Comparative Study of Flow Patterns around Rhizophora and Avicennia Mangrove Roots Using Computational Fluid Dynamics Simulation

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1. Introduction

Coastal defense is one of the more challenging problems faced by the world. One of the simplest solutions, however, is to plant and conserve coastal mangroves. Mangroves are a type of densely vegetated mudflat that grow in brackish or saline water along the coast. Mangrove forests serve an important role in defending the shoreline from natural disasters. The Indian Ocean tsunami which occurred in 2004 wreaked a lot of havoc on some Asian and African countries. Communities located behind mangrove forests, however, were shown to be safer from tsunami destruction than other villages [1].

The roots of mangroves are unique since they have aerial roots that enable the trees to grow securely on the muddy shore. The salty content of the water is separated from clean water by the aerial root, therefore enabling sedimentation to help in preserving the mangrove habitat. Various studies [2–16] have been conducted, numerically and analytically, to investigate and find out the importance of the mangrove forest.

In order to examine wave attenuation over a vegetated region of finite extent, researchers [17] created a small-amplitude periodic wave numerical model in which waves travel through a lattice-like array of vertical cylinders. In the presence of stiff vegetation, researchers provided a refraction-diffraction wave model [18] for assessing wave propagation along a moderate slope zone on the shore. A three-dimensional numerical technique [19] was used to analyze the tsunami wave interacting with mangrove forests. In a recent
study [20], numerical analysis was used to analyze periodic long wave run-up on coastal stiff vegetation sloping beaches. Another research [21] also depicted the energy dissipation during contact with a tsunami using a 2D numerical wave tank model which was based on a porous body model. The data obtained from the study indicated that when plants’ breadth, height, and density grow, the transmission coefficient reduces but the reflection coefficient remains constant.

A research study [22] discovered that in those regions with dense mangrove forests, waves travelling along the roots form jets and these currents prefer to flow about, causing turbulence. The velocity of the waves reduces as a result of friction between the waves and the mangrove forest, as opposed to the friction at the bottom, according to the study. Based on the kind of mangrove species, the wave height and the decrease in the water velocity vary [23]. Some researchers simulated water flow with constant velocity around the mangrove roots form jets and these currents prefer to flow about, according to the numerical simulation research [26] on energy dissipation with the TUNA-RP model [25] indicated that the velocity of fluid was dissipation withint the mangrove forest. Both horizontal and vertical amplitude velocities of the flow reduced by approximately 60% of their original velocity [10].

Mangrove roots perform an important function in lowering wave velocity and protecting the coast, according to a CFD research [27]. CFD research [28] has also been utilized in the analysis of wind flow around the roots of mangroves in order to prevent damage caused by strong winds. CFD analysis [29] of flow patterns around the mangrove roots of Rhizophora has been done in one study, in which it was discovered that the velocity of fluid was reduced by more than 70%.

This research aimed at studying the air flow around roots of the mangroves using a numerical approach to analyze and identify the efficiency of the mangroves in reducing the flow velocity and the comparison of the flow around Rhizophora and Avicennia mangrove roots. It is essential to enhance and expand research in wave velocity propagation around mangrove forests in actual weather situations in order to improve coastline protection systems and to promote the plantation of mangrove trees around the coast to protect villages near the coastal area. This research, therefore, investigates the fluid flow around two prominent mangrove species Rhizophora and Avicennia mangrove roots (stilt and pneumatophore roots) to show their capacity in reducing fluid velocity.

2. Materials and Methods

2.1. Study Area. Pichavaram mangroves (Lat. 11° 26’ N; 79° 48’ E), situated on the southeast coast of the peninsula, are the world’s second largest mangrove forest situated in Tamil Nadu, India. The Pichavaram mangrove wetlands are characterized by many types of mangrove species. It is divided into three different zones: Avicennia zone, Rhizophora zone, and Suaeda zone. The most common mangrove species present in Pichavaram is Avicennia which constitutes about 74% of the total species population, followed by Rhizophora species (15%). This study, therefore, builds on the limited understanding of wave processes that occur in mangrove forests through computational fluid dynamic analysis of wave interaction among the roots of Rhizophora and Avicennia marina mangrove species.

2.2. Study Approach. A two-dimensional unsteady turbulent flow is simulated around the computational model of Avicennia roots and Rhizophora roots by applying inlet velocity. The flow behaviors are analyzed and compared using CFD techniques. The total number of roots considered for Rhizophora and Avicennia are 112 and 224, respectively. The data on root dimensions of mangrove trees were provided by MS Swaminathan Research Foundation (MSSRF), Chennai. The diameters of the stilt roots range between 2 and 3 cm, and the pneumatophore roots vary from 1 to 1.5 cm. A computational model of the geometry was created from the ANSYS workbench. Good quality mesh was created with skewness less than 0.9 using ANSYS Fluent 18.1 CFD software.

2.3. Governing Differential Equations. The equations describing incompressible viscous fluid flow discovered by Navier and Stokes are indicated as follows.

The continuity equation is as follows:

$$\nabla \cdot \overrightarrow{q} = 0. \quad (1)$$

The momentum equation is as follows:

$$\rho \left( \frac{\partial \overrightarrow{q}}{\partial t} + \overrightarrow{q} \cdot \nabla \overrightarrow{q} \right) = -\nabla p + \mu \nabla^2 \overrightarrow{q}. \quad (2)$$

The turbulence effects are investigated using the $k-\varepsilon$ turbulence model. The $k-\varepsilon$ model incorporates the equation of continuity and momentum equations as well as a transport equation for turbulent kinetic energy $k$ and another transport equation for turbulent kinetic energy dissipation rate $\varepsilon$. These equations are given as follows:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + M_k + M_k - \rho e - Y_m,$$

$$\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right]$$

$$+ C_{\varepsilon 1} \frac{\varepsilon}{K} (M_k + C_{\varepsilon 2} M_k) - C_{\varepsilon 3} \rho \frac{\varepsilon^2}{K}. \quad (3)$$

The velocity component in the $x$ direction is represented by $u_t$, $\mu$ is the viscosity, $\mu_t$ denotes the turbulent viscosity, $M_k$ denotes shear stress-related turbulent kinetic energy generation, $M_k$ denotes buoyancy-related turbulent kinetic energy generation, and $Y_m$ denotes the compressibility related kinetic
energy generation. $C_{ε1} = 1.44$, $C_{ε2} = 1.92$; $C_{ε3} = 1.0$; $σ_k = 1$, $σ_ε = 1.3$, and $C_μ = 0.09$ are empirical constants [30].

2.4. Boundary Conditions. Incompressible unsteady viscous air flow is simulated around the *Rhizophora* and *Avicennia* roots using the inlet velocity.

\[
\text{Inlet velocity} = \begin{cases} 
10 \text{ m/s} & 0 \leq t \leq 4 \\
20 \text{ m/s} & 4 \leq t \leq 8 \\
30 \text{ m/s} & 8 \leq t \leq 12.
\end{cases}
\] (4)

In this study, the walls are fixed (no slip boundary condition) and all body forces are ignored. The outlet is indicated as a pressure outlet with a 0 Pascal condition. $\mu = 1.7894e^{-05}$ kg/ms$^{-1}$ (coefficient of viscosity of air), and $\rho = 1.225$ kg/m$^3$ (density of air). The flow is simulated using the turbulence model because the Reynolds number is found to be greater than ten thousand and the flow is incompressible due to the Mach number which is less than 0.3.

2.5. Methodology. The two-dimensional roots of *Rhizophora* and *Avicennia* mangrove trees were first drawn in a 3.5 m-by-3.5 m grid using the ANSYS workbench design modeler V-18.1. Around the root geometry, a far-field open boundary with dimensions of 15 m by 7 m size is built. To recreate realistic circumstances at the boundary, the far-field boundary lowers the influence of the restriction on the fluid and a mesh is generated using ANSYS as shown in Figures 1 and 2. Grid-independent investigation is carried
out to determine the proper amount of grid cells needed to get a grid-independent solution to the problem. In this study, the mesh containing 609036 cells for the *Rhizophora* mangrove roots model and 357384 cells for the *Avicennia* mangrove roots model is used to simulate the flow to reduce the computational time. Figures 3 and 4 represent the

<table>
<thead>
<tr>
<th>Rhizophora Mangrove Roots</th>
<th>Avicennia Mangrove Roots</th>
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<tbody>
<tr>
<td><strong>Wall Yplus</strong></td>
<td><strong>Wall Yplus</strong></td>
</tr>
<tr>
<td>0.00 0.05 0.07 0.10 0.13 0.17 0.20 0.22</td>
<td>0.00 0.07 0.15 0.22 0.29 0.37 0.44 0.49</td>
</tr>
</tbody>
</table>

**Figure 3:** *Rhizophora* mangrove roots grid model created in ANSYS workbench.

**Figure 4:** *Avicennia* mangrove roots grid model created in ANSYS workbench.

**Figure 5:** Wall y⁺: (a) *Rhizophora* mangrove roots; (b) *Avicennia* mangrove roots.
Rhizophora and Avicennia mangrove roots grid model, which is generated in ANSYS workbench. The big circle represents the primary root in both figures. Between the far field’s border and the root geometry, a quadrilateral-dominating mesh is constructed using the size function. Inflation layers are created around the root geometry in order to capture the boundary layer physics. To acquire the $y^+ \sim 1$ (for the turbulence model, increase the wall function $k$–$\varepsilon$), the initial cell height near the roots is modified. Figure 5 shows the wall $y^+$ around the roots. The study is carried out using the finite volume approach.

3. Results and Analyses

The velocity contour of incompressible unsteady air flow at 4 seconds, 8 seconds, and 12 seconds is visualized in Figure 6.
The white circle represents the central stem of the mangrove tree, while the enormous number of little dots represents the Rhizophora and Avicennia mangrove tree roots (stilt and pneumatophore roots). The air flow in the simulation moves from the inlet to the outlet is clearly shown in Figure 6. As a result, the color disparities reflect the flow’s velocity magnitude, from the maximum red to the minimum blue. The propagation and mitigation processes carried out by the stilt and pneumatophore roots were responsible for the variations in velocity magnitude. The red color contour represents the jet flow, while the blue color contour represents the region within which there is turbulence stagnation. The jet flow was formed by the flow moving from the open region to the narrow gap between the mangrove roots. The velocity of stilt and pneumatophore roots at the same position is visualized in Figure 6. Three different roots named a, b, and c of Rhizophora and Avicennia mangrove trees which are at the same distance from the inlet are identified, and the velocity at these points is compared and analyzed.

Tables 1–3 show that there is a small variation of velocities at different positions. The data clearly show that the Avicennia marina roots reduce the velocity more than Rhizophora roots, bearing in mind that the ratio of the number of roots in Rhizophora and Avicennia is 1:2. The data therefore show that the Rhizophora roots are capable of reducing the velocity significantly since the dimensions of these roots are more than those of Avicennia roots.

Figure 7 indicates the XY plots of velocity at the inlet, the outlet, and at the point x = 2.5 m. The data clearly show that both mangrove roots have the capacity to reduce the velocity. By comparing the inlet and outlet velocities of both mangrove roots, Rhizophora mangroves reduced 58% of the initial velocity and Avicennia mangroves reduced 62% of the initial velocity. Figure 6 and Tables 1–3 show that the Rhizophora and Avicennia marina mangrove roots can reduce the flow velocity. At x = 2.5 position, the velocity is reduced to zero as observed in Figure 7.

Table 4 represents the minimum and maximum velocity of flow around Rhizophora and Avicennia mangrove roots at time intervals of 4 seconds, 8 seconds, and 12 seconds, at various velocities of 10 m/s, 20 m/s, and 30 m/s, respectively. It is obvious that both mangrove roots effectively lower the flow velocity to 0 m/s. It is also evident that the maximum velocity obtained in some regions is due to the formation of jet flows caused by turbulence around the roots.

Figure 8 represents the total pressure distribution of Rhizophora and Avicennia mangrove roots and the pressure at different points. The green contour indicates that extremely low pressure is developed near and around the roots, whilst the red contour indicates that very high pressure is found away from the root region.

The pressure distribution of the air flow in Rhizophora mangrove roots, after 4 seconds, 8 seconds, and 12 seconds are illustrated in Figure 8 (left side). The root away from the left side of the primary root (the first enlarged image) shows that the pressure near the roots is 8.2 Pa, 24.7 Pa, and 150.3 Pa (green contour) and 22.3 Pa, 81.2 Pa, and 175.6 Pa (yellow contour). The root near the left side of the primary root (the second enlarged image) indicates the pressure near the root is −5.8 Pa, −31.9 Pa, and −79.3 Pa (green contour); 22.3 Pa, 81.2 Pa, and 175.6 Pa (yellow contour); and 40.8 Pa, 137.9 Pa, and 300.5 Pa (dark yellow contour). The roots near the right side of the primary root (the third enlarged image) represent the pressure near the roots are −39.5 Pa, −88.5 Pa, −137.9 Pa, −300.5 Pa, respectively.
and \(-300.6\) Pa (green contour) and \(22.3\) Pa, \(81.2\) Pa, and \(175.6\) Pa (yellow color).

The pressure distribution of the air flow in *Avicennia* mangrove roots after 4 seconds, 8 seconds, and 12 seconds is indicated in Figure 8 (right side). The root away from the left side of the primary root (the first enlarged image) shows that the pressure near the roots is \(-0.5\) Pa, \(-35.7\) Pa, and \(-50.5\) Pa (green contour) and \(12.5\) Pa, \(18.7\) Pa, and \(150.4\) Pa (yellow contour). The root near the left side of the primary root (the second enlarged image) indicates the pressure near the root is \(12.5\) Pa, \(18.7\) Pa, and \(150.4\) Pa (yellow contour) and \(25.5\) Pa, \(129.2\) Pa, and \(275.4\) Pa (dark yellow contour). The root near the right side of the primary root (the third enlarged image) represents the pressure near the roots is...
Table 4: The minimum and maximum velocity of flow around Rhizophora and Avicennia mangrove roots at time intervals of 4 seconds, 8 seconds, and 12 seconds.

<table>
<thead>
<tr>
<th>Inlet velocities with respect to time</th>
<th>Rhizophora mangrove roots</th>
<th>Avicennia mangrove roots</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Minimum velocity (m/s)</td>
<td>Maximum velocity (m/s)</td>
</tr>
<tr>
<td>4 seconds (10 m/s)</td>
<td>0</td>
<td>17.2</td>
</tr>
<tr>
<td>8 seconds (20 m/s)</td>
<td>0</td>
<td>34.5</td>
</tr>
<tr>
<td>12 seconds (30 m/s)</td>
<td>0</td>
<td>51.7</td>
</tr>
</tbody>
</table>

Figure 8: Pressure distribution of incompressible unsteady air flow at time intervals of 4 seconds, 8 seconds, and 12 seconds.
Table 5: The minimum and maximum pressure of flow around *Rhizophora* and *Avicennia* mangrove roots at time intervals of 4 seconds, 8 seconds, and 12 seconds.

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<tr>
<td></td>
<td>Minimum pressure (Pa)</td>
<td>Maximum pressure (Pa)</td>
</tr>
<tr>
<td>4 seconds (10 m/s)</td>
<td>−160.5</td>
<td>120.6</td>
</tr>
<tr>
<td>8 seconds (20 m/s)</td>
<td>−654.4</td>
<td>477.4</td>
</tr>
<tr>
<td>12 seconds (30 m/s)</td>
<td>−1485.0</td>
<td>1069.8</td>
</tr>
</tbody>
</table>

Figure 9: Pressure changes of unsteady air flow by *Rhizophora* and *Avicennia* mangrove roots at inlet, outlet, and $x = 2.5$ m.
26.6 Pa, −91.7 Pa, and −250.3 Pa (green contour) and −0.5 Pa, −35.7 Pa, and −50.5 Pa (light green contour).

Table 5 represents the minimum and maximum pressure of flow around *Rhizophora* and *Avicennia* mangrove roots at time intervals of 4 seconds, 8 seconds, and 12 seconds with velocities of 10 m/s, 20 m/s, and 30 m/s, respectively.

Figure 9 shows the pressure variations caused by *Rhizophora* and *Avicennia* roots in an x-axis cross section at different time intervals of 4 seconds, 8 seconds, and 12 seconds with variable velocities. Because of the presence of mangrove roots, the pressure decreased to less than zero at the location x = 2.5 m. The pressure at x = 2.5 m in the *Rhizophora* roots illustrated in the left side of Figure 9 represents that the minimum pressure observed in the position near to 1 m, which shows that the density of stilt roots is more in that place than those in others. Similarly, the right side of Figure 9 (*Avicennia* roots) represents the minimum pressure indicated in the position between 2 m

**Figure 10:** Static pressure distribution of incompressible unsteady air flow at time intervals of 4 seconds, 8 seconds, and 12 seconds.
Table 6: The minimum and maximum static pressure of flow around *Rhizophora* and *Avicennia* mangrove roots at time intervals of 4 seconds, 8 seconds, and 12 seconds.

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<th>Avicennia mangrove roots</th>
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<tr>
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<td>Minimum static pressure (Pa)</td>
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<tr>
<td>4 seconds (10 m/s)</td>
<td>−160.5</td>
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</tr>
<tr>
<td>8 seconds (20 m/s)</td>
<td>−654.9</td>
<td>477.2</td>
</tr>
<tr>
<td>12 seconds (30 m/s)</td>
<td>−1487.0</td>
<td>1069.2</td>
</tr>
</tbody>
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**Figure 11:** Convergence plot of incompressible unsteady air flow at time intervals of 4 seconds, 8 seconds, and 12 seconds.
and 3 m, which shows that the density of pneumatophore roots is located more in that place.

In Figure 10, the static pressure distribution of *Rhizophora* and *Avicennia* mangrove roots and static pressure at different points are depicted at different time intervals with changing velocities of 10 m/s, 20 m/s, and 30 m/s.

The static pressure distribution of the air flow in *Rhizophora* mangrove roots after 4 seconds, 8 seconds, and 12 seconds are illustrated in Figure 10 (left side). The root away from the left side of the primary root (the first enlarged image) shows that the static pressure near the upstream side of the roots is 120.6 Pa, 477.2 Pa, and 1069.2 Pa (red contour) and 50.3 Pa, 194.2 Pa, and 430.1 Pa (orange contour). The static pressure near the perpendicular (the first enlarged image) side of the roots is –34 Pa, –145.4 Pa, and –464.5 Pa (dark green contour). The static pressure near the downstream side of the roots is 8.1 Pa, 24.4 Pa, and 46.7 Pa (light green contour); 22.2 Pa, 80.9 Pa, and 174.5 Pa (yellow contour); and 36.3 Pa, 137.6 Pa, and 302.3 Pa (dark yellow contour). The root near the left side of the primary root (the second enlarged image) indicates the static pressure near the upstream side of the root is 50.3 Pa, 137.6 Pa, and 302.3 Pa (light orange contour). The root near the left side of the primary root (the first enlarged image) indicates the static pressure near the upstream side of the root is 50.3 Pa, 137.6 Pa, and 302.3 Pa (light orange contour); 22.2 Pa, 80.9 Pa, and 174.5 Pa (yellow contour); and 8.1 Pa, 24.4 Pa, and 46.7 Pa (light green contour). The static pressure near the downstream (the second enlarged image) side of the roots is –19.9 Pa, –88.8 Pa, and –208.9 Pa (dark green contour).

The static pressure distribution of the air flow in *Avicennia* mangrove roots after 4 seconds, 8 seconds, and 12 seconds is illustrated in Figure 10 (right side). The root away from the left side of the primary root (the first enlarged image) shows that the static pressure near the upstream side of the roots is 102.5 Pa, 402.0 Pa, and 892.7 Pa (red contour) and 50.7 Pa, 71.8 Pa, and 144.4 Pa (light green contour). The static pressure near the perpendicular (the first enlarged image) side of the roots is –65.9 Pa, –259.0 Pa, and –479.2 Pa (dark green contour). The static pressure near the downstream side of the roots is –14.1 Pa, –88.7 Pa, and –215.8 Pa (green contour) and 15.9 Pa, 16.4 Pa, and 19.7 Pa (yellow contour). The root near the left side of the primary root (the second enlarged image) indicated the static pressure near the upstream side of the root is 11.8 Pa, 16.4 Pa, and 19.7 Pa (light yellow contour) and –1.1 Pa, –38.7 Pa, and –105.0 Pa (light green contour). The static pressure near the downstream (the second enlarged image) side of the roots is –27.1 Pa, –148.9 Pa, and –354.5 Pa (dark green contour) and –12.1 Pa, –93.8 Pa, and –229.8 Pa (light green contour).

Table 6 represents the minimum and maximum pressure of flow around *Rhizophora* and *Avicennia* mangrove roots at time intervals of 4 seconds, 8 seconds, and 12 seconds with velocities of 10 m/s, 20 m/s, and 30 m/s, respectively.

The solution converged to 3 decimal places for unsteady incompressible air flow at 4 seconds, 8 seconds, and 12 seconds as displayed in Figure 11. The results obtained in this study were validated with the convergence plot and the previous study from the literature survey [10, 26–29].

4. Conclusion

*Rhizophora* and *Avicennia* mangrove roots and stem have the capacity to reduce the flow velocity to a great extent. The comparison of the inlet and outlet velocity of both the mangrove roots shows that the *Rhizophora* and *Avicennia* mangrove roots reduce around 60% of the inlet velocity. In this study, *Rhizophora* and *Avicennia* roots were considered in the ratio 1:2, which clearly reveals that the *Rhizophora* mangrove roots can reduce the flow velocity to a greater extent because of the complexity and its root dimensions in comparison to *Avicennia* roots. The characteristics and coordination of mangrove roots, however, have a significant impact in reducing the flow velocity. In addition, high root densities and cross-section diameters allowed more velocities to be dissipated in a given area. The study also reveals that the velocity deficit was caused by interaction with jets, eddies, the turbulence scale, and stagnation zones.

It is highly recommended that future research should integrate 3D simulation to study the flow structure in the mangrove root region in more depth. Such a research study is essential for future developments in order to build more effective breakwater models that can reduce wave and high-velocity current using characteristics similar to those observed in mangrove roots.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

References


