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EXPERIMENTAL STUDY ON WAVE ATTENUATION USING DIFFERENT ARMOUR UNITS AND SEA WALLS

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Abstract : Coastal protection structures are essential for mitigating wave-induced erosion and maintaining shoreline stability. This study investigates the hydraulic a of different sea wall geometries, namely stepped, sloped, and curved configurations, through controlled laboratory experiments conducted in a wave flume. The experiments were performed at a constant water depth of 20 cm, with incident wave heights of 0.5 cm, 1.0 cm, and 1.5 cm, generated under steady operating conditions. Measurements were recorded over a duration of 30 minutes at 5-minute intervals to capture the temporal variation in wave-structure interaction.

The performance of each configuration was evaluated in terms of reflected wave height (Hr) and scour depth development at the toe of the structure. The results demonstrate that wave reflection and scouring are strongly influenced by both incident wave height and structural geometry. The stepped sea wall exhibited superior hydraulic performance, characterized by reduced reflected wave heights and minimized scouring, attributed to enhanced energy dissipation through induced turbulence and successive wave breaking. In contrast, the sloped wall showed increased transmission and higher scour depth due to smoother flow conditions, while the curved wall provided moderate performance with improved overtopping control.

The findings indicate that energy dissipation mechanisms governed by structural geometry play a critical role in coastal protection efficiency. The study highlights the effectiveness of stepped configurations in reducing wave energy and bed erosion, offering valuable insights for the design of sustainable and resilient coastal defense systems.

IndexTerms - Wave Generation, Breakwater Design, Armour Units, Wave Dissipation, Coastal Engineering, Hydraulic Model Testing.

INTRODUCTION

Coastal regions are continuously subjected to dynamic hydrodynamic forces due to wave action, tides, and currents, which often result in shoreline erosion, structural instability, and loss of land. With increasing coastal development and climate-induced changes such as sea-level rise and extreme wave events, the need for efficient and sustainable coastal protection measures has become more critical. Among the various protective systems, sea walls are widely adopted as frontline defense structures designed to reduce wave impact and protect coastal infrastructure.

The hydraulic performance of sea walls depends significantly on their geometric configuration and interaction with incident waves. Conventional vertical walls tend to reflect a large portion of wave energy, leading to increased turbulence and potential scouring at the base. In contrast, modified geometries such as sloped, curved, and stepped sea walls are designed to either dissipate or redirect wave energy more effectively. In particular, stepped configurations promote progressive wave breaking and turbulence, thereby reducing the intensity of reflected and transmitted waves.

In addition to wave attenuation, scouring at the toe of the structure is a critical factor influencing the stability and longevity of coastal defence systems. Scour development is primarily governed by wave-induced velocities and turbulence near the seabed. Excessive scouring can undermine the foundation of the structure, leading to failure. Therefore, understanding the relationship between wave characteristics (height, velocity, duration) and scour behaviour is essential for optimizing design.

Several experimental and numerical studies have been conducted to evaluate wave-structure interaction; however, comparative analysis of different sea wall geometries under controlled conditions remains an area of ongoing research. Laboratory-scale wave flume studies provide a reliable approach to simulate and analyse these interactions in a controlled environment.

In this study, a systematic experimental investigation is carried out to assess the performance of stepped, sloped, and curved sea walls under varying wave heights (0.5 cm, 1.0 cm, and 1.5 cm). The experiments are conducted in a wave flume tank with observations recorded over time intervals to capture the transient behaviour of wave interaction. The key parameters evaluated include reflected wave height and scouring depth, which are critical indicators of hydraulic efficiency and structural stability.

The objective of this work is to identify the most effective sea wall configuration that minimizes wave energy and scouring, thereby contributing to the development of efficient and resilient coastal protection systems.

LITERATURE REVIEW

The interaction between waves and coastal protection structures has been extensively studied due to its significance in shoreline stability and infrastructure safety. The performance of sea walls and related structures is primarily governed by their ability to dissipate, reflect, and transmit wave energy, as well as their resistance to scour-induced instability.

Early experimental investigations by Hudson (1959) established fundamental relationships for the stability of rubble mound structures, emphasizing the role of armour units in dissipating wave energy. Subsequent studies by Van der Meer (1988) further refined stability criteria by incorporating wave height, permeability, and structural configuration, highlighting the importance of interlocking and porosity in reducing wave forces.

Research on sea wall geometry indicates that structural shape plays a crucial role in wave attenuation. Losada and Gimenez-Curto (1981) analysed wave interaction with sloped and rough surfaces, demonstrating that sloped structures reduce wave reflection but allow higher transmission. In contrast, vertical and curved walls tend to reflect a significant portion of incident wave energy, which may increase turbulence and local scour near the toe.

Stepped sea walls have gained attention due to their enhanced energy dissipation characteristics. Experimental studies have shown that stepped configurations promote progressive wave breaking, resulting in reduced reflected wave heights and improved hydraulic performance. The turbulence generated at each step contributes to energy loss, making such structures more effective compared to smooth-faced walls.

Scouring remains a critical aspect in the design of coastal structures. Studies by Sumer and Fredsøe (2002) investigated the mechanisms of scour around coastal structures, identifying wave-induced vortices and flow acceleration as primary causes of sediment removal. It has been observed that higher wave heights and velocities significantly increase scour depth, posing risks to structural stability.

Further research has emphasized the importance of combining structural design with material characteristics. Armour units such as Dolos, Tetrapods, and Accropode have been widely studied for their ability to enhance energy dissipation through geometric complexity and interlocking behaviour. Burcharth (1993) highlighted that properly designed armour layers can significantly reduce both wave reflection and scour potential.

Recent studies have also incorporated laboratory-scale experiments using wave flumes to simulate controlled conditions for wave-structure interaction. These studies provide valuable insights into the temporal variation of wave parameters and structural response under continuous wave action.

Despite extensive research, there remains a need for comparative experimental analysis of different sea wall geometries under varying wave conditions, particularly focusing on both wave attenuation and scouring behaviour. The present study addresses this gap by systematically evaluating stepped, sloped, and curved sea walls under controlled laboratory conditions.

4. METHODOLOGY

4.1 Experimental Setup

The experimental investigation was carried out in a rectangular wave flume tank with dimensions of approximately 6 ft length, 1.5 ft width, and 2 ft height. The flume was filled with water to a constant depth of 20 cm. A wave generation system driven by an electric motor (2800 rpm) was used to produce controlled wave conditions within the tank.

Three different sea wall configurations were fabricated and tested:

1. Stepped sea wall
2. Sloped sea wall
3. Curved sea wall

Each model was designed to fit within the flume dimensions and installed at one end of the tank to simulate wave-structure interaction.

4.2 Experimental Conditions

The experiments were conducted under varying incident wave heights:

1. 0.5 cm
2. 1.0 cm
3. 1.5 cm

Wave conditions were maintained as uniform as possible during each test. For every configuration and wave height, the system was allowed to stabilize before recording observations.
Each test was conducted for a total duration of 30 minutes, and measurements were taken at 5-minute intervals to capture the temporal variation in wave behaviour and scouring.

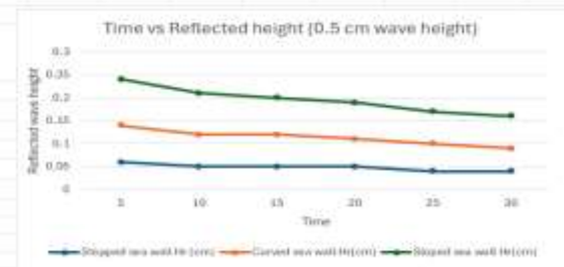
4.3 Measurement Parameters
The performance of the sea wall configurations was evaluated using the following parameters:
1. Reflected Wave Height (Hr):
Measured on the seaward side of the structure using a vertical scale. It represents the portion of wave energy reflected back.
2. Scour Depth (d_s):
Measured at the toe of the structure by observing the depth of erosion in the sand bed.
3. Incident Wave Height (Hi):
Controlled during wave generation and used as a reference parameter.

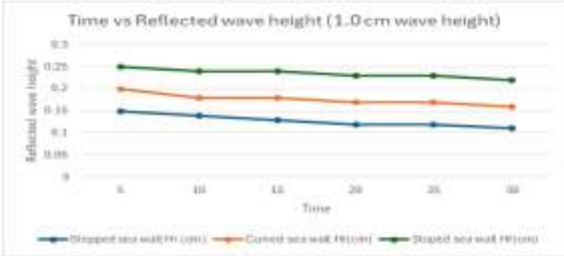
4.4 Measurement Procedure
For each experimental run, the following procedure was adopted:
1. The flume tank was filled to the required water depth.
2. The selected sea wall model was installed firmly at the designated position.
3. A sand layer was prepared at the base for scouring analysis.
4. Waves were generated at the desired height and allowed to stabilize.
5. Measurements of reflected wave height and scour depth were recorded at 5, 10, 15, 20, 25, and 30 minutes.
6. The experiment was repeated for all sea wall configurations and wave heights.
The collected data were analysed to evaluate the performance of each sea wall configuration. The reflection characteristics were assessed using the reflection coefficient (Kr):

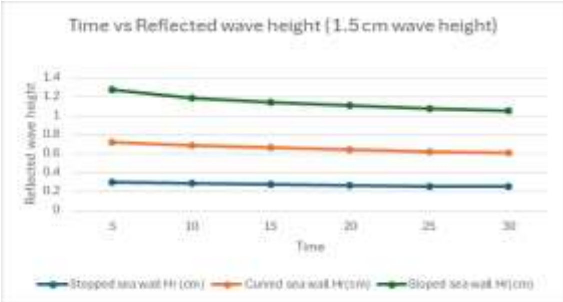
Kr = \frac{Hr}{Hi}
where:
Hr = Reflected wave height
Hi = Incident wave height
The variation of scour depth with time and wave height was also analysed to understand the erosion behaviour near the structure.

4.5 Graphs were plotted between:

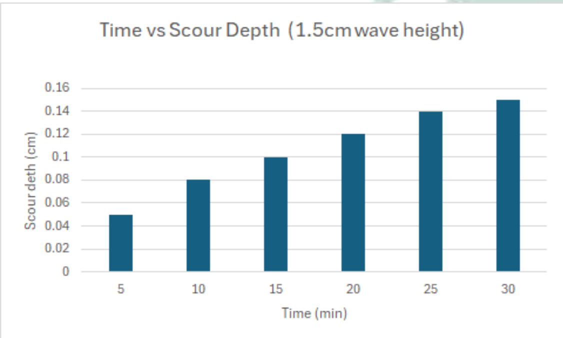
4.5.1. Time Vs Reflected Wave Height

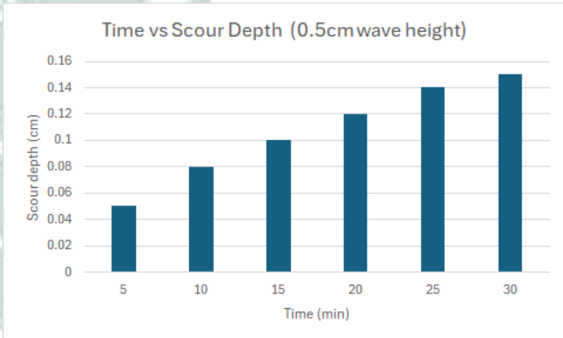


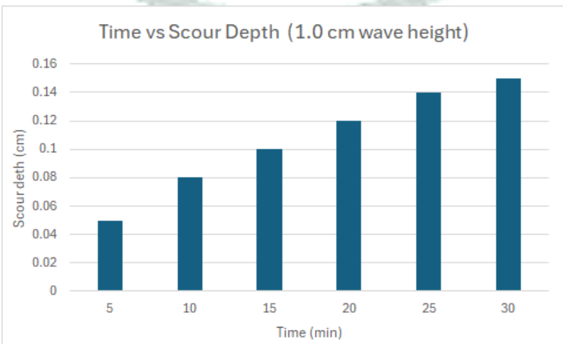




4.5.2. Time vs Scour Depth







4.6 Experimental Limitations

- The study was conducted at a laboratory scale, which may not fully represent field conditions.
- Wave generation was limited to regular waves.
- Measurement accuracy depends on manual observation.

4.7 Summary of Methodology

The methodology involves controlled wave generation, systematic observation, and comparative analysis of different sea wall geometries under varying wave conditions. The approach ensures reliable evaluation of both wave attenuation performance and scouring behaviour, providing a comprehensive understanding of coastal structure efficiency

5. RESULTS AND DISCUSSION

5.1 Effect of Sea Wall Geometry on Wave Reflection

The variation of reflected wave height (Hr) with time for different sea wall configurations under varying wave heights (0.5 cm, 1.0 cm, and 1.5 cm) was analyzed. The results indicate a consistent trend where Hr decreases slightly with time, suggesting stabilization of wave-structure interaction after initial turbulence.

Among the configurations, the stepped sea wall exhibited the lowest reflected wave heights across all wave conditions. This behavior can be attributed to the progressive wave breaking and turbulence induced by the stepped geometry, which enhances energy dissipation. In contrast, the sloped sea wall showed comparatively higher reflected wave heights, particularly at increased wave heights, due to smoother flow interaction and reduced turbulence. The curved sea wall demonstrated intermediate performance, reflecting a moderate portion of wave energy while effectively redirecting wave motion.

It was also observed that reflected wave height increases with incident wave height, indicating that higher energy waves result in greater reflection regardless of the structural configuration. However, the rate of increase was lower for the stepped wall, confirming its superior hydraulic efficiency.

5.2 Temporal Variation of Wave Reflection

The time-based analysis revealed that reflected wave height decreases marginally from 5 minutes to 30 minutes for all configurations. This trend suggests that the wave system attains a quasi-steady state after initial disturbances. The reduction in Hr over time is more pronounced in the stepped wall due to continuous energy dissipation at each step, whereas sloped and curved walls exhibit relatively smaller variations.

5.3 Scouring Behavior

Scour depth development at the toe of the structure was evaluated for all sea wall configurations under different wave heights. The results show that scour depth increases progressively with time, indicating continuous sediment removal due to wave action.

The magnitude of scouring was found to be strongly dependent on both wave height and structural geometry. Higher wave heights (1.5 cm) resulted in significantly greater scour depths compared to lower wave heights (0.5 cm), due to increased wave energy and bed shear stress.

Among the configurations, the sloped sea wall exhibited the highest scouring. This is attributed to the smooth flow acceleration along the slope, which increases velocity near the bed and enhances sediment transport. The curved sea wall showed moderate scouring behavior, while the stepped sea wall demonstrated the least scour depth.

The reduced scouring in the stepped configuration is primarily due to:

- Energy dissipation at each step
- Reduction in near-bed flow velocity
- Increased turbulence that disrupts sediment transport.

5.4 Influence of Wave Height

The influence of wave height on both reflection and scouring was significant. As the incident wave height increased from 0.5 cm to 1.5 cm:

Reflected wave height increased for all configurations

Scour depth increased substantial

Structural performance decreased under higher energy conditions

Despite these effects, the stepped sea wall maintained relatively better performance, indicating its suitability for higher wave conditions.

5.5 Comparative Performance Analysis

A comparative assessment of the three sea wall configurations highlights that:

- Stepped Sea Wall:

Demonstrates maximum energy dissipation, lowest reflected wave height, and minimum scouring.

- Curved Sea Wall:

Provides moderate performance with effective wave deflection and controlled overtopping.

- Sloped Sea Wall:

Shows higher reflection and maximum scouring, making it less effective under high-energy wave conditions.

These results emphasize that energy dissipation mechanisms are more effective than reflection-based approaches in coastal protection design.

5.6 Overall Discussion

The experimental results confirm that both wave characteristics (height and duration) and structural geometry play a crucial role in determining the hydraulic performance of sea walls. The stepped configuration consistently outperformed the other geometries by effectively reducing wave energy and minimizing scouring.

The findings also highlight the importance of time-based analysis, as it provides insights into the stability and long-term behavior of structures under continuous wave action. The gradual increase in scouring over time underscores the need for incorporating erosion-resistant design features in coastal structures.

Key Findings from Results

- Reflected wave height decreases slightly with time due to stabilization
- Scour depth increases continuously with time
- Higher wave heights lead to increased reflection and scouring
- Stepped sea wall shows superior performance in all conditions
- Structural geometry significantly influences wave attenuation and erosion.

6. CONCLUSION

This study presents an experimental investigation on the hydraulic performance of different sea wall geometries—stepped, sloped, and curved—under controlled wave conditions in a laboratory wave flume. The analysis was carried out for varying incident wave heights (0.5 cm, 1.0 cm, and 1.5 cm), with emphasis on key parameters such as reflected wave height and scour depth development. The results demonstrate that structural geometry plays a critical role in governing wave-structure interaction. Among the configurations tested, the stepped sea wall exhibited the most efficient performance, characterized by lower reflected wave heights and reduced scouring at the toe. This behavior is primarily attributed to enhanced energy dissipation through progressive wave breaking and turbulence induced by the stepped profile. In contrast, the sloped sea wall showed higher scouring due to increased flow velocity along the slope, while the curved sea wall provided moderate performance with improved wave deflection but limited energy dissipation.

The study also highlights the significant influence of wave height and duration on structural response. An increase in incident wave height resulted in higher reflected wave heights and greater scour depth for all configurations, indicating increased hydrodynamic loading. Furthermore, the time-based analysis revealed that wave reflection tends to stabilize over time, whereas scouring progresses continuously, emphasizing the importance of considering long-term effects in design.
Overall, the findings confirm that energy dissipation-based designs are more effective than reflection-based structures for coastal protection. The stepped sea wall, in particular, offers a favorable balance between wave attenuation and structural stability, making it a suitable option for mitigating erosion and enhancing the durability of coastal defense systems.
The outcomes of this study provide valuable insights for the design and optimization of sustainable coastal protection measures, although further research involving irregular waves and field-scale validation is recommended to extend the applicability of the results.

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