International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Velocity Dissipation Approach on Drag Analysis Using CFD for Shoreline Defense

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Abstract*: Coastal forest protects the shoreline from erosion and extreme events by attenuating wave and velocity by obstructing the flow of water through the forest. Lack of understanding on tree drag coefficients vary with tree morphology density and arrangement is a major source of uncertainty that close related to the shoreline belt span. This study evaluates the behavior of velocity flow through the mangrove aerial root system. The analysis process starts with the drag value analysis of stilt roots model and continues by analyzing the dissipation behavior of velocity on the analysis path. Both analyses were carried out using Computational Fluid Dynamics (CFD) by ANSYS Fluent program. Root zone of the stilt root model is observed contributes higher velocity dissipation than stem zone. The highest drag value is observed at the average of 32.75% of the stilt root height. Higher density of forest stands contribute to higher dissipation of velocity. The study recommends the minimum span 200 m of shoreline forest belt to allow the ecosystem to be shoreline protector naturally. Therefore this study recommend for artificial protector for mangrove seedlings in the early growth. The results are useful for forest managers to restore mangroves and support the establishment of mangrove seedlings for coastal risk reduction strategies.

***Keywords*: CFD, shoreline, drag, mangrove, velocity**

1. Introduction

Mangroves grow in the upper intertidal zones of soft-sediment shores at tropical and subtropical latitudes [15]. This ecosystem is considered one of the most productive natural ecosystems globally and has a well-established ecological, economic and cultural [10] and supports fisheries and biodiversity, protecting coastlines from erosion and extreme events. These natural defenses are attractive because they are cost-effective solutions that provide multiple benefits, contributing to the community and ecological resilience [26]. The unique architecture of this ecological system makes it capable of absorbing the hydrodynamic turbulence and keeping the function and structure of the ecosystem [28] and attenuating the energy of tsunamis, cyclones and storm surge reducing velocity on channel floodplain [25].

Mangrove roots generate current with jets, eddies and turbulence [12], which dissipates the flow to energize the boundary layer separation, shear layer eddy mixing, and reattach the flow. The wave dissipation is due to the frictional drag of thick trunks and dense roots induced [9], and it strongly depends on the ratio of stem length to water depth and stem density [22] aside from forest density, a diameter of stems and roots, forest floor slope, bathymetry, waves characteristics [1]. However, the velocity fluctuates depending on porosity, with lesser fluctuation behind the higher porous area [14]. This ecosystem could also create bed resistance by obstructing water flow through the forest [7] and is expected to be better than artificial structures to protect coastlines threatened by climate change [16].

Mangroves, considered the stiffest of the vegetation types showed the most rapid decline in drag coefficient as the Reynolds number increased [23] can provide considerable wave damping and decrease flow velocities [29]. Mangroves can reduce wave height of short period wind-generated by limiting fluid exchange across the forest. However, lack of studies on storm surge wave attenuation and the ability of natural habitats to protect against this damage [23]. About 35% of the world's mangrove forests disappeared during the last two decades even diligently protected. The distribution of mangrove stands still decreased significantly, especially after the tsunami in 2004 [10]. Sea level rise may be the other greatest threat to mangroves. Most mangroves affected had broken stems or were uprooted due to massive soil erosion or died due to prolonged inundation [1].

The role of mangrove as a natural wave breaker may depend on mangrove vegetation, the density of the forest, height of the tree, area of root and soil texture, wind speed, tidal wave height, coastal soil erosion level, sea-level rise and other ecological disruptions. Wave and tidal activities change the coastal features and environment; coastal flooding and coastal erosion are severe forms of damage during severe storm events [24]. Wave and storm-surge dampening by wetlands across various storms caused by substantial drag [7] of rigid vegetation influenced by location, density and spacing [18] of coastal forest stands. Therefore, data on the density and width of trees planted and the diameter of trunks and roots, floor shape, bathymetry, and spectral features of waves are essential to maintain the protective function of mangroves [3].

Mangrove ecosystems alone are very effective at preventing soil loss and shoreline erosion [9] by enhancing sediment deposition to strengthen the anchorage of the seedling on the ground and promote tree growth. Rhizophora mucronata settles and dwells in the low to mid intertidal areas, and seedlings invest more in root growth further down the intertidal gradient. The velocity and turbidity of water that causes erosion could be reduced and stabilizes the shoreline [15]. Most studies only focus on the attenuation of regular waves and only over a limited vegetation length distance and still lack the data sets for model validation on the effect of wave characteristics on the emerging and rigid vegetation [22]. However, only a few studies have quantified the level of coastal defense in terms of service and information to the coastal communities and when they can rely on mangroves to reduce risk from coastal hazards [19] and the success is often hampered by a lack of reference to a substrate and hydrological requirements for mangrove establishment [16].

The role of mangroves in reducing the sea-waves velocity has been scientifically proven. For instance, six-year-old mangrove forests of 1.5 km wide will attenuate open sea waves height from 1 m to 0.05 m [13] approximately 70% of the near shore wave height [9]. Research indicates a belt of mangroves can absorb 30 to 40 % of the total force of a tsunami [5] and up to 90 % with a stand density of 3000 trees per hectare [1]. A model estimates 50 % declination in wave energy by going into 150 m of Rhizophora-dominated forest at high tide and 50 % of energy reduction within 100 m belt width of Sonneratia forests [1] that range the total dissipation 200 m - 300 m. This finding is supported by Mcivor et al. [20] that observed the total reduction of 35% over the first 80 m of the forest, which estimates 228.5 m for 100% of energy dissipation. A fully grown mangrove forest could significantly attenuate the wave energy of wind-generated surface by 20% per 100 m [16]. Another study found the capability of mangrove forests to reduce the wave height by about 20% over 100 m and could reach up to 60% over 300 m vegetation width [30]. Both Lee et al. [16] and Volvaiker et al. [30] estimate the 500 m of vegetation width to totally dissipate wave energy. The authors conclude that the above studies summarize that the vegetation width range for total dissipation of wave is in 200 m to 500 m range. These previous studies showed that the minimum shoreline belt width is 200 m to enable the functionality of the coastal forest as a natural shoreline protector.

This study also observes the potential protective role for mangroves that focus on the dissipation process of the waves [12] in root architecture of individual species/trees using the Computational Fluid Dynamics (CFD) with Fluent Program analysis. The numerical model could simulate fluid flow in an open channel in 2D and 3D analyses. The assessment of mangrove protection and the design is referred to by a distributed drag characterized by a tree drag or bed friction coefficient. The drag coefficient (CD) is dimensionless, where the force (F drag) is derived from the average pressure and the shear stress along the surface of the model divided by the dynamic pressure multiplied by the frontal area (A) of the model. So the dynamic pressure was created from the relative velocity (V) of the fluid flow and density (ρ) impact on the model (Equation 1) [11].

$$C_D = \frac{F_{drag}}{1/2 \times \rho V^2 A}$$

However, a lack of understanding of how tree drag coefficients vary with tree morphology density and arrangement is a significant source of uncertainty [15]. Numerical models on a tree drag would allow the mangrove forest manager to effectively design the mangrove restoration to maintain the function of "natural protection" to the coastal communities and assets [3].

Appropriate management of mangrove areas could increase wave attenuation by determining the required forest bandwidth that considers wind and swells waves, a dense mangrove forest, including species with aerial roots [20]. Before this, analysis of drag characteristics in the stilt root model needs to be deepened to see the disturbance created from the stilt root model. The 3D model of stilt root models was developed mimicking the shoreline species. The reduction in drag value could be explained both vertically and horizontally on the velocity behavior in response to the mangrove trees [17]. The fluent analysis was based on certain flow conditions to investigate the seawater flow through the stilt root model, which would slow down the initial velocity. The measurement of velocity dissipation was obtained from the velocity value extracted on the analysis path in the specimen.

In Malaysia, mangroves are mainly used for pole and charcoal production aside from shoreline protection. However, constant pressures exerted from natural events are responsible for its decline at a higher rate [8] and possibly decrease the effectiveness of barrier function against severe storm events. Therefore, forest managers need to preserve and select an appropriate species to make better wave barriers for offering sufficient shoreline protection [1] and contribute to coastal risk reduction strategies [19]. The information of wave dissipation through the coastal forest would lead the forest manager to restorative or planting of mangroves in degraded and deforested settings to support the establishment of mangrove seedlings [20]. Artificial protection might be needed to protect mangrove seedlings, especially at the edge of a mangrove forest, in case of a deeper channel with strong currents [29] to lower the current velocities in the forest and at the same time decrease erosion. These initiatives should be community-based and incorporate mechanisms [16]. The understanding and involvement of coastal communities, planners, managers and engineers are essential to ensure the use of mangroves in coastal defense strategies is successful [19].

2. Materials and Methods

Study site

This study applies two consecutive analysis processes starting with drag value analysis on the stilt root model of shoreline tree stand structure and continuing with velocity reduction analysis and the dissipation behavior of water flow through the stilt root model. The relationship of the velocity flow and the stilt root model would estimate the span of the shoreline belt is where the velocity is dissipated naturally during a tidal surge. Due to data limitations on a single site, the study decided to separate the data collection into different study areas for conclusive research output. Drag value analysis was carried out on the stilt root models collected from study plot Lekir, Perak, while velocity dissipation analysis uses data collected from study plot developed at Pulau Klang, Selangor (Figure 1).
At Lekir, a temporary plot (4.09260, 100.75692) size 10 m x 10 m was established, and information of tree species, diameter breast height (DBH), location and height were collected. The above-ground architecture of stilt roots, such as the diameter of tree trunks and roots, azimuth of roots, height of roots from the ground level, the distance between trees and spacing of plantings, were recorded for analysis drag coefficients on stilt root. At Pulau Klang, three temporary plot sizes, 20 m x 20 m, were established to measure the density of mangrove stand per hectare representing for Low (2125), Average (3850) and High (5250) at (3.06076, 101.30462), (3.05886, 101.30310) and (3.04792, 101.29761) consecutively.

Lekir, Perak

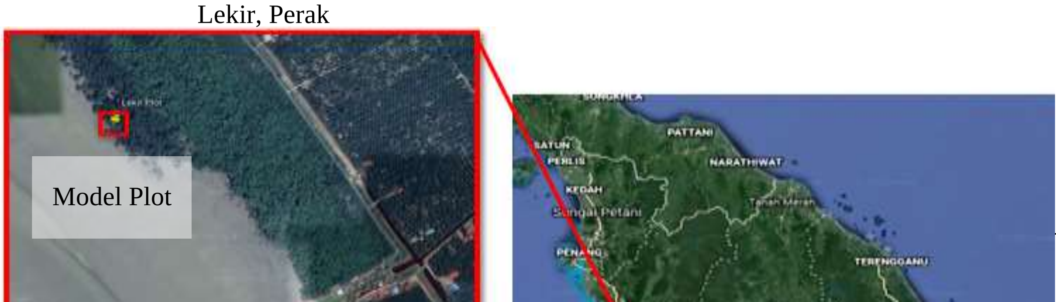

Figure 1: Site study of data collection

Table 1: Trees for stilt root model

Model	Species	Local name	ID	DBH (cm)	Height (m)
1	Sonneratia alba	Perepat	3	47.3	22
2	Rhizophora apiculata	Bakau Minyak	4	23.7	18.5
3	Sonneratia alba	Perepat	6	33	18
4	Rhizophora apiculata	Bakau Minyak	8	18.5	15

Data of the above-ground architecture of the stilt root model were modelled into 3D (Figure 2) using the SketchUp program considering each root's root diameter and orientation. Analysis of drag coefficient on these stilt root models focused on the plane surface parallel to seawater velocity. These plane surfaces were sliced from the stilt root models vertically at constant spacing. These slices contain the root cross-section as the primary geometry input for the simulation.

Model 1 Model 2

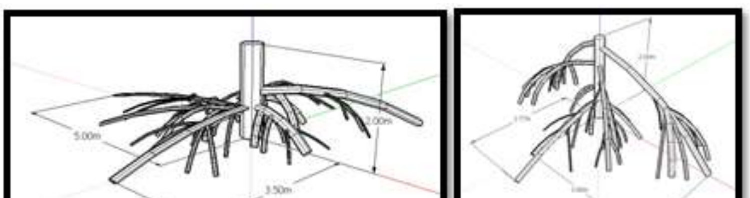

Figure 2: Stilt root models

CFD

The fluent simulation was carried out using Computational Fluid Dynamics (CFD) by ANSYS Fluent program to determine the drag coefficient of the above-ground stilt root system. The same technique was applied to evaluate seawater velocity's dissipation behavior and the inline specimen. The simulations were carried out in two dimensional (2D), and vertical variation is taken into account to reduce the hydrodynamics errors [4]. The first analysis estimates the drag value on the surface plane of sliced cross-sections, while the latter evaluate the velocity dissipation for shoreline belt width.

All 2D specimens were meshed using a triangular method with 0.025 m element size. The seawater density is defined as 1023.387 kg/m^3, and viscosity is 0.000959 kg/m.s for both analyses. Reynolds number for mangrove root drag analysis and velocity reduction is 356,852 and 320,142 consecutively, which categorized both analyses in turbulence flow. Therefore, this study chose a standard k-epsilon turbulent viscous model with SIMPLEC solution type. The analysis was carried out using pressure-based type analysis, absolute velocity formulation and steady time series.

Both analyses applied the average water velocity for inlet representing the average water velocity in a mangrove stands, the average magnitude of the water velocity, around 0.1 m/s [15]. This inlet velocity value was also applied by Shan et al. [25] that satisfied Froude number similarity with accurate field scale of tidal flow and storm surge, 0.2 m/s and 0.5 m/s. Therefore, this study used 0.1 m/s for inlet velocity value for drag analysis of stilt root model and velocity dissipation of tree stand. The result generated from these simulations applying the average velocity magnitude for inlet was multiplied by the velocity ratio of extreme velocity conditions, which is 0.5. The simulation is assumed to have a significant drag value reduction of flow redistribution in the horizontal plane with the channel-average velocity [17].

Stilt Root Drag Value

The first analysis starts with determining the drag value of each stilt root model. Numbers of simulation attempts were carried out in 3D but unfortunately ended up with the error. Performing CFD analysis in a

3D configuration will require a more significant computational workload than 2D, regardless of the numerical strategies and spatial discretization used [2]. The drag is proportional to both frontal area and velocity squared. A flow adjustment that leads to higher velocity in the region of the lower frontal area should lead to an overall reduction in [17]. Therefore the study is considered sufficient to be carried out in 2D configuration. The model is simplified by creating horizontal slices of the stilt root model with 0.25 m vertical interval (Figure 3) in 2D configuration to analyze the drag coefficient of the stilt root model.

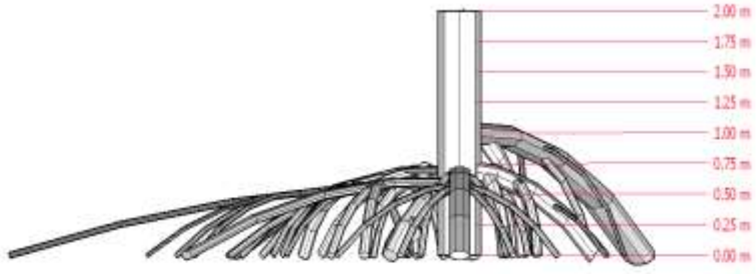

Figure 3: Vertical interval of specimen slices

Based on Figure 3, six (6) slices have been identified as a specimen for drag value analysis consisting of a mangrove stilt root surface cross-section. The simulation for slices above 1.25 m till 2.00 m height is ignored because of a similar cross-section with slice 1.25 m. This study focused on the simulation from 0 m till 1.25 m of the stilt root height to be the effective slices (Figure 4).

Four (4) models of stilt root have been successfully analyzed for drag value analysis and analysis of velocity dissipation. The simulation result of drag value for four (4) stilt root models, which consisted of 26 slices of the specimen, were summarized in Table 2. Image of velocity contour, drag force and drag value along the velocity flow for each slice was recorded for further analysis.

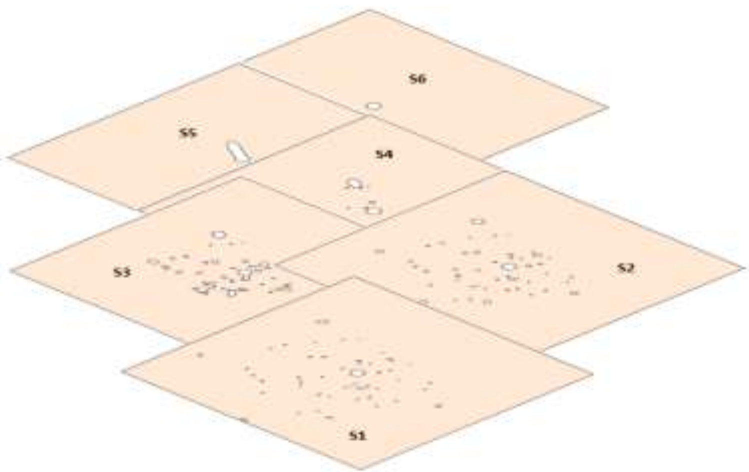

Figure 4: Effective slices of stilt root model ID 3

Table 2: Effective slices of stilt root model and range

Stilt Root	No of Slices	Slice Range (m)	Root Height (m)
Model 1	6	0 - 1.25	1.07
Model 2	9	0 - 2.00	1.91

Model 3	4	0 - 0.75	0.66
Model 4	7	0 - 1.50	1.29

Velocity Dissipation

The velocity dissipation analysis, the specimen preparation applying the slice with the maximum drag value resulted in the previous simulation. The height of the stilt root model at the maximum drag value was used to prepare the specimen in velocity dissipation analysis. The specimens were prepared based on three (3) different densities of tree stands which are 2125, 3850 and 5250 trees per hectare, representing low, average and high stand density consecutively.

The inline velocity distribution of the model significantly diminished relative to the channel average. A lower velocity in line with the trees would also reduce the force on the tree that will also change the drag force over the distance [17]. Therefore, in this analysis, the specimens were prepared with inline distribution according to the density mentioned above with calculated tree gaps spacing are 2.17 m, 1.61 m and 1.37 m for 2125, 3850 and 5250 consecutively (Figure 5).

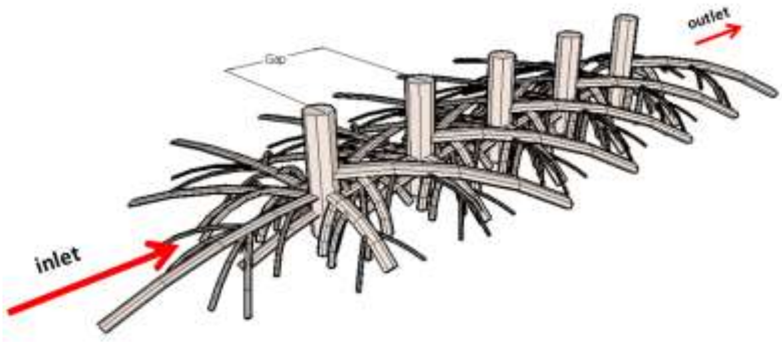

Figure 5: Stilt root models for velocity reduction in-line distribution

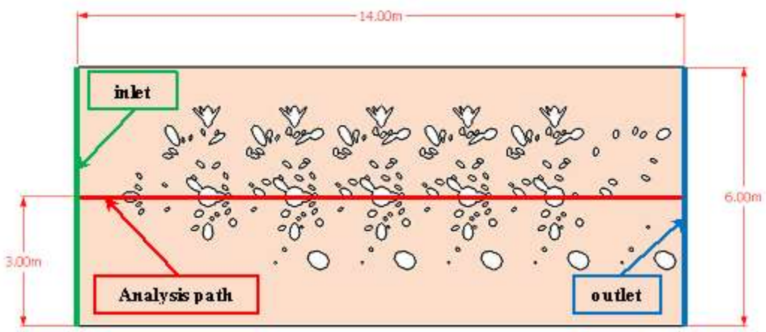

Figure 6: Specimen for velocity reduction in-line distribution

Figure 6 illustrates the boundary condition assigned to the specimen before running the calculation. That analysis path was assigned to the center of the tree stem diameter along with the inline distribution. The velocity magnitudes along the analysis path were recorded to analyze velocity dissipation behavior for each stilt root model. Analysis of velocity dissipation behavior was focused on the analysis path at the center line of the specimen through the fluid domain from inlet to outlet.

This study analyzed four (4) specimens to evaluate the dissipation behavior of the inline tree stand with three (3) densities. The cross-section of the sliced stilt root model on the specimen influenced the result of the velocity that intersected with the analysis path. Therefore, this study assumed that applying only a single path for the analysis within the fluid domain as applicable. These specimens were prepared by a cross-section of the stilt root model at the maximum drag value, which proposed the minimum shoreline belt span for a specific coastal forest stand. This width could be calculated from the equation generated from the trend line when velocity is dissipated or when Y-axis is equal to zero. The outer dimensions of a specimen varied due to different tree gap spacing

3. Results

Stilt Root Drag Value

The maximum drag values were 7.0493, 3.5041, 3.1364 and 1.7067 for Model 1 (Perepat), Model 2 (Bakau Minyak), Model 3 (Perepat) and Model 4 (Perepat) consecutively (Figure 7). The slice height for these values was 0.5 m for Model 1, Model 2 and Model 4, while 0.25 m for Model 3 is the most influenced slice for reducing the velocity magnitude.

The percentage ratio for the height of maximum drag coefficient to mangrove stilt root height from the ground level is 40 % for Model 1, 25 % for Model 2 and 33 % for Model 3 and Model 4. The average height of four (4) stilt root models is 1.233 m. The result showed that the average percentage ratio for the slice's height at maximum drag value is 32.75 % which is about 0.404 m from the ground level. The values of drag coefficients are observed to be reduced from bottom to top of the stilt root models.

When the seawater flows toward the forest, the average velocity flow through each mangrove tree differs based on the drag value. The higher drag value of slices will move slower down the velocity of seawater. The highest velocity is expected to be at the highest vertical slices, which only contain the cross-section of the DBH for that tree. This finding support Maza et al. [17] that the velocity profile was nearly uniform, except close to the bed where the velocity decreased in the root zone and higher above the root zone. The drag coefficient hysteresis results were less satisfactory with experimental results; however, the solver, grid resolution, and numerical scheme used in this study are within acceptable limits [21].

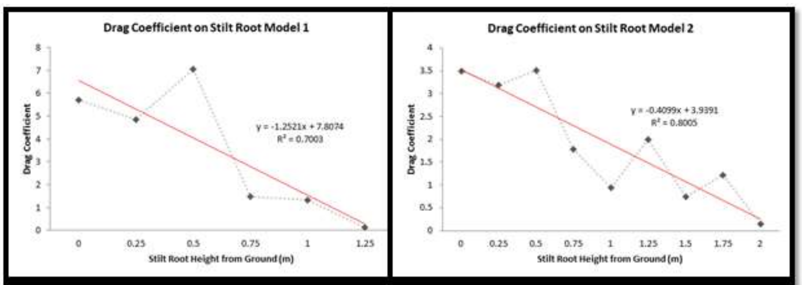

Figure 7: Drag coefficients for all stilt root models

Velocity Dissipation

The flow behavior of velocity in inline model stilt root was observed to three different stand densities that are 2125 (Figure 8), 3850 (Figure 9) and 5250 (Figure 10). The trend line was generated from the velocity values along the analysis path of the specimen model and resulted in the decrease of velocity from inlet to outlet through the analysis path except for the third model specimen of 5250 density. This finding is similar to Jusoh et al. [12] that estimates a 40 % decrease in velocity magnitude of the initial flow. The root architecture such as cross-section, density and coordination is observed to have a significant role in reduction velocity flow at the shoreline.

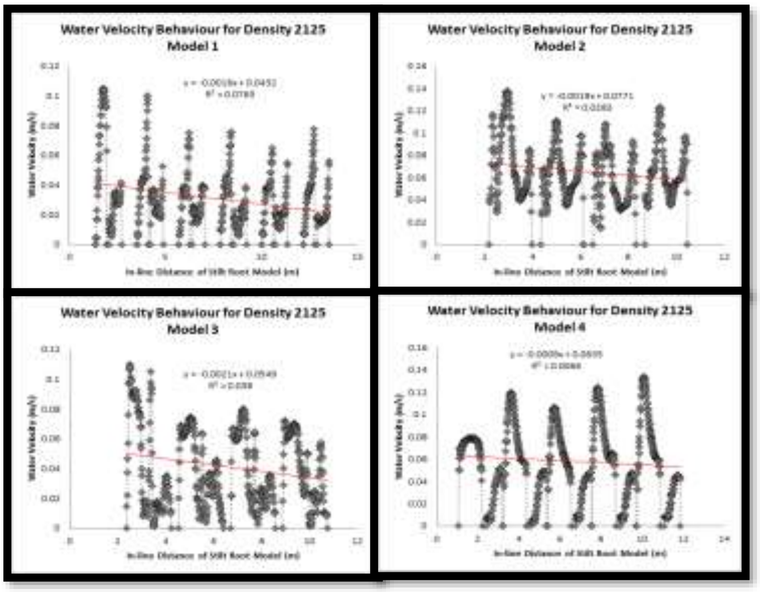

Figure 8: Velocity behaviour of stilt root models for density 2125

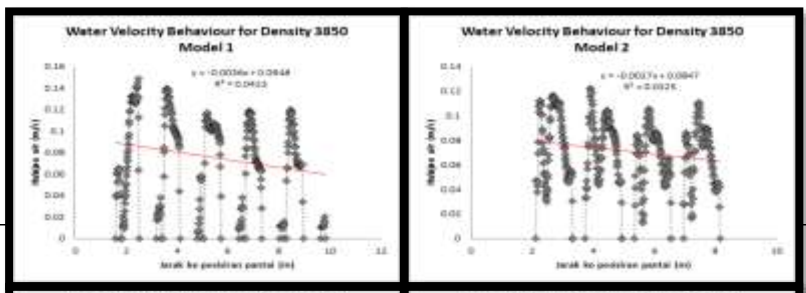

Figure 9: Velocity behaviour of stilt root models for density 3850

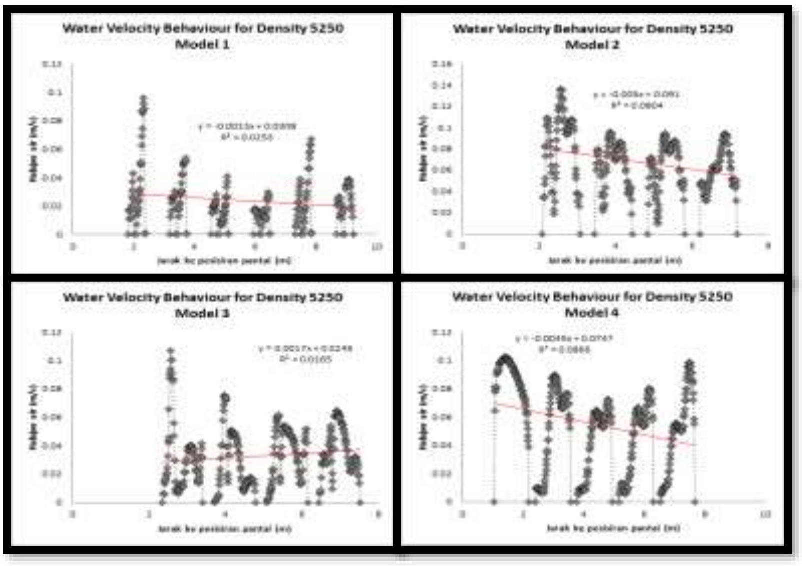

Figure 10: Velocity behaviour of stilt root models for density 5250

The dissipation span is calculated from the linear equation derived from the velocity plot along the analysis path using the average velocity magnitude 0.1 m.s-1 that approach the shoreline forest stand. For the extreme velocity seawater, 0.5 m/.s was applied by multiplying the dissipation span with the velocity ratio, which in this study took as 5.

Estimating the velocity dissipation based on the maximum drag value would provide the information of minimum shoreline belt width of coastal forest to enable the function of shoreline defense. Guannel et al. [9] mentioned that the effectiveness of dissipation is still primarily due to the frictional drag from thick trunks and dense roots induced in the water. The dissipation span for average velocity is 41.08 m, calculated from the lowest density stand (Table 3). Therefore, 205.4 m is the recommended span for a shoreline forest stand. This result is almost similar to Alongi [1] and Mcivor et al. [20] that estimate 200 m and 228.5 m consecutively to dissipate the wave energy

Table 3: Total dissipation lengths for stilt root models 2125 density

Density	Model 1 (m)	Model 2 (m)	Model 3 (m)	Model 4 (m)	Average span (m)
2125	27.00	40.60	26.10	70.60	**41.08**
3850	26.30	31.40	17.30	315.00*	**25.00**
5250	23.70	18.20	-14.40*	16.60	**19.50**

* excluded from average value

The negative value generated from the simulation shows that the drag value is insufficient to dissipate the velocity through the shoreline forest stand. In designing the shoreline forest span, the drag value should be higher than 1, which requires more oversized tree stem.

4. Discussion

The drag distribution in the stilt root model shows an increase toward the ground level. This distribution shows that the water velocity that flows to the coastal stand is more incredibly reduced at the stilt root system part than the stem part. This result shows that the drag value has a strong linear relationship with the cross-section of the stilt root model and is simplified with the stem diameter (DBH) (Figure 11). Generally, a higher DBH of stilt rooted coastal trees would generate a higher drag value for a particular tree stand. This distribution shows that the water velocity that flows to the coastal stand is more incredibly reduced at the stilt root system part than the stem part.

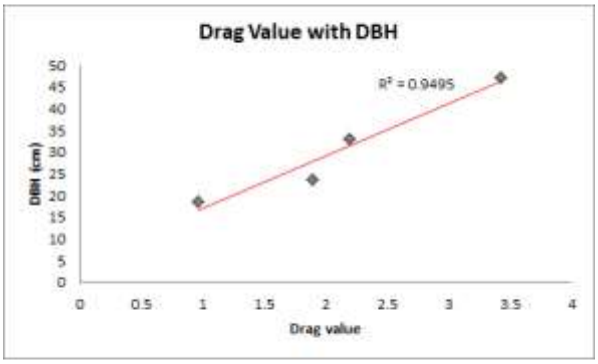

Figure 11: Relationship drag value and DBH

The drag coefficient of stilt rooted coastal species shows a strong relationship with tree DBH. A practical drag value is observed around 33% of stilt root height from ground level, and this value is observed to decrease as the height of stilt root increases. This study also observes the positive relationship between the drag coefficient cross-section areas of slices which are extracted from the stilt root models but not in solid dependency with regression value less than 0.8 and this proves the flow velocity reduction is not only depending on mangrove aerial root system but also the coordination of the root [12].
Study on wave dissipation shoreline forest focuses more on drag force than lift force, and this contradicts designing airfoils that look for the higher lift-to-drag ratio to maintain low and high altitudes and long duration flights [6]. The forest manager could use this technique to evaluate the capability of the current status of shoreline forest stand for natural protector role. The averages of shoreline belt width were plotted against stand density to get the linear trend line and the equation as in Figure 12, where Y-axis is the

minimum shoreline belt width that would dissipate the seawater velocity that flows through mangrove trees at a specific density (X-axis). However, this study suggests having the specific species and density for an exact span of shoreline forest belt for a particular area.

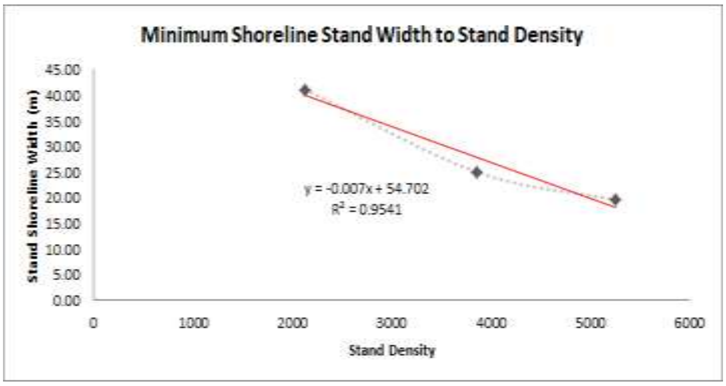

Figure 12: Graph of average shoreline belt width with density

5. Conclusion

This study could conclude that drag analysis could be used to analyze the behavior of water velocity that flows through the mangrove stand to prove this ecosystem as a shoreline protector. The stilt root system can reduce the seawater velocity that flows through shoreline tree stands at the coastal species. The CFD technique could determine shoreline forest span for natural velocity dissipation. This study recommends the minimum 200 m to be the span of the shoreline forest belt to enable the natural protection of the ecosystem width is with the specific minimum tree stem diameter.

The behavior of velocity dissipation that flows through the mangrove stand is significantly influenced by the distribution of drag value of the stilt root model. Higher drag value from the stilt root architecture provides better velocity dissipation, which is mainly caused by the root diameter, root density, arrangement and coordination of root structure and tree stem diameter.

Information of minimum shoreline belt width spacing would be helpful to forest managers to maintain the function of the shoreline ecosystem and plan for planting activities. The current shoreline forest belt span could be evaluated for natural protector. This technique also could be used to identify the minimum planting shoreline belt width for specific areas that would be useful to forest managers to maintain the function of the shoreline ecosystem and planning for planting activities. Therefore, this study strongly recommends the need for artificial protection such as wave breakers to support the establishment of mangrove seedlings at shoreline reforestation

6. Acknowledgement

We gratefully acknowledge use of the same study site by National Hydraulic Research Institute of Malaysia (NAHRIM). This study was funded by Jawatankuasa Teknikal Mengenai Penyelidikan dan

Pembangunan Program Penanaman Bakau dan Spesis-spesis Lain yang Sesuai di Pesisiran Pantai Negara (JTRD), Malaysia.

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