# COMPUTATIONAL FLUID DYNAMIC SIMULATION OF FLOW VELOCITIES DISSIPATION BY MANGROVE ROOTS STRUCTURE

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**ABSTRACT**

The study was investigating the velocity dissipation process of Avicennia marina and Rhizophora apiculata mangrove species by focusing on the root geometrical properties and the water flow structure within the root area. The root properties were investigated by conducting a field work. Hence, a model of the mangrove roots was constructed using the meshing software. The simulations were conducted in Computational Fluid Dynamic (CFD) software using unsteady Spalart-Allmaras turbulence model with water liquid material and by setting the velocity inlet in boundary condition to 6 m/s. It had been observed that mangrove root properties and coordination had a high influence to the flow velocity reduction. An area that had high roots densities and cross-section diameters were capable of dissipating more velocities, especially within the distance 100 cm to 150 cm from the primary trunk. The study also discovered that the contact between jets, eddies, turbulence scale and stagnation areas were contributing to the velocity deficit. The simulation result shows that mangrove roots of both species were capable of decreasing the initial velocity 6 m/s of water flow to almost 2 m/s. The flow velocity dissipation rate and flow structure in the mangrove root area found through this study will provide valuable data in increasing the efficiency of current breakwater models.

**Keywords:** rhizophora, avicennia, stilt roots, pneumatophores.

## INTRODUCTION

The mangrove species had a special adaptation of aerial roots in order for the trees to grow steadily on the loose soil of muddy coastline. In [1, 2] stated that the aerial had the function of filtering the salinity of water for freshwater supply and provide sedimentation assistance in maintaining mangrove ecosystem. Mangrove trees developed different structures of root system and aerial roots according to the species. The common types of aerial roots are stilt roots, Pneumatophores and knee roots. Stilt roots are common to the mangrove species of genus Rhizophora sp., Pneumatophores for Avicennia sp. while knee roots are common to Bruguiera sp. [3]. The roots of mangrove trees played a major role in attenuating the tidal wave. In [4] had found that the rate of wave energy attenuation and velocity dissipation highly influenced by volume ratio of submerged root and the tree frontal area.

In [2] had noted that the mangrove roots create obstacles generating complex two-dimensional current with jets, eddies and as well as vegetation-scale turbulence. However, the eddies and wakes only occur with the wave that flow at high velocity. At low speed, the obstacles have usually created a laminar flow. According to [5], in areas with dense mangrove vegetation, the wave that moves between the mangrove roots are creating jets and the currents are tend to flow around creating turbulence. This study had concluded that the velocity of waves that move through the mangroves reduced from the friction between the waves and the mangrove vegetation instead of the bottom friction.

Consequently, the tsunami run-up simulation study was carried out by researchers from Malaysia and overseas in Penang beaches using non-linear equations of shallow water (NSWE) in order to analyze the breakwater properties of the mangrove species. In [6] had conducted a simulation of tsunami wave mitigation over the shallow coastline of mangrove forests by using TUNA-RP model. The model had similar simulation data of wave height and velocity with a TUNA-M2 model that were used by [7]. From the research, it was concluded that the ratio of wave height and velocity reduction may vary depending on factors such as wave height, wave period and wavelength and the features including the width of the mangrove forest and the density.

Meanwhile, in [8] had used two dimensional depth-integrated mathematical model to study the flow structure of water wave propagation in Merbok Estuary situated in the state of Kedah, Malaysia. The study had used two dimensional hydrodynamic equations in the mathematical model by considering the drag force and effect blocked by the mangrove forest to study the water wave flow structure. The drag force and blockage effects of mangroves on the water flow structure were studied in two situations, which were tidal flow in steady channel flow and tidal flow in a mangrove swamps. In the case of a stable channel flow, it is found that the blockage effects by mangrove trees have increased the velocity in the main channel. However, in the case of tidal flows in a straight creek, it was found that the blockage effects have reduced the velocity of the tidal flow at the peak of the river since the tidal floodplain functions as water storage rather than water flow passage.

Hence, from the above study, it can be observed that most researches had been conducted on the west coast of Malaysia peninsular. The studies also were more focusing on the dissipation process of the wave in

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mangrove forest structure rather investigating on the mangrove trees in individually, and most simulation processes were conducted using numerical models. Thus, this study had taken a different approach by investigating on the mangrove tree structures onthe east coast of Malaysia Peninsular. The study had focused on the roots structured of each mangrove species sample, which then converted into data that appropriate for Computational Fluid Dynamic (CFD) simulation process.

**Study approach**

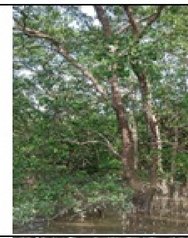
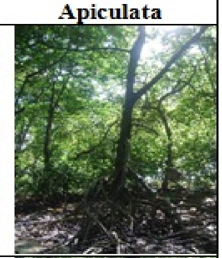
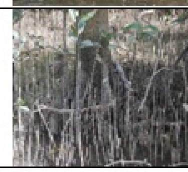
The research had limited the scope of the study within two mangrove species which are Avicennia marina and Rhizophora apiculata. These species are commonly inhabited at Malaysia coastline, especially in the mangrove forest at the study area location. Since the study was focusing on investigating the flow structure around a mangrove tree, the study had selected a sample of tree from each species. The sample was sufficient as similar study was conducted by [2] at Middle Creek, Crains, Australia. His study of vegetation-induced current also used a single model to produce the fine scale flow pattern around Rhizophora roots. He had observed that the roots had created two-dimensional currents, with jets, eddies and stagnation region. He also had created a VORTEX model, which had produced similar flow features to the observed result. Hence, the study decided to take only a tree sample from each species since it was sufficient in observation of water flow pattern in the mangrove root area.

**Field observation**

The study was conducted at Pantai Marina which is located 4°14'20.08" latitude, 103°27'8.69" longitude in Kemaman Terengganu on the East Coast of Peninsular Malaysia. The coast of Pantai Marina is positioned at Kuala Kemaman river mouth where Sungai Kemaman and Sungai Cukai meet to be discharged at the South China Sea. The terrain of Pantai Marina consists sandy beaches on the downstream while the upstream coastlines are covered by mudflat which inhabited by mangrove vegetation. Table-1 shows the samples of mangrove trees for each genus which located at Pantai Marina mangrove swamps.

The mangrove forest at Pantai Marina was known as fringing forests. Mangrove trees were inhabited along the shorelines and mudflat dykes [9]. Since the mangrove forest is located within the estuary of Kuala Kemaman, the water in mangrove swamps had high salinity and the temperature in the area was also high which at ± 30º C. Hence, makes the area suitable for colonization of mangrove trees [10]. The main mangrove trees that grow in the fringe forest are from the species of Avicennia marina and Rhizophora apiculata.

**Table-1.** The roots characteristic of sample mangrove trees.

| | Avicennia Marina | Rhizophora Apiculata |
|---|---|---|
| Sample tree |  |  |
| Aerial roots |  |  |

**Collection of mangrove roots geometrical coordinate and perimeter**

The data collections of mangrove roots geometrical coordinate involve three steps. The first step was to select a sample of mangrove tree from Avicennia sp. and Rhizophora sp. species. The upstream and mid-zone of mangrove forest was scouted to find the suitable tree sample. Trees with GDH between 35 cm to 85 cm were selected as the trees were suitable as samples [11]. The samples also were selected by the location of the mangrove trees, where trees are isolated and the area around the trees is spacious since grid construction process requires an open space.

Secondly, the areas around the mangrove trees where the roots spread was measured for grid construction. Figure-1 shown the data collection site of 300 x 300 cm wide areas which was similar to the method used by [12].The size of the grids are 12.5 x 12.5 cm with the total numbers of grids created inside the collection site was 576 grids.

Lastly, the water traveled direction was decided as x-axis, while a cross section of the water travel inside the mangrove root area was indicated as the y-axis. The geometrical coordinates of the mangrove root then were plotted on grid sheet and numbered. Each perimeter of the mangrove roots is recorded according to the roots numbers for reference in the next data analysis.

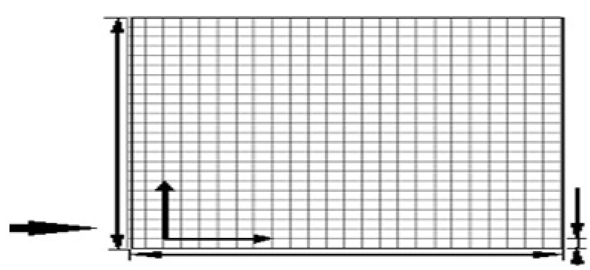


**Figure-1.** The parameter of the grid constructed around the mangrove trees.

## FIELD DATA COMPUTER ANALYSIS

### Mangrove roots mesh creation

The study had followed similar procedures with [13] by producing geometry, generating grid and determine the boundary condition. Thus, mangrove root geometry creation mesh was compiled from the data collected during field studies. Vertex data that contain the mangrove roots coordinate (x, y, z) were connected using circle edge in Gambit interface to form the mangrove roots. An open boundary of farfield had been created around the root geometry to create a mesh between the root geometry and farfield boundary. The farfield boundary was created further from the roots geometry to reduce the effect of the boundary on the flow and to have more accurate boundary conditions. Since the roots geometrical coordinate were complex, an unstructured mesh had been created in the farfield boundary by using size function. Furthermore, boundary layers had been created around the root geometry to produce more accurate results of the simulation. The mesh was then exported into a mesh file to be transferred into CFD software for simulation purpose.

### Mangrove roots CFD simulation preparation

The simulation of the mangrove root geometry had been conducted using CFD software. The simulations were run with the environment of pressure based solver and Spalart-Allmaras turbulence model with unsteady iteration time. The pressure-based solver had been defined by calculating the Mach number (M). Hence, turbulence model was used due to the Reynolds number was larger than 5.0 x $10^5$ (Re > 5.0 x $10^5$) which is considered turbulence for external flow. The Spalart-Allmaras turbulence model was used in the simulation. The turbulence model had been run on unsteady time (time dependence) in order to capture more clear movement of the mitigated water flow.

### Mangrove roots CFD simulation procedure

The mesh data were imported into CFD software for simulated process. The scale of the grid of the mesh was scaled in centimeter (cm) and the model solver was set to Spalart-Allmaras turbulence model. Hence, the water-liquid ($H_2O$-liquid-) material was imported from FLUENT database and the density of the water was set to 1000 kg/$m^3$. Considering the wind speed velocity as the water velocity entering the mangrove swamps, the inlet velocity was set to 6 m/s which are the velocity that was obtained through field work at Kuala Kemaman estuary and Pantai Marina coastline. Next, since the simulation was run with time dependence, it was required to calculate the value of the time step and the number of time steps. The value of the time step and the number of time steps was set to 0.03s while the number of time steps, N was set with the minimum. The simulation was run with max iteration per time step 10 and was increased until the solution converged.

## RESULTS AND DISCUSSION

### Mangrove roots geometrical coordinate and characteristic

Avicennia sp. or commonly known as Api-Api Jambu or Merah in Malaysia have Pneumatophores aerial roots which the roots grow vertically upward from the mudflat. The aerial roots distribute densely around the mangrove trees which required a fixed area of the grids that covered of 3 x 3 m to collect the geometrical coordinate of roots. Figure-2 shows the distribution of the Pneumatophores aerial roots of the Avicennia sp., which was collected at designated area. Each section is represented by A until I, the red dot marked with T is the coordinate of the primary trunk while the blue dots are the coordinate of the aerial roots. The total number of the roots located in the data collection area is 226.

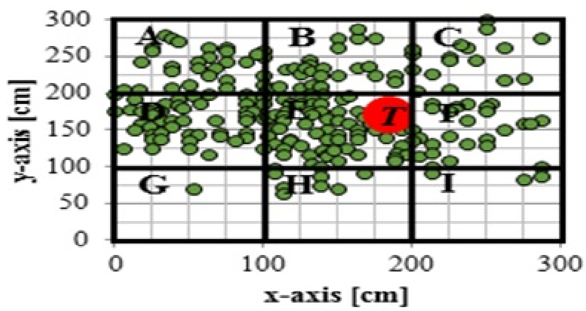



**Figure-2.** The density of Avicennia marina Pneumatophores.

The cross section diameter of the Pneumatophores aerial roots was measured and the roots distribution in each section was tabulated and summarized in Table-2.

**Table-2.** Pneumatophores aerial roots density and diameter of each section.

| Section | Pneumatophores Density [nu/$m^2$] | Cross Section Diameter [cm] |
|---|---|---|
| A | 25 | 0.95 ± 0.15 |
| B | 29 | |
| C | 16 | |
| D | 49 | |
| E | 67 | |
| F | 25 | |
| G | 1 | |
| H | 9 | |
| I | 5 | |
| Total | 226 | |

From Table-2, the Pneumatophores density are higher in section D and E compare to the other section while section G, H and I have considerably lower numbers of roots in 1 $m^2$ wide area. The diameters of the Pneumatophores roots are very small and the perimeter of the roots is almost similar, where the average of the diameters is 0.95 with ± 0.15 cm.

Meanwhile, Rhizophora sp. mangrove trees have a special adaptation known as stilt roots, which allow the trees to elevate above water and to discharge oxygen even while the lower roots are submerged in the water. Thus, Figure-3 shows the geometrical coordinate of the Rhizophora sp. mangrove species stilt roots.

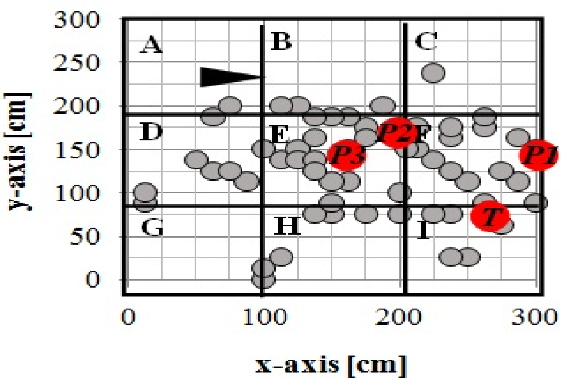



**Figure-3.** The density of Rhizophora apiculata stilt roots in 1 x 1 m wide area.

The stilt roots coordinate was plotted following the original grids where the red circles indicate the Rhizophora stilt-root. Similarly, the water flows through the data collection area in the x-direction and y-direction is the cross section area of the water travels through the mangrove roots area. Circle T represents the primary root, where the root grows in-line with the Rhizophora main tree trunk. Thus, the circle P1, P2 and P3 in Figure-3 indicates the primary prop roots (aerial roots originating from the bole) in which the other stilt roots sprout[2].

Similarly to Avicennia sp. case, the density of the stilt roots were calculated by dividing the data collection area into 9 sections where each section was represented by the letters A until I. From Figure-3, it can be observed that the roots were spread away from the tree trunk and growing against the direction of water traveled which is similar to Avicennia sp. species Pneumatophores analysis result.

Furthermore, it also can be observed that the stilt roots are concentrated at the sections D, E, F, H and I where the root density is higher toward the open water area. The stilt root densities in each section were tabulated in Table-3. It shows that the total number of the stilt roots collected in the study area is 58, which is much lower compared to Avicennia sp.

Although the cross section diameters of the roots were varied, but almost all the stilt roots grow within the diameter range of 2 to 5 cm. Thus, circle P1, P2 and P3 in indicate the primary prop stilt roots of the mangrove tree. The primary prop roots have much larger cross section diameter that nearly 9 cm. Although the primary root or the tree trunk located at section I, the area has a much lower root density compare to section E and F.

**Table-3.** Stilt roots density and range of cross section diameters for each section.

| Section | Stilt Roots Density [num/m$^2$] | Range of Cross Section Diameter [cm] |
|---|---|---|
| A | 0 | |
| B | 0 | |
| C | 1 | 1.71 |
| D | 8 | 0.73 - 1.71 |
| E | 19 | 0.73 - 3.39 |
| F | 14 | 0.73 - 3.43 |
| G | 1 | 0.98 |
| H | 7 | 0.73 - 2.45 |
| I | 8 | 0.61 - 3.43 |
| Total | 58 | |

The spatial distribution densities of the stilt roots in this study are considered small if compare with the research done by [14]. They had conducted a study at fringe and overwash forests located Tampa Bay, Florida. From their observation, they had found that the mean spatial densities of stilt roots were 60/m$^2$ infringing forest and 62/m$^2$ in overwash forest respectively. Their studies indicated that the number of roots of Rhizophora mangrove trees was significantly different between mangrove forest. The differences in stilt roots spatial density might be also due to the factor of different type of mangrove sample. Both researchers had selected Rhizophora mangle as study target. While for this study,Rhizophora apiculata was selected as the case study. Moreover, there were significant differences in roots complexity between the two mangrove species Rhizophora apiculata and Rhizophora mangle. The root complexity in total area is 58 in this paper, while 167 in [14] study. Thereby, the differences in spatial distribution stilt root density in both studies were occurred by taking the consideration of the above factors.

**Simulation of Pneumatophores and stilt roots using CFD**

The simulation of Avicennia sp.Pneumatophores roots mesh was conducted using Computational Fluid Dynamic software. The full simulation of the root mesh files was executed in 2D with turbulent flow with unsteady state. These due to the turbulent flows are considered transient in which the flow condition changes over the time. Henceforth, as the complexity of Pneumatophores roots mesh may consume time for iteration process, Spalart-Allmaras turbulence model was chosen since the turbulence model compute faster compare to k-ω and k-ε models. Moreover, the Spalart-Allmaras model also was proven to produce comparativelygood results as the other turbulence models. The mesh had been iterated using inlet velocity 6 m/s and time step size 0.03 s with minimum time step until it reaches convergence. Thus, the simulation result of Pneumatophores mesh can be observed in Figure-4.

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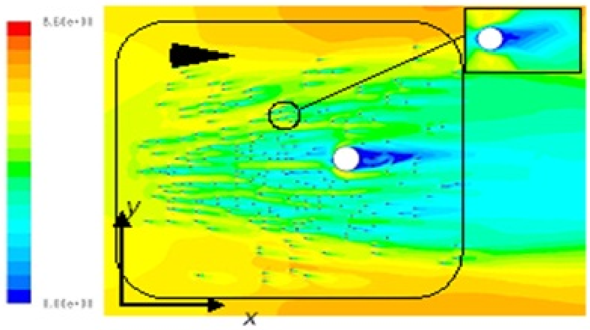


**Figure-4.** Simulation result of Avicennia marina Pneumatophores.

The white circle indicates the primary trunk mangrove tree while the large number of small dot representing the roots geometrical coordinate. The water flow used during the simulation had traveled from x-axis where indicated by the red to blue color. Thus, the differences in color represented the velocity magnitude of the flow from the highest red to the lowest blue. The changes of the velocity magnitude were due to the propagation and mitigation process conducted by the Pneumatophores. Water flow that in red indicated the jet flow while the flow that in blue indicated the turbulence stagnation area. The jet flow was created due to the movement of flow from the open area in the small opening of space between the Pneumatophores [2]. From Figure-4, it was recorded that the maximum velocity of jet flow was over 8 m/s.

Meanwhile, the properties of stagnation areas were affected by the velocity of water flow and the Reynolds number. In [15] had found that as the Reynolds number decreased, the stagnation points change shape from parabolic to skew. The transition process from turbulent to laminar begin as the flow moving throughout the farfield area. This could be observed from the shape change of stagnation points. The shape was parabolic at x=0~100, while starting to change into skewed starting at x=100.

Furthermore, Figure-4 also shows that the velocity of the water flow gradually decreasing as the flow was mitigated by the Pneumatophores roots. These can be observed by the significant different colors of velocity in the far field area. The Pneumatophores root area which indicates by the blue color steadily became larger and had created a large stagnation area at the end of the root area. Thus, to observe the velocity changes of the water flow in the Pneumatophores root area, line surfaces were created at every 50 cm of the x-axis cross section. Figure-5 shows the total changes of velocity magnitude against the geometrical coordinate of mangrove roots, where the velocity magnitude of the water flow decreased in certain coordinate of the roots.

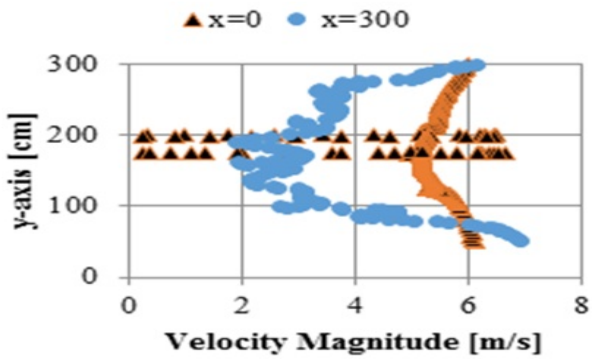


**Figure-5.** Velocity dissipation by Pneumatophores at x-axis cross section.

The significant differences of velocity magnitude between the cross sections can be observed from Figure-5. At the cross section x = 300 it can be observed clearly that the velocity magnitude decreased almost to 2 m/s which was 60 % of the initial velocity. This phenomenon was similar to the result from the research done by [16]. They had conducted laboratory experiment using flume with Avicennia sp. artificial roots model. Thus, they had observed that the velocity gradually decreased at every 50 cm, as the water travel along the 6 m long of the root area. The initial velocity of 5 m/s was reduced to 3 m/s which were about 40% of the initial flow.

In [6] also indicated through their numerical simulation of Avicennia with TUNA-RP model where the velocity of wave that travel through the mangrove forest was decreased depending on the width and the density of the forest. Similarly, in [17] study on the energy dissipation within the mangrove forest using numerical simulation found that the mean velocity of the wave gradually decreased at every 20 m cross sections of the mangrove forest. The horizontal and vertical amplitude velocities respectively decreased about 60% of the initial velocity of the flow [16].

Henceforth, the simulation of the stilt roots was also conducted by using the same parameters as the Pneumatophores. The simulation result of Rhizophora sp. stilt roots can be observed in Figure-6. The white circle indicates the spatial distribution of the stilt roots. Similar to Avicennia sp., the water flows from x-axis and the significant differences of colors represented the velocity magnitude of the flow. The highest velocity magnitude was represented by red while lower velocity was represented by the blue color.

These changes of the velocity magnitude were also created by the propagation and mitigation process conducted by the mangrove roots. Thus, we can observe clearly the multiple jet flows and the turbulence stagnation areas which created during the mitigation process [2]. It also can be seen that the areas with the minimum velocity gradually increasing as the water flow through the area of the stilt roots. Thus, the large stagnation area had been created at the end of the root area, which was similar to the result provided by the Pneumatophores simulation.

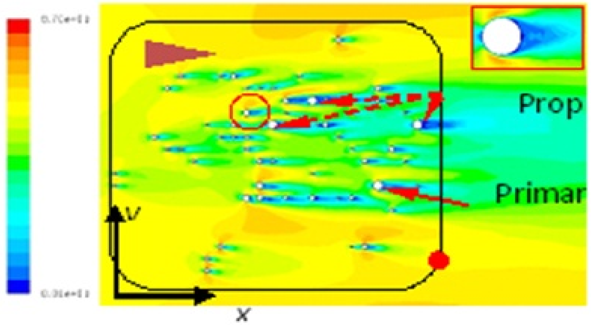


**Figure-6.** Simulation result of Rhizophora apiculata stilt roots.

Hence, using the same method as the Pneumatophores simulation, line surfaces were created at every 50 cm interval of the stilt root area.

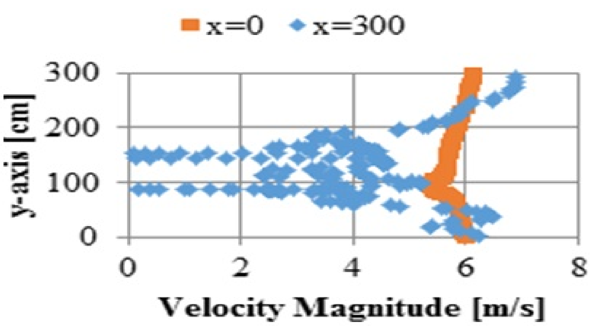


**Figure-7.**Velocity dissipation by stilt roots at x-axis cross section.

From Figure-7, it can be observed that the maximum velocity deficit can be observed at x = 300 with the velocity magnitude close to 2 m/s. The mean velocity of the flow was at 4 m/s where 33 % of the initial velocity was mitigated. The mean velocity deficit by the stilt roots in the computational simulation was much smaller compared to the video camera analysis data taken by [2]. They had recorded that the velocity deficit was almost 50% of the initial velocity. However, it can also be observed in Figure-4 and Figure-6 that there was an existence of velocity magnitude that was close to 0 m/s in both data analysis of Pneumatophores and stilt roots. These phenomena had occurred due to the interaction of the water flow with the root edges at the collision point hence created stagnation area. The stagnation areas located behind the individual root had velocities magnitude close or equal to 0 m/s.

Furthermore, from Figure-5 and Figure-7 it can be seen that at some point of distance there existed velocity magnitude that almost reach to 8 m/s. These had occurred due to the creation of jet flow between the spaces of the individual roots. The jet flows were produced during propagation and mitigation process creates high velocity of current in which the jet flows will have 2 or 3 times of the initial velocities [2, 5]. Hence, the simulation result had shown that the maximum velocity of the jet flow increased up to 30% of the initial velocity which was much lower compare to [2].

From the both simulation results, it can be seen that the velocity of water flow gradually decreasing as the water travel into the root area. It also can be observed that velocity deficit was much higher for Pneumatophores compare to stilt roots where there was almost 2 m/s gap of velocity deficit in the mitigation process. The velocity gap between the two mangrove species occurred due to differences in root density. Henceforth, high root density created large obstacle against the water flow thus decreasing of the water velocity magnitude [2, 5]. Since Pneumatophores had a larger density compared to stilt roots, it creates more disturbance to the water flow while reducing the flow velocity.

From Figure-4 and Figure-6, it can be analyzed that the obstacle created by roots generated an area of the low velocity turbulent region behind the individual roots which was called stagnation region [2]. The size of stagnation regions was depended on the flow velocities and the cross section diameter of the roots. The size of stagnation areas could reach 2 to 3 times of the diameter of the each individual roots. Furthermore, it also can observe that the stagnation region had increased in consistence with the root density. An area with a higher root density had generated much larger turbulent intensity [16]. This shows that the generation of stagnation regions was related to roots spatial density since higher roots density create a much larger obstacle to the flow.

However, it also can be observed that although the spatial density of stilt roots were much smaller compared to Pneumatophores, it can greatly reduce the flow velocity where the velocity deficit was comparable to the Pneumatophores. The ratio of roots spatial density between the both mangrove species was 1: 4. Therefore, at every of 50 cm interval of x-axis cross section, Avicennia sp. will have 70 % more roots compare to Rhizophora sp.. Even though Rhizophora sp. had 70% less of root density, the stilt roots manage to mitigated 33% of the initial velocity magnitude of the flow and capable of reaching at the same velocity point as Pneumatophores at cross section x = 300 cm. Rhizophora sp. was able to mitigated the water flow velocity as efficient as the Avicennia sp. was due to the factor of the cross section diameters of the stilt roots.

## CONCLUSION AND RECOMMENDATION

Meanwhile, this paper had concluded that mangrove root properties and coordination had a high influence to the flow velocity reduction. An area that had high roots densities and cross-section diameters were capable of dissipating more velocities. The study also discovered that the contact between jets, eddies, turbulence scale and stagnation areas were contributing to the velocity deficit. Though CFD simulation, the paper also can clearly observe the flow structures including the creation of jets, eddies and extracting more accurate velocity magnitude in the mangrove roots. Thus, the obstacles created by the Pneumatophores and stilt roots had increased the turbulent intensity of the water flow. Thus, this had led to the reaction between the stagnation regions, eddies and jet flows. The reaction between regions and jet flows create dissipation effect which had a capability to reduce the water flow velocity from 30% to 60% of the initial velocity. It also can be observed that the velocity magnitude had an inverse relation with the turbulent intensity where the velocity became lower at the high turbulent intensity.

It is proposed for future study to use 3D simulation in order to observe more details on the flow structure in the mangrove root area. It was also recommended in the future to create an actual model of mangrove roots and breakwater for in-house simulation. This is because the simulation result of the mangrove roots and the breakwater model through in-house experiment could provide more accurate validation data of the CFD simulation result. Furthermore, an actual implementation of the breakwater model in the study site is also recommended for future study. By conducting experiments at the actual environment will provide valuable data for the efficiency of the breakwater model. This study is important for future contribution in order to design more efficient breakwater models that are capable dissipate wave and high velocity current based on the properties as the mangrove roots. The significant of the study also will contribute to the shoreline conservation project by designing breakwater models that have sedimentation properties.

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