observed to determine the gate-opening velocity. If the gate-opening velocity is insufficient, part of the upstream water may be retained by the gate, resulting in a lower wave height than

expected. Therefore, the gate-opening height follows the reference proposed by Benazir *et al* [10]. To achieve the required flow velocity in the channel, a load of 280 kg is used to ensure that the gate opens rapidly. The relationship between gate-opening height and time observed in the laboratory is presented in Figure 5.

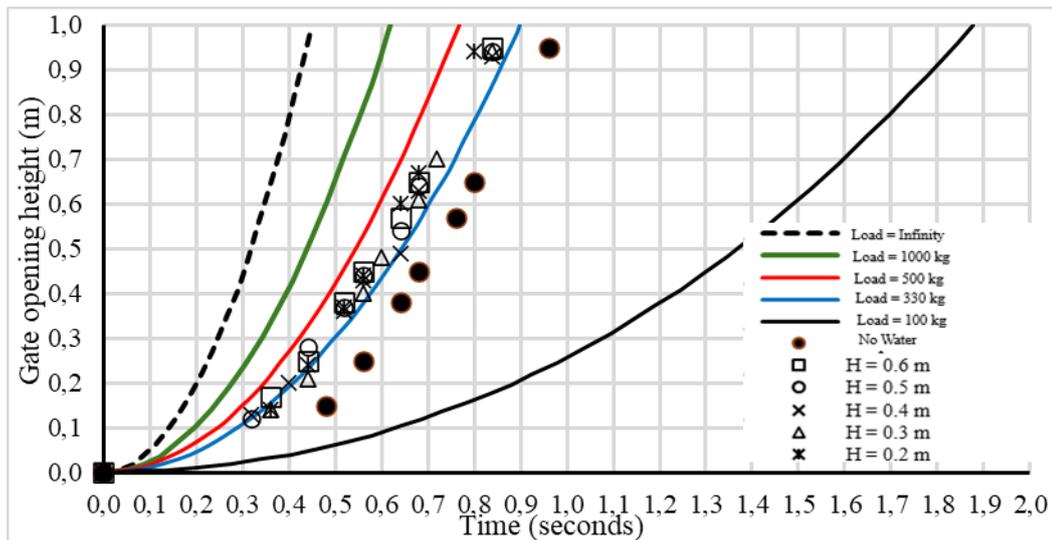


Figure 5. Gate opening height with time from research and Triatmadja, R 2010

Model of Casuarina Equisetifolia in Laboratory

The coastal forest (*greenbelt*) examined in this study consists of *Casuarina equisetifolia* trees. The casuarina tree model without a canopy was constructed using vertical rods with a diameter of 6 mm and a height of 55 cm. The vegetation density used in this model was based on field measurements, where the spacing between tree trunks in the model was set at 7.5 cm, corresponding to a measured density value of ζ (density) = 0.0011.

To prevent the 50 cm-high model from collapsing during the experiment, modifications were made to both the flume and the multiplex base. The multiplex base was doubled because the iron rods were embedded 5 cm deep, while the flume was modified by increasing the base depth by 5 cm (Figure 6).

For the vertical rod vegetation model, three different forest lengths were tested: 1 m, 2 m, and 3 m. For the 3 m forest length configuration, a total of 255 rods and 18 multiplex panels were installed prior to the experiment.

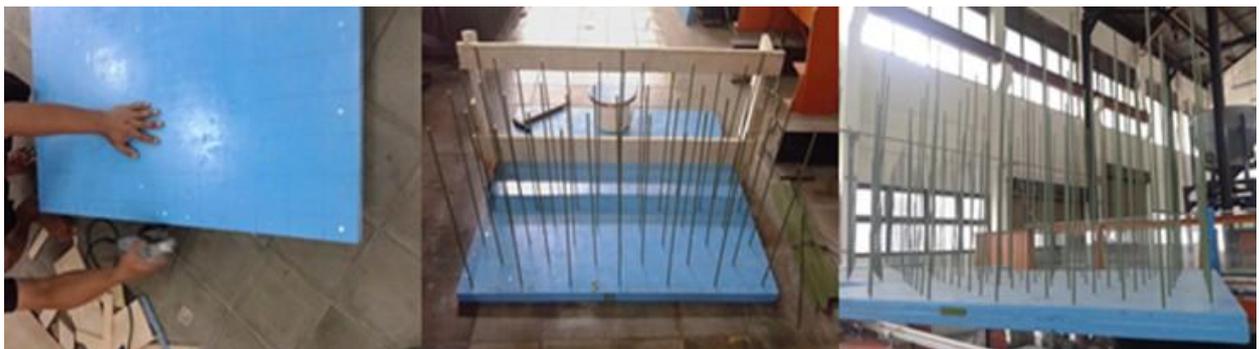


Figure 6. Casuarina model without canopy

The development of the tree canopy model requires consideration of three main plant components: the root structure, the stem, and the dense cover of branches and leaves known as the canopy. When coastal forests are used as greenbelts to reduce tsunami velocity and wave height, these three structural components play different roles in the attenuation process. The density of roots and stems primarily influences tsunami attenuation when the wave height is lower than the canopy level. However, when the tsunami height reaches the canopy, all plant components—roots, stems, and canopy—contribute collectively to the overall vegetation density that affects flow resistance. Anjum *et al.* investigated the parameters of coastal vegetation and their drag coefficients in relation to tsunami flows using mangrove and coastal pine models [21].

Figure 7 shows the casuarina vegetation model with a canopy. The number of models and the spacing

between the canopy model and the vertical rod model are the same, with a distance of 7.5 cm between rods. For the 3 m forest length configuration, a total of 255 rods were used. The fundamental difference between the two models lies in the presence of the canopy structure.

The vegetation density of the tree group was calculated based on the ratio between the volume of water displaced and the volume occupied by the model. The canopy model was constructed using palm fiber material, with a uniform spacing of 7.5 cm between trees. This configuration resulted in two vegetation density values: ζ_1 (density) = 0.0178 and ζ_2 (density) = 0.0356. The first density represents a planting pattern where four trees occupy one square area, while the second density represents a configuration where five trees occupy the same area.

The canopy height measured from the bottom of the channel is $4/5 H_m$, where H_m represents the total model

height. The total height of the vegetation model is 50 cm, consisting of a 10 cm stem height from the base and a 40 cm canopy height above the stem.



Figure 7. Casuarina model with canopy

Variation Simulation

The laboratory simulations conducted in this study included variations in model configuration, model dimensions, and tsunami wave height in the form of a bore. These variations are described as follows.

1. Forest length variation

The forest length was varied at 1 m, 2 m, and 3 m for both models without canopy and with canopy. These three forest-length variations were used to analyze the effect of forest length on the reduction of tsunami surge velocity as the wave propagates through the coastal forest model.

2. Wave height variation

Wave heights were varied by setting the upstream water levels at 0.2 m, 0.4 m, and 0.6 m. These water levels represent different tsunami magnitudes, corresponding to small, medium, and large tsunami events.

To measure tsunami surge velocity in the laboratory simulations, sensors were installed at several positions along the flume. The first sensor was placed at a distance of $1/2 L$ in front of the model, the second sensor was located at the front of the model, the third sensor was positioned at the rear of the model (L), and the fourth sensor was placed at a distance of $1/2 L$ behind the model, where L represents the length of the forest model. Figures 12 and 13 illustrate the experimental setup used to measure the tsunami surge velocity using four sensors for each variation in forest length and vegetation density.

Measurement Surge Tsunami Velocity

The measurement of surge tsunami velocity differs between simulations conducted without the forest model and those conducted with the forest model. For the

simulation without the forest model, the wave probe positions were arranged as follows: probe 1 was placed 2 m from the gate, probe 2 at 5 m from the gate, probe 3 at 8 m from the gate, and probe 4 at 10 m from the gate.

For simulations using the forest model, the probe positions were adjusted relative to the model location. Probe 1 was positioned at a distance of $1/5 L$ in front of the model, probe 2 at the front of the model (point 0), probe 3 at the rear of the model (L), and probe 4 at a distance of $1/5 L$ behind the model, where L represents the length of the coastal forest model used in the laboratory.

The surge tsunami velocity was determined by visually observing the time when the wave front reached each probe. By calculating the time difference between wave arrivals at probes located at known distances, the surge velocity could be obtained. In this study, the measurements of tsunami height and velocity focused on the surge front. The observed surge propagation time between probes was generally less than one second. The surge velocity can therefore be expressed as a function of distance and time as shown in the following equation.

$$U = \frac{\frac{x_{1-2}}{t_{1-2}} + \frac{x_{2-3}}{t_{2-3}} + \dots + \frac{x_{n-n+1}}{t_{n-n+1}}}{n_t} \quad (1)$$

where :

x_{1-2} : distance of sensor 1 and sensor 2 (m)

t_{1-2} : wave propagation time between sensor 1 and sensor 2

n_t : total distance between sensors from all sensors in the channel

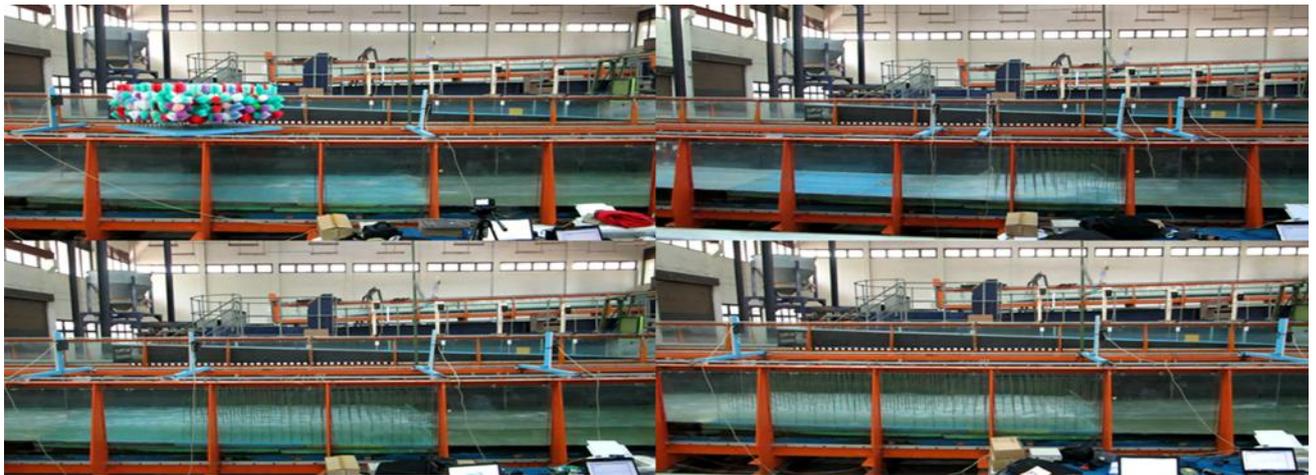


Figure 8. Simulation and Observation of Surge Tsunami in the Laboratory between without Forest and without Canopy Forest 1 m, 2 m, and 3 m



Figure 9. Simulation and Observation of Surge Tsunami in the Laboratory between without Forest and with Canopy Forest 1 m, 2 m, and 3 m

III. RESULTS AND DISCUSSION

The measurement of surge tsunami propagation after the wave breaks and reaches land was carried out through physical model simulations in the laboratory by calculating the time differences between wave arrivals. These time differences were obtained by observing video recordings that captured the movement of the surge front between probes, specifically from the first probe to the second probe, from the second probe to the third probe, and from the third probe to the fourth probe. The video recordings were then analyzed using the Ulead software. The movement of the tsunami surge could be observed frame by frame depending on the camera specifications and frame rate. The observed data were subsequently processed using Equation (1), and the calculation results are presented in Figures 10–12.

The results of the laboratory measurements using video observations show that, in the absence of the forest model, the surge velocity at a distance of 5 m from the gate for $d_0 = 0.6\text{ m}$ was 3.97 m/s, while the velocity at a distance of 8 m from the gate decreased to 3.12 m/s (Figure 12). This reduction in velocity occurs due to the influence of the channel bed slope (1:20) and the propagation distance. Therefore, the velocity can be

expressed as a function $V = f(m, L, n)$, where n represents the bed roughness coefficient.

The surge-type tsunami examined in this study represents a tsunami wave that has reached coastal areas and propagates inland as a surge flow after wave breaking occurs. In this study, the surge tsunami wave was generated using a dam-break mechanism in a laboratory channel, which is commonly used to simulate bore-type flows resembling tsunami propagation in shallow coastal regions. Previous analytical research described the hydrodynamic behavior of surge waves generated by dam-break flows and showed that such flows can approximate the propagation characteristics of tsunamis when the waves reach coastal areas [22]. Relationship between surge velocity, water depth, friction factors, and propagation time, providing a theoretical basis for interpreting the experimental observations in this study.

The comparison between the analytical solution and the laboratory measurements obtained in this study shows that both exhibit similar trends in the reduction of surge velocity as the wave propagates along the channel. As shown in Figure 3, the measured surge velocity gradually decreases with increasing distance from the

gate. This observation is consistent with theoretical predictions that energy losses due to channel bed friction and flow resistance reduce the momentum of the surge front over time

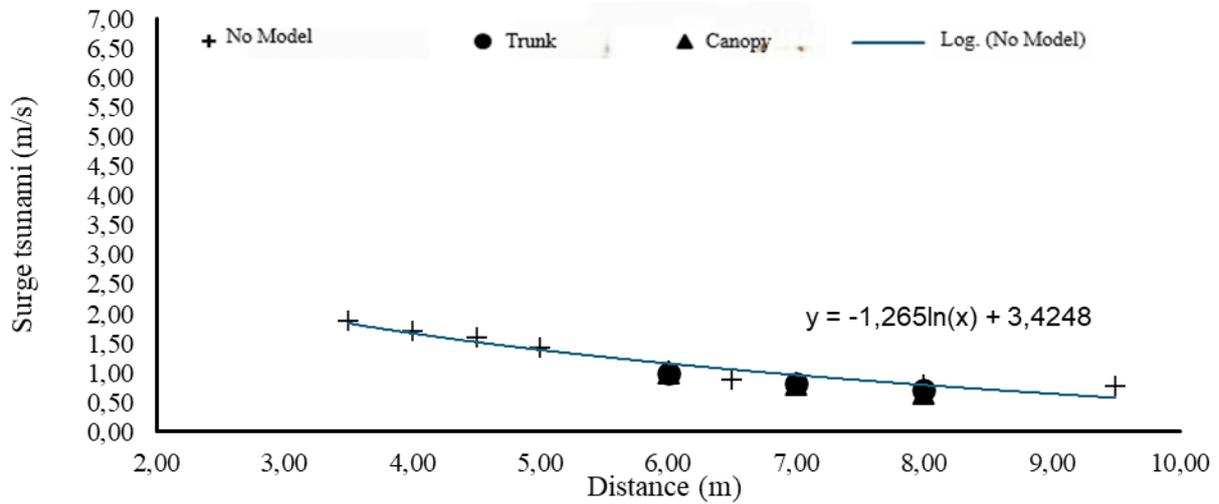


Figure 10. The surge tsunami front in channel $d_0 = 0.2$ m and $i = 1 : 20$

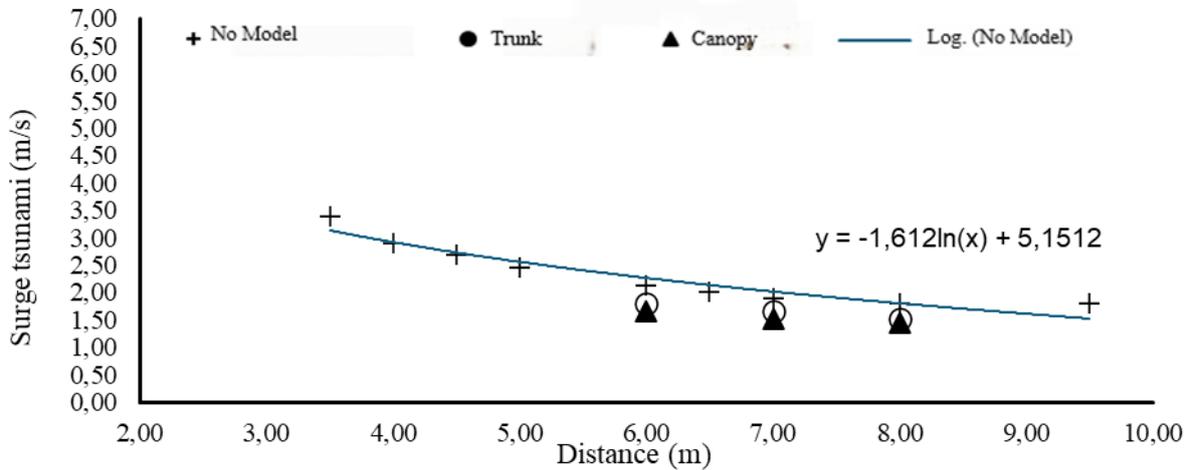


Figure 11. The surge tsunami front in channel $d_0 = 0.4$ m and $i = 1 : 20$

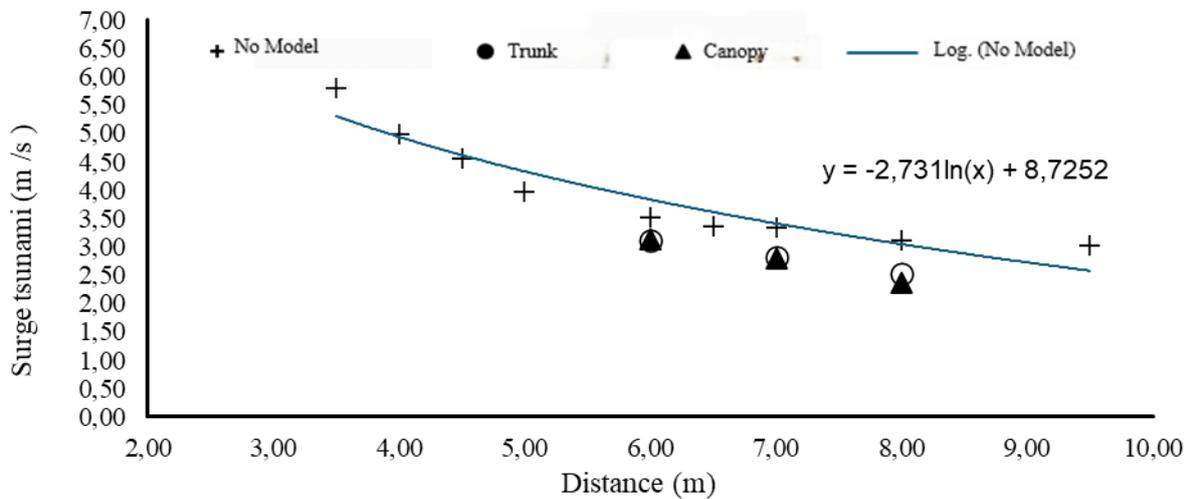


Figure 12. The surge tsunami front velocity profile in channel $d_0 = 0.6$ m and $i = 1 : 20$

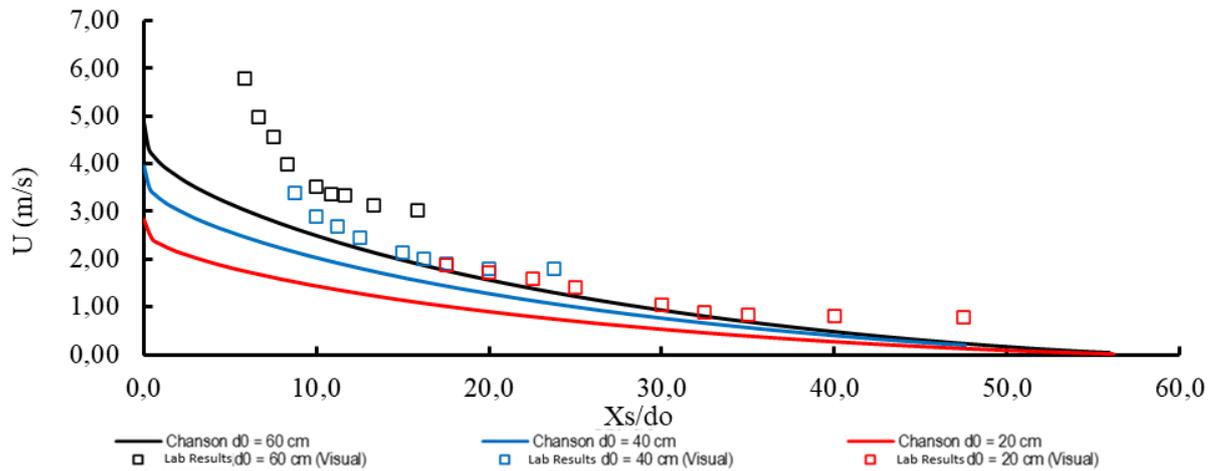


Figure 13. Comparison of surge tsunami between Chanson 2005 and research

Figure 14 shows the relationship between surge tsunami velocity and distance both in front of and behind the model for forest lengths of 1 m, 2 m, and 3 m. The reduction in water velocity for the model without a canopy after passing through the forest model was 21.09% for the 1 m model, 29.36% for the 2 m model, and 36.50% for the 3 m model. For the canopy model, the reduction in surge velocity was 21.71% for the 1 m model, 29.67% for the 2 m model, and 40.00% for the 3 m model. After the installation of the vegetation model in the channel, the velocity function changes to $V = f(m, L, n, \xi)$, where m represents the vegetation model parameters, L is the forest length, n is the bed roughness coefficient, and ξ represents the vegetation density factor. Among these parameters, the vegetation drag density factor has the most dominant influence on the reduction of surge velocity, compared with the channel slope and bottom roughness factors.

An analytical approach using Equation (1) was applied to compare the experimental results with existing theoretical models. The analysis indicates that the solution proposed by Aureli *et al.* provides a good approximation of the experimental results obtained in this study [23]. The tsunami surge velocity can therefore be expressed as $U = k\sqrt{gH}$, which describes the relationship between surge velocity and flow depth.

The results of this study show that flow passing through vertical rods is influenced by friction between the flow and the rods, as well as friction with the channel bed and channel walls. This friction generates resistance that reduces the flow velocity and causes an increase in water surface elevation. These findings are consistent with previous studies stating that surface friction in open-channel flows plays an important role in controlling energy distribution and flow velocity. Higher friction results in greater energy dissipation, which causes the water surface to rise in order to compensate for the energy losses [24].

As the flow passes through the vertical rod model, the resulting resistance increases turbulence and modifies the velocity distribution within the flow. Vertically oriented obstacles in a flow field can significantly

increase local turbulence and alter the velocity profile. This indicates that the interaction between the flow and vertical rods affects not only the flow velocity but also the energy distribution within the surrounding water column [25].

Simulations using the canopy model show that the flow characteristics in front of the canopy differ significantly from those around the vertical rods. The canopy structure, which has a high density and large surface area, produces a stronger blocking effect. Structures with low porosity and large surface areas, such as dense canopies, can significantly reduce flow velocity and increase energy accumulation in front of the structure, creating a damming effect [26].

The blocking effect generated by the canopy results in a substantial reduction in flow velocity and energy behind the model. This observation is consistent with previous studies indicating that dense structures within a flow can create stagnation zones downstream, leading to significant energy loss. Therefore, although friction between the rods, channel bed, and channel walls still contributes to flow resistance, the resistance generated by high-density canopy structures becomes the dominant factor influencing the overall flow characteristics [27]. The application of tsunami mitigation in this study involved the establishment of coastal forests and the monitoring of tree growth in the field. Coastal forests function as natural barriers that can reduce the impact of tsunami waves by absorbing wave energy and slowing water flow. This finding is consistent with previous studies highlighting the protective role of mangroves and coastal vegetation in reducing the impacts of storm surges and tsunamis. By measuring tree dimensions and growth rates, researchers can evaluate the effectiveness of forest structures in mitigating tsunami impacts over time [28]. The parameters observed include vegetation density based on planting patterns, root depth, root system structure, growth rate, and canopy development. In addition, efforts to facilitate evacuation and rescue during tsunami events were implemented by creating mitigation pathways between trees in a zig-zag pattern, as shown in Figure 19.

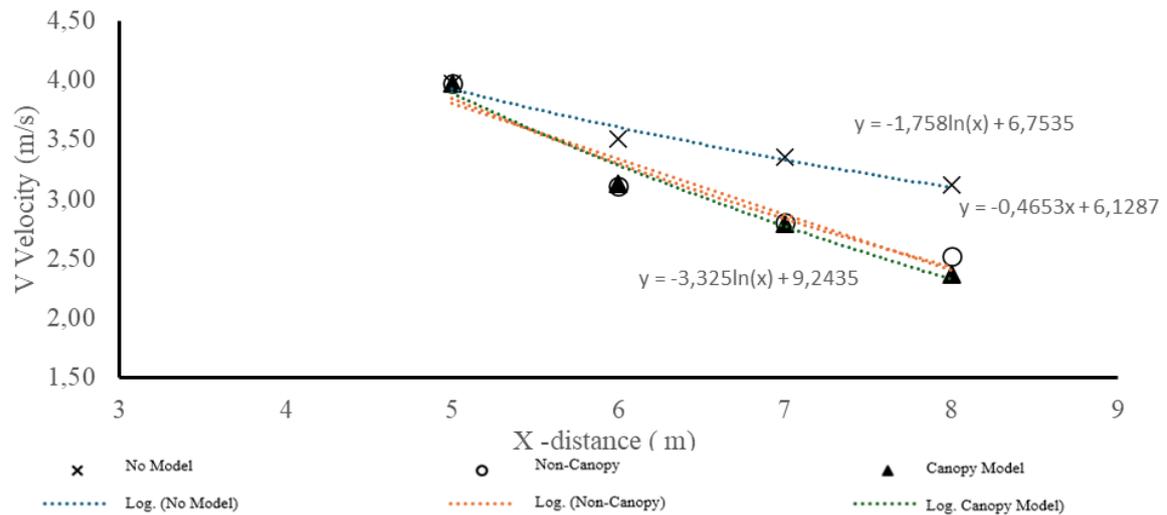


Figure 14. Relationship of surge tsunami to distance in the laboratory $d_0 = 0.2$ m; $d_0 = 0.4$ m; $d_0 = 0.6$ m at the front of the model and behind the model for model lengths of 1 m, 2 m and 3 m.

Observations and measurements of tree growth were conducted to develop a vegetation model that incorporates planting patterns and tree density. These findings are consistent with previous studies on the growth of *Casuarina equisetifolia* along the Pacitan and Samas coasts [29], which emphasize that the spatial arrangement and density of trees significantly influence root development, canopy coverage, and overall forest resilience. Such models help predict how different planting strategies can affect coastal protection and energy dissipation during tsunami events.

Tree characteristics, including density, root depth, root system structure, growth rate, and canopy development, were measured for trees aged between 1.5 and 9 years. Deeper root systems and denser canopies enhance the ability of coastal forests to reduce wave energy and protect inland areas. These measurements provide important data for understanding how forest maturity and structural characteristics influence the effectiveness of tsunami mitigation over time [29].

To support tsunami evacuation and rescue operations, mitigation pathways were designed between trees in a zig-zag pattern. This approach is consistent with the findings of Rodrigues *et al.*, which suggest that well-planned access routes within coastal forests can improve emergency response while maintaining the protective function of vegetation [30]. By integrating the structural characteristics of coastal forests with human safety considerations, this study proposes a comprehensive disaster mitigation approach that not only enhances the ecological role of coastal forests in reducing tsunami energy but also facilitates practical evacuation and rescue efforts. This approach is supported by previous studies, which emphasize that well-designed vegetation density, root structures, and access pathways can simultaneously strengthen natural coastal defenses and improve emergency response, demonstrating that ecological protection and human safety can be effectively integrated in coastal management strategies [31].



Figure 15. Mitigation track from tsunami (NAS, Purwono, 2022)

Overall, the experimental results clearly demonstrate that the presence of coastal forest structures significantly influences the hydrodynamic behavior of surge tsunami propagation. The reduction in surge velocity observed in this study indicates that vegetation structures act as effective flow resistance elements that dissipate tsunami

energy as the wave propagates through the forested area. The results also reveal that the effectiveness of tsunami attenuation is strongly influenced by the structural characteristics of the vegetation model, particularly forest length and canopy density. Increasing the forest length from 1 m to 3 m consistently resulted in greater

velocity reduction, indicating that wider vegetation belts provide greater resistance to the incoming surge flow. In addition, the canopy model produced a higher reduction in velocity compared to the non-canopy model, demonstrating that the presence of dense canopy structures increases the drag force and enhances energy dissipation within the vegetation zone.

These findings highlight the important role of vegetation structure in controlling tsunami flow dynamics. The interaction between the surge flow and the vegetation elements generates drag forces, turbulence, and energy losses that collectively reduce the flow momentum. From a hydrodynamic perspective, the drag force generated by vegetation density becomes a dominant factor influencing tsunami attenuation compared to other hydraulic parameters such as bed slope and bottom roughness. The experimental observations therefore indicate that vegetation density and canopy structure significantly modify the velocity profile and energy distribution within the flow, resulting in a gradual reduction of surge energy as the wave passes through the forest model.

The results of this study provide important insights into the role of coastal vegetation as a nature-based mitigation measure for tsunami hazards. The ability of *Casuarina equisetifolia* forest models to reduce surge velocity suggests that coastal greenbelt systems composed of this vegetation type can function as natural barriers that dissipate tsunami energy before it reaches inland areas. The findings of this research therefore contribute to a better understanding of the hydrodynamic interaction between tsunami surge flows and coastal forest structures, particularly for non-mangrove vegetation such as *Casuarina equisetifolia*. This experimental evidence supports the potential use of coastal forest belts as part of integrated tsunami mitigation strategies in vulnerable coastal regions

IV. CONCLUSION

This study analyzed the propagation behavior of surge-type tsunami waves and evaluated the effectiveness of *Casuarina equisetifolia* coastal forest models in reducing tsunami flow velocity using a laboratory-based physical modeling approach. The results show that the presence of coastal forest structures significantly influences the hydrodynamic characteristics of surge tsunami propagation. The experimental results indicate that increasing the forest length from 1 m to 3 m leads to a greater reduction in surge velocity, demonstrating that wider vegetation belts provide higher resistance to incoming tsunami flows.

The comparison between vegetation models with canopy and without canopy also shows that the presence of canopy structures enhances the attenuation effect by increasing drag forces and promoting greater energy dissipation within the vegetation zone. However, for lower tsunami wave heights, the attenuation effect becomes less significant because the surge flow can still propagate beneath the canopy and through the gaps between tree trunks.

Overall, the results indicate that *Casuarina equisetifolia* coastal forests have the potential to function

as natural barriers capable of reducing tsunami surge velocity and dissipating wave energy before reaching inland areas. Scientifically, this study contributes to a better understanding of the hydrodynamic interaction between surge tsunami flows and coastal vegetation structures, particularly for non-mangrove species such as *Casuarina equisetifolia*. Practically, these findings can serve as a basis for the planning and design of coastal greenbelt systems, especially in determining the optimal forest width and vegetation density to enhance the effectiveness of tsunami mitigation in coastal areas.

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