

IMPLEMENTATION OF POROUS PILE CONE BREAKWATER FOR PROTECTING SHORELINE AND PRESERVING MARINE BIODIVERSITY

Muhammad Fauzi^{a*}, Eldina Fatimah^a, Mohamad Hidayat Jamal^b,
Qurratul 'Aini Benti Nasaiy^a, Vira Mawaddah^a

^aCivil Engineering Department, Engineering Faculty, Syiah Kuala University, 23111, Banda Aceh, Aceh, Indonesia

^bDepartment of Water and Environmental Engineering, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history

Received

7 July 2025

Received in revised form

16 August 2025

Accepted

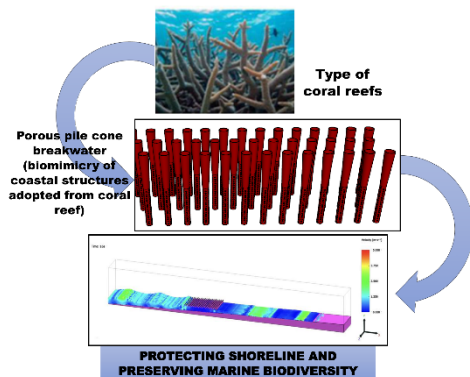
2 September 2025

Published Online

16 June 2026

*Corresponding author
fauzi.yosa@usk.ac.id

Graphical abstract



Abstract

In the last decade, marine structures have impacted biodiversity loss and ecosystem degradation. As a mitigation effort, artificial coral reef structures have been designed to dissipate wave energy through turbulence, creating microhabitats that attract marine organisms to interact and thrive. A biomimetic design adopted from coral reefs, called porous pile cone breakwater (PPCB), has been introduced, combining a porous pile with a conical pile head (CPH). Breakwater piles and CPHs have proven effective in protecting shorelines and maintaining water quality for marine life. The CPH design reduces wave energy and velocity, enhancing the abundance of marine life. This study investigated wave velocity (V_x) characteristics around PPCBs using the mesoscopic Lattice Boltzmann Method (LBM) within a CFD application. Three-dimensional fluid motion was modeled for Series-1 (emerged type) and Series-2 (submerged type) with porosity $p=0.4$, wave steepness $0.058-0.068$ in a 30m wide numerical basin. Both configurations reduced V_x in the structure area by over 90%, with the submerged PPCB achieving up to 11.3% greater reduction and maintaining 80–88% lower V_x behind the structure. These findings indicate the submerged PPCB offers superior shoreline protection, while both designs maintain maximum velocity and Froude Number values suitable for sustaining coastal ecosystems.

Keywords: Computational Fluid Dynamics (CFD), marine biota, numerical models, porous pile cone breakwaters, wave velocity

Abstrak

Dalam dekad yang lalu, struktur marin memberi kesan kepada kehilangan biodiversiti dan degradasi ekosistem. Sebagai langkah mitigasi, struktur terumbu karang tiruan direka untuk menyuraikan tenaga ombak melalui turbulens, mewujudkan mikrohabitat yang menarik organisma marin untuk berinteraksi dan berkembang. Reka bentuk biomimetik daripada terumbu karang, iaitu penahan ombak berbentuk kon bertiang berliang (Porous Pile Cone Breakwater, PPCB), diperkenalkan dengan gabungan tiang berliang dan kepala kon (Conical Pile Head). Tiang penahan ombak dan kepala kon, terbukti berkesan melindungi garis pantai serta mengekalkan kualiti air. Reka bentuk CPH mengurangkan tenaga ombak dan kelajuan yang menyokong kelimpahan biota marin. Kajian ini meneliti ciri halaju ombak (V_x) sekitar PPCB menggunakan kaedah Lattice Boltzmann (LBM) dalam aplikasi CFD.

Pergerakan cecair tiga dimensi dimodelkan untuk Siri-1 (jenis timbul) dan Siri-2 (jenis tenggelam) dengan porositi $p=0.4$, kecuraman ombak (H_i/gT^2) 0.058–0.068 dalam kolam gelombang numerical selebar 30.0m. Kedua-dua senario mengurangkan halaju di kawasan struktur lebih daripada 90%, dengan PPCB tenggelam mencapai pengurangan sehingga 11.3% lebih besar dan mengekalkan V_x yang 80–88% lebih rendah di belakang struktur. Penemuan ini menunjukkan PPCB tenggelam menawarkan perlindungan pantai yang lebih unggul, manakala kedua-dua reka bentuk mengekalkan nilai halaju maksimum dan Nombor Froude yang sesuai untuk mengekalkan ekosistem pesisir.

Kata kunci: Computational Fluid Dynamics (CFD), biota marin, model berangka, porous pile cone breakwaters, halaju ombak

© 2026 Penerbit UTM Press. All rights reserved

1.0 INTRODUCTION

Currently, the number of studies highlighting the negative impacts of marine structures has been increasing, including the loss of biodiversity and the degradation of marine ecosystems. However, structural measures, such as breakwaters and seawalls inevitably need to be built to provide security, reduce erosion and sedimentation, facilitate ships' movement, reclaim new land, and other socio-economic benefits. Continued coastal erosion can lead to vulnerability to flooding due to tidal waves. This phenomenon will affect the buildings around the coast and cause physical, economic, and environmental damage [1]–[3]. In strengthening and protecting the coast, natural stone and concrete materials have been used to withstand, deflect and reduce wave energy. However, both of these materials can disrupt the balance of marine life. The degradation of marine lives can indirectly affect humans by causing loss of food security and livelihoods [4]. One of the strategies to protect the environment and ecology is to use natural elements and processes or mimic the characteristics of natural features (biomimicry) to preserve and regenerate ecological results.

The loss of biodiversity and degradation of marine ecosystems due to the negative impacts of marine structures has drawn much attention. The structures, such as gravity breakwaters, withstand extreme wave forces to maintain the stability of harbor pools, solve beach erosion problems, and restore the profile and shoreline. This type of structural handling exploits the abundant availability of armor materials, damaging the environment, triggering changes in the balance of sediment transport, and disrupting the life of marine biota [5], [6].

A shoreline structure that mimics the form and function of mangroves has been designed [7]. Further observations show that vertical seawalls combined with mangrove root patterns reduce waves and increase marine growth [8], [9]. Coral reefs, seagrass beds, and marine algae are marine biotas that provide shelter, habitat, food sources, and spawning

grounds for marine species [10], [11]. Marine biotas are also natural coastline protectors [12].

The artificial type of coral reefs is designed concerning several factors such as depth and function [13]. Environmental characteristics, such as water currents are essential variables in distributing nutrients and organic elements for the needs of marine life. Ocean eddies, wave pressure, and wave ripples affect the types of fish and aquatic plants in the vicinity. Some fish live in fast currents, and others like to live in calm currents and sheltered places. This phenomenon has proven that environmental conditions affect the types of marine biota. Froude number = 0.09 is the best condition for marine life [14]. Research and observation of the concrete artificial reef blocks developed by the National Hydraulic Research Institute of Malaysia (NAHRIM), known as the Wave Breaker and Coral Restorer (WABCORE), have shown that this structure can protect the shoreline from erosion while promoting the development of new marine ecosystems. The wave energy dissipation produced by this artificial reef reaches nearly 60% of the incident wave height, primarily due to structural friction against wave motion. Furthermore, over three years, coral growth has significantly increased from 8.66% to 29.75% of the total WABCORE surface area [15], [16].

Other studies indicate that the hexagonal artificial reef structure could dissipate wave energy through generated when waves impact the upper surface of the structure [17]. The resulting turbulence creates pressure waves that attract fish, enhancing marine life interaction with the reef. The reduced flow velocity around the structure also facilitates the emergence and growth of marine organisms [18].

Various types of innovative breakwaters that are environmentally friendly have been studied, such as floating breakwaters [19], submerged breakwaters [20], [21], and pile breakwater [22]. Pile breakwaters are suitable for marinas, safe recreation zones, and fishing ports that do not require extreme wave protection [23]. Although breakwaters have been widely studied for their ability to reduce wave energy and coastal erosion, as well as for their ecological contributions, their simultaneous optimization for both

engineering performance and ecosystem preservation has received limited attention, particularly by mimicking the complex morphology and functionality of coral reef systems.

This study presents the biomimicry of coastal structures adopted from coral reefs of the *Acropora* genus (Figure 1a) [24]. The shape of this coral resembles cylindrical poles. It has a cylindrical or conical branching structure that extends upwards. Several of its species exhibit small holes (corallites) along the branches, resembling perforations or pores. Piles breakwater has become an interesting issue for researchers. Previous researchers have shown that perforated piles with a porosity of 6.25% can reduce wave energy more than non-perforated pile breakwaters, although not significantly, especially at greater wave steepness (H_i/gT^2) [22]. Perforated piles increase the turbulence that occurs, thus enlarging the energy dissipation obtained. The pile breakwater design was later modified by emptying the inside and widening the top of the pile, called the conical pile head breakwater (CPHB) (Figure 1b)[23]. This modification construction can free the flow of water and sediment from entering the structure. Widening the top of the pile reduces the distance between the piles. They believe that the presence of CPHB will not interfere with sediment movement, where sediment can move between piles and water quality is maintained. CPHB is classified as a permeable breakwater, where turbulence processes and energy dissipation only occur between pile arrangements. It is likely to trigger scour at the foot of the pile and produce a large wave velocity.

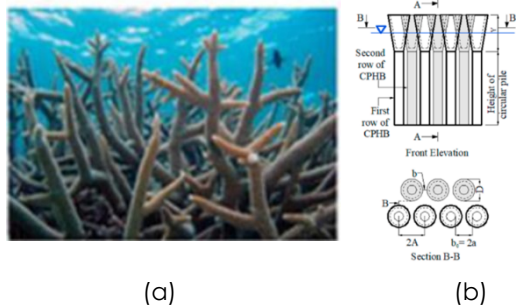


Figure 1 (a) *Acropora* coral reef formations [24]; and (b) Modification of pile breakwater [23]

The purpose of this study is to modify porous circular pile breakwater [22] and conical pile head breakwater [23] by considering the concept of *Acropora* coral reefs, in which some of the trunks are perforated with perforations (p) set at 40% (Refer Figure 2). The benefit of permeable piles is not cause severe erosion downdrift because sediment can pass through the porous holes. This modeled structure is called a porous pile cone breakwater (PPCB). This structure not only maintains water quality, the balance of sediment transport, and the problem of distance between piles but also increases the ability to dissipate energy by reducing the velocity of

particles, which is crucial for marine biota. Through this modification, the structure is intended to fulfill a dual function: to enhance wave energy dissipation and shoreline protection for coastal hazard mitigation, and to promote a marine environment conducive to ecosystem preservation and biodiversity support.

2.0 METHODOLOGY

This study is conducted as a numerical model simulation using a planned structure and shoreline slope model. The biomimicry concept proposed is presented in Figure 2. This structure uses a porous pile-cone system, consisting of an array of cone-shaped piles arranged systematically within a wave basin. Each pile has a height of 6.5 meters, composed of a 3-meter conical head and a 3.5-meter cylindrical body (Figure 2a and 2b). The first and third rows are arranged symmetrically, whereas the second row is arranged asymmetrically to enhance wave energy dissipation (Figure 2c).

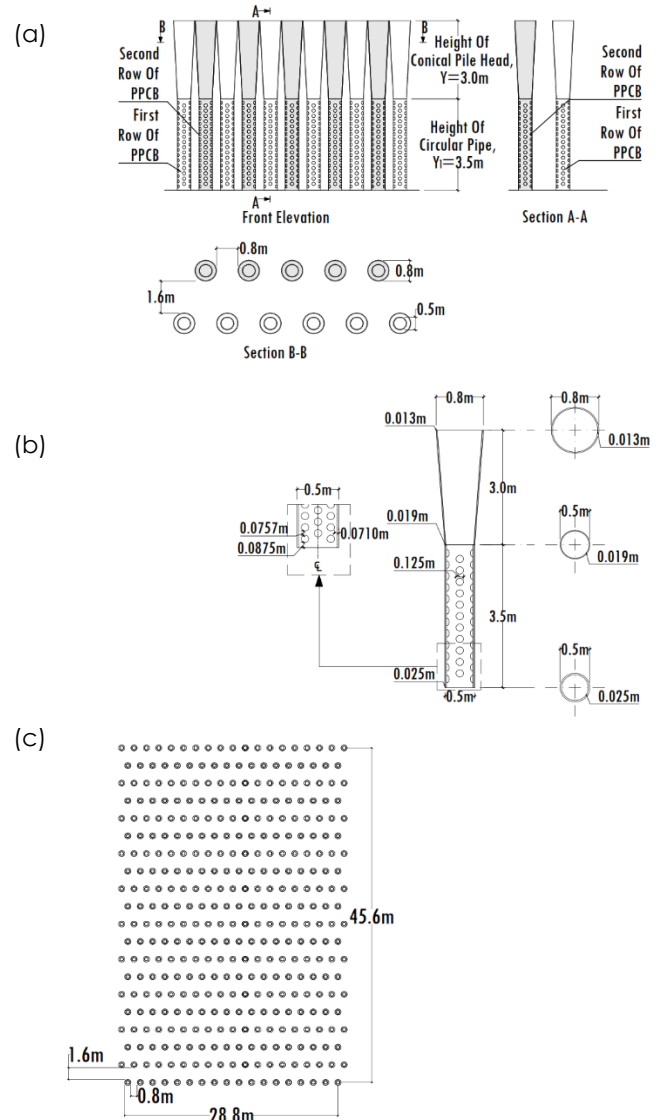


Figure 2 (a) Pile cone model arrangement (front view); (b) pile cone dimension details; and (c) Pile cone model arrangement (top view)

This model arrangement is placed on a planned average shoreline slope of 0.0274 based on the characteristics of the East-North coast of Aceh, Indonesia.

In this numerical modeling, wave simulation is performed using the Computational Fluid Dynamics (CFD) numerical method. This method is a numerical calculation with control of dimension, area, and volume by utilizing computer computational assistance to perform calculations on each dividing element. In making the object model, the required wave data is entered and adjusted to the model. After creating the domain model, a simulation is carried out using Next Limit XFlow software [25]. The method employed is a particle-based approach, where the simulation process no longer relies on a grid but instead presents results in the form of clearer and more detailed particle movements. Hydraulic parameters such as wave velocity (V_x), fluid flow, and energy dissipation around porous pile cone breakwaters (PPCB) were examined using the mesoscopic Lattice Boltzmann Method (LBM) with that of CFD application tool. The Lattice Boltzmann Method (LBM) is classified as a computational fluid dynamics (CFD) approach for simulating fluid flows. LBM is not used to directly derive the Navier-Stokes equations but rather to solve fluid flow simulations. Currently, LBM has emerged as a promising tool for modeling the Navier-Stokes equations and simulating complex fluid flows [26], [27]. LBM is based on microscopic models and mesoscopic kinetic equations. From certain perspectives, it can be considered a finite difference method for solving the Boltzmann transport equation. Moreover, the Navier-Stokes equations can be recovered from LBM with the appropriate choice of collision coefficients. By employing the general form of the Boltzmann method, the equations can subsequently be derived into the Navier-Stokes equations [28].

XFlow provides a wizard to configure progressive waves in free-surface simulations. The parameters used in this wizard include the type of wave (i.e., linear wave), water channel dimensions, liquid depth, current velocity, and progressive wave characteristics (amplitude A and frequency f). The wizard automatically calculates the wave velocity and consistent laws to describe the initial free surface profile and the inlet wave function. According to linear wave theory, the velocity law reads as follows [25]:

$$v_x = v_w + \frac{A\omega}{\sinh kh} \cosh k(h + y) \sin(\omega t - kx) \quad (1)$$

$$v_y = \frac{A\omega}{\sinh kh} \sinh k(h + y) \cos(\omega t - kx) \quad (2)$$

Where x is the horizontal position and y the vertical one, t is the time, g is the gravity, ω is the angular velocity ($\omega=2\pi f$) and k is the wave number, given by the following equation:

$$\omega^2 = gk \tanh(kh) \quad (3)$$

Consistently, the Water initial surface is given by:

$$\text{Initial water surface} = -A \sin(kx) \quad (4)$$

$$\text{Water inlet wave function} = A \sin(\omega t + k \frac{L}{2}) \quad (5)$$

Simulation results are presented based on data placed on predetermined sensors' data reading readout. Simulations were carried out on two model series with different placement designs or pile cone positions, as described in the following section.

2.1 Series 1

In this series, the position of the first line of pilecones is at a water depth of 4m from the seabed. Some of the tops of the pilecones are above the water's surface, and some are below (emerged type). The design model in the wave basin is positioned as shown in Figure 3, while the position of the data reading sensor placement is presented in Figure 4.

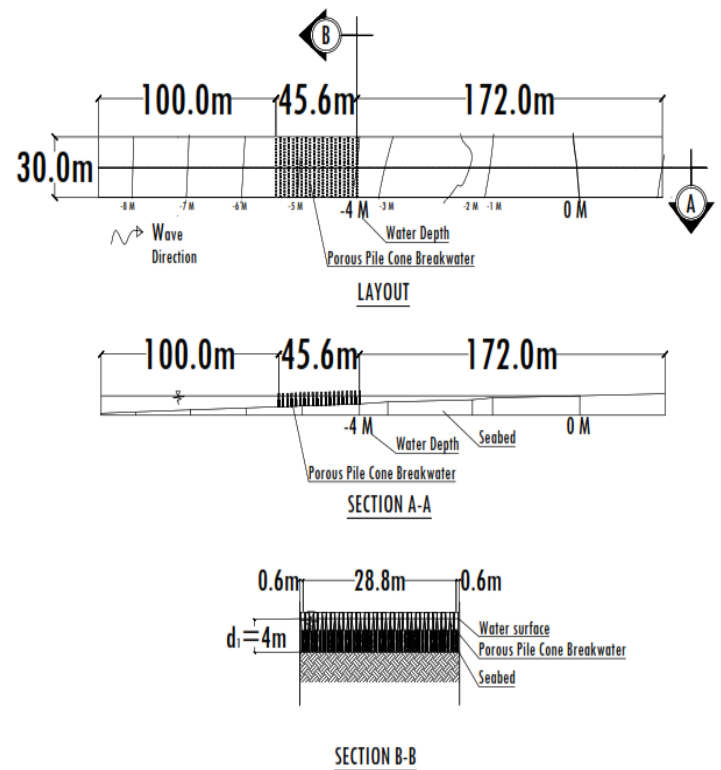


Figure 3 Laying Position of the Series 1 Model in a Numerical Wave Basin

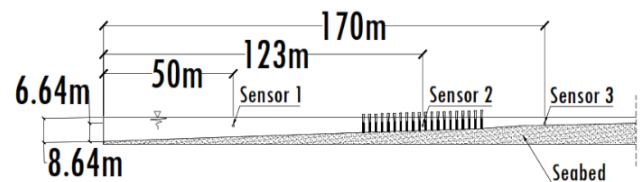


Figure 4 Data Reading Sensor Laying Position (Series 1)

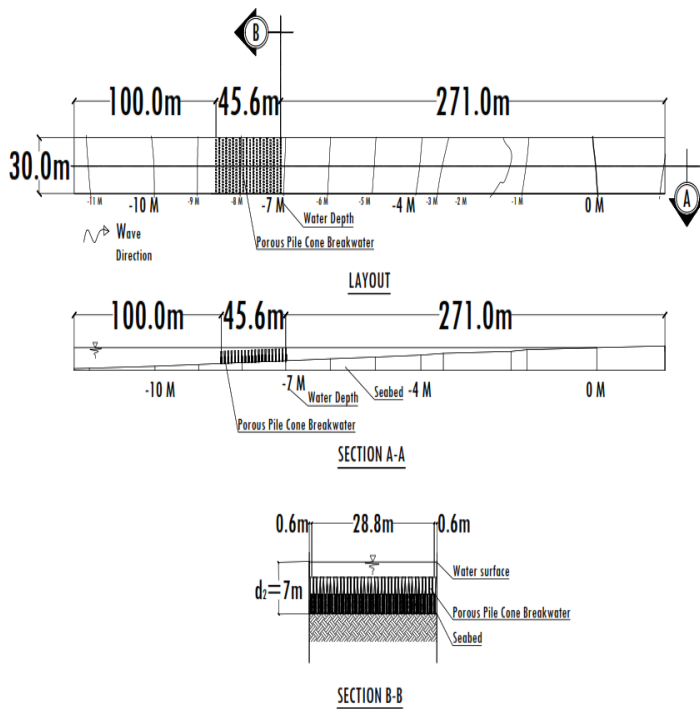


Figure 5 Laying Position of the Series 2 Model in a Numerical Wave Basin

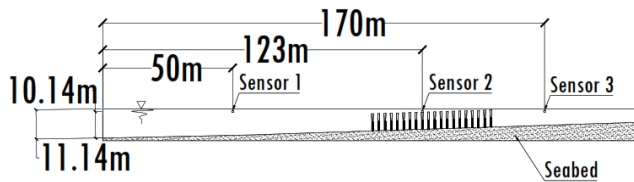


Figure 6 Data Reading Sensor Laying Position (Series 2)

2.2 Series 2

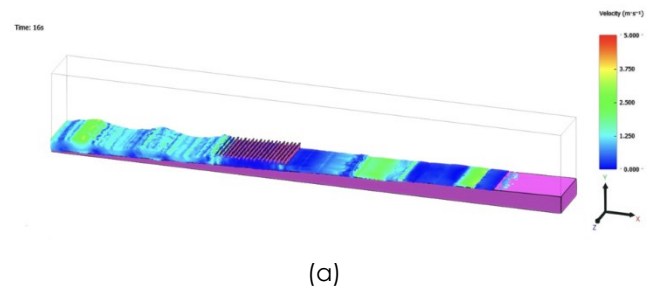
In this series, the position of the first row of PPCB is 7m from the seabed. The entire top of the PPCB is below the water level (submerged type). The position of this design model in the wave basin is shown in Figure 5, while the position of the data readout sensor is presented in Figure 6. The simulation designs are presented in Table 1.

Table 1 Simulation Designs

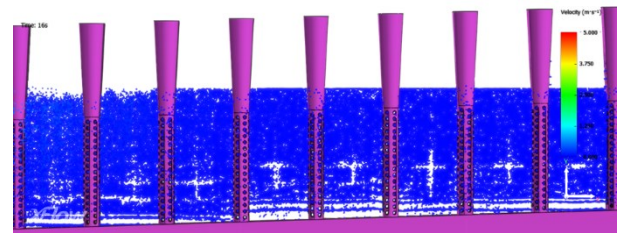
d design	H and T design	Variations design
$d_1 = 4.0\text{ m}$	$H_1 = 2.0\text{ m}, T_1 = 4.8\text{ s}$	$d_1H_1T_1$
$d_2 = 7.0\text{ m}$	$H_2 = 3.0\text{ m}, T_2 = 6.05\text{ s}$	$d_1H_2T_2$
	$H_3 = 4.52\text{ m}, T_3 = 7.94\text{ s}$	$d_1H_3T_3$
		$d_2H_1T_1$
		$d_2H_2T_2$
		$d_2H_3T_3$

3.0 RESULTS AND DISCUSSION

The parameters recorded from the numerical simulation are the horizontal particle velocity parameters (V_x) that occur at the reading points (sensors). Data readouts were taken for the 60s at three sensors. The wave propagation in the wave basin at 16s are shown in Figure 7 for series 1 and Figure 8 for series 2. The visualization of the numerical results shows that waves approaching from the left undergo changes as they pass through the PPCB structure. The waves experience a gradual reduction in velocity while passing through the pile cone columns, as indicated by the color changes observed.

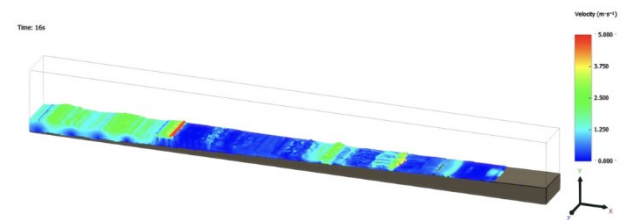


(a)

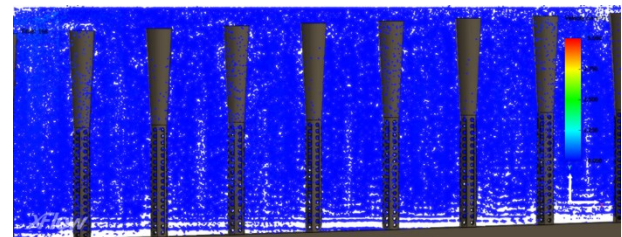


(b)

Figure 7 (a) 3D profile of velocity distribution in series 1; (b) visualization of velocity distribution inside the building in series 1



(a)



(b)

Figure 8 (a) 3D profile of velocity distribution in series 2; (b) visualization of velocity distribution inside the building in series 2

3.1 Verification and Validation of Numerical Data Results

This process needs to be done to ensure that the numerical data results collected are accurate to minimize human and research instruments error. Without this process, there is a risk of making decisions based on imperfect data that does not accurately represent the actual situation [29]. This study's verification and validation process was done by comparing calculated and numerically generated data. The data to be compared is horizontal velocity data (V_x) on a shoreline model without slope and using the wave parameters $H = 2\text{m}$, $T = 8\text{s}$, $d = 15\text{m}$. Analytical calculations and the numerical model data readout are carried out on sensor coordinates (x,y) at sensor 5 (50,-5), as shown in Figure 9. The data velocity validation results show that the numerical results are close to the analytical results, as presented in Figure 10.

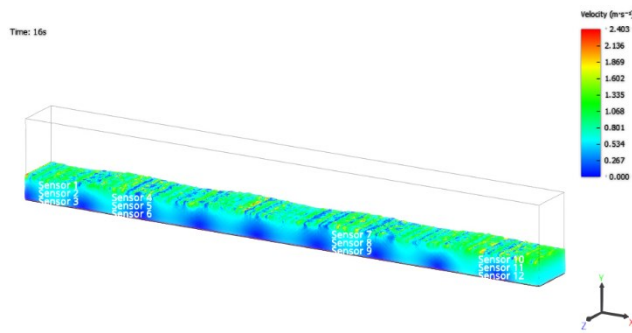


Figure 9 Placement of Validation Sensors in a Wave Basin

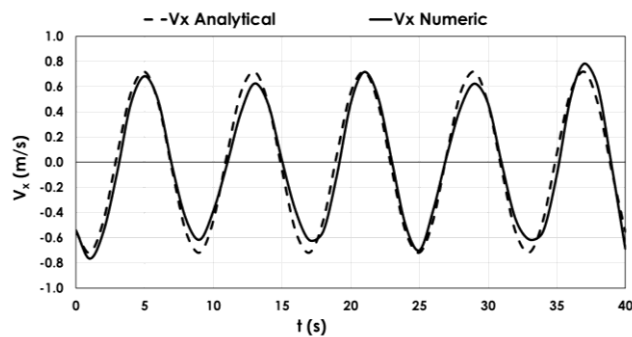


Figure 10 V_x Sensor Validation Results

3.2 Velocity Distribution (V_x)

The V_x velocity data was determined when the resulting flow profile was stable, starting at $t=16\text{s}$. The observation results in series 1 (d_1) (Figure 11) indicate a velocity reduction of V_x as large as on sensors 2 and 3, as well as the results in series 2 (d_2) (Figure 12). It shows that the planned structure effectively protects the shoreline area from abrasion by reducing the energy of incoming waves. These results align with those

reported in [30]. Furthermore, observations based on sensor placement at sensor 2, located in the structure area, revealed that for the wave variations H_1T_1 and H_2T_2 , both series models showed a reduction in V_x values of 92.8–98.6%. The percentage reduction in V_x for series 1 model (d_1) was 2.5–5% higher compared to series 2 model (d_2) for these wave variations. However, under the highest wave condition (H_3T_3), the series 2 model (d_2) recorded a V_x value that was 11.3% lower than that of series 1. This indicates that the submerged-type structure creates a calmer flow around the structure compared to the emerged type. This is attributed to the conical pile head, which functions effectively as a wave energy dissipator [31]. Water entering the funnel-shaped openings exits with additional energy loss. A higher blockage area increases the effectiveness of wave energy dissipation, causing waves to break over the structure along with greater wave reflection.

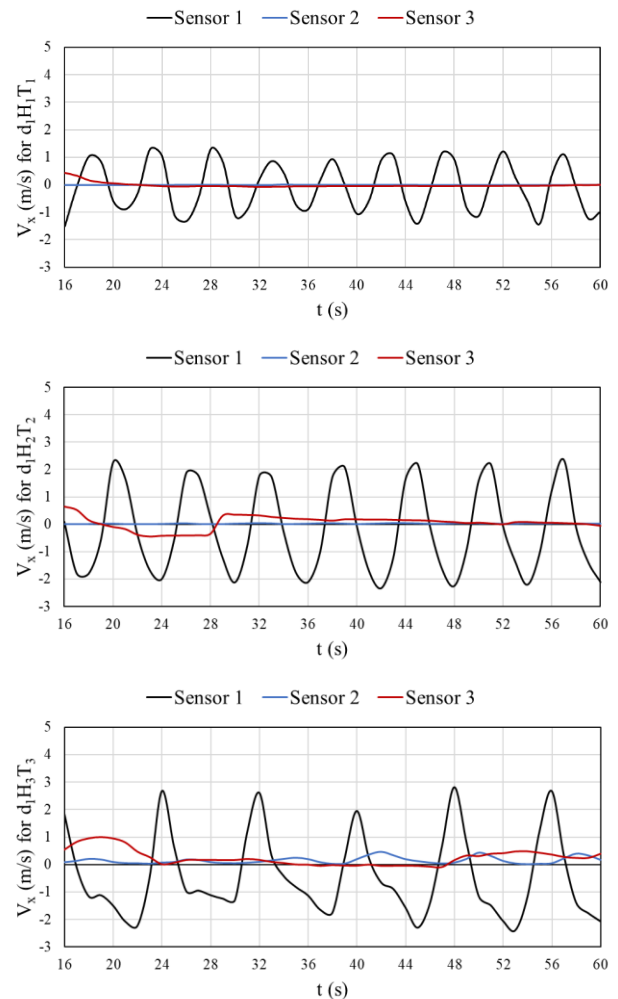


Figure 11 Velocity Distribution (V_x) in Series 1

On the contrary, the placement of sensor 3 in the shoreline area behind the structure shows that the series 2 model produced a smaller V_x on wave variations H_1T_1 and H_2T_2 compared to the series 1

model. The velocity reduction achieved by series 2 ranged between 80–88%, whereas series 1 exhibited a reduction of 67–72%. It indicates that the series 2 structure model (the submerged-type structure) provided more security to the shoreline area than the series 1.

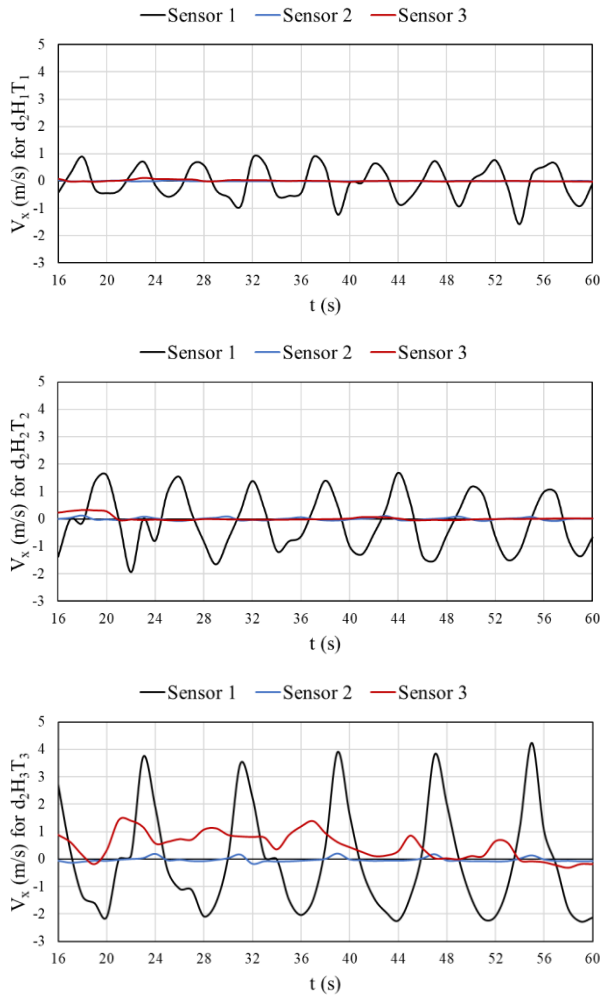


Figure 12 Velocity Distribution (V_x) in Series 2

3.3 Maximum Velocity Against Wave Steepness

The results of data readout in series 1 and 2 show that the wave steepness (H_i/gT^2) affected the maximum velocity (V_{max+} and V_{max-}) produced by the two models (Figure 13). The greater the steepness of the waves formed, the greater the resulting maximum velocity on each sensor d_1 and d_2 . This phenomenon results from the influence of wave slope and steepness on wave deformation, which consequently affects the distribution of turbulence and flow vorticity [32], [33]. It can also be identified that there was a decrease in the maximum velocity on sensors 2 and 3, where the minimum V_{max} was generated on sensor 2 (shoreline structure area). Series 1 and 2 have the same phenomenon, where the maximum velocity was on sensor 1. It reflects that turbulence and beneficial

vertices occur in the pile cone's perforated part and on coherent eddies with the upward and downward flow in conical part piles.

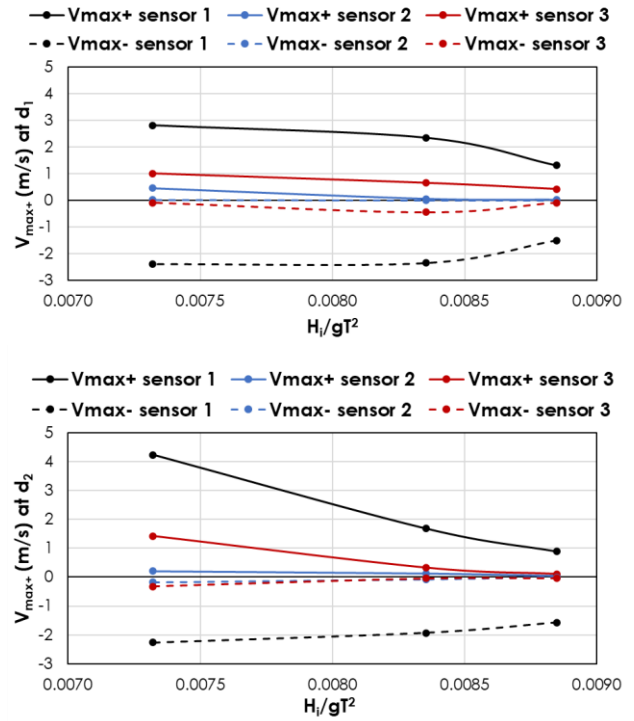


Figure 13 Effect of Wave Steepness (H_i/gT^2) on V_{max+} in Series 1 and 2

In the previous statement that the best conditions for the life of marine biota are flow conditions with $Fr = 0.09$ [14]. So, it can be determined that the maximum velocity allowed inside the structure (on sensor 2) was 0.63 m/s (on series 1) and 0.80 m/s (on series 2). The observation results presented in Figure 13 shows that the PPCB shoreline structure's design is predicted can preserve the life of marine biota because the velocity generated in the structure area is less than the velocity allowed. This statement can be proven from the Fr calculation results on each sensor in each series, as presented in Table 2. The analysis results identify that the Fr value on sensor 1 is greater than 0.09. Meanwhile, sensors 2 and partially sensor 3 produce a value of $Fr < 0.09$.

Table 2 Froude number (Fr) on each sensor each series

Variety	H_i/gT^2	Fr for V_{max+} at Sensor			Fr for V_{max-} at Sensor		
		1	2	3	1	2	3
$d_1H_1T_1$	0.0088	0.159	0.003	0.079	0.152	0.001	0.011
$d_1H_2T_2$	0.0084	0.284	0.007	0.121	0.237	0.000	0.058
$d_1H_3T_3$	0.0073	0.341	0.065	0.185	0.241	0.002	0.012
$d_2H_1T_1$	0.0088	0.108	0.005	0.019	0.159	0.001	0.005
$d_2H_2T_2$	0.0084	0.203	0.017	0.060	0.195	0.009	0.006
$d_2H_3T_3$	0.0073	0.512	0.030	0.262	0.229	0.020	0.043

4.0 CONCLUSION

The porous pile cone breakwater (PPCB) model series 1 and 2 are promising shoreline structure models that effectively reduce the wave velocities. Both types of breakwaters were able to reduce the velocity (V_x) in the structure area by more than 90%. Under the highest wave condition, the submerged PPCB reduced the velocity by 11.3% more compared to the emerged PPCB. Furthermore, the submerged PPCB also produced lower V_x values in the coastal area behind the structure, ranging from 80% to 88%. These findings indicate that the submerged PPCB demonstrates better performance in protecting the shoreline against abrasion through the dissipation of incoming wave energy.

However, based on the analysis of maximum velocity (V_{max}) and Froude number (Fr), both PPCB models can be shoreline structures that can preserve the life of marine biota, as the maximum velocity and Fr values generated by each model in the structure area are suitable for the growth of coastal ecosystems.

Acknowledgement

The authors are grateful for the support of the Institute for Research and Community Service (LPPM) for facilitating the implementation of activities and funding this research with contract number 143/UN11/SPK/PNBP/2022 on February 11, 2022.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

- [1] Haryani, Irianto, A., and N. Syah. 2019. Study of Coastal Abrasion Disasters and Their Causes in Pariaman City. *IOP Conference Series: Earth and Environmental Science*. 314 (012009): 1–11. <https://doi.org/10.1088/1755-1315/314/1/012009>.
- [2] Ishak, M. 2023. Abrasion Disaster Profile, Impact and Abrasion Mitigation Efforts in East Java Province. *Jurnal Indonesia Sosial Teknologi*. 4(12): 2324–2332. <https://doi.org/10.59141/jist.v4i12.835>.
- [3] Palisu, B. J., M. R. Fiqri, and F. M. Assidiq. 2022. Investigasi Bencana Abrasi di Berbagai Wilayah Masyarakat Pesisir di Indonesia. *Riset Sains dan Teknologi Kelautan*. 5(2): 148–152. <https://doi.org/10.62012/sensistek.v5i2.24264>.
- [4] Cooke, Steven J., Diana M. P. Galassi, Bronwyn M. Gillanders, Steven J. Landsman, Neil Hammerschlag, Austin J. Gallagher, Erika J. Eliason, Christopher E. Kraft, Michael K. Taylor, Charles M. Crisafulli, Dan H. Shugar, and Robert J. Lennox. 2023. Consequences of 'Natural' Disasters on Aquatic Life and Habitats. *Environmental Reviews*. 31(1): 122–140. <https://doi.org/10.1139/er-2022-0050>.
- [5] Anton, I. A., M. Panaitescu, F. V. Panaitescu, and S. Ghiță. 2019. Impact of Coastal Protection Systems on Marine Ecosystems. *E3S Web of Conferences*. 85(07011): 1–7. <https://doi.org/10.1051/e3sconf/20198507011>.
- [6] Suedel, Burton C., J. Calabria, M. V. Bilskie, J. E. Byers, K. Broich, S. K. McKay, A. S. Tritinger, C. B. Woodson, and E. Dolatowski. 2022. Engineering Coastal Structures to Centrally Embrace Biodiversity. *Journal of Environmental Management*. 323: 116138. <https://doi.org/10.1016/j.jenvman.2022.116138>.
- [7] Van De Riet, K. 2019. Biomimicry of Mangroves Teaches How to Improve Coastal Barriers. *ANSYS Blog*. Accessed online. <https://www.ansys.com/blog/biomimicry-mangroves-improve-coastal-erosion-coastal-barriers>.
- [8] Kazemi, A., K. Van de Riet, and O. M. Curet. 2017. Hydrodynamics of Mangrove-Type Root Models: The Effect of Porosity, Spacing Ratio and Flexibility. *Bioinspiration & Biomimetics*. 12: 056003. <https://doi.org/10.1088/1748-3190/aa7ccf>.
- [9] Kazemi, A., H. B. Evans, K. Van de Riet, L. Castillo, and O. M. Curet. 2018. Hydrodynamics of Mangrove Roots and Its Applications in Coastal Protection. In *OCEANS 2018 MTS/IEEE Charleston*. 1–8. Charleston, SC, USA, October 22–25, 2018. <https://doi.org/10.1109/OCEANS.2018.8604931>.
- [10] White, Alan T., Chua L. Ming, M. W. R. N. De Silva, and F. Y. Guarin. 1990. *Artificial Reefs for Marine Habitat Enhancement in Southeast Asia*. Manila, Philippines: International Center for Living Aquatic Resources Management.
- [11] Perricone, V., M. Mutalipassi, A. Mele, M. Buono, D. Vicinanza, and P. Contestabile. 2023. Nature-Based and Bioinspired Solutions for Coastal Protection: An Overview among Key Ecosystems and a Promising Pathway for New Functional and Sustainable Designs. *ICES Journal of Marine Science*. 80(5): 1218–1239. <https://doi.org/10.1093/icesjms/fsad080>.
- [12] Van Hespden, R., C. E. J. Van Bijsterveldt, C. M. L. Camargo, M. M. Stoorvogel, and T. J. Bouma. 2023. How Can Nature Protect People against Sea-Level Rise? *Frontiers for Young Minds*. 11: 910803. <https://doi.org/10.3389/frym.2023.910803>.
- [13] Harris, L. E. 2009. Artificial Reefs for Ecosystem Restoration and Coastal Erosion Protection with Aquaculture and Recreational Amenities. *Reef Journal*. 1(1): 235–246.
- [14] Nakamura, M. 1985. Evolution of Artificial Fishing Reef Concepts in Japan. *Bulletin of Marine Science*. 37(1): 271–278.
- [15] Desa, S. M., O. A. Karim, and A. Mohamed. 2016. Submerged Breakwater Hydrodynamic Modeling for Wave Dissipation and Coral Restorer Structure. In *Proceedings of the 3rd International Conference on Biomedical and Bioinformatics Engineering (ICBBE 2016)*. 98–101. New York: Association for Computing Machinery. <https://doi.org/10.1145/3022702.3022726>.
- [16] Rashidi, A. H. M., M. H. Jamal, M. Z. Hassan, S. S. M. Sendek, S. L. M. Sopia, and M. R. A. Hamid. 2021. Coastal Structures as Beach Erosion Control and Sea Level Rise Adaptation in Malaysia: A Review. *Water*. 13(1741): 1–34. <https://doi.org/10.3390/w13131741>.
- [17] Armono, H. D., A. Winarto, Sujantoko, and I. K. Suastika. 2021. A Laboratory Study on Wave Transmission over Hexagonal Artificial Reef. *IOP Conference Series: Earth and Environmental Science*. 799(012011): 1–9. <https://doi.org/10.1088/1755-1315/799/1/012011>.
- [18] Armono, H. D., K. R. Hall, and A. S. J. Swamidass. 2001. Wave Field Around Hemispherical Shape Artificial Reefs Used for Fish Habitat. In *Proceedings of the Canadian Coastal Conference 2001*. Canadian Coastal Science and Engineering Association.
- [19] Zhao, X. L., D. Z. Ning, Q. P. Zou, D. S. Qiao, and S. Q. Cai. 2019. Hybrid Floating Breakwater–WEC System: A Review. *Ocean Engineering*. 186: 106126. <https://doi.org/10.1016/j.oceaneng.2019.106126>.
- [20] Koraim, A. S., E. M. Heikal, and A. A. Abo Zaid. 2014. Hydrodynamic Characteristics of Porous Seawall Protected by Submerged Breakwater. *Applied Ocean Research*. 46: 1–14. <https://doi.org/10.1016/j.apor.2014.01.003>.

- [21] Saengsupavanich, C., E. H. Ariffin, L. S. Yun, and D. A. Pereira. 2022. Environmental Impact of Submerged and Emerged Breakwaters. *Heliyon*. 8(12): e12626. <https://doi.org/10.1016/j.heliyon.2022.e12626>.
- [22] Rao, S. S., N. B. S. Rao, and V. S. Sathyanarayana. 1999. Laboratory Investigation on Wave Transmission through Two Rows of Perforated Hollow Piles. *Ocean Engineering*. 26(7): 675–699. [https://doi.org/10.1016/S0029-8018\(98\)00021-3](https://doi.org/10.1016/S0029-8018(98)00021-3).
- [23] Sathyanarayana, A. H., P. S. Suvarna, P. Umesh, and K. G. Shirlal. 2021. Performance Characteristics of a Conical Pile Head Breakwater: An Experimental Study. *Ocean Engineering*. 235: 109395. <https://doi.org/10.1016/j.oceaneng.2021.109395>.
- [24] Saputra, A., D. Permana, F. D. Cahyo, Arif, and E. A. Wijonarko. 2021. Coral Reef Transplantation *Acropora* spp. for Coral Reef Rehabilitation on Panjang Island, Teluk Banten. *Jurnal Kelautan dan Perikanan Terapan*. 4(2): 105–115. <https://doi.org/10.15578/jkpt.v4i2.10074>.
- [25] Anonim. 2023. *XFlow 2022 User Guide*. <https://www.technia.com/software/simulia/xflow-cfd/>.
- [26] Altoyran, W., and J. J. Alonso. 2023. Accelerating the Lattice Boltzmann Method. In *2023 IEEE Aerospace Conference*. <https://doi.org/10.1109/AERO55745.2023.10115537>.
- [27] Sheikholeslami, M., and E. Abohamzeh. 2022. Lattice Boltzmann Method. In *Advanced Computational Techniques for Heat and Mass Transfer in Food Processing*. Boca Raton, FL: CRC Press. <https://doi.org/10.1201/9781003159520-6>.
- [28] Bao, Y. B., and J. Meskas. 2011. *Lattice Boltzmann Method for Fluid Simulations*. Simon Fraser University.
- [29] Pereira, F. S., F. F. Grinstein, D. M. Israel, and L. Eça. 2022. Verification and Validation: The Path to Predictive Scale-Resolving Simulations of Turbulence. *Journal of Verification, Validation and Uncertainty Quantification*. 7(2): 1–13. <https://doi.org/10.1115/1.4053884>.
- [30] Fauzi, M., E. Fatimah, and Q. Aini. 2025. Biomimicry Approach in the Design of Coastal Protection Structures. In *Inclusive and Integrated Disaster Risk Reduction*, edited by A. Opdyke and L. Pascua de Rivera. *Springer Proceedings in Earth and Environmental Sciences*. Cham: Springer. https://doi.org/10.1007/978-3-031-81072-5_26.
- [31] Sathyanarayana, A. H., P. S. Suvarna, P. Umesh, K. G. Shirlal, H. Bihs, and A. Kamath. 2022. Numerical Modelling of an Innovative Conical Pile Head Breakwater. *Water*. 14(24): 1–21. <https://doi.org/10.3390/w14244087>.
- [32] Nurzaman, L., P. T. Juwono, V. Dermawan, and I. Wijatmiko. 2024. The Effectiveness of Inclined Pile Breakwater on the Transmission Coefficient. *Civil Engineering Journal*. 10(6): 1863–1873. <https://doi.org/10.28991/CEJ-2024-010-06-09>.
- [33] Sugianto, D. N., R. Widiaratih, S. Widada, Suripin, E. P. Handayani, and P. Cahyaningtyas. 2022. Analysis of Structural and Non-Structural Disaster Mitigation Due to Erosion in the Timbulsloko Village, Demak–Central Java. *Journal of Ecological Engineering*. 23(2): 246–254. <https://doi.org/10.12911/22998993/144559>