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Slope Profile Dynamics Analysis in Response to Erosion Control Measures of Coastline Dynamics in Southern Java, Indonesia

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Abstract. This research explores the morphodynamic evolution of the coastal barrier and dune system in South Java, focusing on slope profile changes due to wave action. It examines natural erosion and the breaching of coastal barriers. Traditional coastal protection methods like seawalls often worsen the damage, highlighting interest in green engineering alternatives, such as vegetative coastal protection. Nature-based solutions, particularly coastal vegetation, have shown promise in protecting tropical coastlines. Field observations along the Pandansari-Samas Coast in Yogyakarta, Indonesia, revealed that areas with vegetation and dunes experienced less erosion compared to bare areas. The study uses FLOW-3D, a computational fluid dynamics (CFD) software, to analyze the relationship between wave steepness and sediment elevation change, particularly the effects of incorporating coastal vegetation. Results showed a 10% reduction in wave steepness and a 14.37% decrease in erosion in vegetated areas, along with a 4.65% increase in sediment accumulation. Vegetated areas had a net sediment elevation change of 0.25 meters, while non-vegetated areas saw a 1.74-meter loss. These findings support the Integrated Coastal Zone Management (ICZM) approach, highlighting the effectiveness of nature-based solutions like vegetative protection as an alternative to traditional methods, offering environmental and economic benefits for coastal management in Indonesia.

Introduction

The coastal regions of southern Java, Indonesia, are increasingly confronted with significant challenges arising from morphodynamic changes, which are largely driven by the relentless force of intense wave activity. These powerful waves play a critical role in reshaping the coastal landscape, leading to notable alterations in the beach slope profiles. The ongoing changes not only affect the physical structure of the coastline but also have profound implications for the local ecosystems and the infrastructure established along these coastal areas [1]. Analyzing these changes is crucial for understanding how coastal dynamics can be effectively managed, particularly in addressing the ongoing issue of erosion [3].

Traditional coastal protection methods, such as seawalls and breakwaters, are increasingly viewed as unsustainable due to their high costs, inflexibility, and adverse effects on coastal ecosystems [35]. In response, nature-based solutions are gaining traction as eco-friendly alternatives that offer multiple ecosystem services while providing effective coastal defense [22]. Therefore, another alternative is the utilization of natural coastal vegetation buffer zones. Coastal vegetation structures could directly reduce wave energy and, indirectly, mitigate impacts through the stabilization and formation of sediments [17].

The coastal area of Pandansari-Samas in Yogyakarta, Indonesia, is one of the regions vulnerable to erosion and was therefore chosen as the site for this study. Field observations in this area indicate that regions with dense vegetation and sand dunes tend to experience lower levels of erosion compared to areas with less vegetation. This research focuses on how coastal vegetation can serve as an effective green solution in mitigating the negative impacts of erosion, and how this solution can be integrated into broader coastal management strategies [17].

As an alternative, green engineering that incorporates coastal vegetation is gaining recognition as an effective nature-based solution [26, 29-30]. Vegetation such as Pandanus (*Pandanus tectorius*) can serve as a bioshield, reducing wave energy and stabilizing sediments (Fig. 1), thus decreasing erosion rates [2]. In the face of climate change, coastal vegetation also contributes to climate change mitigation by absorbing carbon dioxide (CO_2) and providing habitats for various species, which are crucial for sustaining human life [30].

(a) (b) (c)

Figure 1. Photographs of *Pandanus tectorius* in Southern Java. (a) Mid-age Pandanus grown in Pandansari Coast, (b) Root system of vegetations (including Pandanus) in sand dunes, (c) A group of mid-age Pandanus with a mid-age tree in Samas Coast.

In order to quantify and simulate the effects of coastal vegetation on erosion and wave energy dissipation, numerical modeling becomes essential. For this study, FLOW-3D (a computational fluid dynamics software) was utilized as a robust tool to model the complex hydrodynamic interactions between waves, sediment transport, and vegetation. The software's ability to simulate free surface flows with high precision allowed for an in-depth analysis of how vegetation like Pandanus influences wave propagation and sediment dynamics. By employing FLOW-3D, this research captures the intricate processes at play, offering valuable insights into the effectiveness of green engineering solutions in coastal environments [6].

As part of global efforts to implement Integrated Coastal Zone Management (ICZM), the approach used in this study is expected to make a significant contribution to more resilient coastal planning and management in Indonesia. By integrating nature-based solutions such as coastal vegetation, the findings of this research will support the development of policies that not only protect the shoreline from erosion but also enhance overall environmental resilience [25].

Methods

Wave Steepness. In this study, wave steepness (*S*) is analysed using the non-dimensional parameter. This formulation is particularly useful for understanding the relative steepness of a wave in relation to gravitational forces and temporal variation [11]. The wave steepness, *S* is calculated as:

$$S = \frac{H}{gT^2} \quad (1)$$

where H is the wave height, g is the acceleration due to gravity, and T is the wave period.

This method provides a dimensionless steepness parameter that helps in comparing wave conditions across different coastal environments. By incorporating g and T^2, the steepness reflects the balance between wave energy and the force of gravity, making it a crucial factor in evaluating the potential erosive power of waves on a coastline [11].

FLOW-3D Fundamentals. FLOW-3D is a computational fluid dynamics (CFD) software that uses the Finite Volume Method (FVM) to solve the governing equations of fluid dynamics. It is particularly adept at simulating complex fluid-structure interactions, making it suitable for coastal engineering applications [6].

Navier-Stokes equations are the backbone of the simulations, governing the motion of incompressible fluids by solving for velocity, pressure, and turbulence within a control volume [6]. These equations are expressed as:

$$\frac{\partial \rho u}{\partial t} + \nabla\cdot(\rho u u) = -\nabla p + \mu \nabla^2 u + F \tag{2}$$

Where ρ is the fluid density, *u* is the velocity vector, *t* is the time *p* is the pressure, μ is the dynamic viscosity, and *F* represents external forces, such as gravity.

The Continuity equation represents the conservation of mass for incompressible flow [6]. The equation is expressed as:

$$\nabla\cdot u = 0 \tag{3}$$

This ensures that the fluid volume remains constant within the domain.

Volume of Fluid (VOF) Method are utilized to track the interface between fluids (e.g., water and air), FLOW-3D uses the VOF method. The VOF function $F(x,t)$ is defined as the fraction of a control volume occupied by water, where F=1 indicates the control volume is full of water, and F=0 indicates it is full of air [6]. The advection of this fraction is governed by:

$$\frac{\partial F}{\partial t} + u \cdot \nabla F = 0 \tag{4}$$

FLOW-3D includes several turbulence models to represent the effects of eddies and turbulence in the flow. The RNG (Renormalization Group) k-ε turbulence model is used in this study to model turbulence within the coastal domain. It is an enhancement of the standard *k*-ε model and is particularly effective for flows with high strain rates and rapidly changing turbulence, making it suitable for coastal wave simulations [6].

The RNG *k*-ε model solves two transport equations such as turbulence kinetic energy (*k*), which governed by:

$$\frac{\partial k}{\partial t} + u \cdot \nabla k = \nabla\cdot \left(\frac{\nu_t}{\sigma_k} \nabla k\right) + P_k - \in \tag{5}$$

Where *k* is the turbulent kinetic energy, P_k is the production of turbulent kinetic energy, ∈ is the dissipation rate of turbulent kinetic energy, ν_t is the turbulent viscosity, and σ_k is the turbulent Prandtl number for *k*.

Sediment Transport in FLOW-3D is modeled through equations that account for both bedload and suspended sediment transport. The Meyer-Peter and Müller equation is commonly used to estimate bedload transport in coastal and riverine environments [6]. In this study, it is used to calculate the sediment transport rate due to wave action. The bedload transport rate (q_b) is given by:

$$q_b = 8\,(\theta - \theta_c)^{1.5} \sqrt{g\,(s-1)\,d^3} \tag{6}$$

Where q_b is the bedload transport rate per unit width, θ is the Shields parameter, a non-dimensional number representing the ratio of fluid forces to gravitational forces on the sediment particles, θ_c is the critical Shields parameter, which is the threshold value above which sediment transport begins, g is the gravitational acceleration, $s = \rho_s/\rho_f$ is the relative density of the sediment (ρ_s) to the fluid (ρ_f), and d is the sediment particle diameter.

This study used Soulsby-White Formula to get the Shields Parameter, which particularly effective in describing sediment transport under combined wave and current action. This approach modifies the bed shear stress based on both wave and current effects, making it suitable for coastal environments where waves dominate sediment transport. The critical Shields parameter, θ_c is determined based on empirical data and indicates when sediment motion begins.

FLOW-3D Simulation Setup. The simulation setup in FLOW-3D for analyzing coastal erosion and slope dynamics involves several steps to integrate field observation and numerical model. The model setup is based on the Free Surface – TruVOF. Simulation is set for 600 second finish time. Gravity and Non-Inertial, Moving Objects, Sediment Transport, and Turbulence and Viscosity is activated for this simulation. Fluid properties are based on the density of seawater. Sediment properties uses a single sediment species of 0.6mm grain size diameter and density of 1500kg/m^3. An upstream wave generator modeled by moving object with prescribed sinusoidal wave which move in translation in the x-axis direction to make long-linear waves of 3m wave height in 12 seconds of period.

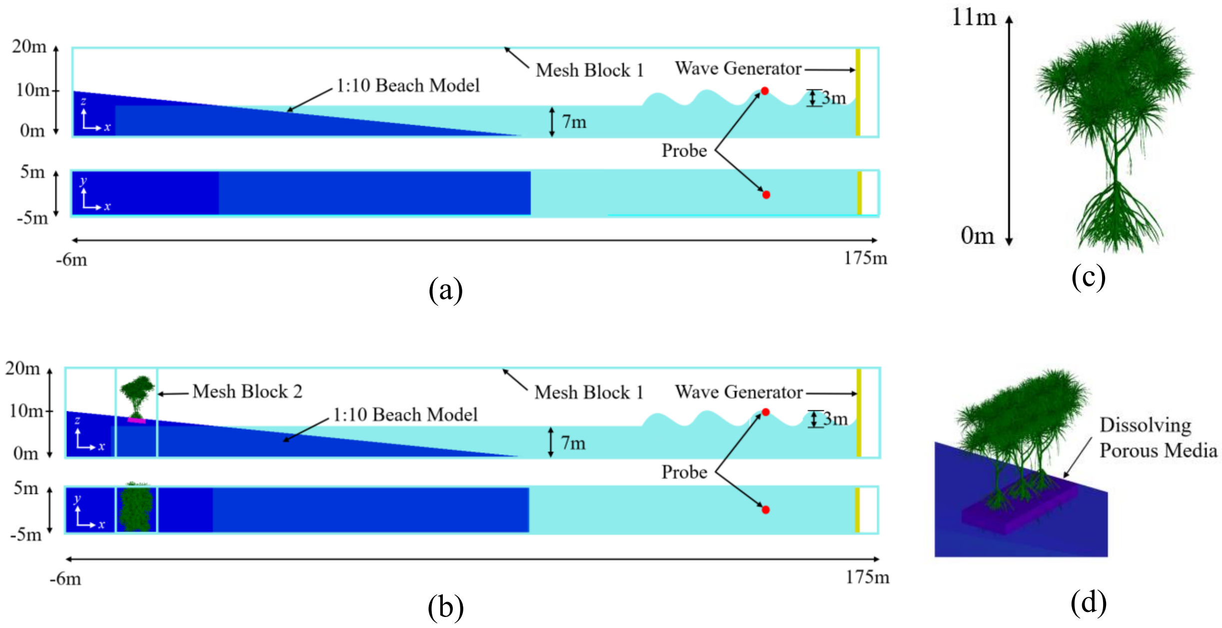

Figure 2. Geometry configuration of computational Model. (a) 2D views of simulation setup without vegetation, (b) 2D views of simulation setup with vegetation, (c) Single *Pandanus tectorius* 3D model, (d) 3D Configuration of three Pandanus models with dissolving porous media around the root.

Three typical models of *Pandanus tectorius* were defined using an imported STL file (Fig. 2c) and activated as rigid bodies. A dissolving porous media, representing the fine roots of Pandanus, was modeled around the root system (Fig. 2d) with a depth of 1 meter and a length of 4 meters, using a porosity coefficient of 0.7. A beach slope with a 1:10 gradient and a width of 10 meters was included in the simulation to mimic the median field slope conditions.

For the non-vegetated model, a single mesh block was employed (Fig. 2a), covering the entire geometry with a mesh size of 0.5 meters. In contrast, for the vegetated model, an additional mesh block was applied from x=6m to x=14m (Fig. 2b), using a finer mesh size of 0.1 meters. The total number of cells was approximately 280,000 for the non-vegetated model and 1,600,000 for the vegetated model, all within a three-dimensional (3D) domain.

Table 1. The parameters used in FLOW-3D simulation

Parameter	Value/option	
Mesh size	Non-vegetated model = 0.5m; Vegetated model = 0.1m	
Turbulence Model	RNG Model; maximum turbulent mixing length for RANS models was dynamically computed.	
Fluid region initial condition	x_{min}=4m, x_{max}=170m y_{min}=-5m, y_{max}=5m z_{min}=0m, z_{max}=7m	
Wave generator: moving object properties	Type: prescribed motion; Amplitude = -1.57m/s; Frequency = 0.08333 Hz	
Boundary Condition	Mesh Block 1: x_{min}=Wall, x_{max}=Wall y_{min}=Symmetry, y_{max}= Symmetry z_{min}=Wall, z_{max}=Pressure	Mesh Block 2: x_{min}= Symmetry, x_{max}= Symmetry y_{min}=Symmetry, y_{max}= Symmetry z_{min}= Symmetry, z_{max}= Pressure

Boundary conditions, initial fluid regions, and other simulation parameters are detailed in Table 1. Numerical options for the Volume of Fluid (VOF) method were set to split Lagrangian to maximize the accuracy of wave propagation. Measurements of flow depth and net change in sediment elevation were recorded, and a probe was placed at x=150m to assess the time history of fluid behavior and initial wave characteristics which attenuate to the beach model.

Result and discussion

Validation of The Wave Model. The validation of the FLOW-3D model was conducted by comparing graph of simulated water surface elevation during wave propagation with theoretical linear wave collected during storm conditions (H=3m, T=12s) in Samas and Pandansari Coast, representing long wave hydrodynamics. The simulation was run for 600 seconds, and wave characteristics were assessed in the non-vegetated model using diagnostic data from a general history probe, recorded after the flow had reached a dynamic stability state, as shown in Fig. 3.

From the comparison of flow depth, it can be observed that the computational results reasonably predict the wave height, with only a slight underestimation, but still within an acceptable range. Based on these results, we can confidently proceed to model wave steepness and cross-shore profiles using the vegetated model.Sediment elevation net changes in both the non-vegetated and vegetated models were then compared. Both simulation comparison provided in Fig. 4.

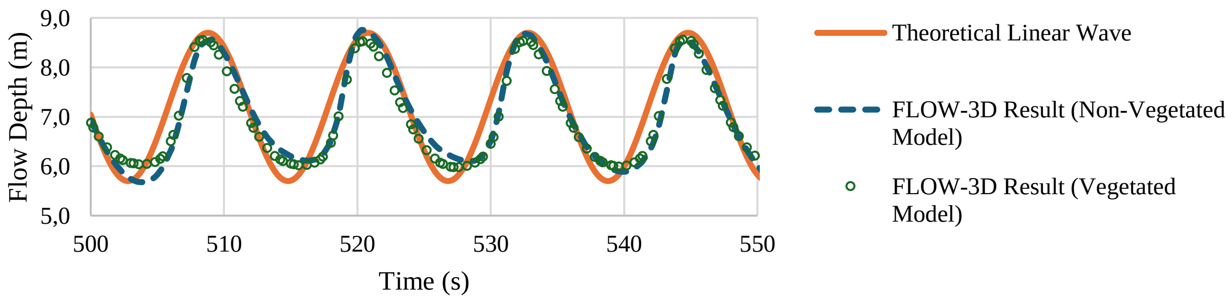

Figure 3. Time history of flow depth during initial wave propagation from at t = 500s – 600s.

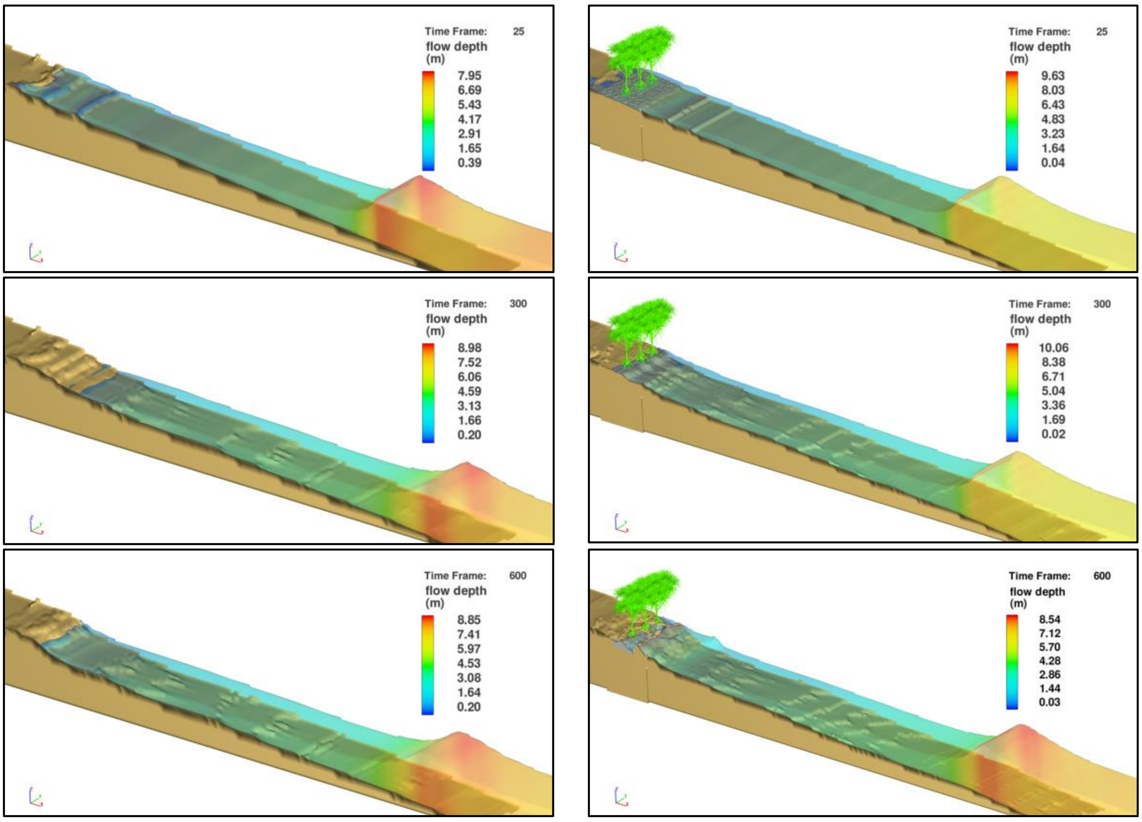

Figure 4. The result of FLOW-3D simulation comparison, resulting difference of fluid flow depth at initial (t=25s), middle (t=300s), and final (t=600s) time frame on non-vegetated (left) and vegetated model (right).

Development of The Wave Steepness. The wave steepness defined by Eq.1 plays a pivotal role in coastal erosion dynamics. In the non-vegetated model, the average wave steepness observed was approximately 0.0020. This elevated steepness resulted from direct wave action on the shoreline, leading to higher wave energy reaching the coast. The absence of vegetation meant there were no natural barriers to dissipate this energy, causing significant impacts on the beach slope. Areas where the waves interacted most aggressively showed considerable erosion, which was exacerbated during high-energy events, resulting in the destabilization of the slope profile.

In contrast, the vegetated model demonstrated a wave steepness of approximately 0.0018, indicating a significant reduction due to the influence of coastal vegetation. The presence of *Pandanus*

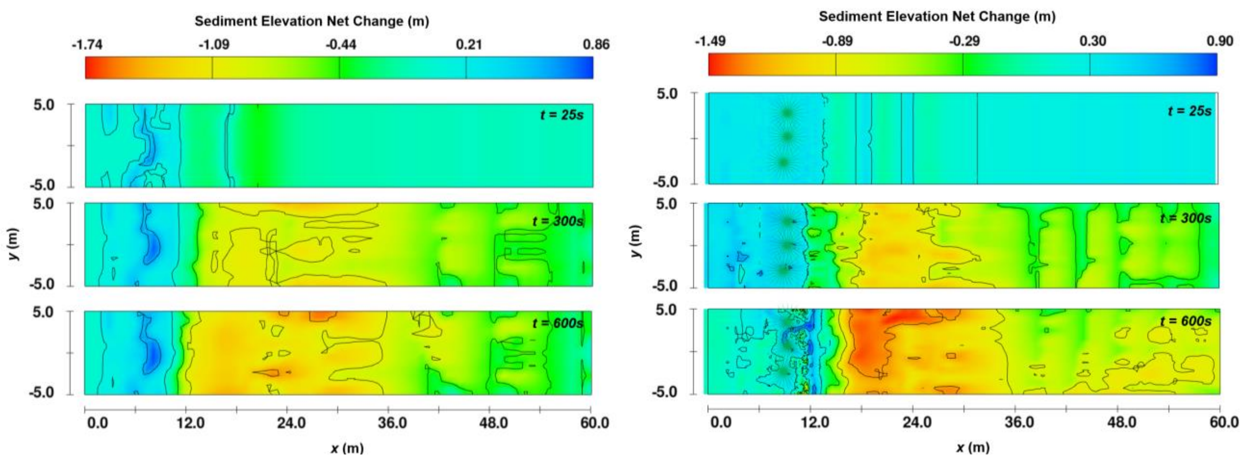

Figure 5. Color shaded with contour result comparison of sediment elevation net change at initial (t=25s), middle (t=300s), and final (t=600s) time frame on non-vegetated (left) and vegetated model (right).

tectorius provided a natural buffer that absorbed wave energy, thereby decreasing the overall steepness of incoming waves. This reduction by 10.71% in steepness translates to lower energy reaching the shoreline, which directly contributes to enhanced coastal stability. The vegetation not only mitigated wave action but also facilitated sediment accumulation by slowing down water flow, allowing sediments to settle rather than being eroded.

Development of Slope Profile. The comparative analysis between the non-vegetated and vegetated models shows clear differences in sediment elevation changes. In the non-vegetated model, sediment elevation dropped to -1.74 meters, indicating significant erosion, while the maximum accumulation reached 0.86 meters. In contrast, the vegetated model had less erosion, with a minimum elevation of -1.49 meters, and slightly more accumulation at 0.90 meters. Coastal vegetation reduced erosion by 14.37% and increased sediment accumulation by 4.65% compared to the non-vegetated model.

FLOW-3D analyzed 2D sediment elevation changes (Fig. 5-6), highlighting greater sediment loss in the non-vegetated model, with shoreline recession caused by high-energy waves. This erosion disrupts the beach profile and local ecosystems. These findings support previous research showing the limitations of traditional coastal protection methods that ignore natural sediment dynamics.

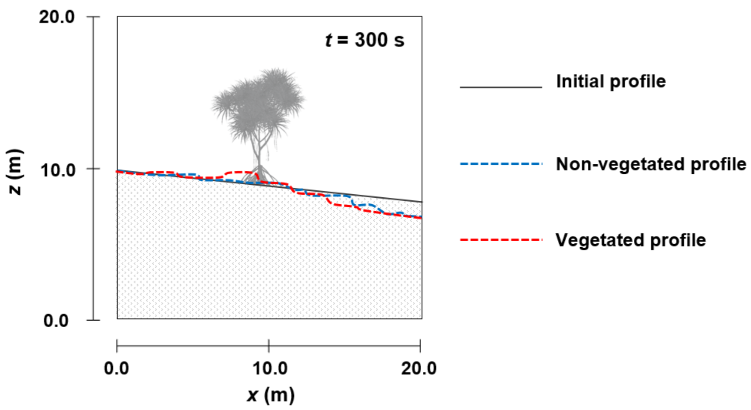

Figure 6. 2D Cross-shore comparison of erosion development, indicating an improvement on terain elevation caused by vegetation.

The vegetated model showed a 0.25-meter net sediment elevation increase, with Pandanus tectorius roots playing a key role in stabilizing the sandy substrate and reducing erosion. This suggests that nature-based solutions, like coastal vegetation, are effective for erosion control and support the concept of Integrated Coastal Zone Management (ICZM), which emphasizes ecological processes in coastal management.

Although the vegetated model showed significant benefits in reducing erosion, the simulation results at *t* = 569s revealed the collapse of the sand dune slope due to the hydrodynamic forces of waves around the vegetation. This phenomenon occurred because of the concentrated wave energy near the vegetation, causing slope instability. However, after the slope collapse, the minimum elevation at the front of the model at *t* = 600s (the final time frame) reached *z* =-1.49 meters, indicating that despite the collapse, the vegetation still maintained a higher elevation compared to non-vegetated areas. This suggests that vegetation serves as a buffer that helps mitigate further erosion impacts, even after initial instability.

This temporary collapse highlights that while vegetation is effective in retaining sediment, it remains vulnerable to stronger hydrodynamic forces at certain points. This underscores the need for further research into the effects of vegetation layout and type on the stability of sand dunes under more extreme hydrodynamic conditions.

The vegetated model's terrain contours showed a more stable beach profile, reinforcing the effectiveness of green engineering solutions. Successful sediment retention not only controls erosion but also aids habitat restoration and resilience against climate change. These findings highlight the importance of incorporating natural solutions into coastal management for long-term sustainability.

Conclusion

This study demonstrates the effectiveness of Pandanus tectorius in mitigating coastal erosion in Southern Java. Numerical simulations and field observations at Pandansari-Samas Coast showed that non-vegetated areas experienced significant erosion, with a 1.74-meter net loss in sediment elevation, while vegetated areas accumulated 0.25 meters of sediment. Vegetation also reduced wave steepness from 0.0020 to 0.0018, stabilizing sediment and dissipating wave energy. Despite a temporary slope collapse at t = 569s due to wave hydrodynamics, the minimum elevation remained at -1.49 meters by t = 600s, indicating vegetation's stabilizing effect post-collapse.

These findings highlight the importance of considering local hydrodynamic impacts when designing nature-based coastal protection. Pandanus tectorius effectively reduces sediment loss by 14.37% and increases accumulation by 4.65%, offering a sustainable alternative to traditional erosion control methods. Future research should focus on long-term vegetation impacts with random wave parameter under tidal conditions to better match real-world scenarios to further validate these solutions.

Author contribution statement

Oki Setyandito: Conceptualization, Analysis, Narrative Discussion, Methodology, Review. **Nizam**: Investigation, Analysis, Computational, Supervision, Review. **Benazier**: Investigation, Review. **Muhammad Hafiz Aslami**: Methodology, Computational, Narrative Discussion, Review. **Andrew John Pierre**: Computational, Analysis, Writing and Edit.

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