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Experimental analysis of a submerged rubble mound breakwater in a 2D flume: Advancing sustainable development goals through innovative coastal engineering solutions

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Abstract

This study investigates submerged rubble mound breakwaters as an eco-friendly alternative for coastal protection. The purpose of this research is to experimentally analyze the effectiveness of different core configurations of submerged rubble mound breakwaters in dissipating wave energy and reducing coastal erosion. The study utilized a 2D wave flume to simulate coastal wave conditions, testing various breakwater models reinforced with geotextiles, geotubes, and without additional reinforcement. The experimental results demonstrate that submerged rubble mound breakwaters can significantly attenuate wave energy, with reinforced models showing enhanced structural stability and reduced material displacement. The findings suggest that incorporating geotextile or geotube materials improves the performance of the breakwaters, particularly in high-energy wave conditions. This research aligns with the Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 9 (Industry, Innovation, and Infrastructure), providing valuable insights for sustainable coastal management. These findings support the development of more resilient coastal defenses that protect against wave-induced damage while maintaining ecological integrity.

Keywords: Experimental, Geotextile, Geotube, Submerged rubble mound breakwater, Sustainable development goals.

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1. Introduction

Coastal regions worldwide face increasing challenges due to climate change, rising sea levels, and extreme weather events, leading to severe coastal erosion and infrastructure vulnerability [1, 2]. Traditional coastal protection methods, such as seawalls and groynes, often have negative environmental impacts, disrupting sediment transport and marine ecosystems

[3, 4]. In response, submerged rubble mound breakwaters have emerged as an innovative and eco-friendly solution to mitigate wave-induced damage while maintaining natural coastal dynamics [4].

Submerged rubble mound breakwaters function by dissipating wave energy before waves reach the shoreline, reducing erosion and protecting coastal infrastructure. Unlike conventional breakwaters, their submerged nature minimizes visual and environmental disturbances, allowing for sediment deposition and marine habitat preservation [5]. However, their effectiveness depends on various factors, including wave conditions, structural geometry, and material composition, necessitating experimental studies to optimize their design and performance [6].

This study focuses on the experimental analysis of sloping-side submerged breakwater models in a 2D flume featuring artificial rock layers in the form of tetrapods. Different core layer variations were tested, including geotextiles, geotubes, and configurations without additional core layer materials. Through a series of controlled laboratory tests, wave transmission and energy dissipation were evaluated under varying breakwater configurations and wave conditions [7].

The findings contribute to the development of sustainable coastal protection measures aligned with Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 9 (Industry, Innovation, and Infrastructure). By investigating the efficiency of submerged rubble mound breakwaters in reducing wave energy and enhancing coastal resilience, this research provides valuable insights for engineers and coastal planners. The study highlights the potential of these structures as sustainable alternatives to traditional coastal defenses, supporting long-term environmental and infrastructural sustainability [6].

The increasing impacts of climate change and urbanization on coastal zones have intensified the demand for innovative, sustainable solutions in coastal engineering. Traditional coastal defense structures, such as seawalls and above-water breakwaters, have proven effective in protecting shorelines from wave energy but are often criticized for their negative ecological and aesthetic impacts [8]. As a result, recent research in coastal engineering has focused on submerged rubble mound breakwaters as a more environmentally sustainable alternative that aligns with the United Nations Sustainable Development Goals (SDGs), particularly those focused on sustainable infrastructure (SDG 9) and climate resilience (SDG 13) [9].

Conventional coastal defenses, including vertical seawalls and emerged breakwaters, are widely used to mitigate wave-induced erosion and protect coastal infrastructure. While effective at reducing wave energy and protecting coastlines, these structures often disrupt natural sediment transport processes, degrade marine habitats, and obstruct scenic coastal views [10]. Research by Corte, et al. [11] Highlights that hardened shoreline structures can lead to "coastal squeeze," where natural habitats are confined between fixed infrastructures and rising sea levels, resulting in habitat loss and reduced biodiversity. For instance, coastal armoring impacts beach sediment dynamics, inducing erosion and habitat loss, thereby threatening biodiversity processes and the functional roles of sandy beach ecosystems [12].

In response to the limitations of traditional coastal defenses, there has been a shift toward sustainable and ecologically friendly designs. The concept of "green infrastructure" in coastal engineering emphasizes structures that work in harmony with natural processes rather than disrupting them. Submerged rubble mound breakwaters represent one such innovation, designed to dissipate wave energy below the waterline, thereby reducing shoreline erosion without obstructing views or interfering significantly with coastal ecosystems [8]. These submerged structures offer the dual benefits of protecting coastlines while minimizing visual impact and fostering ecological connectivity.

Submerged rubble mound breakwaters function by dissipating wave energy through a series of submerged rocks or rubble positioned at calculated angles and depths to optimize wave attenuation. Studies by Peng, et al. [13] and Zanuttigh, et al. [14] suggest that submerged breakwaters can reduce wave height by up to 80% under specific design conditions, with effectiveness depending on factors such as wave period, breakwater slope, and water depth. Additionally, research by Sharifahmadian [15] Indicates that rubble mound materials and geometry significantly influence a breakwater's resilience against high-energy wave conditions, a factor critical for their application in exposed coastal areas.

The previous research has been done by Subeno [16]” The Influence of Leadership Situation on Organisational Climate at the Balimester Village Office, Jatinegara District, East Jakarta Administrative City, DKI Jakarta Province.” This study explored the relationship between leadership situations and organizational climate, specifically at the Balimester Village Office. The findings showed a significant positive correlation between leadership situations and the organizational climate, with a correlation coefficient of 0.5713, indicating a strong relationship.

Fiedler [17] “The Effectiveness of Contingency Models of Leadership: A Study on Leader Behavior and Situational Factors in Organizational Settings.” This study examined the effectiveness of contingency models in leadership, focusing on how leadership behavior must align with situational factors to be successful. It concluded that situational leadership models are most effective when leaders adapt their behaviors based on the specific demands of the situation, including factors like leader-member relationships, task structure, and position power.

This research presents a unique examination of the leadership situation at the Bantaeng Regency Agriculture Office, using a one-sample t-test for hypothesis testing, which contrasts with previous studies that typically employed qualitative or correlation-based analyses. Additionally, it explores the specific dimensions of leadership, including leader-member relationships, task structure, and leader power position, providing a fresh perspective on leadership effectiveness in government organizations, particularly in the context of local agricultural offices.

The purpose of this research is to assess the leadership situation at the Bantaeng Regency Agriculture Office by evaluating the relationship between leaders and subordinates, the clarity of task structure, and the strength of the leader's position, to identify areas for improvement to create a more conducive and effective organizational environment.

2. Materials and Methodology

In fluid engineering, particularly for complex coastal structures like submerged rubble mound breakwaters, analytical solutions are often insufficient due to the intricate dynamics involved. Observing these systems at full scale in the field is costly, time-consuming, and carries a significant risk of failure. As a solution, engineers use scaled-down models, known as model studies, in laboratory settings to simulate and analyze various planning scenarios. These laboratory models, while smaller in scale, are designed to replicate the geometry and function of the real structure, allowing for accurate experimentation and analysis.

The experiment was conducted in a controlled wave flume at the Laboratory Balai Pantai, Ministry of Public Works, Buleleng, Bali, Indonesia. The flume, measuring 40 meters in length, 0.6 meters in width, and 1.2 meters in depth, provided a stable environment for replicating coastal wave conditions and evaluating the hydrodynamic response of submerged rubble mound breakwater models. A piston-type wave generator was employed to create regular waves with adjustable parameters, including wave height (ranging from 0 to 25 cm), frequency (0.385 to 1 Hz), and period (1 to 2.6 s). This setup enabled the simulation of realistic wave conditions, ensuring meaningful observations of wave interactions with the breakwater structures.

Wave measurement was conducted using three strategically placed wave probes to capture key wave parameters such as height, frequency, and energy dissipation:

1. Wave Probe 1: Positioned 11.5 meters from the origin at a height of 0.30 meters above the baseline.
2. Wave Probe 2: Located 24.5 meters from the origin, also at 0.30 meters above the baseline.
3. Wave Probe 3: Placed 26.5 meters from the origin, again at 0.30 meters above the baseline.

These probes provided high-precision data at critical points in the flume, allowing for a detailed analysis of wave transformation and the effectiveness of submerged breakwaters in dissipating wave energy. As depicted in Figure 1, the side view of the wave flume illustrates the positioning of the probes and the arrangement of submerged breakwater models within the flume. This controlled setup ensured that the hydrodynamic performance of the breakwaters was evaluated under conditions analogous to natural coastal environments.

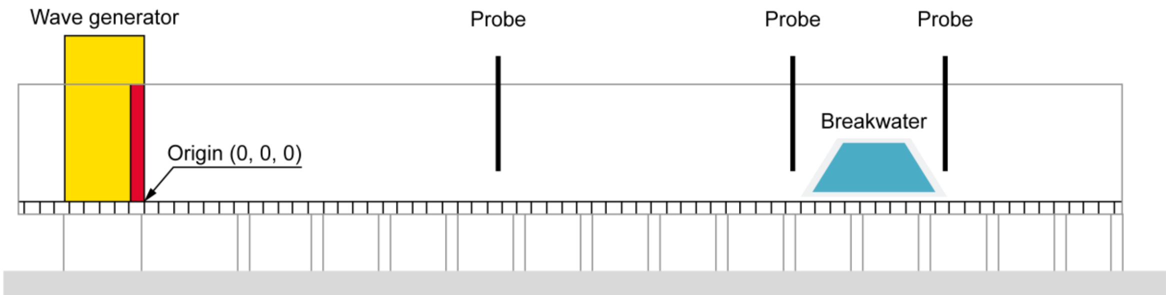

Figure 1.
Side view of the wave flume setup showing probe arrangement and submerged rubble mound breakwater models.

1.1. Rubble Mound Breakwater Model Design

The laboratory tests in this study focused on the experimental evaluation of sloping-side breakwater models reinforced with artificial rock layers composed of tetrapods. To investigate the influence of core materials, the study examined three distinct core layer variations:

1. Core layers without additional materials
2. Geotextile-reinforced core layers
3. Geotube core layers

As illustrated in Figures 2–3, a transverse view of the breakwater models showcases the different core configurations, allowing for a comparative analysis of their hydrodynamic performance and structural stability.

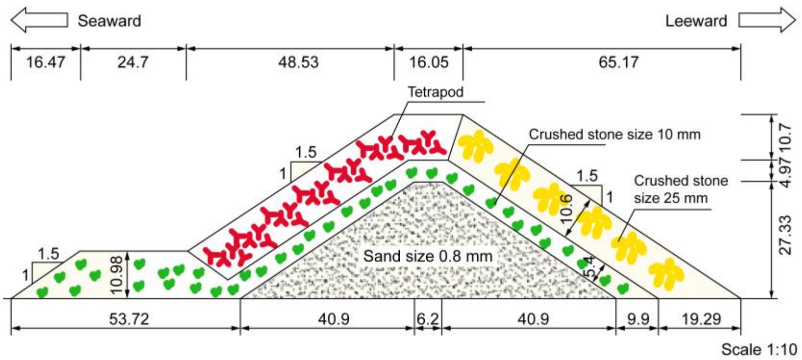

Figure 2.
A transverse view (cross-section) of a rubble mound breakwater model with tetrapods as the primary layer on a 1:1.5 slope.

Figure 2 presents a transverse view (cross-section) of the rubble mound breakwater model, featuring tetrapods as the primary armor layer on a 1:1.5 sloped configuration. In this setup, the core layer is constructed without additional reinforcement materials, such as geotextiles or geotubes, allowing for a direct evaluation of the tetrapod layer's structural resilience and stability under regular wave conditions.

The tetrapods are strategically positioned along the slope to dissipate wave energy effectively. The 1 slope angle facilitates wave breaking upon impact, promoting energy loss through turbulence and reducing both wave reflection and energy transmission. This configuration serves as a baseline assessment, providing insights into the hydrodynamic performance and durability of an unreinforced tetrapod-armored breakwater.

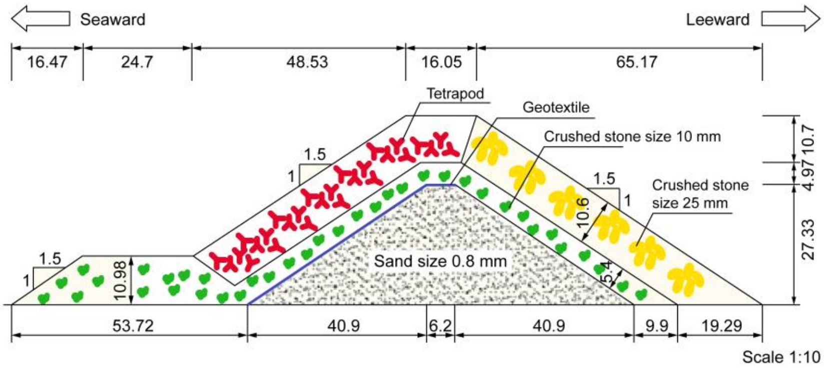

Figure 3.
A transverse view (cross-section) of a rubble mound breakwater model that includes tetrapods as the main layer and a geotextile layer in the core.

Figure 3 illustrates a transverse view of the breakwater model, featuring tetrapods as the primary armor layer and a geotextile-reinforced core on a 1:2.0 slope configuration. Compared with steeper designs, this gentler slope enhances wave interaction while maintaining structural stability.

The tetrapods serve as the first line of defense, reducing wave impact and minimizing energy transmission. Beneath them, the geotube core layer provides structural stability and additional mass, reinforcing the breakwater against hydrodynamic forces. Geotubes, typically composed of durable, permeable fabric filled with sand or other materials, play a crucial role in erosion prevention while allowing controlled water permeability to relieve internal pressure within the breakwater structure [18]]. This combined configuration of tetrapods and geotubes enhances wave energy absorption and mitigates structural damage, making it particularly effective for high-energy coastal environments requiring robust protection.

This two-dimensional breakwater model was designed with three distinct slope configurations—1:1.5, 1:2, and 1:2.5—facing the incoming waves. The experimental tests simulated regular wave conditions to evaluate the structural stability and wave energy dissipation performance of each configuration under varying water levels. Specifically, the study considered the following conditions:

1. Submerged Condition: A water level of 70 cm, where the breakwater is entirely below the water surface.
2. Overtopped Condition: A water level of 63 cm, allowing waves to break over the structure.
3. Non-Overtopped Conditions: Water levels of 38 cm and 54 cm, where the breakwater remains exposed above the water surface.

These variations enabled a comprehensive assessment of how different slope configurations and core materials influence breakwater effectiveness across diverse wave conditions and water depths.

1.2. Wave Generation and Test Conditions

Wave height and energy dissipation were measured using a series of wave probes strategically positioned both in front of and behind the breakwater models. These probes recorded key wave parameters, including wave height, period, and frequency, to quantify the extent of wave energy reduction for each breakwater configuration [19]. The collected data were used to compute the wave transmission coefficient (K_t), a critical parameter for evaluating the breakwater's effectiveness in wave attenuation. The transmission coefficient is given by the following formula:

$$K_t = \frac{H_t}{H_i} \quad (1)$$

where
H_t Is the transmitted wave height (measured behind the breakwater).
H_t Is the incident wave height (measured before the breakwater).

A lower K_t Value signifies greater wave energy dissipation, highlighting the breakwater's effectiveness in reducing wave transmission and enhancing coastal protection. Conversely, a higher K_t Value indicates increased wave energy transmission, suggesting reduced wave attenuation.

To assess the structural stability of each breakwater design, cameras were strategically positioned to monitor potential displacement or deformation within the rubble mound throughout the testing process. During high-energy wave simulations, the recorded footage facilitated detailed visual inspection, with particular emphasis on shifts or movement in the upper layers of the mound where wave forces are most pronounced. This observational approach enabled precise evaluation of structural integrity under varying wave conditions, providing valuable insights for identifying potential design improvements to enhance breakwater resilience and effectiveness.

2. Data Analysis

Performance metrics, including the wave transmission coefficient and structural stability, were analyzed across the different breakwater configurations. This comparative assessment facilitated the identification of optimal design parameters for two-dimensional submerged rubble mound breakwaters. Configurations that demonstrated high wave attenuation—effectively dissipating wave energy—while maintaining structural integrity and minimizing environmental impact were deemed most effective. The findings provide valuable insights into the development of efficient and sustainable breakwater designs that enhance coastal protection while balancing ecological considerations.

Integrating the Sustainable Development Goals (SDGs) framework into the durability assessment provides a meaningful perspective by aligning breakwater designs with broader global objectives, including climate resilience (SDG 13) and innovation and infrastructure (SDG 9). Evaluating durability through this lens underscores each design's potential for long-term viability, reduced ecological impact, and contribution to sustainable coastal management. This approach not only enhances engineering best practices but also ensures that infrastructure development aligns with global sustainability targets [20].

This comprehensive methodology enabled a detailed evaluation of two-dimensional submerged rubble mound breakwaters across a range of simulated environmental conditions. By integrating wave attenuation measurements with structural stability assessments, the study provided a multi-dimensional analysis of breakwater performance and sustainability. The findings offer critical insights for optimizing breakwater designs in practical coastal applications, highlighting the significance of environmentally compatible and resilient structures. Ultimately, this research advances the field of sustainable coastal engineering, emphasizing the importance of eco-friendly, durable designs in protecting coastlines and mitigating climate-related impacts.

3. Discussion

3.1. Rubble Mound Breakwater using Tetrapods with a 1:1.5 Slope

This design approach provides notable advantages in both stability and wave energy dissipation. A steeper slope enhances the breakwater's capacity to attenuate wave energy, making it particularly suitable for high-energy coastal environments. However, steeper slopes may also experience greater wave-induced forces, potentially increasing maintenance requirements and necessitating structural reinforcements over time, especially under extreme wave conditions. The statistical analysis of wave height variations across different water levels is presented in Table 1.

Table 1.
Average wave height and average wave period with water level variations for rubble mound breakwater using tetrapods.

Water Level (m)	Wave Probe	Duration			
		2000 seconds		6000 seconds	
		H (m)	***T*** (s)	***H*** (m)	***T*** (s)
0.70	1	0.071	2.001	0.070	1.970
	2	0.221	2.023	0.217	2.020
	3	0.064	1.014	0.064	1.011
0.63	1	0.169	1.999	0.178	2.028
	2	0.410	2.025	0.421	2.028
	3	0.107	17.219	0.117	80.680
0.54	1	0.109	2.018	0.115	2.015
	2	0.190	2.018	0.200	2.017
	3	0.432	2.016	0.447	2.017
0.38	1	0.131	2.392	0.126	2.573
	2	0.084	1.493	0.083	1.366
	3	0.262	2.562	0.256	2.574

This analysis reveals a significant relationship between water level, wave height, and wave period about the breakwater structure. When the water level reaches 0.63 m, corresponding to the height of the breakwater crest, wave height peaks, likely due to direct interaction with the structure. However, as the water level surpasses 0.70 m, submerging the breakwater, wave height decreases, suggesting that submerged conditions facilitate greater wave energy dissipation rather than reflection or amplification.

The observed increase in wave period at Wave Probe 3 for the 0.63 m water level suggests a more complex hydrodynamic interaction at this depth, where waves may experience deceleration or transformation due to the breakwater's influence. Additionally, the finding that average wave heights remain consistent over 2,000 and 6,000 seconds indicates that time duration does not significantly affect wave interaction, except at specific water levels such as 0.63 m, where notable variations occur.

These insights are critical for optimizing breakwater design, ensuring that structures are tailored to specific sea levels where they provide the most effective wave attenuation and coastal protection. The wave transmission coefficient at the 0.70 m water level (submerged condition) is defined as follows:

$$K_t = \frac{0.064}{0.221} = 0{,}289$$

Since $K_t = 0{,}289 < 0.3$ Means strong energy dissipation, minimal wave transmission, excessive reflection, and force may destabilize the structure.

Figure 4.
A rubble mound breakwater model with a 1:1.5 slope and a tetrapod main protective layer under a 0.70 m water level.

Figure 4 (water level: 0.70 m, Submerged Condition): The structure exhibits significant core erosion, characterized by a high rate of material displacement within the core layer. This erosion compromises the stability of the sloping-side breakwater, ultimately resulting in structural failure under submerged conditions. These findings highlight the critical need for reinforcing the core and protective layers in submerged scenarios, particularly when tetrapods are used as the primary defense against wave action. Strengthening the structural integrity of the core material and optimizing the interlocking arrangement of tetrapods can help mitigate erosion, enhance durability, and ensure the long-term effectiveness of the breakwater in high-energy coastal environments.

3.2. Rubble Mound Breakwater using Tetrapods with a 1:1.5 Slope and Geotextile Integration

The integration of geotextile between the core and crushed stone layers enhances the structural integrity of the sloping-side breakwater model by improving load distribution and increasing resistance to displacement under wave forces. By acting as a filter and separation layer, the geotextile prevents material migration, thereby reducing internal erosion and maintaining the stability of the breakwater over time.

Table 2 presents the average wave height measured in front of a rubble mound breakwater with a tetrapod main protective layer at a 1:1.5 slope, comparing conditions with and without the addition of geotextile. The findings indicate that incorporating geotextile between the core layer and the crushed stone layer significantly reduces wave height. This reduction suggests that the geotextile enhances the breakwater's effectiveness in dissipating wave energy by improving structural integrity and minimizing erosion and material displacement. By stabilizing the core layer, geotextile integration contributes to more efficient energy dissipation, thereby enhancing overall breakwater performance. These results highlight the potential advantages of geotextile application in breakwater design, not only in improving structural stability but also in mitigating wave action. Furthermore, this approach supports more sustainable coastal engineering practices by reducing the risks of coastal erosion and structural failure.

Table 2.
Average wave height measured in front of a rubble mound breakwater with a tetrapod main layer at a 1:1.5 Slope, with and without the addition of geotextile.

Water Level (m)	**H_{ave} (m)**	
	Without Geotextile	**With Geotextile**
0.70	0.221	0.087
0.63	0.410	0.175
0.54	0.190	0.185
0.38	0.126	0.128

The statistical data presented in Table 3, which detail wave height variations across different water levels, provides valuable insights into the geotextile's impact on breakwater stability. This analysis helps quantify the effectiveness of geotextile reinforcement in mitigating structural displacement and enhancing overall resilience under varying hydrodynamic conditions.

Table 3.
Statistical analysis of wave height at varying water levels for a rubble mound breakwater with tetrapods at a 1:1.5 slope, incorporating geotextile between the core and crushed stone layers.

Water Level (m)	**Wave Probe**	**Wave Height (m)**	**Wave Runup (m)**	**Wave Rundown (m)**
0.70	1		Overtopping	0.065
	2	0.087		
	3	0.080		
0.63	1		Overtopping	0.255
	2	0.215		
	3	0.175		
0.54	1		Overtopping	0.195
	2	0.185		
	3	0.130		
0.38	1			
	2	0.140	0.260	0.060
	3	0.128	0.185	0.080

The integration of geotextile between the core and the crushed stone protection layer in the breakwater model significantly influences wave dynamics and erosion patterns. Initially, the average wave height follows a similar trend to the scenario without geotextile, increasing with the water level until it aligns with the breakwater's height. However, the inclusion of geotextile results in a notable reduction in average wave height, demonstrating improved wave attenuation. At lower water levels (0.38 m), material creeping within the core layer is observed; however, this diminishes as the water level rises, suggesting that geotextile enhances core stability, particularly under higher water levels [21].

Overtopping occurs at a water level of 0.54 m, with erosion primarily confined to the breakwater's side.

This side erosion, concentrated on the exposed sand within the core layer, indicates that while geotextile effectively mitigates material displacement at the front, the sides remain susceptible to water ingress. Furthermore, at a submerged water level of 0.70 m, the wave transmission coefficient is calculated as follows:

$$K_t = \frac{0.080}{0.087} = 0.919$$

Since $K_t > 0.6$This indicates that a significant amount of wave energy passes through, reducing the breakwater's protective effectiveness and increasing the risk of scour. These findings underscore the necessity of implementing additional protective measures along the sides to enhance overall erosion control and improve structural resilience.

3.3. Rubble Mound Breakwater Utilizing Tetrapods (1:1.5 Slope) with a Geotube Core

In the sloping-side breakwater model featuring a tetrapod main protective layer with a 1:1.5 slope, a geotube was incorporated into the core layer to evaluate its effectiveness in enhancing structural stability and performance under varying water levels. Laboratory tests were conducted at water levels of 0.38 m, 0.54 m, 0.63 m, and 0.70 m, with a constant wavelength of 4 m and a wave period of 2 seconds.

Table 4.
High wave data statistics for rubble mound breakwater with tetrapods and geotube core at a 1:1.5 slope under varying water levels.

Water Level (m)	**H_{ave} (m)**	**Runup (m)**	**Rundown (m)**	**Description**
0.70	0.070			Overtopping
0.63	0.124			Overtopping
0.54	0.016		0.135	
0.38	0.078	0.195	0.075	

Table 4 presents statistical data on wave parameters observed during the tests, offering insights into the wave conditions experienced by the breakwater model. Key metrics, including wave height, wave period, and wave energy, were analyzed to evaluate wave-structure interactions. The inclusion of geotubes in the core layer is expected to enhance stability and erosion resistance by reinforcing structural integrity and reducing displacement, particularly under high-energy wave conditions.

The results in Table 4 indicate that integrating geotubes within the core layer of the sloping-side breakwater model—featuring a tetrapod main protective layer with a 1:1.5 slope—effectively reduces wave height compared to configurations using geotextile between the core and crushed stone layers. This reduction reflects an improved capacity to attenuate wave energy, thereby enhancing overall stability and performance under varying water levels.

In this experimental setup, overtopping of the breakwater begins at a water level of 0.63 m, aligning with the structure's height. This threshold is critical as it marks the point where wave conditions exceed the breakwater's capacity to retain and dissipate wave energy effectively. Managing overtopping is essential for preserving the breakwater's integrity and ensuring coastal protection against dynamic environmental forces.
Additionally, at a submerged water level of 0.70 m, the wave transmission coefficient is determined as follows:

$$K_t = \frac{0.078}{0.087} = 0.897$$

Since $K_t > 0.6$A substantial portion of wave energy passes through the breakwater, diminishing its protective capability and heightening the risk of scour. This result is consistent with findings from submerged rubble mound breakwaters utilizing geotextile, suggesting that modifications to the slope of the breakwater may be necessary to enhance its performance.

3.4. Rubble Mound Breakwater Utilizing Tetrapods (1:2 Slope) with a Geotube Core

The evaluation of the sloping-side breakwater model, designed with a 1:2 seaward-facing slope and geotube placement in the core layer, provides valuable insights into its structural stability and performance. As presented in Table 5, laboratory tests were conducted at water levels of 0.38 m, 0.54 m, 0.63 m, and 0.70 m, offering a comprehensive assessment of the breakwater's effectiveness in wave attenuation and resilience.

Table 5.
Statistical analysis of wave height at varying water levels for a rubble mound breakwater with tetrapods and geotube core at a 1:2.0 slope under varying water levels.

Water Level (m)	Wave Probe	Wave Height (m)	Wave Runup (m)	Wave Rundown (m)
0.70	1	0.132	Overtopping	
	2	0.139		
	3	0.089		
0.63	1	0.198	Overtopping	
	2	0.190		
	3	0.150		
0.54	1	0.125	0.433	0.008
	2	0.182		
	3			
0.38	1	0.135	0.140	0.008
	2	0.135		
	3			

The use of a 1:2 slope combined with geotube placement is expected to influence the breakwater's hydrodynamic response. The geotubes can enhance structural integrity by providing additional support to the core layer, which may result in improved resistance to wave forces and reduced wave height transmitted across the breakwater. Observations regarding wave transmission, overtopping, and any erosion or instability at the various water levels will be crucial for assessing the overall effectiveness of this design configuration.

Additionally, at a submerged water level of 0.70 m, the wave transmission coefficient is determined as follows:

$$K_t = \frac{0.087}{0.147} = 0.640$$

Since $K_t = 0.640$64% of the incoming wave energy is transmitted through the submerged rubble mound breakwater, while only 36% is dissipated or reflected. By modifying the slope from 1:1.5 to 1:2.0, the wave transmission coefficient significantly decreases from 0.897 to 0.640. The flatter slope (1:2.0) enhances wave breaking and energy dissipation before transmission, resulting in a 28.6% reduction in wave transmission (from 89.7% to 64.0%), thereby improving overall stability. Although $K_t = 0.640$ It is much lower than 0.897, meaning the breakwater is now more effective in reducing wave energy; a significant 64% of wave energy is still transmitted, potentially allowing considerable wave activity behind the structure.

A steeper slope (1:1.5) tends to cause wave overtopping and reflection, which can lead to armor displacement and structural instability. By transitioning to a gentler slope (1:2.0), the breakwater experiences less direct wave force, reducing damage risks. However, $K_t = 0.640$ Remains above the optimal range (0.3 – 0.5) for effective wave dissipation. Further modifications, such as adjusting the slope to 1:2.5 instead of 1:2.0, may help achieve better energy dissipation and reduce wave transmission to an optimal level.

3.5. Rubble Mound Breakwater Utilizing Tetrapods (1:2.5 Slope) with a Geotube Core

This section analyzes a sloping-side breakwater model with a 1:2.5 seaward-facing slope and the incorporation of geotubes within the core layer. The study aims to assess how slope modification and geotube integration influence the structural stability, wave dissipation, and overall performance of the breakwater. By introducing a gentler slope (1:2.5) compared to steeper alternatives, the design is expected to enhance wave energy dissipation while reducing wave reflection and overtopping risks. Additionally, the inclusion of geotubes within the core layer is intended to improve internal stability, enhance energy absorption, and optimize material efficiency.

Table 6 presents the statistical analysis of wave parameters recorded during testing, offering detailed insights into wave height, period, and transmission effects under different conditions. These findings provide a basis for evaluating the breakwater's effectiveness in reducing wave transmission and improving coastal protection.

Table 6.
Statistical analysis of wave height at varying water levels for a rubble mound breakwater with tetrapods and geotube core at a 1:2.5 slope under varying water levels.

Water Level (m)	Wave Probe	Wave Height (m)	Wave Runup (m)	Wave Rundown (m)
0.70	1	0.133	Overtopping	
	2	0.143		
	3	0.086		
0.63	1	0.151	0.220	0.137
	2	0.154		
	3	0.067		
0.54	1	0.112	0.490	0.115
	2	0.153		
	3	0.032		
0.38	1	0.161	0.140	0.065
	2	0.145		
	3			

Table 6 presents the statistical wave data collected during the experiments, including wave height and observed overtopping incidents at specified water levels. The wave transmission coefficient at a submerged water level of 0.70 m is determined as follows:

$$K_t = \frac{0.086}{0.143} = 0.601$$

These findings provide insights into how variations in slope and core materials influence the performance of sloping-side breakwaters, contributing to more resilient coastal protection designs. Understanding the interaction between wave dynamics and structural configurations is crucial for optimizing breakwater designs in response to environmental challenges.

Modifying the slope to 1:2.5 resulted in a significant reduction in wave height at the breakwater's face compared to the 1:2 slope, indicating enhanced wave energy dissipation due to the gentler gradient. This adjustment facilitated better wave interaction, improving overall stability. In this breakwater model, overtopping was observed at a water level of 0.70 m, corresponding to submerged conditions. While the structure demonstrated improved stability, it remains vulnerable to extreme conditions, highlighting the need for further design considerations for higher wave scenarios. The analysis suggests that a 1:2.5 slope enhances structural stability compared to a 1:2 slope with geotube placement, implying that a gentler slope can improve the breakwater's resilience against wave forces.

Table 7.
Wave height, runup, and rundown for sloping-side breakwaters with tetrapods and geotube placement in the core layer.

Slope	H_s (m)	Runup (m)	Rundown (m)	Runup–Rundown (m)
1:1.5	0.131	0.195	0.065	0.130
1:2.0	0.126	0.200	0.090	0.110
1:2.5	0.116	0.205	0.185	0.020

The data in Table 7 underscores the significant impact of slope design on wave interaction and energy dissipation in rubble mound breakwaters with tetrapods and geotube cores. The smallest wave height at the breakwater's face occurs at a slope of 1:2.5, indicating the highest wave energy dissipation. This aligns with the expectation that a more gradual slope reduces the direct impact of incoming waves. Runup and rundown serve as key indicators of wave energy transfer and structural interaction. The 1:1.5 slope exhibits the greatest runup, likely due to its steeper gradient promoting more vertical wave action and increasing wave energy climbing the structure. In contrast, the 1:2.5 slope demonstrates the highest attenuation of wave energy, effectively dissipating wave forces and reducing structural loads. These findings suggest that a 1:2.5 slope offers an optimal balance between wave energy dissipation and structural stability. Future analyses should incorporate additional metrics, such as stability coefficients, wave overtopping rates, and structural durability under varying wave conditions, to refine these conclusions further. Wave transmission at a water level of 0.70 m (submerged) is presented in Table 8. The lowest wave transmission coefficient is observed for structures with a 1:2.5 slope, indicating that the gentler gradient effectively reduces wave energy transmission beyond the breakwater. This finding further supports the 1:2.5 slope as the optimal design for maximizing energy dissipation.

Table 8.
Wave transmission coefficients of submerged rubble mound breakwaters with tetrapods and geotube core placement.

Slope	H_t (m)	H_i (m)	K_t
1:1.5	0.078	0.087	0.897
1:2.0	0.087	0.147	0.640
1:2.5	0.086	0.143	0.601

These findings confirm that a gentler slope (1:2.5) plays a crucial role in improving the stability and effectiveness of submerged rubble mound breakwaters. By enhancing energy absorption, this design helps to minimize both rundown and overtopping. The results indicate that implementing a 1:2.5 slope in future breakwater designs could improve resilience against wave forces while reducing environmental impacts.

Overall, this study highlights the significance of slope configuration in breakwater construction and its relevance to sustainable coastal management. Further research should investigate the influence of different wave conditions and sediment transport processes to enhance design recommendations for practical applications.

4. Conclusions

The findings indicate that the 1:2.5 slope configuration, combined with geotube placement in the core layer, delivers optimal performance in wave attenuation and structural stability. These results emphasize the critical role of slope design in enhancing the effectiveness of submerged rubble mound breakwaters and strengthening coastal defense strategies. Further studies should explore the practical implications of these findings for coastal management and their integration into sustainable engineering solutions. Observations of rundown and overtopping across various water levels provide key insights into the hydrodynamic performance of different breakwater configurations. The increasing rundown values suggest that a gentler slope (1:2.5), in combination with geotube placement in the core layer, enhances wave energy absorption and dissipation, thereby reducing the forces acting on the structure. While overtopping thresholds indicate potential failure points, the 1:2.5 slope exhibits lower overtopping rates compared to steeper alternatives, reinforcing its superior resilience. Furthermore, the lowest wave transmission coefficient is recorded for the 1:2.5 slope with geotube placement in the core layer, confirming its effectiveness in minimizing wave energy transmission beyond the rubble mound breakwater and validating its optimal design for energy dissipation.

These findings support the hypothesis that a 1:2.5 slope, when combined with geotube placement in the core layer, significantly enhances the stability and performance of submerged rubble mound breakwaters. By improving energy absorption, this design effectively reduces both rundown and overtopping. For future submerged rubble mound breakwater designs, adopting a 1:2.5 slope with geotube placement in the core layer could improve resilience against wave action while minimizing environmental impacts.

Overall, this analysis highlights the importance of slope design and geotube placement in submerged rubble mound breakwater construction and its implications for sustainable coastal management. Further research should examine the effects of varying wave conditions and sediment transport dynamics to refine design guidelines for real-world applications. While this study provides fundamental insights, future research should focus on field-based validation of laboratory findings to assess long-term performance and ecological impacts. Additionally, testing advanced materials and exploring diverse coastal environments could further optimize submerged rubble mound breakwater designs. Ultimately, this research contributes to the development of sustainable, resilient, and ecologically integrated coastal engineering solutions.

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