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A Multi-Physics Climate Resilience Model Along the Coast of Perumathura Region

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ABSTRACT: Coastal erosion is the wearing away and landward retreat of shorelines caused by waves, tides, currents, and wind-driven water, which remove sediment and rocks. Coastal erosion in Kerala is a severe, escalating crisis with roughly 63% of its 590 km coastline undergoing erosion. Coastal regions like Perumathura have adapted traditional tetrapod seawalls for protection against tidal surges. However, these structures have proven increasingly inefficient due to significant scouring at the base and subsequent soil erosion, which destabilizes the barrier and compromises hinterland safety. This study proposes an innovative self-elevating sea wall—a buoyant, passive-response system that elevates automatically using hydrostatic pressure as a superior alternative to static tetrapods. It has a curved profile to optimize wave reflection and prevent erosion. This reflective action reduces direct impact on the coast and improves overall protection. The research begins with a geotechnical site investigation at Perumathura to determine the particle size distribution and relative density of the local soil. The simulation aims to model the dynamic response of the self-elevating wall and quantify the potential reduction in scouring and erosion compared to conventional structures. The project involves the future development of a scaled physical prototype to validate numerical findings. This model will feature a self-elevating mechanism to demonstrate the real-time functionality of the seawall under simulated hydraulic pressure. Beyond technical efficiency, this study holds significant social relevance by addressing the recurring threat of coastal displacement and livelihood loss in Perumathura. By proposing this responsive defense system, the project aims to enhance public safety while preserving the natural beach landscape and local tourism, which are currently hindered by inefficient traditional seawalls.

INTRODUCTION

Coastal regions are among the most vital and dynamic environments on the planet, supporting a significant portion of the global population and contributing substantially to economic, social, and ecological activities. India, with its extensive coastline of 7,516 km comprising 2,700 km on the eastern coast, 3,000 km on the western coast, and 1,800 km along its islands is particularly reliant on these maritime zones. Within this national context, the state of Kerala occupies a critical position with a coastline stretching 593 km and a width of approximately 67 km. However, these areas are constantly exposed to natural hazards such as coastal erosion, flooding, and powerful monsoon surges.

Much of Kerala's shoreline is increasingly vulnerable to environmental shifts. This vulnerability is acutely observed along the Perumathura coast (Latitude: 8.6231°N, Longitude: 76.7967°E) near Thiruvananthapuram. This region faces persistent erosion and structural damage despite the widespread adoption of traditional hard engineering methods. Current coastal protection strategies generally fall into two categories. Hard engineering solutions like traditional seawalls, groynes, and breakwaters are designed to provide a physical barrier against wave impact. Soft engineering natural methods such as beach nourishment and mangrove plantations aimed at ecological restoration.

While these structures provide immediate defense, they are often rigid and static. In regions like Perumathura, conventional seawalls often fail during harsh waves and coastal flooding, as they cannot withstand the height and energy of extreme tides. Designed based on historical data, they lack the adaptability required to face the rapidly changing climate, rising sea levels, and increased storm intensity. There is an urgent need for innovative engineering solutions that move beyond static barriers. This project explores the development of a Multi-physics Climate Resilience Model focused on a curved self-elevating seawall.

1.2 Multi Physics Climate Resiliance Model

In recent years, the growing complexity of climate-related coastal hazards has encouraged the adoption of multi-physics simulation frameworks in coastal engineering. Traditional single-domain analyses, which treat hydrodynamic, structural, or geotechnical behaviors independently, are often inadequate to capture the true response of coastal protection systems under real environmental conditions. A multiphysics model integrates these different physical processes such as fluid dynamics, structural mechanics, sediment transport, and energy interactions into a unified analytical platform. This integrated approach enables engineers to study

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the coupled effects of waves, currents, soil behavior, and structural deformation simultaneously, thereby providing a more realistic assessment of performance and resilience.

This concept helps to predict the seawall's adaptive response under various climate-induced loading conditions. The concept of climate resilience in engineering models emphasizes adaptability, robustness, and recovery capability. A Climate Resilience Model not only assesses structural stability but also simulates how a system responds to projected climate scenarios such as sea-level rise, higher wave energy, and temperature variation. The integration of multiphysics modelling with resilience principles allows engineers to evaluate not just how a structure performs today, but how it will behave decades into the future under changing climatic conditions. The Multiphysics Climate Resilience Model is applied to analyze and optimize the performance of a Self-Elevating Seawall. The model couples hydrodynamic forces (wave and surge pressure) with structural mechanics (stress, deformation, and elevation mechanism) and, where relevant, energy systems if the seawall is designed to be self-powered.

SELF ELEVATING SEAWALL

A self-elevating seawall is a movable coastal defense structure designed to protect the cost from erosion, tsunamis, storm surges and rising sea levels. A self-elevating seawall acts as an effective low-pass filter system. They are hard engineering shore-based structures that protect the coast. They can be created using materials such as Reinforced Cement Concrete (RCC), Steel reinforcement bars, coarse aggregates, fine aggregates, and cement mortar. RCC is commonly used because it provides high compressive strength and durability against strong wave forces and coastal erosion. Steel reinforcement can be added to increase the tensile strength of the structure and prevent cracking. Sometimes rock armor or concrete blocks can be used to reduce the impact on the seawall. In this particular study, hydrogel mechanisms are also incorporated.

Hydrogels are polymer-based materials capable of absorbing and retaining large quantities of water relative to their own mass due to their three-dimensional structure. Due to this structure, they can swell when they come in contact with water. The absorbed water is stored inside the gel structure without dissolving the material.

There are many ways by which we can make self-elevating seawalls some of the common ones are:

Vertical Type Seawalls

Vertical seawalls are the simplest and most space-efficient and one of the first types of seawalls built. The vertical vinyl walls protect the land from erosion overtime. They are highly space efficient and commonly used when land availability is less. They have straight panels that extend vertically and act as a barrier. They are relatively easy to construct. However, they reflect large portions of the waves back to the sea which causes scouring at the base of the wall and increases structural stress.

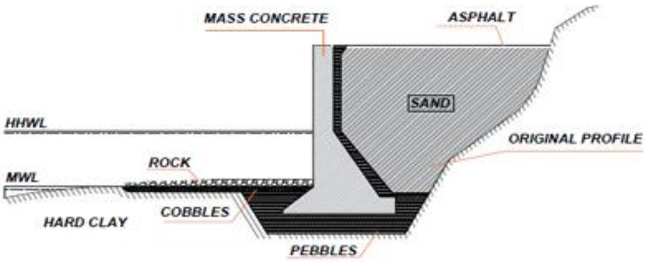

Fig.1.1 Vertical type seawall

Curved (Concave or Convex) Seawalls

These types of seawalls redirect the waves upwards and back towards the ocean, thereby decreasing the force exerted on the base of the structure. Their shape helps in spreading the waves of energy over wider area thereby reducing the impact. Due to these advantages, curved seawalls are constructed in coastal regions that experience strong wave activity.

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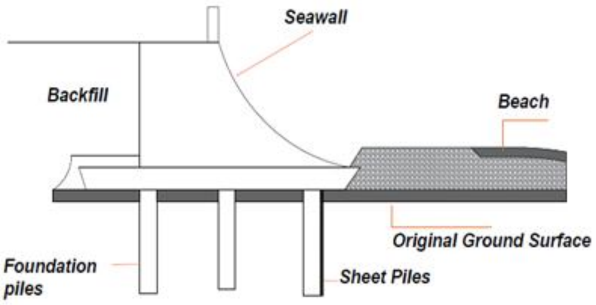


Fig.1.2 Curved type seawall

Stepped Seawalls

It has multiple levels arranged in ~~a~~ step~~-~~like pattern. They break the moment of the incoming waves and reduce their energy gradually through turbulence and wave breaking. As the wave energy decreases~~,~~ the force on the walls also ~~decreases.~~ This design reduces wave impact and wave splash~~,~~ thereby making pedestrian areas safer. These types of seawalls can be used with mechanisms such as rotational, telescopic~~,~~ and buoyancy-based lifting. But their construction is more complex and expensive compared to other types. Each shape can be integrated into a self-elevating mechanism depending on the operational requirement—such as rotational, telescopic, or buoyancy-based elevation systems. The choice of shape ultimately depends on coastal topography, expected wave conditions, and the level of adaptability required for climate resilience.

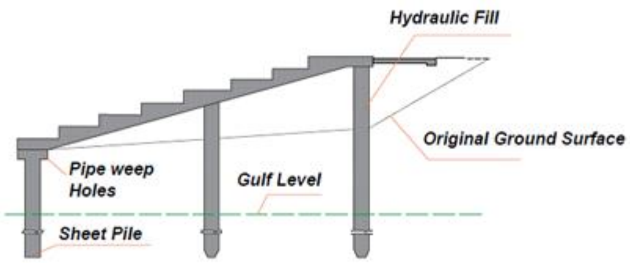
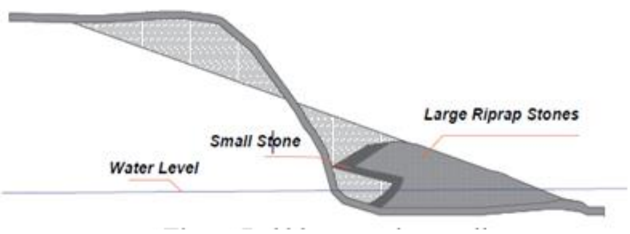


Fig.1.3 Stepped seawall

Rubble mound Seawalls

These kinds of seawalls were cheaper and easier for construction and designing and could protect the energetic action of waves substantially. Mound form of seawalls built by using rip rap or revetments, and usually in less requiring applications used, where erosion process with low energy occurs. The least rate of exposure means the lower bulkheads' cost and revetments' sandbag. These are serving to shores' armour and reduce erosion, also can either be waterproof or porous form, allowing the filtering of water after the dissipation of the waves' power.



Multiphysics modelling is used to analyze the interaction between buoyancy, hydrostatic pressure, material stiffness, and soil resistance beneath self-elevating seawall. This model combines structural behaviour with water flow equations to simulate how the wall moves during extreme events. The inclusion of sediment moment and erosion factors help to ensure the seawall does not harm the natural shape of the coast. Most systems work using natural water pressure or buoyancy, so they need very little external energy. Overall, self-elevating seawalls are a sustainable and climate resilient alternative to traditional fixed seawalls.

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METHODOLOGY

Geotechnical Analysis and Soil Characteristics

Geotechnical analysis is carried out to understand the physical and mechanical properties of the soil at the coastal site. This stage includes field investigations and laboratory tests to determine important soil parameters such as particle size distribution, moisture content, density, shear strength, permeability, and bearing capacity of the soil. These properties help us understand how the soil will behave under loads from the seawall structure and wave forces. The results help identify soil layers, groundwater conditions, and stability of the foundation. Understanding soil characteristics is essential for designing a stable and safe structure because weak or loose soil can cause settlement or failure of the seawall. The information obtained in this step forms the basis for selecting suitable foundation types and construction methods. Proper geotechnical analysis ensures that the seawall design can safely withstand environmental loads and long-term coastal conditions.

Data Analysis

Data analysis involves examining and interpreting all the information collected from field investigations, laboratory tests, and previous studies. In coastal engineering projects, this includes analysing parameters such as wave height, tidal variations, storm surge levels, shoreline changes, and sediment movement. Soil data obtained from geotechnical tests are also analysed to determine the strength and stability of the foundation. Statistical methods and engineering calculations are used to identify patterns and relationships in the data. This step helps in understanding the environmental conditions that influence the design and performance of the seawall. By analysing the data carefully, engineers can identify potential risks such as erosion, flooding, or structural instability. The results of the analysis are used to establish design parameters that will guide the development of the seawall model. Proper data analysis ensures that the design is based on accurate information and realistic assumptions, which improves the reliability and effectiveness of the final coastal protection structure.

Baseline Model Calibration and Validation

A baseline model representing the seawall system and coastal environment is developed using the analyzed data. The model may be a numerical or physical representation that simulates wave interaction, water levels, and structural response. Calibration is carried out by adjusting model parameters so that the results closely match real-world observations and measured data. This step ensures that the model accurately represents the actual conditions of the study area. After calibration, validation is performed by comparing the model predictions with independent data sets or observed results. Validation confirms whether the model can reliably simulate coastal processes and structural behavior. A properly calibrated and validated model is essential for predicting how the seawall will perform under different environmental conditions such as storms or high tides. This stage improves the accuracy and credibility of the study and ensures that the model can be confidently used for design and performance evaluation.

Conceptual Model Design

Conceptual model design involves developing the initial design idea for the seawall structure based on the analyzed data and modelling results. At this stage, the shape, size, and structural components of the seawall are determined. The design considers important factors such as wave forces, water levels, soil conditions, and coastal erosion patterns. The design may include curved walls, buoyancy elements, or protective layers to reduce wave impact and improve stability. The conceptual design also considers the materials to be used, such as reinforced concrete, fiber-reinforced composites, or other durable materials suitable for the environment. Environmental and economic factors are also taken into account to ensure that the design is practical and sustainable. This stage provides a clear framework for further detailed design and analysis of the seawall system.

Performance Evaluation

Performance evaluation is conducted to assess how effectively the proposed seawall design can withstand coastal forces and protect the shoreline. The conceptual model is tested under different environmental scenarios such as varying wave heights, tidal levels, storm surges, and extreme weather conditions at this stage. Numerical simulations or experimental testing may be used to analyse the structural behavior and stability of the seawall. Parameters such as wave reflection, energy dissipation, overtopping rates, and structural stress are evaluated. This analysis helps determine whether the design can reduce wave impact and prevent coastal erosion. If weaknesses or limitations are identified, modifications can be made to improve the design. Performance evaluation also ensures that the seawall meets safety and durability requirements over its expected lifespan. By carefully analyzing the results, we can confirm whether the design provides adequate protection and stability for the coastal area before moving to the final design stage.

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Optimization And Final Design

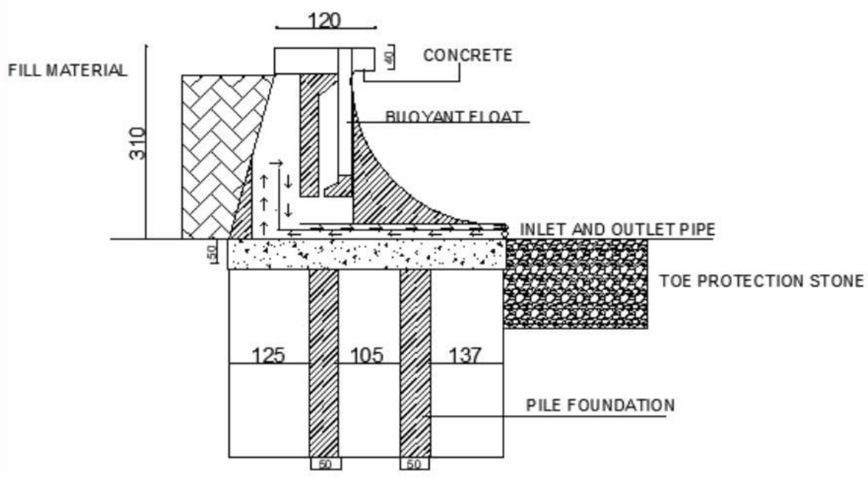
Optimization and final design involve refining the seawall structure to achieve the best possible performance, safety, and cost efficiency. Based on the results obtained from performance evaluation, design parameters such as wall height, curvature, foundation depth, and material properties may be adjusted. The aim is to enhance structural stability while minimising construction and maintenance costs. We also consider factors such as environmental impact, durability in marine conditions, and ease of construction. Advanced modelling techniques may be used to test different design variations and identify the most effective solution. The final design includes detailed structural drawings, material specifications, and construction guidelines. Safety factors are incorporated to ensure the structure can withstand extreme coastal events such as storms or high tides. This stage results in a complete and optimised seawall design that can be practically implemented to provide long-term coastal protection and improve resilience against coastal hazards

WORKING

The working mechanism of the self-elevating seawall is a passive, buoyancy-driven process that automates coastal protection without the need for external power. During high tide or storm surges, seawater is directed through an inlet pipe into an underground basin located beneath the seawall. As the water level within the chamber increases, it generates a hydrostatic buoyant force that pushes the wall upward along a set of vertical guide rails. Once fully deployed above ground level, the wall's curved geometry is designed to deflect incoming wave energy upward and back toward the ocean, while the internal water pressure holds the structure firmly in place to withstand the lateral forces of the tide.

As the tide recedes, the system undergoes an automatic retraction phase to restore the natural beach environment. Water within the underground chamber drains through a specialized one-way valve, leading to a gradual reduction in the buoyant force supporting the structure. Under the influence of gravity, the seawall settles back into its subsurface housing until the top plate is once again flushed with the ground level. This cyclical process ensures that beach access and coastal aesthetics are maintained during calm periods, while providing a reliable, self-activating barrier that is ready for the next rising tide or surge event.

CONCEPTUAL DESIGN



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RESULT

Wave height	Dynamic pressure acting on the seawall	Hydrostatic moment	sliding	Overturning	Overtopping	Dn50
0.5	15.21	18.39	2.309	3.66	2.64	0.157
0.6	16.91	21.45	2.139	3.2	2.2	0.189
0.7	18.51	24.33	2	2.86	1.88	0.220
0.8	20.54	27.93	1.85	2.53	1.65	0.252

CONCLUSION

The study concludes that the proposed self-elevating curved seawall offers a more effective and adaptive solution compared to traditional coastal protection methods. Conventional tetrapod seawalls are found to be less efficient due to scouring and lack of flexibility under extreme wave conditions. By integrating Multiphysics modelling, the research successfully demonstrates how the seawall can respond dynamically to changing environmental forces such as wave pressure, tides, and soil interaction. The curved design further helps in reducing wave impact and minimizing erosion. Seven soil samples were collected and analyzed, and based on the test results, it was concluded that the soil is poorly graded sand. Sieve analysis was carried out to determine the particle size distribution and shear strength test was conducted to analyze the shear strength parameters of the soil. The case with a wave height of 0.8m is the most suitable as it provides balanced values for sliding, overturning, and overtopping. The dynamic pressure and hydrostatic moment indicate a stable structural response. Hence, the 0.8m case is the most efficient and reliable design option. The results obtained from the test are consistent and validate the suitability of the selected soil parameters for coastal structure design. Overall, the model shows strong potential in improving coastal resilience, enhancing structural stability, and reducing long-term damage to the shoreline. It also supports environmental sustainability and helps protect local communities and livelihoods in erosion-prone areas like Perumathura.

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