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Impacts of Biomimetic Mangrove Structures on Wave Attenuation in Kuala Sepetang, Perak

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ABSTRACT

Biomimicry is introduced as an approach to develop an ecologically-informed design solution. The study proposes a regenerative design solution through hydrodynamic effects of the complex mangrove roots system that is applied to a biomimetic structural column design, with consideration on interactions between root porosity, water flows, and sediment transportation. Sangga Besar River, Perak is chosen as the key parameters of the flow. The roots are modelled with a circular array of cylinders (patch) with different porosities and varying spacing ratios. 15 patches are derived from 3 main sets where each set consisted of five patches with varying porosities. The simulation of each case to understand the impacts of different patch porosity on the flow structure is carried out using Ansys Fluent Student Version 2021. The study found that turbulence is impacted, but not directly proportional to the patch porosity where there could be an optimal porosity of the patch that generates maximum yield of turbulent kinetic energy dissipation rate with minimum sediment erosion for the onset of sediment deposition. The patch with ϕ=40% has the highest turbulence dissipation rate which relatively coherent with the range of porosity that would likely be encountered in natural mangrove ecosystem.

1. Introduction

Exponential growth of human population over the years contributes to the increasing needs of food, water, air, and shelter to survive. According to Stachew *et al.,* [1], the continuous increase in human population leads to the exploration and migration to urban and coastal areas, causing the expansion of built environment over natural ecosystems. The climate change effects intensify the impacts causes by these changes, leading to a shift in built environment paradigm to co-exist with nature.

Malaysia is among the countries in Southeast Asia that has the largest extents of mangroves which provide extensive and important ecosystem goods and services, including stabilizing the shoreline, storm protection, maintaining water quality, and providing forestry products [2]. However, due to current environmental challenges, the coastline of Malaysia is exposed to the threats of rising

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sea levels and coastal degradation. National Coastal Erosion Study 2015 outlined that 15% of 8840 km coastline are currently degrading and one-third of those critically require further protection [3]. The impacts of anthropogenic activities, for instance, the coastal reclamation, combined with natural forces on the coastal erosion, are exacerbated by climate change. Without proper adaptation measures, sea level rise of one meter is expected to cause 180,000 ha agricultural land loss and 15%-20% of coastline mangrove forest loss while subsequently threatening coastal population and development [4]. In addition, study by Omar *et al.,* [2] shows that the expansion of settlement and industrial areas over mangrove forest are among the prominent factors contributing to the rate of mangrove deforestation in Malaysia 0.1% per year between 1990 and 2017.

Thus, the understanding of morphologic processes in the mangrove forests due to waves and tidal currents is fundamental for the preservation of these mangrove coasts as well as the communities and infrastructures behind the embankments. Existing artificial barriers, while being expensive to build and maintain, are influencing sediment transport, thus reducing the ability of the shoreline to respond to environmental challenges. Besides, artificial structures are deemed no longer sustainable due to the constant increase of cost over the years [5]. The issues with artificial barriers are encouraging researchers to shift their focus of study by referring to the natural defence mechanism in terms of coastal and infrastructure protection against the impacts from the intensifying natural occurrences.

Due to the ecosystem services that can be provided by mangrove forest including the ability to increase accretion while reducing erosion, Malaysian government has also begun to invest in mangrove restoration and conservation as long-term, sustainable, and cost-effective coastal protection initiatives [6,7]. The presence of vegetation evidently contributes to wave dissipation and structural fragility reduction as opposed to bare-earth area [8]. However, these efforts remain challenging due to the time required for the establishment as well as uncertainties in mangroves functionality and persistence which depends on a range of environmental conditions [9]. Furthermore, this direct planting method is not often successful without the removal of stressors and provision of suitable environments to facilitate the reestablishment [10]. Therefore, the integration of mangrove potential into built environment would provide an opportunity for a betterment in both architectural and ecological aspects.

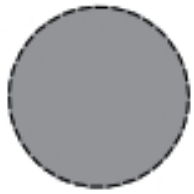
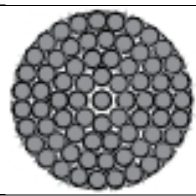
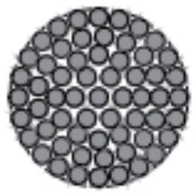
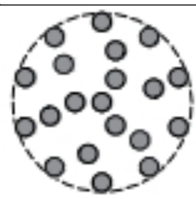
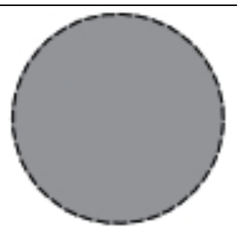
2. Methodology

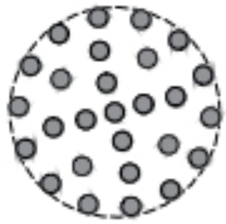
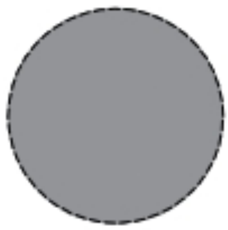
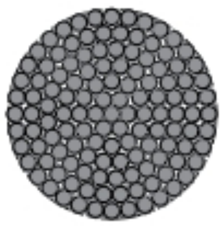
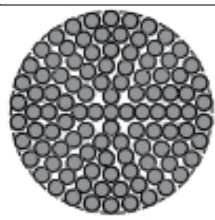
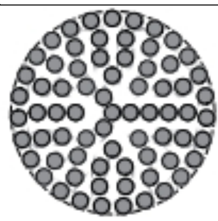
The study area is located along the Sangga Besar River, Perak, which is within the Matang Mangrove Estuaries, west coast of Malaysia. The Sangga Besar River basin depth ranges between 4-6 m with shallower depth near the mudflat area (1-3m) [11]. Referring to Saleh *et al.,* the average velocity of the river is estimated to be around 0.9 m s^{-1} with the Rhizophora sp. and Brugeira sp. being the dominated species [12].

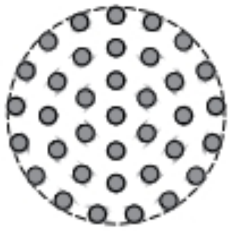
To understand the impacts of different patch porosity on the flow structure, the simulation of each case is carried out using Computational Fluid Dynamic (CFD) software, ANSYS Fluent Student Version 2021, subject to unidirectional flow. Previous studies show that the ANSYS Fluent software can simulate, analyse, and compare the fluid flow pattern around the roots of Rhizophora sp. and Avicennia sp. using an unsteady k-ε turbulence model [13-15].

The experiment sets are categorised according to the diameter of the patch, D. The diameter of the patches refers to the typical size of a column, D=600 mm, D=700 mm, and D=800 mm. Geometric properties of mangrove (Rhizophora sp.) prop roots is generated and scaled from model studied by Zhang *et al.,* [16]. The patch consisted of cylinders with diameter, d, of 60 mm and fixed throughout all porosity variations. These cylinders demonstrate the solidity of the columns and the integration of the simplified mangrove roots properties. 15 patches are derived from the 3 main sets where each set consisted of five patches with varying porosities, namely 28%, 40%, 60%, 80%, and 100%. The patch porosity is defined as ϕ=1-β, where β is patch solidity [17]. The porosity of the patch is achieved by altering the number of cylinders in each patch, while keeping the diameter of the cylinder, d, constant. Through this methodology, it is to note that the minimum porosity achievable for D=600 mm is 28%, and thus the porosity is maintained for D=700 mm and D=800 mm.

Table 1
Summary of cases

Experiment Sets	Case No	Patch diameter, D (mm)	Cylinder diameter, d (mm)	Porosity, % (ϕ)	
D = 600	1	600	60	0	
	2	600	60	28	
	3	600	60	40	
	4	600	60	60	
	5	600	60	80	
D = 700	6	700	60	0	

	7	700	60	28	
	8	700	60	40	
	9	700	60	60	
	10	700	60	80	
D = 800	11	800	60	0	
	12	800	60	28	
	13	800	60	40	
	14	800	60	60	

	15	800	60	80	

The study follows similar procedures for all cases including the construction of geometry, generating mesh, and determining the boundary conditions, for instance, as shown in Figure 1. The computational model of the two-dimensional root geometry is constructed using the ANSYS Workbench design modeller on a 2.5 cm x 2.5 cm grid, enabling further analysis with the ANSYS Fluent CFD. The inlet flow distance anterior to reaching the centre of the patch is fixed at 5m while both walls are distanced 6m from the centre. This far-field boundary minimises the impact of the walls on the flow structure. The simulation is carried out using a k − ε turbulent model with the turbulent intensity of the inlet is set at 5% and initial inlet velocity of 0.9 m s^{-1}, consistent with the velocity of the Sangga Besar River.

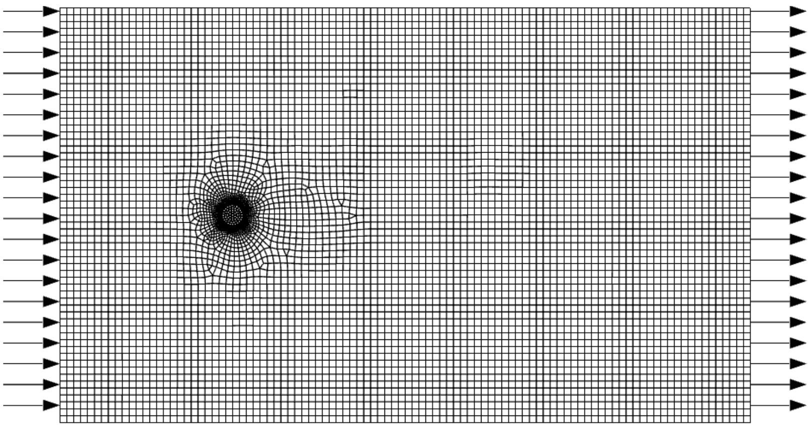
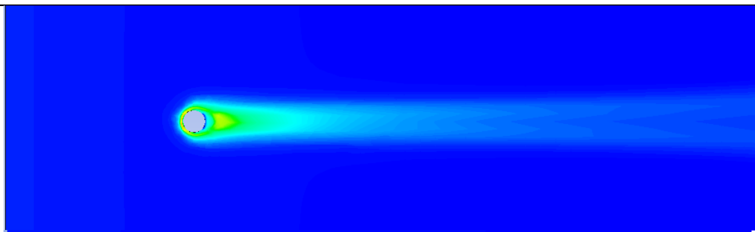
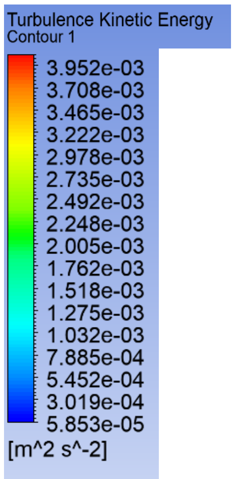
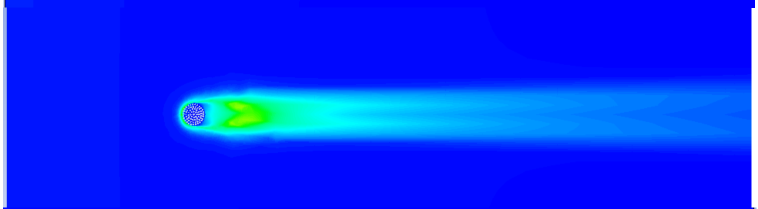
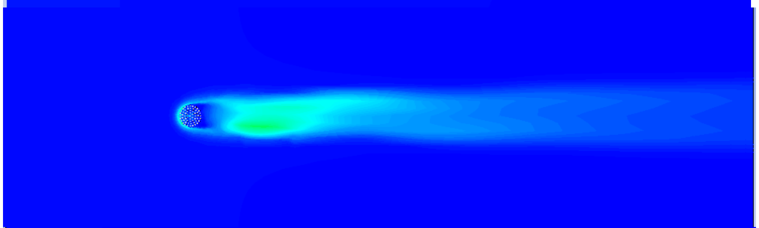
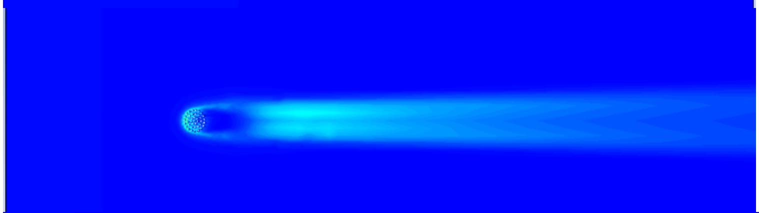
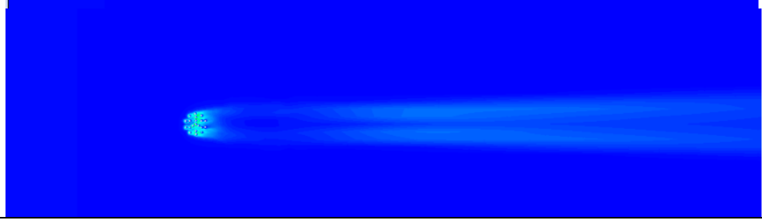
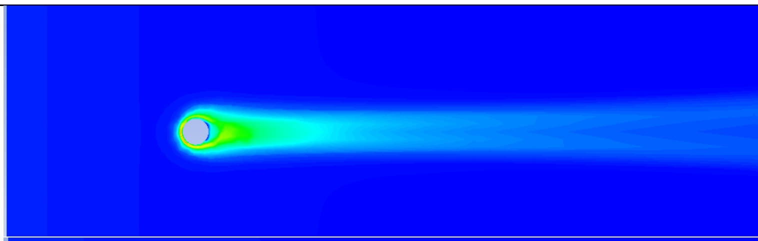
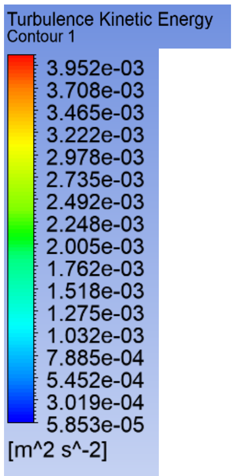
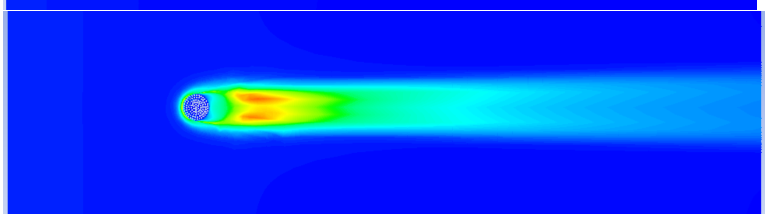
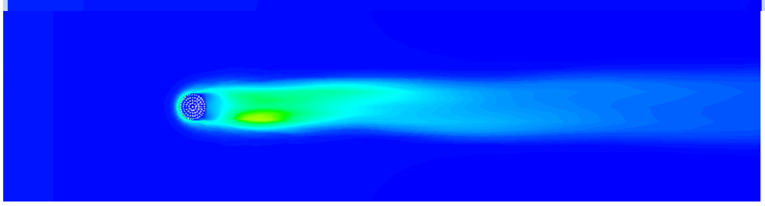


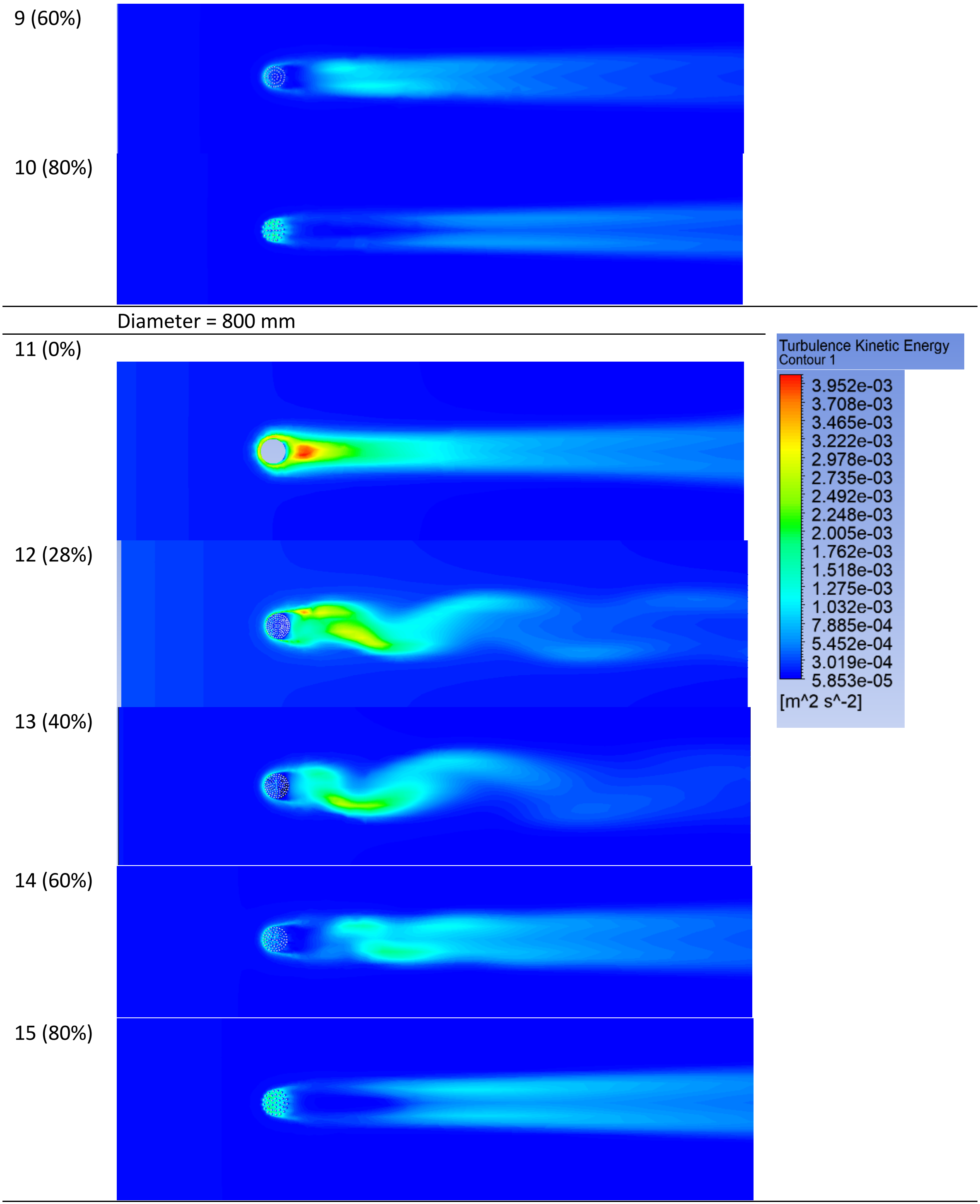
Fig. 1. Geometry and mesh setup for D=700 mm, ϕ=40%

3. Results

Turbulence is one of the key parameters in determining the wave attenuation and the onset of the sedimentation motion as would occur in natural mangrove roots system. Turbulent kinetic energy (TKE) is a quantitative measure that demonstrates the flow behaviour and defined as ‘kinetic energy per unit mass of the eddies in a turbulent flow’, m^2 s^{-2}. The increase in turbulent kinetic energy depicts that higher energy from the mean flow is transferred to the turbulence, thus leading to the dissipation of the tidal energy. Table 2 shows the two-dimensional simulation results of the TKE for the unidirectional flow in a k- ε model.

Table 2
Turbulent kinetic energy of the unidirectional flow

Case	Turbulent kinetic energy ($m^2\ s^{-2}$)	
	Diameter = 600 mm	
1 (0%)		
2 (28%)		
3 (40%)		
4 (60%)		
5 (80%)		
	Diameter = 700 mm	
6 (0%)		
7 (28%)		
8 (40%)		



The turbulent kinetic energy profile of each case as the flow passes through the patches with varying porosities, i.e., ϕ= 0%, 28%, 40%, 60%, and 80% for D = 600 mm, 700 mm, and 800 mm is presented. Complex secondary flow posterior to the patch can be observed for cases 2, 3, 7, 8, 12, and 13. As the porosity increases, the patch effect shows the decays in turbulent kinetic energy until the patch porosity reaches 40%. At ϕ=80%, the patch effect decays due to the mean velocity becomes independent of the Reynolds number [18]. This depicts that at ϕ=80%, the proposed models are unable to attenuate much current energy, causing minimal impact on the initial water flow as less tidal energy is converted into turbulence kinetic energy.

The peak turbulent kinetic energy (k) of the unidirectional flow passing through the porous patch for D=600 mm, 700 mm, and 800 mm is demonstrated in Figure 2, 3, and 4, respectively. 0 m denotes the central position of the patch, as well as the permeable boundary layer which therefore demonstrates the blockage effect of the patch to the flow structure.

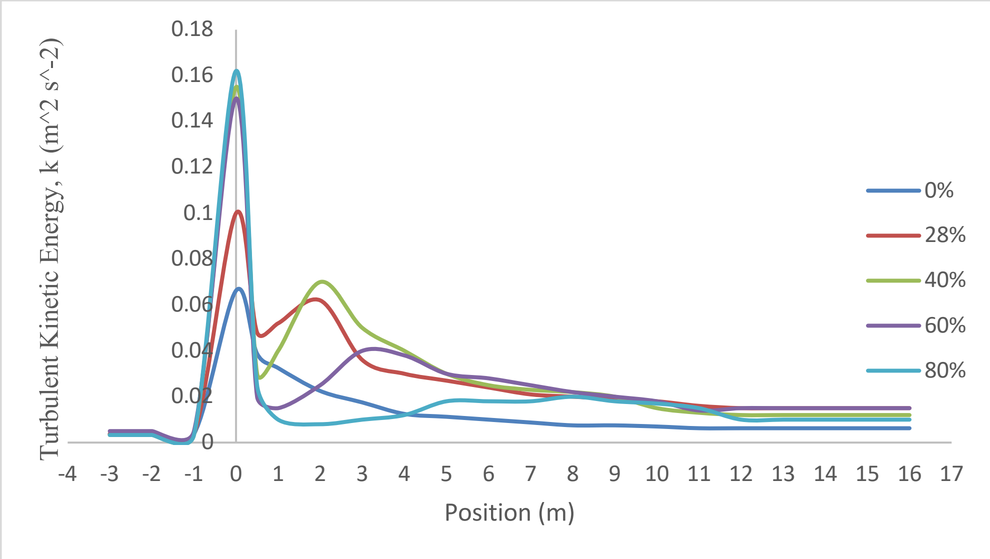


Fig. 2. Peak Turbulent Kinetic Energy, (k) of the fluid along the distance for D=600 mm

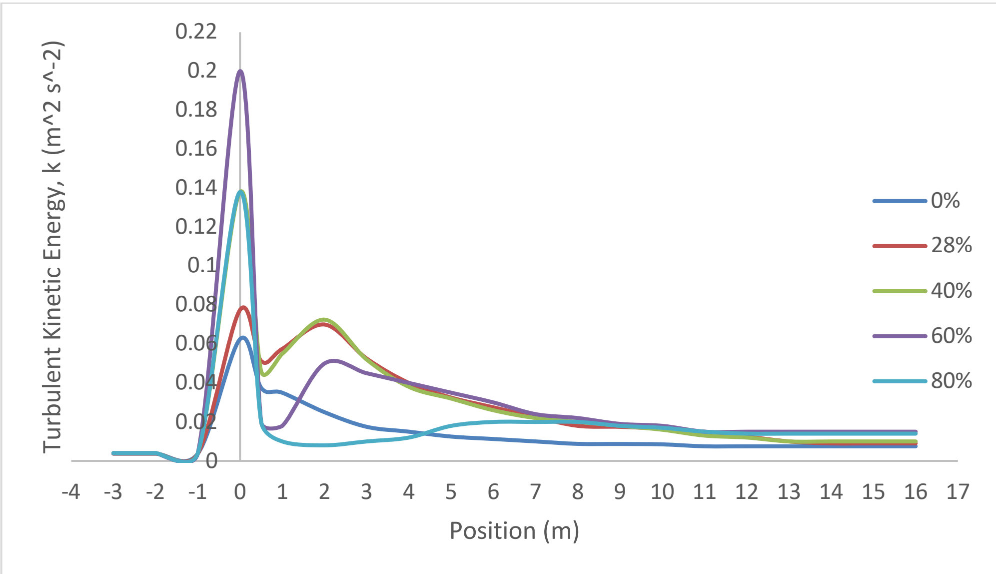


Fig. 3. Peak Turbulent Kinetic Energy, (k) of the fluid along the distance for D=700 mm

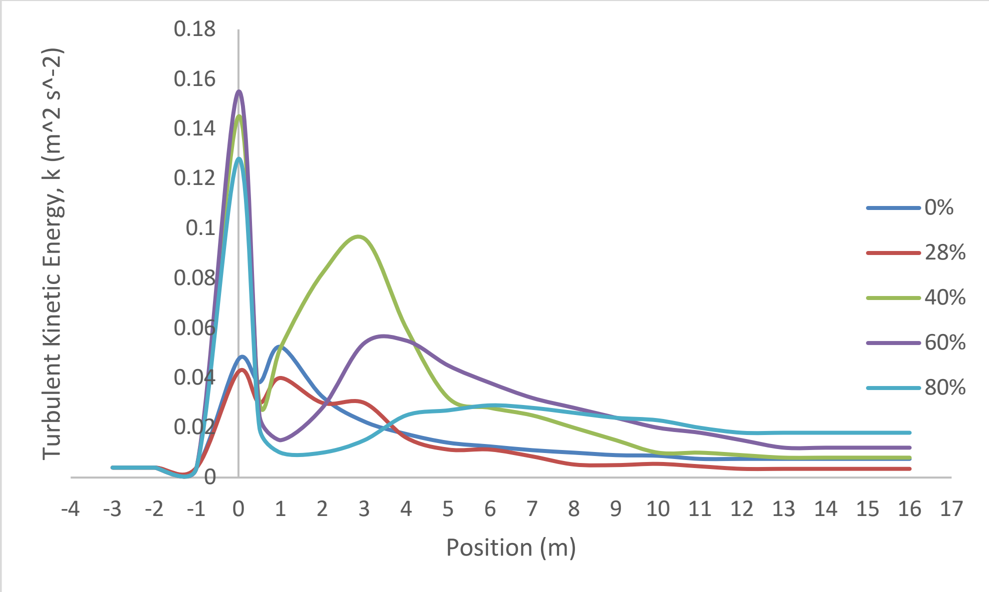


Fig. 4. Peak Turbulent Kinetic Energy, (k) of the fluid along the distance for D=800 mm

To further analyse impact of the porosities on the flow structure of the water, the study therefore compares the turbulent kinetic energy of each case at 2 m, which is the area posterior to the patch. Referring to Figure 2, 3, and 4, it can be observed that for each diameter, the flow structure for the patch with porosity ϕ=40% shows higher turbulent kinetic energy as opposed to other porosities. This suggested that these patches can attenuate more tidal energy, thus are more efficient to be integrated into structural columns. On the other hand, the patch with ϕ=80% consistently shows lowest conversion of tidal energy into turbulent kinetic energy.

Figure 5 below shows the correlation between the turbulent dissipation rate, ε (m2s-3) and the patch porosity, ϕ (%) for all simulated cases. Although turbulence estimates vary across the position, TKE dissipation is always prominent and increased at the border position, in this case, upon the blockage of the porous patch of the cylinders [19]. TKE dissipation rate relates to the onset of sedimentation which naturally occurs in the mangrove roots. Higher TKE dissipation rate encourages higher sediment deposition posterior to the patch [18]. This reflects the onset of the sedimentation processes as would occur in natural mangrove ecosystem, allowing the roots to rise in concert with the sea level. Consistently, all the patch with 40% porosity shows the highest turbulent dissipation rate followed by 28% patch porosity. In terms of the diameter of the patch, D, the highest dissipation rate is observed to be caused by the patch porosity of 40% for D=700 (28.5 m^2 s^{-3}).

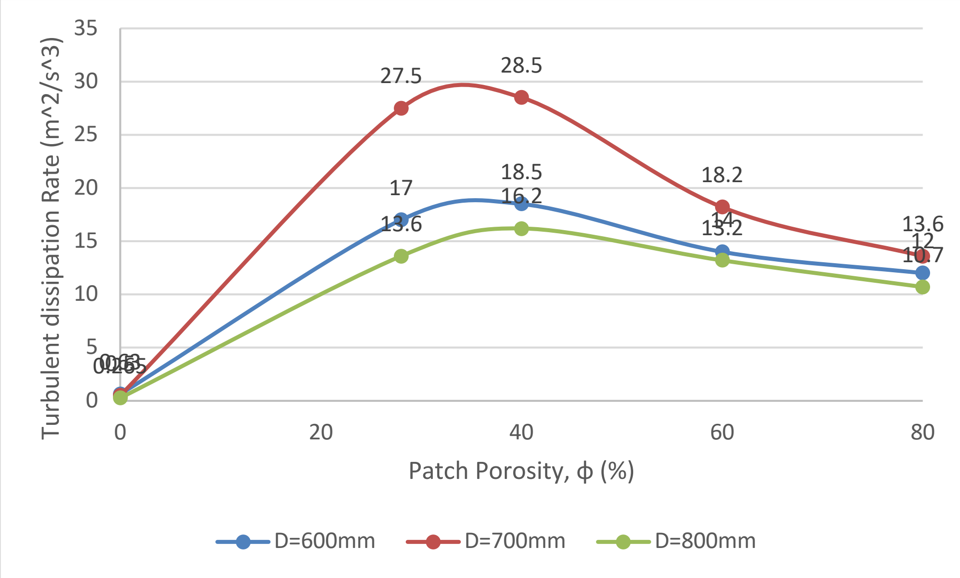


Fig. 5. Peak Turbulent Kinetic Energy, (k) of the fluid for ϕ=40%

4. Conclusions

Based on the study, it is found that turbulence is impacted by, although not directly proportional to the patch porosity. This therefore suggested that there could be an optimal porosity of the patch that generates maximum yield of turbulent kinetic energy dissipation rate with minimum sediment erosion for the onset of sediment deposition. The simulation study found that the patch with ϕ=40% has the highest turbulence dissipation rate which relatively coherent with the range of porosity that would likely be encountered in natural mangrove ecosystem with the porosity up to 45% as suggested by Furukawa *et al.,* [20]. Comparatively, D=700 shows higher turbulence dissipation rate as compared to the other column diameter. On the other hand, D=800 mm denotes higher turbulent kinetic energy of the flow structure (referring to Figure 6).

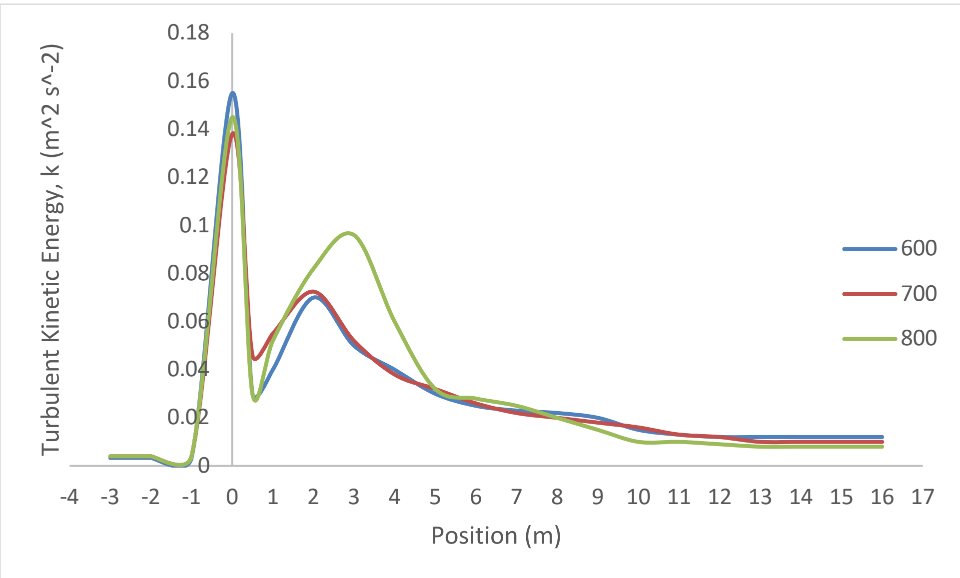


Fig. 6. Peak Turbulent Kinetic Energy, (k) of the fluid for ϕ=40%

While this could contribute to the design and geometric arrangement of near-shore building, especially on the elements that are directly related to the water flow and waves, further study could be conducted on the optimal porosity that could suggest the column design with both higher turbulent kinetic energy and TKE dissipation rate.

In addition, further detailed research on critical velocity, drag, mean flow, and skin friction coefficient can be conducted to deduct on the optimal porosity of the patch. Nevertheless, the factor influencing the flow structure is not limited to patch porosity, as other flow parameter including Re number, spacing ratio, frontal area, the cylinders arrangement, and wave characteristics also contributed to the wave attenuation properties of the mangrove-inspired model. Furthermore, as this paper focuses on the morphology of the structural column proposal in terms of attenuating waves, further study can be conducted on the compressive strength, structural integrity, and other relevant structural behaviour of the column.

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