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Numerical Investigation of Flow Hydrodynamics Around the Gap Region of Finite Coastal Vegetation Patches

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Abstract

This study investigates the role of coastal vegetation patches in reducing tsunami damage by addressing the "danger zones" that form between vegetation gaps. These gaps, where the velocity and turbulence of tsunami flows are higher, increase the risk of destruction. The research explores three gap configurations, including straight, inclined, and staggered, by using numerical simulations to evaluate the internal flow properties within these gaps. The Reynolds-Averaged Navier-Stokes (RANS) equations were used in setup with a seven-equation Reynolds stress model (RSM) for turbulence closure. The analysis, conducted using ANSYS Workbench, focuses on the flow dynamics around short submergent and tall emergent mangrove trees. Initially, the model was validated by comparing results with experimental data. The results showed that the inclined gap between vegetation patches (named as Case 2) reduced near-bed velocity by 18.6% and turbulence kinetic energy (TKE) by 40%, while the staggered gap (Case 3) provided the most effective mitigation, reducing velocity by 22.7% and TKE by 41.8%. These findings suggest that adjusting the gap configuration can optimize the effectiveness of coastal vegetation in mitigating tsunami damage. The study holds practical significance for policymakers and coastal engineers, as it provides insight into optimizing vegetation-based coastal defenses to reduce disaster risks, emphasizing the potential of staggered vegetation gaps with a mix of tree types as a promising strategy for enhancing coastal protection and promoting sustainable solutions for disaster resilience.

Keywords: Coastal Vegetation patches; Gap Zone; Numerical modeling ; Flow Velocity; Terbulent kinetic Energy; Turbulence intensity.

1. Introduction

Tsunamis and floods are natural disasters that lead to the overflow of water onto land, causing widespread destruction. Tsunamis are typically triggered by underwater earthquakes, volcanic eruptions, or landslides, generating large, fast-moving waves that travel across the ocean [1]. As these waves approach shallow coastal areas, they increase in size and intensity, posing a significant risk to coastal communities [2]. Floods, on the other hand, occur due to excessive rainfall, snow-melt, or storm surges, leading to the overflow of rivers and drainage systems, and causing damage to infrastructure and displacement of populations [3]. Both events have devastating consequences for human populations and ecosystems. Although the mitigation strategies have gone a long way in the management of tsunamis, there is still a gaping hole in the knowledge on how a vegetation patch structure affects the flow behaviour in the gap zones. This gap can be addressed to enhance the protection measures against disasters and improve the coastal protection systems. The 2004 Indian Ocean Tsunami was a particularly catastrophic event, highlighting the need for effective mitigation strategies [4]. Among the techniques employed to reduce tsunami damage, the use of coastal vegetation such as mangroves and coral reefs has proven effective [5-13]. These natural barriers dissipate wave energy, protect shorelines from erosion, and reduce the extent of flooding. Nevertheless, a considerable amount of previous research was directed at studying continuous vegetation belts, and little is made on finite vegetation patches and the gap areas surrounding them. The study builds upon the previous studies by examining the effect of various gap configuration on hydrodynamic behavior, turbulence, and energy dissipation. Coastal vegetation plays a vital role in absorbing and diffusing the energy of moving water, trapping debris, and minimizing secondary damage to infrastructure [14]. Nonetheless, gaps that exist between the vegetation patches, which is the gape zone, poses an issue, since the tsunami waves travel through the gape zones at a greater speed, which provides danger areas along the coast [14] as depicted in Fig. 1. The treatment of this study is unique as it dwells on the impacts of submergent as well as emergent mangrove trees on flow hydrodynamics in previous studies. The study offers a more detailed insight into the combined effect of these two types of vegetations on tsunami mitigation by taking into account the two vegetation types. The study will examine the behaviour of flowing in various forms of a gap area and how various vegetation setups can make their sheltering capability as effective as possible. Through a well-planned change in the gap spacing and vegetation patch arrangement, this research aims at minimizing tsunami wave effects on the susceptible coastal regions to increase the strength of the coastal communities and to encourage sustainable and natural-based solutions to disaster mitigation. The results of this study have practical implications to policymakers and coastal engineers because they give information on how to develop more efficient vegetation-based coastal defense structures. Recent numerical investigations by Amina and Tanaka [15] demonstrated the potential of 3D modeling to accurately simulate the flow dynamics around finite emergent vegetation, providing insights into how different vegetation arrangements influence wave propagation. Additionally, Abbas et al. [16] explored the flow structures around horizontal layered trees and identified the significant role of tree configuration in mitigating flood and tsunami damage. Other studies, including Abbas and Tanaka [17], have investigated the effects of combined submergent and emergent vegetation layers, emphasizing the importance of vegetation density in controlling water flow and enhancing protective functions during extreme events. These findings contribute to the understanding of vegetation's role in disaster risk reduction and highlight the potential for optimizing natural defenses to safeguard coastal populations [18].

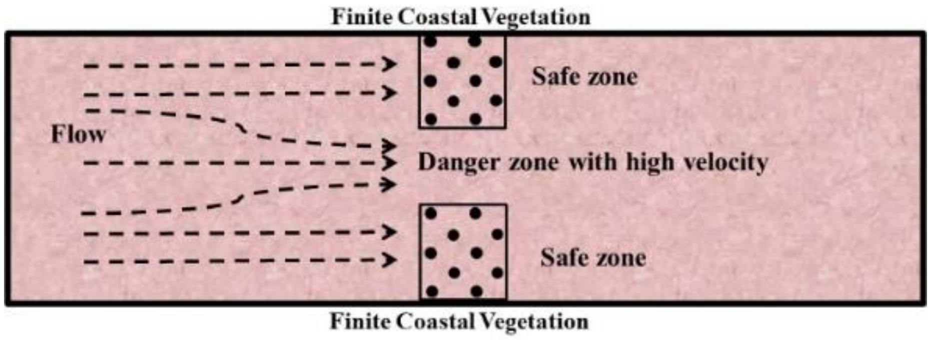

Figure 1. Danger Zone formation between Finite coasal vegetation.

2. Materials and Methods

2.1 Experimental Setup for Model Validation:

The numerical model was tested with the help of experimental data by Amina and Tanaka [19] to validate the current model. The experiment was prepared in an experimental channel that had the dimension of a rectangle (500 cm in length (L), 70 cm in width (w) and 50 cm in height (H)) and placed at Saitama University, Japan. This was a series of wooden cylinders in staggered order laid out in the vegetation on the bottom of the channel at the centre of the width of the stream. The size of the vegetation model and hydraulic conditions were similar, the density was rated to be sparse (S/d = 2.13) [20].

2.2 Validation of Numerical Model.

The calculated streamwise velocity profiles at chosen locations were compared with the experimental findings of Amina and Tanaka [19] to validate the accuracy of the computational model depicted in Fig. 2. The calculated outputs exhibit a strong similarity and favourable alignment with the experimental findings. They demonstrate the accuracy of the numerical model.

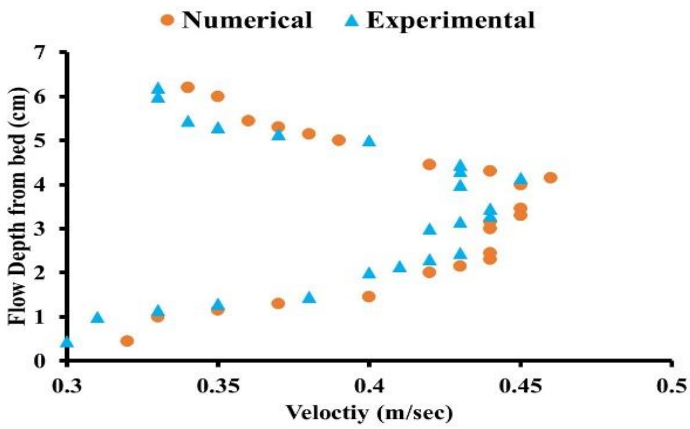

Figure 2. Comparison between Experimental and Numrical results.

2.3 Conditions for present Numerical Model:

The current computational domain was represented by a rectangular channel of 2.5 meters in length and 0.5 meters in width. Three different cases with straight, inclined and staggred gap between vegetation patches were considered as shown in Fig. 3. The whole methodology is elucidated in Fig.4.

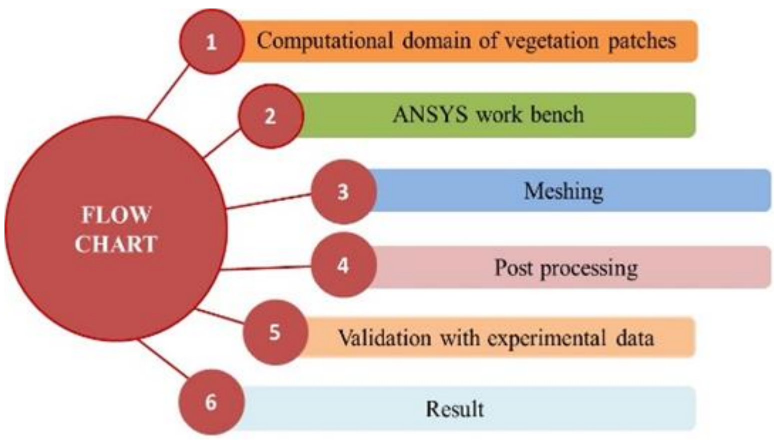

Figure 3. Methodology

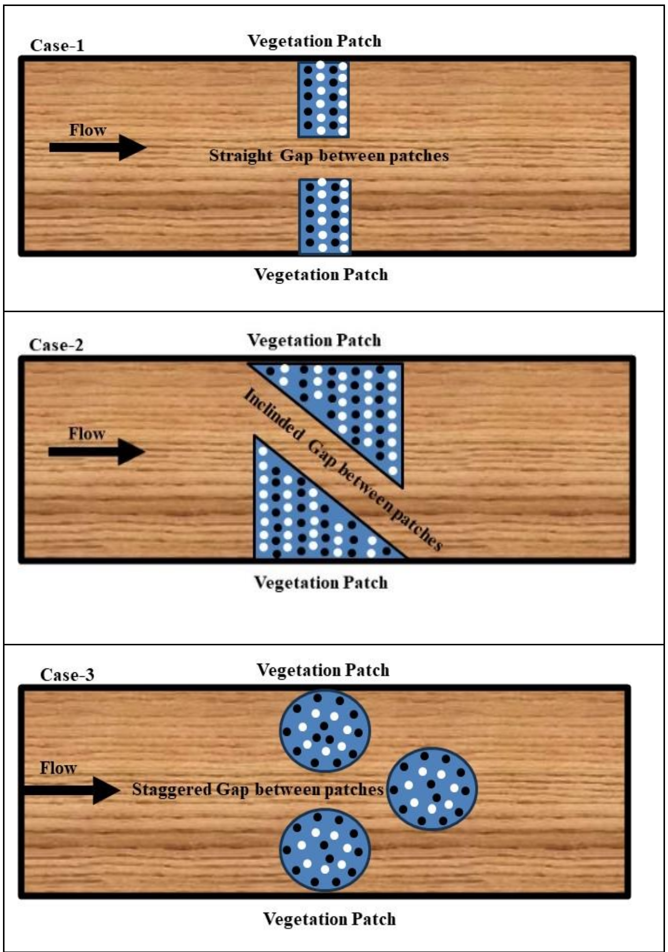

Figure 4. Schematics of Gap Configurations

Precise measurements were taken for vegetation height, width, and length, along with gap characteristics like width, orientation, and arrangement [19]. These geometries formed the foundation for subsequent flow simulations. Three cases were analyzed with different gap configurations and dense vegetation patches, as shown in Table 1.

Table 1. Details of gap regions around Finite vegetation patches.

Case No	Gap Type	Vegetation Configurations	Vegetation Density	Froude No
1	Straight	Staggered	Dense patches	0.7
2	Inclined	Staggered	Dense patches	0.7
3	staggered	Staggered	Dense patches	0.7

3. Results and discussion

3.1 Velocity Profile:

3.1.1 Contour Plots of streamwise velocities

Velocity contours at the bed of the channel (z = 0.01m) were recorded, as shown in Figure 5. The results indicated a decrease in velocity of 18.6% for the inclined gap and

22.7% for the staggered gap compared to the straight gap configuration. Among the three configurations, the staggered gap demonstrated the greatest reduction in velocity, thus offering the safest zone. This reduction in velocity suggests that staggered gaps facilitate a more uniform distribution of flow energy, which minimizes localized high-velocity zones that could exacerbate erosion and infrastructure damage. This reduction of 22.7% in velocity in the staggered gap configuration indicates more effective dissipation of energy and better control over water flow. The lower velocity in the staggered gap minimizes potential hazards associated with high-velocity water flow, reducing the danger zone between the vegetation patches and lowering the risk of devastation during tsunami events Although the inclined gap configuration also significantly reduces velocity, it is less effective than the staggered gap due to the formation of concentrated turbulence pockets near the vegetation boundaries. These turbulent pockets can lead to unstable flow conditions, which may compromise the protective function of the vegetation patches over time.

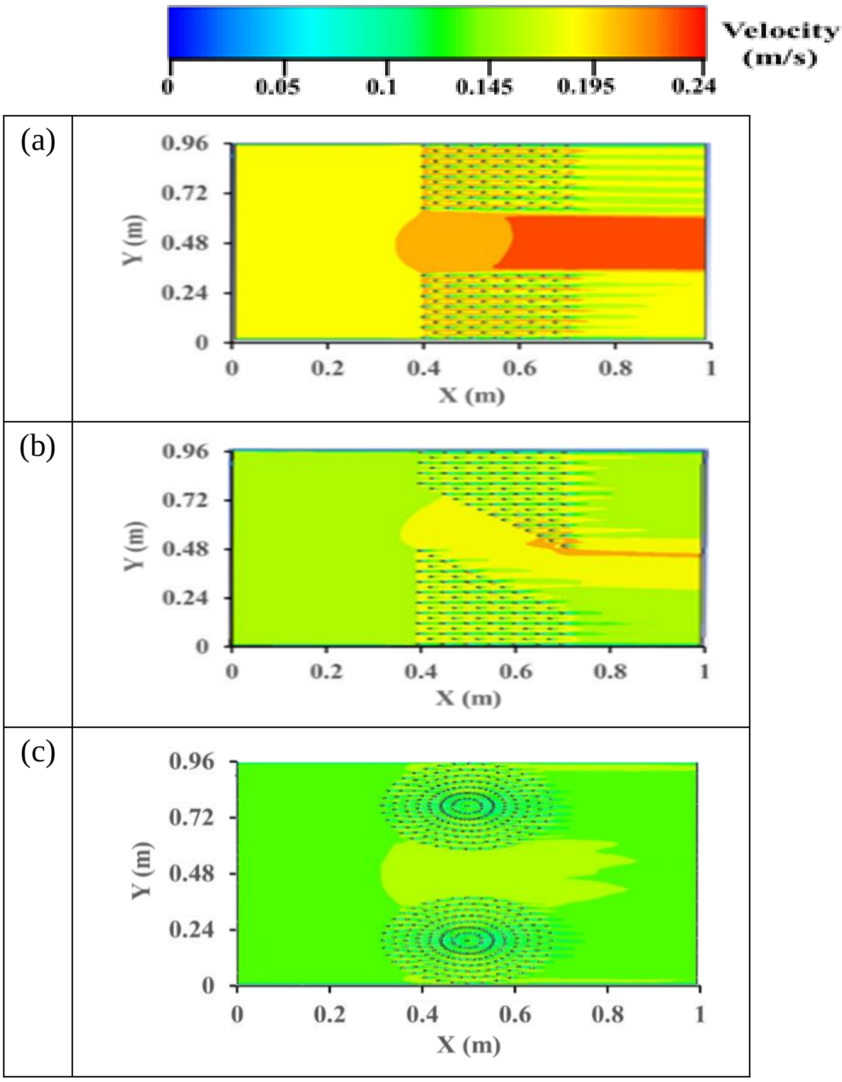

Figure 5. Velocity contours at bed Z=0.01m (a) straight (b) Inclined (c) staggered.

3.1.2 Velocity Contours along cross streamwise direction

The contours of velocity in the gap zone show that staggered gap arrangement offers the best conditions compared to the two other setups investigated. The speed in this set up is 22.7 percent lower than that of the other sets. This reduction shows that there is a better dissipation of energy, and control of the flow of water, which eventually reduces the large velocities of the water in the regions of the gap between patches of vegetation. This means that in actual life protective measures of the coast, the staggered vegetation patterns may offer an increased protection against the water movements caused by tsunami as the flow energy will not suddenly be redirected.

Artificial mitigation measures like seawalls and breakwaters, on the contrary, tend to reflect the waves thereby causing higher turbulence and secondary damage. As opposed to these man-made structures, vegetation-based solutions enable the control of the energy dissipation, which minimises the chances of excessive flow velocity outside the vegetation patches.

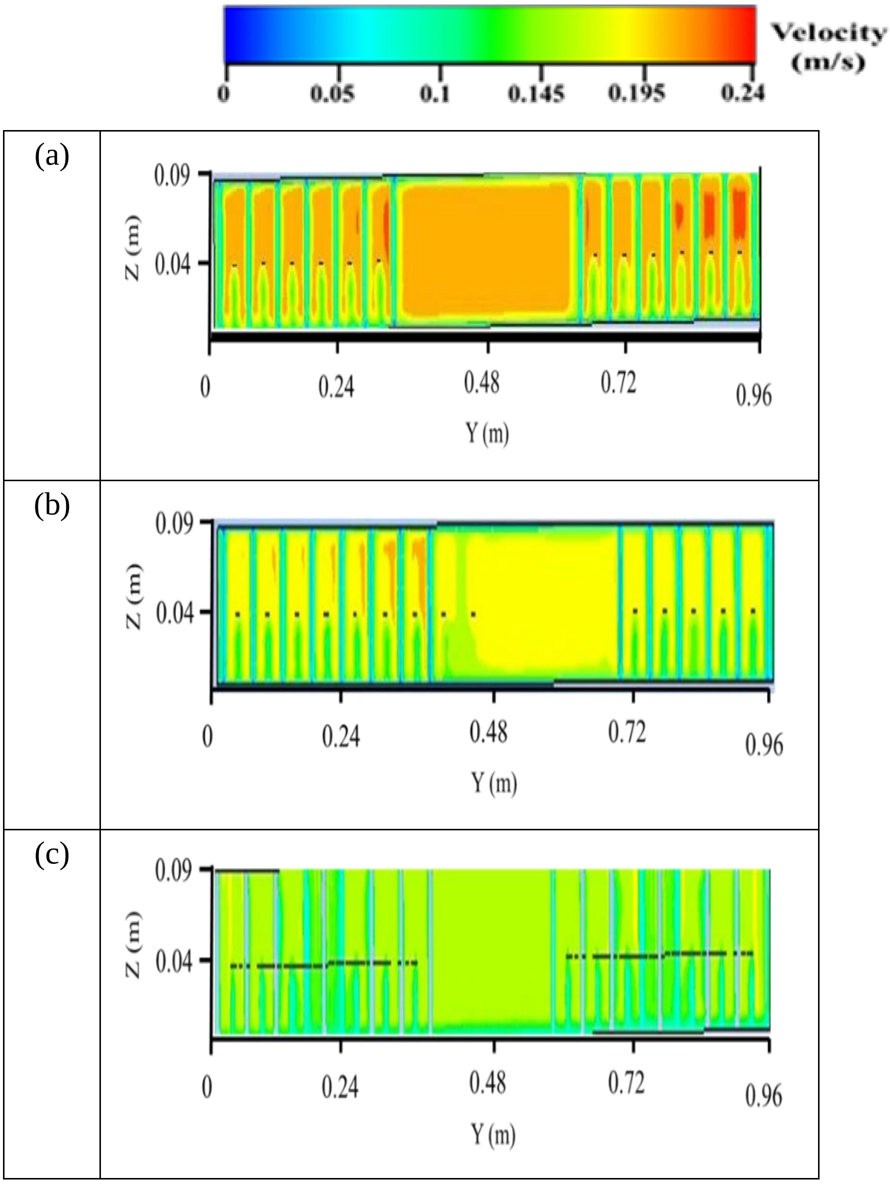

Figure 6. Velocity contours along Cross streamwise direction.

3.2 Turbulent Kinetic Energy Profile:

3.2.1 Contour plots of streamwise Turbulent kinetic energy:

The turbulent kinetic energy (TKE) contours at the bed of the channel (z = 0.01m) show that, among the three configurations, the staggered gap offers the safest conditions. The turbulence kinetic energy is significantly reduced by 40% in the inclined gap and

41.8% in the staggered gap when compared to the straight gap, which develops a higher turbulence zone. This reduction indicates enhanced control over turbulent flow, making the staggered gap configuration the most effective option for improving coastal resilience. The lowered TKE in the staggered gap provides better protection against the adverse effects of high turbulence during tsunami-induced flooding

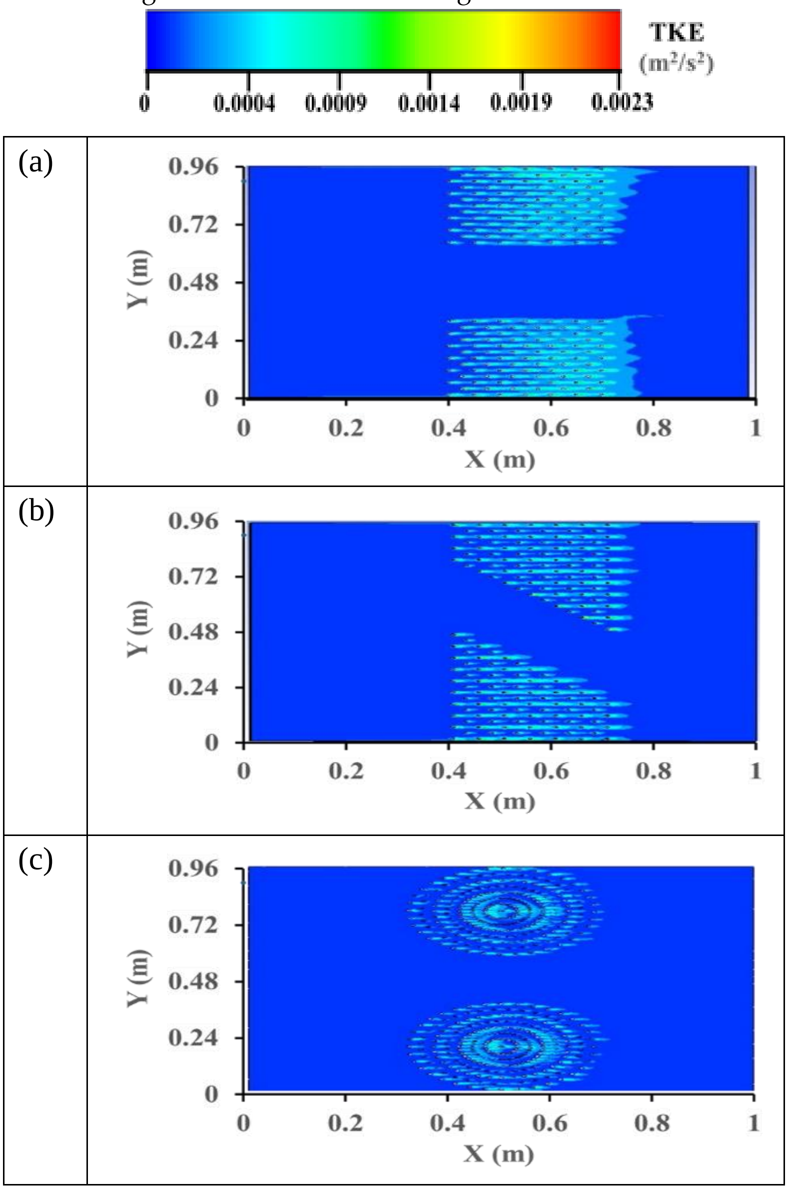

Figure 7. Contour Plots of Terbulent Kinetic Energy (TKE)

3.2.2 Contour Plots of Turbulent Kinetic Energy along cross streamwise direction:

The benefits of the staggered gap configuration are also demonstrated by the turbulence kinetic energy contours. The difference in the TKE of the inclined gap and staggered gap of 40 percent and 41.8 percent respectively with the straight gap which has a danger zone characterized by increased velocity and turbulence highlights the safety and efficacy of the staggered gap configuration. The staggered gap arrangement is more protective against the adverse impact of high turbulence because the danger zone is significantly reduced. The staggered arrangement of gaps decreases the TKE level so that the interaction of tsunami waves and vegetation can be controlled more, and minimizes the potential of uprooting and structural damage of the coastal ecosystem.

Further enhancement of the practical applications can be done by researching on hybrid solutions combining patches of vegetation and artificial structures in the future. As an example, the effective placement of permeable submerged obstacles along with the staggered patches of vegetation might increase the wave attenuation and not excessive transport of sediment.

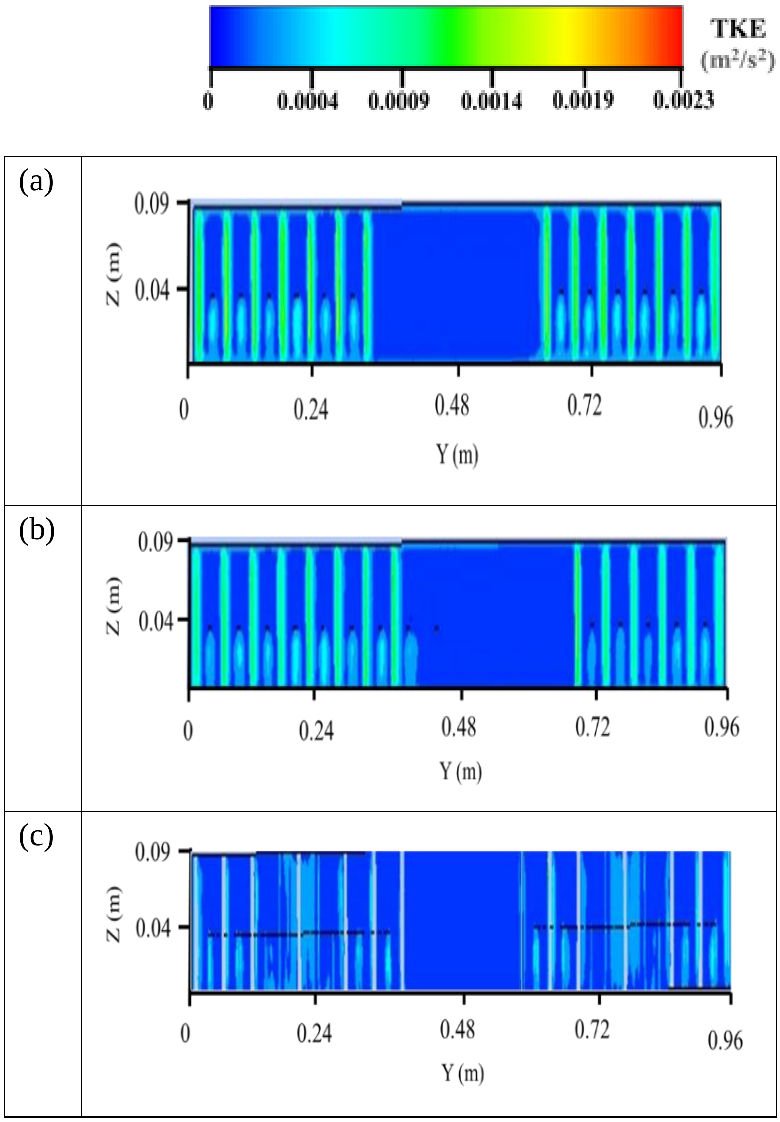

Figure 8. Terbulent Kinetic Energy (TKE) contours at middle section X=0.05m

4. Conclusions

This study offers a detailed analysis of internal flow properties within gap zones of coastal vegetation patches to better understand and enhance natural barriers against tsunami-induced flooding. The primary objective was to examine the effects of different gap configurations on flow dynamics and identify the optimal design for mitigating the dangers posed by these gaps. Numerical simulations conducted in ANSYS Workbench focused on flow behavior around short submergent and tall emergent mangrove trees, with three configurations—straight, inclined, and staggered—investigated.

The findings highlight the significant role of gap zone orientation in affecting flow properties and the protective capabilities of coastal vegetation. Key results include:

- Straight Gap Configuration: Exhibited the highest near-bed velocity and turbulence, posing the greatest risk to infrastructure downstream of the gap.
- Inclined Gap Configuration: Resulted in an 18% decrease in near-bed velocity and a 40% reduction in turbulent kinetic energy (TKE), indicating improved energy dissipation and lower flooding risk.
- Staggered Gap Configuration: Led to a 22.7% decrease in velocity and a 41.8% reduction in TKE, offering a balanced approach with effective flow management and enhanced safety.

These results can be used to support a larger scale of disaster risk reduction processes because they indicate that vegetation-based solutions may be used as an alternative to conventional coastal defence systems like seawalls and breakwaters, which are both economical and environmentally friendly. The findings will give insight on how engineers and policy makers can maximize vegetation schemes to reduce the impact of the tsunami to minimize the economic costs and improve community resilience.

The staggered configuration has some potential trade-offs although it has benefits. The increased turbulence in the middle depth may also cause localized sedimentation, which may have an impact on the stability of vegetation in the long term. Also, it might be necessary to maintain staggered patterns, which can only be achieved through active management so that the natural growth does not disturb the pattern of any optimization. Future research studies should examine them in terms of ecological effects in the long term and their ability to adjust to different coastal conditions.

To execute it effectively, staggered vegetation cover and artificial mitigation features, including permeable submerged barriers, can be combined to increase the amount of energy dissipated by the tsunami as well as reduce erosion. The coastal planners would need to take into account site specifics like the wave energy, the dynamics of sediment transport and vegetation growth to be fully effective in the long run. Such findings could be used to develop guidelines that could assist in mass implementation of vegetation-based defenses in coastal areas that are vulnerable.

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