



INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Evaluating Breakwater Effectiveness In Mitigating Wave Action Along Chellanam Coastline

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Abstract: The Chellanam coastline in Kerala, India, faces numerous challenges due to wave action. Coastal erosion, triggered by wave activity, results in the loss of land, damaging homes and infrastructure. Flooding occurs when high waves inundate coastal areas, impacting livelihoods and properties. Beach degradation is another concern, as wave action destroys beach habitats, affecting marine biodiversity. The consequences of wave action also extend to displacement of families, loss of livelihoods in the fishing and tourism industries, and damage to infrastructure such as roads, bridges, and buildings. This project investigates the challenges posed by wave action and assesses the effectiveness of breakwater construction in mitigating these issues. The objectives of the project include investigating coastal dynamics and coastal erosion, evaluating the design and of breakwaters, and analysing their impact on wave attenuation and shoreline protection. Through desk studies, wave modelling using MIKE 21 and analysis of coastal dynamics, the project identifies key factors influencing wave behaviour and assesses the effectiveness of breakwaters in reducing wave energy. The expected outcomes include identification of critical factors influencing shoreline dynamics, evaluation of breakwater effectiveness, and recommendations for optimal breakwater.

The expected impact includes improved coastal protection and management strategies, enhanced resilience of coastal communities and infrastructure. By addressing these critical issues, this project provides valuable insights into mitigating wave action and protecting Chellanam coastline.

Keywords: Coastal erosion, Shoreline dynamics, Wave modelling, Breakwaters, wave attenuation.

- **Introduction**

Chellanam, a coastal village in Kerala's Ernakulam district, faces significant challenges from wave-driven erosion, flooding, and saltwater intrusion. Its 17 km-long shoreline, with a mixed sand and mud composition and a southwest orientation, is highly exposed to the Arabian Sea's wave energy. The low-lying elevation of the region increases its vulnerability to coastal hazards, resulting in land loss, infrastructure damage, and freshwater contamination. These environmental issues also degrade the beach, impacting marine biodiversity and the livelihoods of local communities that rely on fishing, tourism, and agriculture. Fishing remains a primary source of income, while tourism holds growth potential. Additionally, crops like coconut and rice are cultivated in the coastal plains.

To address these coastal vulnerabilities, various protection measures are essential, with breakwaters being one of the most effective solutions. Breakwaters are engineered structures designed to shield coastlines by absorbing or deflecting wave energy. They are generally constructed parallel to the shoreline, extending into the sea to reduce wave impact. Different types of breakwaters, such as rubble mound, vertical, and composite structures, offer distinct advantages depending on factors like wave characteristics, water depth, and coastal geology. By minimizing wave energy, breakwaters protect coastal infrastructure, properties, and ecosystems.

This project aims to investigate the challenges posed by wave action in Chellanam and assess the effectiveness of breakwater construction in mitigating these issues. Key objectives include understanding coastal dynamics, evaluating coastal erosion patterns, analyzing breakwater design, and assessing their impact on wave attenuation and shoreline protection. The study employs desk research, wave modeling using MIKE 21, and a comprehensive analysis of coastal dynamics to identify critical factors influencing wave behavior and shoreline changes.

The expected outcomes of this project include the identification of significant factors affecting shoreline dynamics, a detailed evaluation of breakwater performance, and recommendations for optimizing breakwater design. The insights gained will contribute to the development of effective coastal management strategies, enhancing the resilience of Chellanam's coastline against erosion and flooding while safeguarding local communities and ecosystems.

- **AREA OF STUDY**

Chellanam is a coastal village located in the Ernakulam district of Kerala, India, at $(9^{\circ}48'26''N\ 76^{\circ}16'39'E)$. It is positioned along the Arabian Sea to the west and bordered by the expansive Vembanad Lake backwaters to the east, creating a unique geography that blends marine and inland aquatic ecosystems. The terrain of Chellanam primarily consists of sandy coastal plains, interspersed with mangroves and intertidal zones.

The area features narrow stretches of land that transition from beaches and fishing harbors to lush, waterlogged regions connected to Kerala's intricate backwater network. This geographical setup plays a crucial role in the village's economy and lifestyle, with fishing being the dominant livelihood. The region's natural features include sandy shores, which are susceptible to erosion, and low-lying terrains that face challenges from frequent flooding during monsoons and high tides.

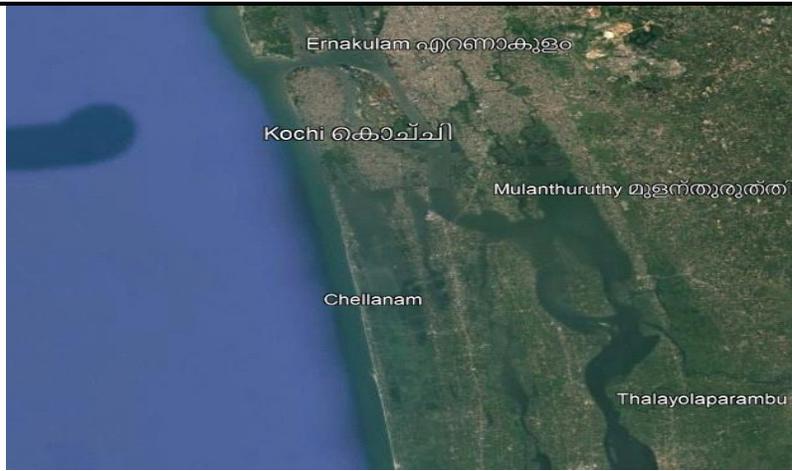
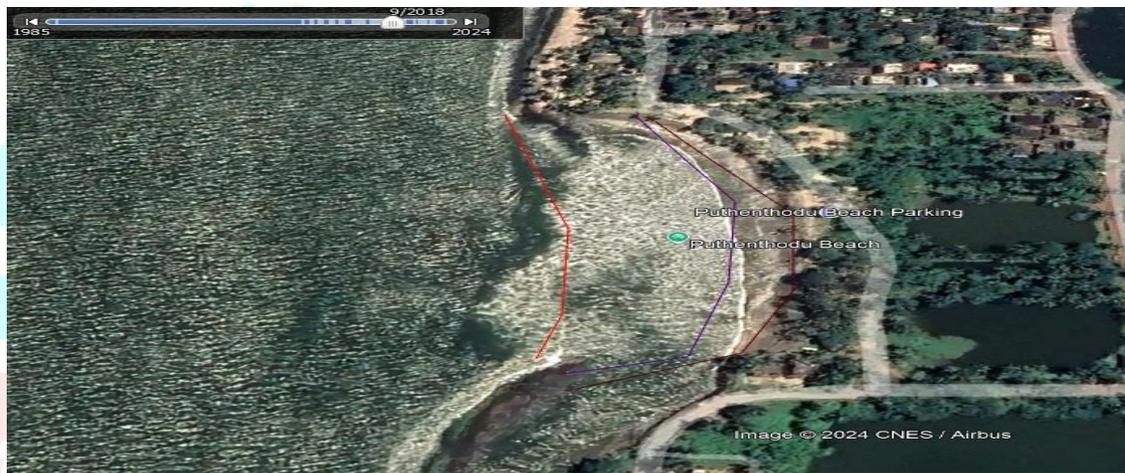


Figure 1. Map of Chellanam

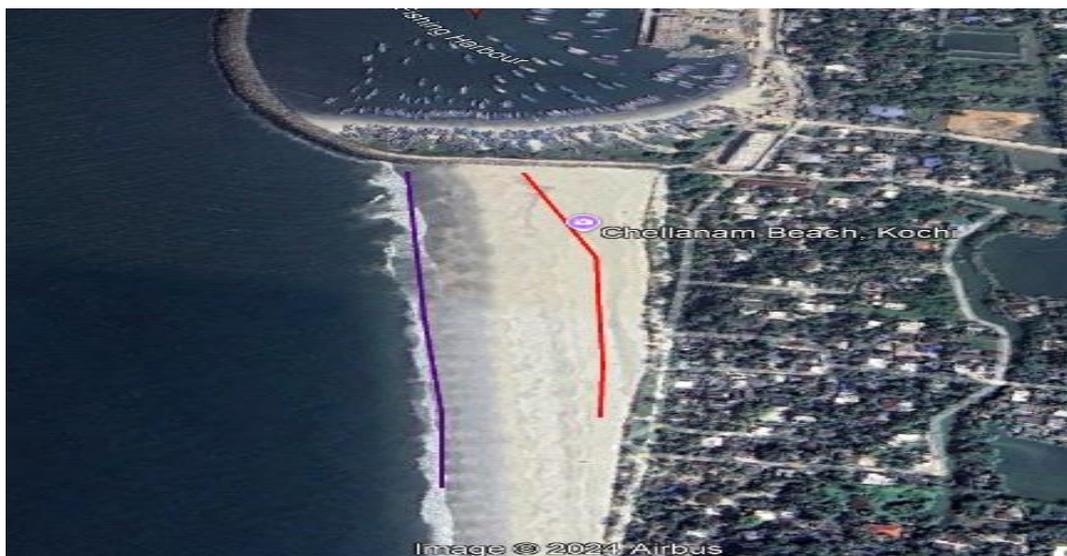
ANALYSIS USING SATELITE PUTHENTHODU BEACH



Analysis of satellite images revealed the significant impact of Cyclone Ockhi on Puthenthodu Beach in 2017. The beach's shoreline retreated by 48.74 meters due to intensified wave action and storm surges, demonstrating its vulnerability to extreme weather events. The cyclone's destruction compromised the beach's natural protective barrier, leaving it exposed to further erosion. In 2018, the situation worsened as severe floods caused an additional 68.37-meter shoreline retreat. The damaged seawall from Ockhi failed to protect the coastline, resulting in accelerated erosion. These consecutive disasters highlight the cascading impacts on coastal infrastructure and ecosystems, emphasizing the urgent need for reinforced coastal defenses.

By 2023, the shoreline had receded by a total of 39.02 meters from its 2012 position, reflecting the long-term effects of these extreme events. While minor recovery was observed, the cumulative impact of Cyclone Ockhi and the 2018 floods weakened the beach's resilience. This 12-year analysis underscores the susceptibility of Kerala's coast to climate-driven events and the necessity for proactive coastal management. Implementing sustainable shoreline protection measures, maintaining seawalls, and conducting ongoing monitoring are essential to mitigate further erosion, safeguard infrastructure, and preserve the beach's ecological and economic importance.

• CHELLANAM FISHING HARBOUR



Satellite image analysis highlights the significant impact of Chellanam Fishing Harbour on sediment transport dynamics. Before construction began in 2012, natural longshore currents ensured the steady movement of sediment from the southern to the northern side. However, the harbour's presence has disrupted this process, leading to sediment accumulation on the southern side. The sediment deposition increased from 62.79 meters to 120.25 meters, indicating the harbour's role in trapping sediment and altering the coastal environment.

This disruption has caused severe consequences, including reduced sediment supply to the northern side, resulting in increased erosion. On the southern side, excessive sedimentation threatens harbour operations and nearby ecosystems. Additionally, the altered coastal morphology may impact local hydrodynamics and water quality, while the disruption of natural beach nourishment further accelerates erosion. These findings underscore the need for adaptive management strategies like dredging or artificial beach nourishment to mitigate negative impacts, ensure the harbour's sustainability, and protect the surrounding coastal environment.

Wave Height

Wave height is typically measured from the wave crest to the trough, often referenced to Mean Sea Level (MSL) or Chart Datum to account for tidal variations. Significant Wave Height (H_s) is commonly used in marine engineering, representing the average height of the highest one-third of waves. The data shows that from January to April and in October and December, most waves are around 1 meter, indicating calmer seas. During May to September, wave heights increase, with frequent waves of 2 meters and occasional peaks up to 4.5 meters, particularly during the monsoon season.

Months	Most frequent wave height	Maximum wave height
January	1	3
February	1	4.5
March	1	4.5
April	1	4
May	1.5	4.5
June	2	4.5
July	2	4.5
August	2	4.5
September	2	4.5
October	1	4.5
November	1.5	4
December	1	4

Wave Direction

Wave direction, measured relative to true north on a 360-degree scale, indicates seasonal variations driven by wind and currents. From January to February, waves primarily come from the north-northwest (340°), shifting to south-southeast (150°) in March and April. From May to October, a steady westerly direction (270°) dominates due to the Southwest Monsoon. In November, it shifts slightly to the west-southwest (240°), and by December, waves predominantly originate from the south (180°).

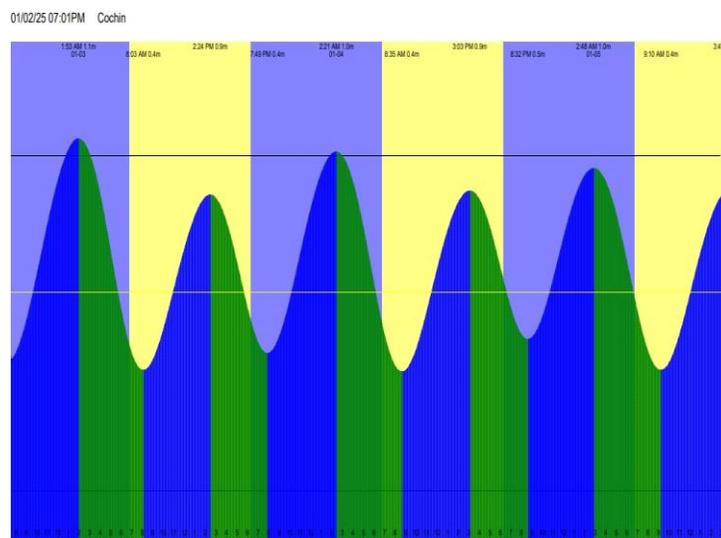
Months	Most dominant wave direction
January	340
February	340
March	150
April	150
May	270
June	270
July	270
August	270
September	270
October	270
November	240
December	180

Wave Frequency

Wave frequency significantly impacts coastal dynamics. In Chellanam, Kerala, the highest wave frequencies occur during the Southwest Monsoon (June to September), peaking at 4.878% in June. This period experiences stronger winds and rougher seas. In contrast, the lowest wave frequencies are recorded in January at 0.173%, reflecting calm conditions. April and May show moderate increases in wave frequency as pre-monsoon winds intensify.

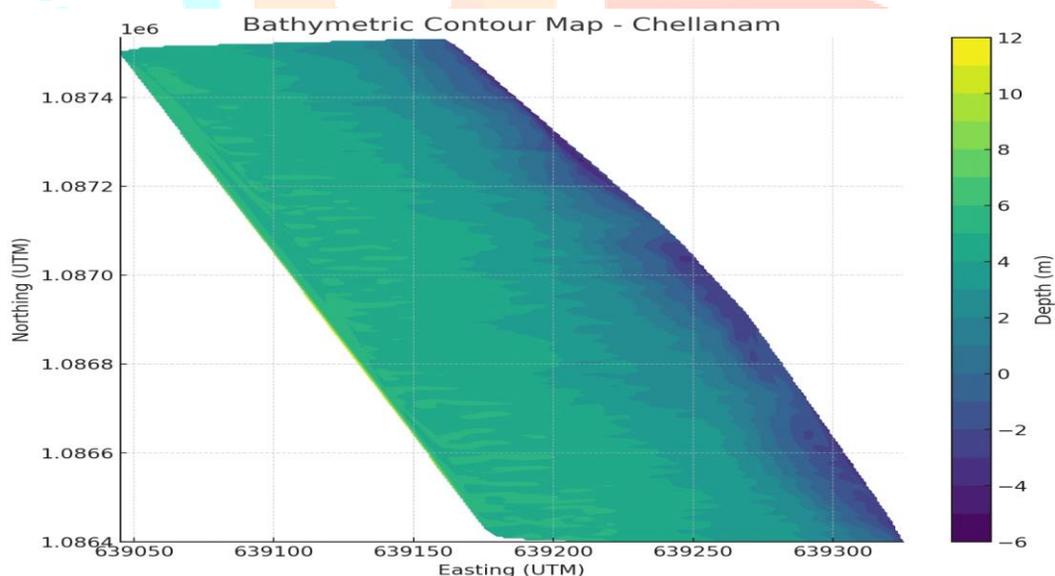
Months	Highest Wave frequency	Lowest wave frequency
January	1.9031	0.173
February	2.6971	0.2075
March	2.5	0.2083
April	2.985	0.2488
May	3.1835	0.1873
June	4.878	0.1626
July	4.7706	0.1835
August	2.6646	0.1567
September	2.8529	0.1502
October	2.2913	0.1637
November	2.8333	0.1667
December	2.109	0.1757

Tide



Tides in Cochin follow a semi-diurnal pattern, experiencing two high and two low tides daily. On January 2, 2025, the first high tide at 1.53 AM reached 1.1 meters, while the second high tide at 2.24 PM measured 0.9 meters. The tidal range varied between 0.6 to 0.7 meters, primarily influenced by the gravitational pull of the Moon and Sun.

Bathymetry



The image is a bathymetric contour map of the Chellanam coastline, illustrating the underwater depth variations in the region. Bathymetry involves mapping the seabed to understand its shape and depth changes. This map provides valuable insights into the underwater topography, which is essential for coastal management, navigation, and environmental studies. The map uses a color gradient to represent depth variations, with a scale on the right indicating depth values in meters. The color gradient ranges from dark blue and purple, representing deeper areas to green and yellow, indicating shallower regions. The seabed near the coast appears shallower, while it deepens as one moves offshore. These variations in depth can influence ocean currents, sediment transport, and wave behavior, which are crucial factors in coastal erosion and marine ecosystem studies. The axes of the map are labeled with Easting (UTM) and Northing (UTM) coordinates, which help pinpoint the exact location of the surveyed area using the Universal Transverse Mercator (UTM) coordinate system. This ensures that the data can be used for accurate mapping, navigation, and further research. The bathymetric information displayed in the image is particularly useful for planning marine infrastructure, such as harbors and breakwaters, and for studying how tides and waves interact with the seabed.

Statistical Analysis

Pre-Monsoon: During January to April, wave heights of 1 to 2 meters are most frequent, persisting for approximately 350 hours. Larger waves above 3 meters are rare.

Monsoon: From May to August, wave activity increases, with 1.5 to 2-meter waves occurring for around 550 hours. Higher waves above 3 meters appear occasionally due to stronger winds.

Post-Monsoon: From September to December, waves of 1 to 2 meters dominate for 450 to 500 hours. Waves above 3 meters are uncommon, except for occasional spikes.

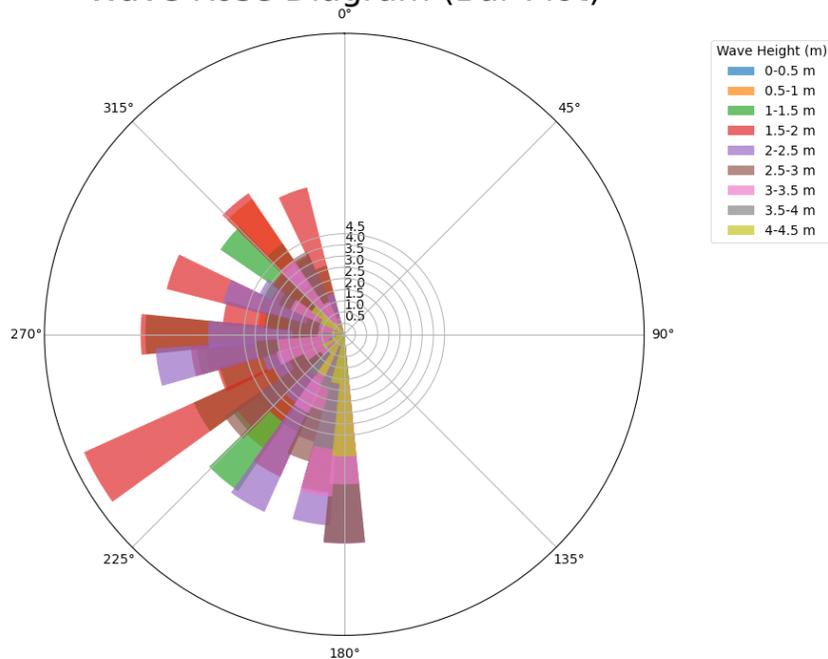
Maximum and Significant Wave Height

Maximum wave heights (Hmax) remain consistent at 3.51 meters from February to October, with slightly lower values of 3.12 meters in April, November, and December. Significant wave heights (Hs) follow a similar pattern, peaking at 1.95 meters during the monsoon season and reducing to 1.3 meters in January.

Months	Hmax	Significant height (Hs)
January	2.34	1.3
February	3.51	1.95
March	3.51	1.95
April	3.12	1.733
May	3.51	1.95
June	3.51	1.95
July	3.51	1.95
August	3.51	1.95
September	3.51	1.95
October	3.51	1.95
November	3.12	1.733
December	3.12	1.733

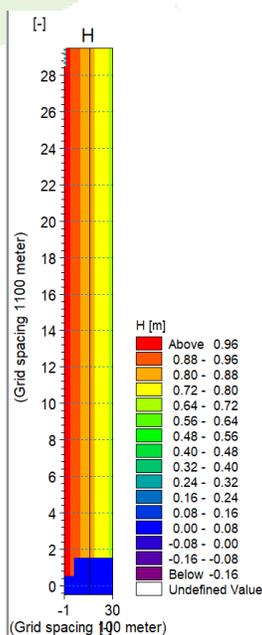
Wave Rose Diagram

Wave Rose Diagram (Bar Plot)



The wave rose diagram visually represents wave height and direction using polar coordinates. Dominant wave directions in Chellanam are primarily from the southwest (225°) and west-northwest (280°), exhibiting higher wave heights and frequent occurrences. Shorter bars in other directions signify less frequent and lower waves. This analysis aids in designing coastal infrastructure by understanding wave behavior, ensuring structures are resilient to seasonal wave conditions.

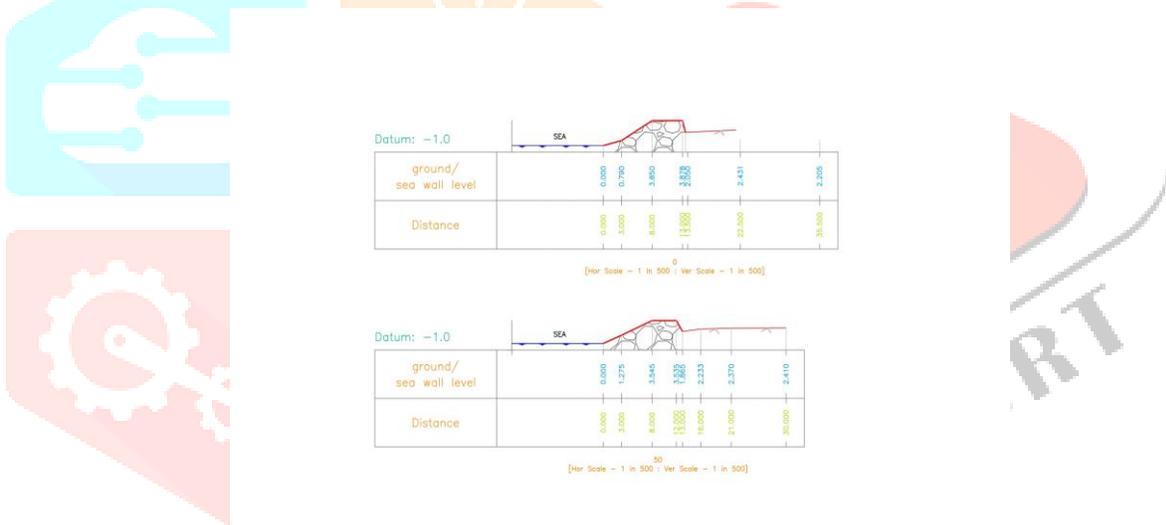
Wave Model



The graph, generated using MIKE 21, illustrates wave height transformation as waves propagate from deep water towards the Chellanam coastline, with a color gradient representing wave heights. In deep water, waves retain their energy with minimal dissipation, but as they enter shallower regions, interactions with the seabed increase, causing energy loss through bottom friction, shoaling, and breaking. Wave breaking occurs when the wave base slows due to seabed friction while the crest maintains speed, leading to instability and energy conversion into turbulence and heat. Seabed topography significantly influences this process, with gentle slopes causing gradual shoaling and energy dissipation, while steep slopes lead to abrupt breaking. The simulated wave height reduction suggests a moderate to steep slope along the Chellanam coastline, providing insights for coastal management and infrastructure planning.

Root Cause Analysis

When designing breakwaters for Chellanam, opting for a gradual slope is a more effective choice due to its superior ability to dissipate wave energy. Unlike steeper slopes that reflect more wave energy, a gradual incline minimizes the impact on the structure, reducing the risk of damage and lowering maintenance costs. Additionally, gradual slopes contribute to coastal protection by decreasing erosion along the shoreline. The importance of selecting an appropriate slope is underscored by the region's dynamic wave climate and bathymetric characteristics. In the past, steeper slopes used in breakwaters at Chellanam proved less effective, leading to greater structural stress and a higher likelihood of failure. A gradual slope, however, enhances wave energy dissipation, making the breakwater more resilient to harsh wave conditions. Careful consideration of the slope ensures better stability and longevity for the structure, particularly in areas prone to extreme weather events.



Moreover, data analysis suggests that the required armour unit weight for breakwaters along the Chellanam coastline is approximately 766.34 kg. Despite this, historical records and field observations reveal that the old sea walls were constructed using significantly lighter stones, contributing to their instability and eventual collapse under strong wave action. Another key issue is the potential underestimation of wave energy, as the region often experiences higher-than-expected wave forces. Additionally, wave reflection caused by improper slope selection can exacerbate erosion and undermine the structure’s foundation. The choice of materials is equally crucial; armour stones must possess sufficient density and interlocking capability to resist displacement. Without proper design adjustments, even the improved breakwaters may fall short of withstanding the local wave conditions. Therefore, a comprehensive reassessment of slope design, wave energy assumptions, and material selection is essential to ensure the long-term stability and effectiveness of Chellanam’s coastal protection structures.

	Depth	Tide	Surge	Depth	Hmax	Hs	H^3	Wr	Ws	KD	Sr	CotANGL	Armour	Armor (kg)
South Chellanam	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34
Company pady	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34
Kandakkadavu	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34
Kannamaly	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34
Cheriyakadavu	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34
Saudi	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34
Fort Kochi	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	1.00	2.59	1.50	0.7663	766.34

CORRECTIVE ACTION PLAN

To ensure long-term protection against wave action in Chellanam, the following improvements should be considered:

- Increase the Weight of Armour Units – Given the high wave energy in the region, revising the design to use heavier armour units (well above 766 kg) should be explored. Using concrete tetrapods or geotextile bags filled with heavy material may enhance stability.
- Optimized Breakwater Slope – A more gradual slope will help dissipate wave energy more effectively and reduce stress on the structure. The design should consider a slope that maximizes stability while minimizing erosion.
- Use of Multiple Layers – A multi-layered structure with a core, secondary, and primary armour layer will improve resilience. Larger, more stable rocks should be used in the outer layer.
- Regular Monitoring and Maintenance – Continuous assessment of wave impact, settlement, and displacement of armour units will help identify vulnerabilities

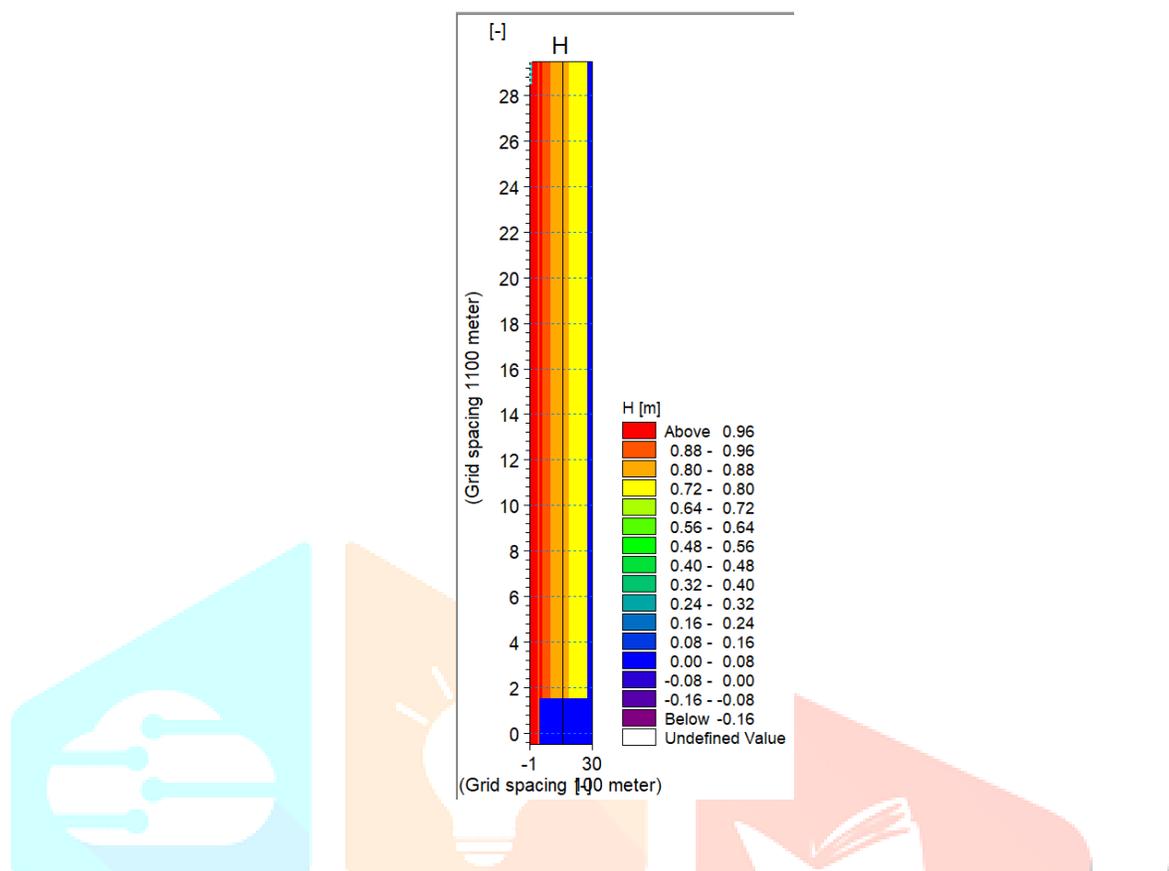
DESIGNING MOST SUITABLE ARMOUR UNIT USING HUDSON FORMULA

Selecting a suitable armour unit is crucial to mitigate wave energy and protect the shoreline. Among the available options, Dolos stands out due to its exceptional stability and energy dissipation capabilities, with the highest KD values (15.8 for breaking waves and 31.8 for non-breaking waves) and 63% porosity. These characteristics make Dolos ideal for high-energy wave environments like Chellanam. However, Tetrapod has emerged as a practical alternative due to its relatively high KD values (7.0 and 8.0) and 50% porosity. It offers good stability and energy dissipation while being cost-effective and widely available. Although the Modified Cube, with moderate KD values (6.5 and 7.5) and 47% porosity, is a potential option, its performance is comparatively lower. Ultimately, Tetrapod's balance of performance, affordability, and availability makes it a suitable choice for Chellanam's coastal protection.

	Depth	Tide	Surge	Depth	Hmax	Hs	H^3	Wr	Ws	KD	Sr	CotANGL	Armour	Armor (kg)
South Chellanam	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48
Company pady	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48
Kandakkadavu	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48
Kannamaly	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48
Cheriyakadavu	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48
Saudi	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48
Fort Kochi	-1	1	0.5	2.5	1.95	1.05	1.15	2.65	1.03	7.00	2.59	1.50	0.1095	109.48

The advantages of Tetrapods are evident in their higher stability coefficient (KD of 7.00), which surpasses conventional rock armour. Their interlocking design enhances overall stability, minimizing displacement and ensuring resilience against wave forces. This structural integrity is particularly beneficial in high-energy environments like Chellanam. Additionally, Tetrapods allow for significant weight reduction in coastal protection projects. While the calculated armour weight for rock armour was around 766.34 kg, the required weight using Tetrapods is reduced to just 109.48 kg. This reduction makes them a cost-effective and practical solution. Furthermore, the Tetrapod's unique shape facilitates water flow around the structure, reducing wave

impact energy and minimizing scouring at its base. These factors contribute to Tetrapods being a reliable and long-lasting solution for coastal defense in Chellanam.



The effectiveness of Tetrapods in wave attenuation is further demonstrated through the wave height reduction graph. The color scale indicates wave heights, with red and orange representing higher waves (above 0.96 m) and blue and purple denoting lower or negative wave heights (below 0.16 m). As waves move from offshore to the shoreline, their height decreases due to energy dissipation, refraction, and shoaling. A sharp reduction in wave height is observed upon reaching the Tetrapod-covered coastline, confirming their role in effectively dissipating wave energy. The irregular shape and porosity of Tetrapods disrupt wave momentum, increase turbulence and friction, and reduce wave reflection. This minimizes coastal damage and scouring, protecting infrastructure and stabilizing the shoreline. The results validate Tetrapods as a highly efficient coastal protection measure, ensuring long-term resilience against wave-induced forces.

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