Computational Fluid Dynamic Analysis of Flow around Mangrove roots.

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Abstract: The objective of this paper is to study the flow patterns around mangrove roots to understand its significance in coastal risk reduction. A computational model of two-dimensional Pneumatophores mangrove roots is developed, and flow is simulated using ANSYS software with a predefined mathematical model and boundary conditions. Computational fluid dynamic analysis of a two-dimensional, viscous, incompressible, turbulent flow under steady and unsteady boundary condition is performed using the Finite volume method. Detailed velocity profiles, residual plots, pressure distributions, vectors of the velocity magnitude and pressure and velocity at different positions around the mangrove roots are presented to visualize the importance of mangroves in reducing the wave velocity. The simulation outcome confirms that the mangrove roots of mangrove species can reduce the initial velocity of water flow. The flow patterns and flow structures around the root in the mangrove forest establishes precious data in increasing the effectiveness of current breakwater model.

Key words: Mangroves, Pneumatophores, Computational Fluid Dynamic Analysis, Finite Volume.

Introduction
Natural calamities caused by tsunamis, flooding & Mudslides pose a great threat to human civilization. Thousands of people who live along the coastal areas, mountain sides & river banks every year become victims of these disasters. The ecosystems along the coast like the mangrove forests are becoming prominent tools for coastal defense strategies. ¹Spalding M et al (2014) explained that in order to reduce wave height, maintain sediment balance, reduce tsunami flood depth, and reduce wind and waves on top of surge, there must be sufficient concentrations of mangrove forests. The mangrove forests help in the prevention of erosion and encourage the buildup of active soil. For all aspects of coastal protection, a healthy mangrove is necessary. ²Furukawa K et al (1997) explained in detail about how the mangrove roots play a significant function in securing the coastal area by dissipation of incoming wave energy, reducing the coastal erosion and efficient sediment trapping mechanism. This enables the mangrove trees to serve as natural breakwaters.

The specialty of mangrove roots is that it has aerial roots which help the trees to firmly grow on the muddy coastline. ³Lee S.Y et al (2014) explained that the aerial root has the capacity of separating the salt content of water for pure water and allow sedimentation to help maintain mangrove environment.
McIvor A. L et al (2012), in their study, discussed that each Mangrove species adapt diverse forms of root formation and aerial roots. There are mainly three kinds of aerial roots, which are Prop(stilt) roots, Pneumatophores, and knee roots. Prop roots are related to Rhizophora, Pneumatophores for Avicennia, while knee roots are associated with Bruguiera mangrove species. The mangrove tree roots play a significant role in reducing the force of the tidal wave.

Furukawa K et al (1997) stated that roots of the mangrove tree generate barrier that produce complex two-dimensional current with jets, eddies as well as vegetation-scale turbulence. The vortexes and wakes which appear with high velocity of water stream. At low velocity of water stream, causing the obstacles to create a laminar flow. Burger B (2005) found that in areas with thick mangrove forest, waves that move among the mangrove roots create jets and the currents tend to flow around, giving rise to turbulence. This study further concluded that the speed of the waves that flow through the mangroves was decreased due to friction between the waves and the mangrove forest compared to bottom friction.

Mohamed Zamin Mohamad Jusoh et al in 2016 performed CFD simulation of two-dimensional water flow using unsteady Spalart-Allmaras turbulence model with inlet velocity set to 6 m/s to analyze the velocity dissipation process of two different mangrove species, Avicennia marina and Rhizophora apiculata. They investigated on the properties of these roots and the structure of water flow within the root area. Aziz N.A et al (2012) recorded the total number of roots for their study as 224 in one sample tree. Mohamed Zamin Mohamad Jusoh et al (2016) considered total number of roots in one mangrove tree as 226. The diameter of the Pneumatophores roots of the mangrove tree was considered as 0.95 ± 0.15 cm in their study. Their simulation results showed that mangrove roots of both species reduced the initial velocity.

Majority of the studies were focused on the dissipation process of the wave in mangrove forest rather than investigating the roots of individual mangrove tree. This study focuses on extracting information from the roots structure of Avicennia Marina, which will then be converted into data that will be subjected to appropriate Computational Fluid Dynamic (CFD) simulation and analysis.

Study approach

The two dimensional steady and unsteady turbulence flow patterns around Avicennia roots are investigated in this study by performing Computational fluid dynamic simulation and analysis. The diameter of the Avicennia roots are almost not variable. The roots of mangroves trees are complex, and it may vary depending on the size of the tree. The total number of roots considered in this study is 223. The Pneumatophores diameter of the roots is taken from 0.8-1.1 cm. Consequently, in this study, the authors decided to take only the roots of one tree because it is sufficient to understand the flow patterns around the mangrove roots. Computational Fluid Dynamic Simulation using different turbulence models are performed with the environment of pressure-based solver. The constant velocity of 6 m/s is considered at the inlet for Case 1. In reality, the inlet velocity will change with respect to time and hence in case 2 the inlet velocity is modeled as a step function. Different turbulent models namely Spalart-Allmaras model, k-ω and k-ε model are used to solve the problem and the results are compared.

Governing Differential Equation:

Navier-Stoke’s system of equations governing incompressible viscous fluid flow are as follows:

Continuity Equation:
\[ \nabla \cdot \vec{q} = 0 \]

Momentum Equation:
\[ \rho \left( \frac{\partial \vec{q}}{\partial t} + \vec{q} \cdot \nabla \vec{q} \right) = -\nabla p + \mu \nabla^2 \vec{q} \]  \( (1) \)
Boundary condition

The two-dimensional flow of water from the inlet to the Mangrove root structure is studied using Computational fluid dynamic simulation. The turbulence model is used to simulate the flow because, the Reynolds number calculated for this flow was larger than 5.0 x 10^5. The velocity at the inlet is 6m/s for both steady and unsteady flow in Case 1. In reality the inlet velocity is not constant during the heavy flow of waves in the mangrove forest. So, inlet velocity is modelled as step function.

\[
\text{Inlet velocity} = \begin{cases} 
3\text{m/s}, & 0 \leq t \leq 2 \\
6\text{m/s}, & 2 < t \leq 4 \\
10\text{m/s}, & 4 < t \leq 6
\end{cases}
\]

Different turbulent models namely Spalart-Allmaras, k-\omega and k-\varepsilon models are used in this study. The walls are fixed. Incompressible Viscous flow is considered. The outlet assigned as pressure outflow condition is taken as 0 Pascal. The body forces are ignored. The physical properties of water namely density \( \rho = 998.2 \text{ kg/m}^3 \) and coefficient of viscosity \( \mu = 0.001003 \text{ kg/m/s} \) are used in this study.

Methodology:

The computational model geometry of the mangrove roots is generated using the Ansys workbench design modeler V-18.1 as shown in ‘figure1’. At the outset, the two-dimensional roots plotted in a 3m by 3m grid. An open boundary of far field with dimensions 14m by 6m is created around the root geometry. The far field boundary reduces the impact of the boundary on the fluid to simulate realistic conditions at the boundary. Grid Independent study is conducted to arrive at correct number of grid cells required to get the grid independent solution for the problem. So, the mesh contains 357372 number of cells in this study. A quadrilateral dominant mesh using size function is generated between the boundary of the far field and the root geometry. The Inflation layers are created around the root geometry to capture the boundary layer physics. The first cell height near the roots is adjusted to get the \( y^+ \approx 1 \) (for turbulence models Spalart-Allmaras, k-\omega, enhance wall function k-\varepsilon). Mesh is exported to Ansys Fluent 18.1 software. Finite Volume method is used for analysis. The number of iterations is set as 1000, in all the cases.
Analysis and Result

Figure 2. Steady Turbulence Models Velocity profiles in case 1

Figure 3. Steady Turbulence Models Vectors of Velocity Magnitude in case 1

Figure 4. Steady Turbulence Models Total pressure distributions in case 1

Figure 5. Steady Turbulence Models Velocity iteration plots in case 1
Figure 6. Unsteady Turbulence Models Velocity profiles in case 1

Figure 7. Unsteady Turbulence Models Vectors of Velocity Magnitude in case 1

Figure 8. Unsteady Turbulence Models Total pressure distributions in case 1

Figure 9. Unsteady Turbulence Models Velocity iteration plots in case 1
In Case 1, the simulation of steady and unsteady fluid flow around the mangrove roots is performed using Spalart-Allmaras, k-ω and k-ε turbulence models. All three turbulence models have similar trends in dissipating the velocity around the mangrove roots. The comparison of velocity profile of steady and unsteady turbulent flows around the mangrove roots are presented in ‘figure 2’ and ‘figure 6’. The results are almost same in both steady and unsteady cases with different turbulence models as clearly viewed in these figures. In these figures, the Primary trunk of the mangrove tree is shown as white circle and the Pneumatophores roots represent as small dots. The velocity and pressure distribution on and around the roots can be observed using different contours beginning from blue (least value) to red (highest value). The enlarged image in ‘figure 2’ and ‘figure 6’ indicates that the velocity dissipation is more significant in the region with excess mangrove roots. The velocity contours of different turbulent models also show that the water flow velocity slowly diminishes as the flow is attenuated by the Pneumatophores roots.

The velocity magnitude vectors of steady and unsteady flows using Spalart-Allmaras, k-ω and k-ε turbulence models in case1 are visualized in ‘figure 3’ and ‘figure 7’. The velocity vectors represented by red contour indicates the jet flow and the flow represented in blue contour indicates the turbulence stagnation area. The maximum velocity of jet flow was over 9 m/s as observed from ‘figure 3’ and ‘figure 7’. The maximum velocity of jet flow around 60% more than the initial velocity in all the cases. These occurrences are due to the formation of jet flow around the individual roots.

The pressure distribution of steady and unsteady turbulent flow models around the mangrove roots are given in ‘figure 4’ and ‘figure 8’. The results are almost same in both steady and unsteady cases with different turbulence models as clearly viewed in these figures. It is seen that very low pressure is found near and around the roots indicated by yellow contour whereas very high pressure is observed in the far field area indicated by red contour. The solution converges correct to 3 decimal places for steady and unsteady turbulence models in Case1 as presented in ‘figure 5’ and ‘figure 9’.
A line surface at x=3m is created in the x-axis cross section to observe the velocity and pressure changes in the Pneumatophores root area as presented in ‘figure 10’. ‘Figure 11’ shows the complete changes of velocity magnitude against the geometrical coordinate of mangrove roots at inlet, outlet and x=3m. The velocity magnitude of the water flow decreases at certain positions of the roots. It is clearly observed that the velocity magnitude decreases by more than 3m/s at x=3m, which shows that the velocity is decreasing to more than 50% of the initial velocity in case 1. It also shows that the inlet velocity magnitude decreases significantly at outlet.

It is observed in Case 1 study that, there is not much variation in the results of simulation using Spalart Allmara, k-ω and k-ε Turbulence Models under both steady and unsteady state conditions.
Figure 13 Unsteady k-ε Model Pressure distribution around the Pneumatophores roots at different time intervals in case2

Figure 14. Unsteady k-ε Model Velocity as step function iteration plots in case2

Figure 15. Unsteady k-ε Model Velocity dissipation by Pneumatophores at x-axis cross section in case2

Figure 16. Unsteady k-ε Model Pressure changes by Pneumatophores at x-axis cross section in case2
**Case2 with inlet velocity Modelled as Step Function (Unsteady Flow)**

In Case 2, k-ε Turbulence Model is used to study the mean flow characteristics under unsteady state condition. In reality the inlet velocity is not constant during the heavy flow of waves in the mangrove forest. Hence the inlet velocity is modelled as a step function. The flow pattern around the Pneumatophores mangrove roots has been observed at different time interval at 2 seconds, 4 seconds and 6 seconds with varying velocities as 3m/s,6m/s and 10m/s as shown in ‘figure 12’. It is observed that the Pneumatophores mangrove roots play a vital role in dissipating the velocity at different positions at different time intervals. The velocity values corresponding to different contours are shown in the figures. On comparing the velocity magnitude at different positions, it can be observed that the speed of the flowing water slowly decreases as the water flows into the root area. However, it can also be noticed that at various locations, velocity magnitude is close to 0 m/s. This is as a result of the interaction of the water flow with the root edges at the impact point which in turn creates stagnation area resulting in the reduction of wave velocity. The areas of stagnation that are located behind the individual root has velocity magnitudes close or equal to 0 m/s, as seen in the enlarged image of Pneumatophores root in ‘figure 12’. The roots far away from the primary trunk represented by red contour indicates the jet flow while the flow represented in blue contour indicates the turbulence stagnation area in ‘figure 12’. The maximum velocity of jet flow around 60% more than the initial velocity in all the cases. These occurrences are attributed to the jet flow that was created around the spaces of the individual roots.

The pressure distribution of Pneumatophores mangrove roots has been observed at different time interval at 2seconds,4seconds and 6 seconds with varying velocities as 3m/s,6m/s and 10m/s shown in ‘figure 13’. It is seen that very low pressure is found near and around the roots indicated by yellow contour whereas very high pressure is seen in the far field area indicated by red contour. The solution converges correct to 3 decimal places in Case 2 as presented in ‘figure 14’.

A line surface at x=3m and x=5m are created in the x-axis cross section to observe the velocity and pressure changes in the Pneumatophores root area as presented in ‘figure 10’. The velocity dissipation by Pneumatophores roots in x- axis cross section at different time intervals, 2 seconds, 4 seconds and 6 seconds with varying velocities as shown in ‘figure 15’. The magnitude of the velocity of the water flow decreases at certain positions of the roots. It is clearly observed that the velocity magnitude decreases by more than 3m/s at x=3m, which shows that the velocity is decreasing to more than 50% of the initial velocity in case 2. It also shows that the inlet velocity magnitude decreases significantly when the water flows through the Pneumatophores roots.

The pressure changes by Pneumatophores roots in x- axis cross section at different time intervals namely 2 seconds, 4 seconds and 6 seconds with varying velocities are visualized in ‘figure 16’. It clearly shows that the pressure decreases at many positions at x=3m and x=5m, because of the existence of mangrove roots.

**Conclusion**

In this paper, we conclude that mangrove roots play an essential role in reducing the wave velocity and protect the coast as natural break water model. It is observed that, there is not much variation in the results of simulation run by Spalart-Allmara, k-ω and k-ε Turbulence Models under both steady and unsteady state conditions. This study also forecasts the advantages of CFD in generating an actual environment at minimum cost to estimate and analyze the flow structures, generate the velocity magnitude near and around the root area at different time intervals. Analysis and Simulation results show that low velocity has been observed near the root area and the area that had more roots density. From all simulation results, it can be observed that the speed of water stream steadily decreases to more than 50% of the initial velocity as the water flows into the Pneumatophores mangrove roots zone. We
also observe the formation of jet flows and the turbulence stagnation areas due to the water flow near and around the roots. The maximum velocity of jet flow is around 60% more than the initial velocity in all the cases. The CFD results obtained are consistent with the results found in the literature [2,7]. Convergence of the solution correct to three decimal places is monitored for all cases to validate the results.

Limitations and future scope

Three-dimensional study will be considered in future to discuss the problem in a more realistic environment. Moreover, a real execution of the breakwater model in the examination site is likewise suggested for future investigation. This investigation is significant for future commitment so as to plan and design more productive barrier models.

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