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Coastal Erosion and Engineering Solutions along Visakhapatnam Coastline East Coast of India

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ABSTRACT

Utilizing the primary field data collected concerning bathymetry, topography, and ocean parameters, a numerical simulation analysis (DELFT-3D) was conducted. A comparison between the numerical model of outcomes and the existing field data suggests a reasonable alignment regarding hydrodynamic factors. Several mitigation strategies were tested during the simulation study, taking into account their effectiveness, cost-efficiency, durability, and ease of installation. After careful consideration, the 'perched beach' concept has been selected as the most suitable options. This mitigation measure consists of three key elements. Creation of a perched beach stretch of desired width along Ramakrishna Beach Road was carried out by sand nourishment. This nourishment can be sourced from Catamaran Beach Bund, where the required quantity of sand is presently available and is likely to be replenished naturally during NE monsoon. The transport of sand from catamaran beach to RK beach stretch can be done by a land-based pipeline. Installation of a 2 km long 'Sill' is required to retain the nourished sand from sliding into steep slopes in surf-zone. This shall be a geo-synthetic tube filled with sand to act as retaining structure up to 2 m depth. This operation is season-independent as the sill can be installed from land-based pumping of slurry. Installation of 2 km long submerged artificial reef to reduce the wave energy incident on the beach will aid in beach building process over the seasons. This shall be made up of artificial concrete blocks like tetrapod laid over a width of 12 m and a height of 2 along 3 m depth contour and smaller in shallow waters.

Keywords: DELFT 3D, perched beach, sand nourishment, submerged reef, geo-tubes.

INTRODUCTION

The Eastern Naval Command of the Indian Navy is stationed along this coast, enhancing its strategic significance. The region also offers cultural attractions such as the INS Kursura Submarine Museum, Kailasagiri Hill, and VUDA Park, providing insights into the city's rich history and culture. Despite its allure, the Visakhapatnam coast faces the challenges related to coastal erosion, driven by factors like wave patterns, sand deposition, and human activities. This necessitates continuous erosion studies and engineering solutions to safeguard the coastline and its infrastructure. Additionally, being susceptible to natural disasters like cyclones and tsunamis, preparedness and disaster management are crucial aspects of life in this dynamic coastal area. Since 2014, there has been a noticeable shift in shoreline behavior, with multiple factors contributing to this change. It is imperative to thoroughly analyze these factors without bias. Various user agencies and research organizations possess substantial data on shoreline alterations, dredging activities, wave patterns, etc.

To address these challenges, a numerical simulation analysis was conducted, utilizing the collected data on bathymetry, topography, and met-ocean parameters, supplemented by field data. A comparison between the numerical model (DELFT-3D) results and the existing field data indicates a reasonable alignment concerning hydrodynamic factors. On the basis of the validation of the field data and numerical modelling after few modeling trails with different combinations three suitable measures were proposed by taking into account their effectiveness, cost-efficiency, durability, and ease of installation.

Allsop's (1983) paper likely builds upon a foundation of the research related to coastal protection, breakwater design, wave-structure interaction, and the influence of wave randomness. The study findings contribute to the understanding of low-crest breakwaters and their effectiveness in mitigating wave energy in random wave conditions, providing valuable insights for coastal engineering and design practices. Ahrens (1987) focuses on the specific characteristics of reef breakwaters, including their design parameters, hydrodynamic performance, and potential ecological benefits. It also provides valuable insights into the behavior of reef breakwaters and their suitability for coastal protection and environmental conservation efforts.

Almaghraby et al. (2022) evaluated partially submerged breakwaters in comparison to traditional breakwater designs. Their findings indicated enhanced efficiency, particularly in the areas with short coastal waves. Moreover, the integration of artificial shell blocks on the crest led to a notable reduction in the width of submerged breakwaters, sometimes to less than half of their original width. Experimental data and findings related to wave propagation over a submerged bar and results on how waves interact with bars, including changes in wave height, wave breaking patterns, and energy dissipation was investigated by Beji and Battjes (1993). This information is valuable for coastal engineers and researchers working to understand coastal processes and design effective coastal protection measures. Bremner et al. (1980) paper on the concept of dual breakwaters and its design principles and application to Townsville, Australia. The findings and lessons learned from this case study may be valuable for coastal engineers and researchers seeking innovative solutions to coastal protection challenges, especially in the regions with unique coastal conditions like Townsville.

Wave transmission behind low crested structures and the influence wave transformation and energy reduction was studied by Briganti et al. (2003). Additionally, it may provide insights into the practical applications of low crested structures for coastal protection and beach management. Black and Mead's (2001) discuss the design of the Gold Coast Reef, with a particular focus on its impact on surfing conditions, beach amenity, and coastal protection. The results show the optimized benefits not only to the protection of the coastline but also the local surfing community and tourism industry. Conceptual approach for predicting wave transmission through low crested breakwaters was presented (Buccino and Calabrese 2007), whereas the theoretical framework (and models used to estimate wave transmission, taking into account factors such as breakwater geometry and incident wave conditions were established (Gravesen et al., 1980; d'Angremond et al., 1996; Pilarczyk 2003). A methodological approach for assessing wave transmission to optimize low crested breakwater design to achieve specific goals, such as reducing wave energy while maintaining desirable beach and harbor conditions has to be developed.

Behavior of low-crested and submerged breakwaters when subjected to broken waves was studied by Calabrese et al. (2003). The studies discuss structural interaction with complex wave patterns, the extent of wave energy dissipation, and their effectiveness in mitigating coastal erosion. Munireddy and Neelamani (2004) paper presents experimental results related to the hydrodynamic behavior of a vertical seawall protected by a low-crested breakwater as a primary defense system to protect the seawalls and also the effectiveness of the combination of a vertical seawall and low-crested breakwater in mitigating wave impact and protecting coastal areas.

Shirlal et al. (2008) reported the performance of a submerged reef – a physical model study and gave the results, as this study experimentally examined the stability of armor stones on a submerged reef and assesses the influence of varying distances from the shore on ocean wave transmission. An equation for the stability of a submerged reef has been derived. Results indicate that a reef with a height of 0.25 m (7.5 m), a crest width of 0.1 m (3.0 m), and constructed with an optimal armor weight of 30 gms (0.81 ton) at a seaward distance of 4 m (120 m) in water depths up to 0.4 m (12 m) can achieve a wave transmission of 51% under the tested wave conditions.

This paper likely presents findings from the field experiments of Hamaguchi et al. (1991) on the Niigata Coast to assess the wave-dissipating effect of artificial reefs. The paper may discuss the experimental setup, data collected, as well as the implications of the study for coastal protection and management. The contributions of this paper may include insights into the effectiveness of artificial reefs in reducing wave energy and preventing coastal erosion in the specific context of the Niigata Coast. Additionally, it may provide valuable information for coastal engineers and researchers seeking to implement similar coastal protection measures in the regions facing wave-induced challenges.

According to Shivakumar and Karmakar (2022), among impermeable-type models, the tandem arrangement of a thin-walled reef structure positioned ahead of a primary submerged breakwater demonstrates efficient performance in energy dissipation and provides optimal wave transmission for both short and long wave conditions. Additionally, permeable and rubble mound trapezoidal tandem breakwaters offer superior energy dissipation compared to other types. Incorporating a reef structure enhances the structural stability of submerged breakwaters, acting as a defense system for the primary breakwater while creating an energy dissipation zone that preserves shore dynamics. This makes tandem models particularly effective in harbor regions, considering design considerations and structural stability.

Van der Meer's (1990) technical report presents the data and findings related to wave transmission due to overtopping of coastal structures. The report discusses the methodology used to collect data, experimental results, and implications for coastal protection and engineering. This report includes valuable data on wave transmission during overtopping events, which is essential for designing resilient coastal defenses. It may serve as a reference for coastal engineers and researchers seeking to improve the design and performance of coastal structures in the areas prone to wave overtopping. The study findings suggest that the primary factor contributing to erosion is the insufficient availability of sand, influenced by wave patterns and the physical characteristics of a steep surf zone. Sand scarcity can be linked to disruptions in sand bypassing, particularly on the southern side, in the relatively recent past.

STUDY AREA

The Visakhapatnam coastline, located on the eastern shores of India along the Bay of Bengal, holds significant geographical, economic, and cultural importance. Covering approximately 25 kilometers, this coastal region is renowned for its natural beauty, including captivating beaches like Ramakrishna Beach, Rushikonda Beach, and Yarada Beach, which attract tourists and locals alike. The Visakhapatnam Port, often referred to as "The Gateway to the East Coast of India," is a prominent feature of this area, playing a vital role in maritime trade.

The specified geographical area falls within the coordinates of 17° 32' 0" to 17° 43' 23.16" N latitude and 83° 5' 0" to 83° 18' 18.36" E longitude, situated in the Visakhapatnam district (Figure 1). Encompassing a coast length of 135 km, this district boasts a distinctive geographic setting. Marked by diverse climatic conditions throughout the year, Visakhapatnam is surrounded by the eastern ghats and the Bay of Bengal.

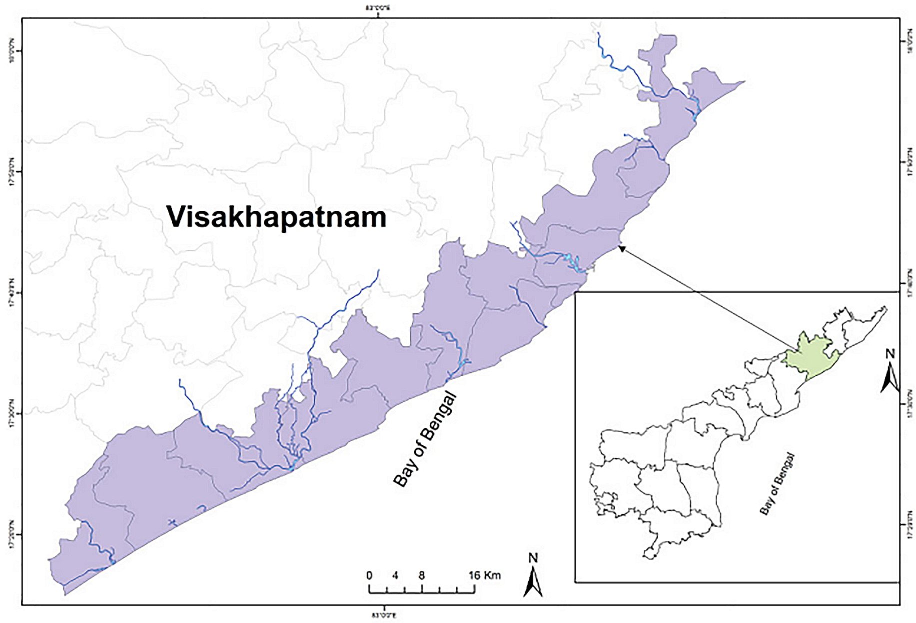

Figure 1. Study area

The region hosts numerous perennial watersheds, with the eastern ghats showcasing valleys and extensive forests. Additionally, the Bay of Bengal, prone to cyclones year-round, contributes to the district's lush greenery.

METHODOLOGY

The process for conducting studies in coastal engineering involves several crucial steps, including data collection, numerical modeling, and analysis, as shown in (Figure 2). An overview of the steps involved in the analysis for the project is presented below:

- collection of secondary information– the initial phase involves gathering secondary data from various relevant agencies such as the VPT (Visakhapatnam Port Trust), NIO (National Institute of Oceanography), etc. This data includes historical records, environmental data, and other relevant information.
- preliminary coarse scale modelling – a coarse-scale numerical model is developed to assess the hydrodynamics of the coastal area. This helps in planning the physical oceanographic measurements, which may include data on tides, waves, currents, wind patterns, and bathymetry (seafloor topography). Short-term met-ocean observations are conducted to validate and refine the model.
- detailed numerical modelling – a more detailed numerical model is created to simulate the existing conditions in the coastal area. This step is essential for calibrating and verifying the accuracy of the model, ensuring that it represents the real-world conditions effectively.
- morphological studies – morphological studies involve an analysis of the coastal landforms and sediment dynamics in the area. This

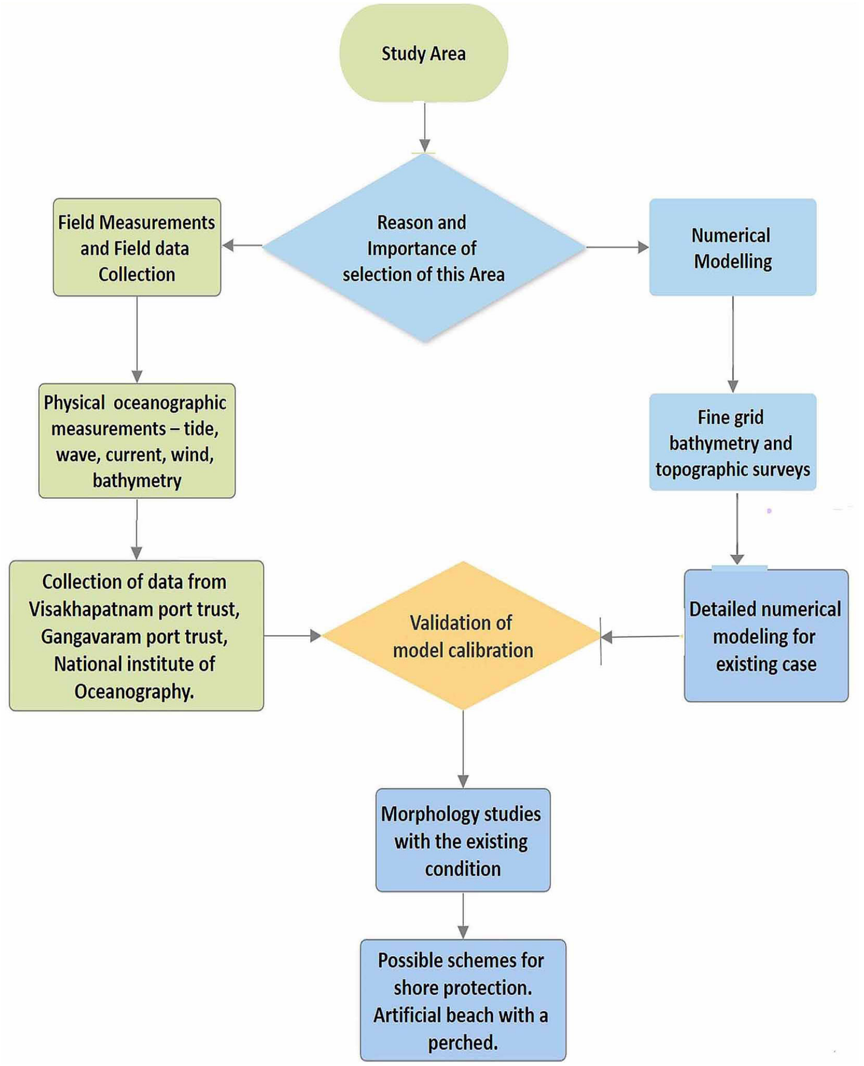

Figure 2. Methodology

step assesses the existing conditions and explores potential schemes for shore protection. It helps in understanding erosion and sediment transport patterns.

- detailed model simulations – once a shore protection scheme is selected, detailed model simulations are performed. For example, if the chosen scheme involves creating an artificial beach with a perched configuration, the model takes into account factors like existing slopes, grain size of sediments, wave breaking characteristics, and hydrodynamics. These simulations help evaluate the effectiveness of the proposed intervention.
- engineering design – on the basis of on the results of the simulations and analysis, an engineering design for the intervention elements is developed. This includes specifying the design of structures or modifications required for shore protection.

This comprehensive approach, which combines data collection, numerical modeling, and detailed analysis, is crucial in coastal engineering studies. It enables researchers and engineers to make informed decisions about coastal management, erosion control, and the protection of coastal areas while considering the complex dynamics of coastal environments.

Chart datum is a crucial reference point for navigation and coastal engineering. It provides information about the water level at which depths and heights on nautical charts are measured. This data is essential for understanding the relationship between tide levels and the seabed in the area. Dredging is a common practice in ports and coastal areas to maintain navigational depths. Understanding the volume and location of dredging activities is essential for assessing their impact on sediment transport and coastal dynamics. The details of the volumes of sediment that were dredged in the area.

Soundings refer to depth measurements taken in a specific area. These measurements are vital for creating accurate bathymetric charts, which show the seafloor topography. They help in understanding the depth variations in the coastal region. Pre- and post-dredging soundings provide valuable data on how the seafloor depth changes before and after dredging activities. This information is used to assess the effectiveness of dredging operations and their impact on navigational depths.

NUMERICAL MODELING

A hydrodynamic model for the area has been setup using Delft3D. The hydrodynamic model is developed with a curvilinear grid, and is based on three zones of refinement (Figure 3). Domain decomposition methodology has been utilized for the same. The inner most grids have an approximate resolution of 5 m, intermediate grids of 15 m resolution and outer are 50 m in resolution. The boundary forcing was adopted from Topex-Poseidon corrected tide data available through dashboard application. Bathymetry, NCEP wind data has been used for the study. A separate numerical model is setup with SWAN Wave model, two ways coupled to Delft3D to study local circulations induced by wave radiation. The SWAN grid is a rectilinear grid (Figure 4) adopted for the area and spans 150 offshore and 300 m along shore, with nested refined sections near the area of interest. The wave model is coupled to transfer the wave parameters and read the hydrodynamics at every 2 hr interval on a coarse coupling scale. Finer coupling times would help in better wave current interaction.

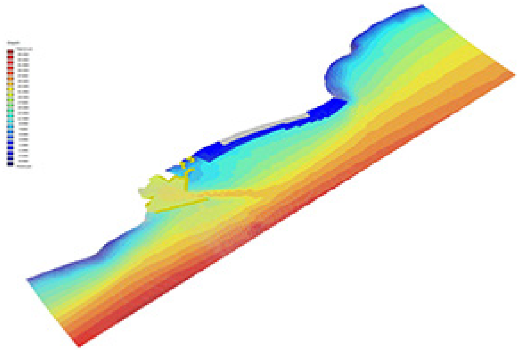

Figure 3. Model grid developed for hydrodynamic model with multiple domains

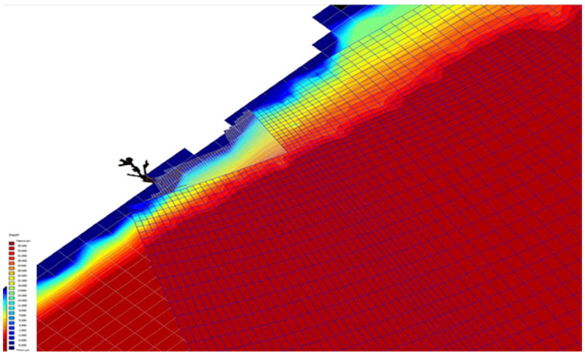

Figure 4. SWAN grid nested at various resolutions

MODEL CALIBRATION

The model results (Figure 5) are validated against measurements. The results agree qualitatively. There are several short span drifts in the observation, due to local sediment dumping carried by the Vishakhapatnam port trust dredger. Moreover, the model is based on NCEP wind data set, which is a blended and smoothed output. Short term gusting and local winds variations are absent in such data set and hence are not reproducible in the model.

MORPHO-DYNAMIC SIMULATION

The morpho-dynamic model has undergone a rerun, now incorporating the features of a perched beach, submerged reef, and the relevant roughness scales. Within the numerical model, the geosynthetic tube is represented as both a submerged weir and as a source of roughness. To account for artificial wave energy dissipation, the model has integrated d'Angremond's formulation, although it is worth noting that the wave approach angle has shown minimal influence on the dissipation process. Additionally, the model simulates the loss of material over extended morphological time scales and considers the replenishment of resources from offshore borrow pits. It has been observed that there is a substantial reduction in beach erosion (Figures 6 and 7) across varying climatic conditions throughout a representative year. This reduction may be attributed to the obstruction of material transport, primarily due to the presence of the sill. Moreover, the diminished wave energy also plays a significant role in stabilizing the material along the beach slope.

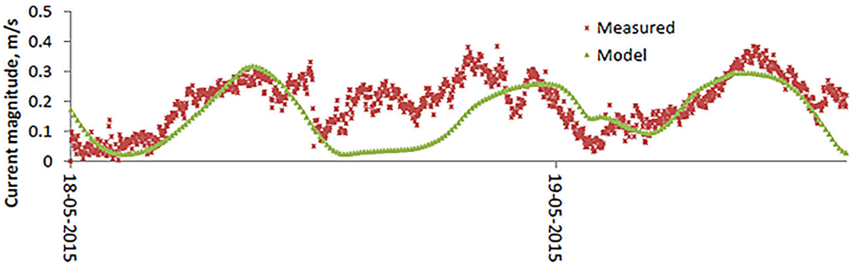

Figure 5. Comparision of model current magnitude with measurement at the location

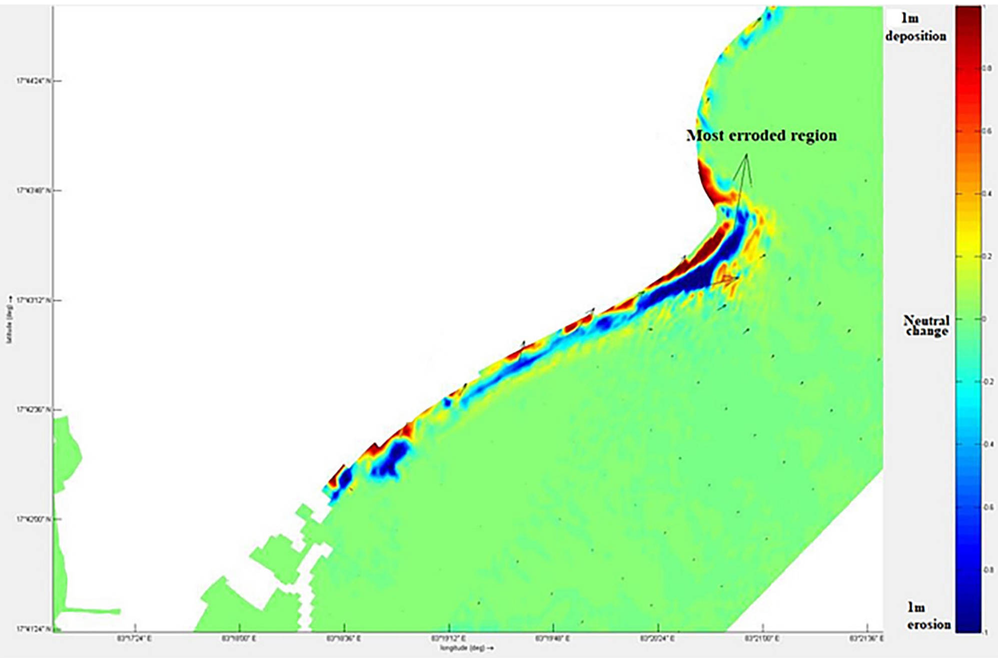

Figure 6. Mean sediment direction with cumulative erosion – deposition over a morphological SW Wind Wave tide combination

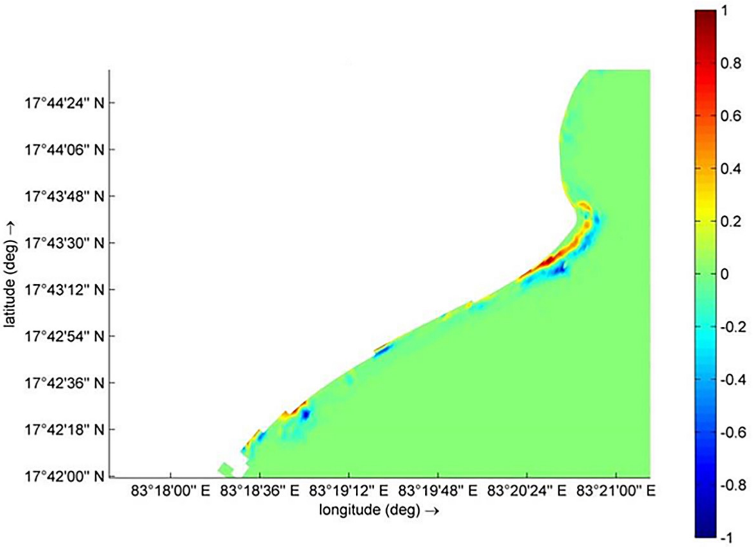

Figure 7. Anticipated reduction in erosion or deposition with proposed mitigation

CONCLUSIONS

Kiran et al. (2008) reported on the performance of a submerged reef – a physical model study and proposed an equation for the stability of submerged reef; simultaneously, some suitable dimensions were proposed for height and crest width. With these dimensions a wave transmission of 51% can be achieved, whereas in the present paper, with the introduction of perched beach and sill concept to submerged reef breakwaters, much lesser wave transmission than the normal submerged reef can be achieved. Considering all these aspects, the mitigation measures are proposed below.

Different mitigation alternatives were simulated during the simulation study, taking into account their effectiveness, cost-efficiency, durability, and ease of installation. After careful consideration, the 'perched beach' concept has been selected as the most suitable option. This mitigation measure consists of three key elements.The first component of this mitigation strategy involves establishing a perched beach of the desired width along the beach through the process of sand nourishment. It is important to note that this operation is not dependent on a specific season and should be executed prior to the next cyclone season to prevent any further deterioration of the beach road.

The second element of this mitigation plan involves the installation of a 2.0 km long 'Sill' designed to prevent the nourished sand from shifting into the steep slopes within the surf zone. This Sill will be constructed using a geo-synthetic tube filled with sand, serving as a retaining structure up to a depth of 2.0 meters. Importantly, this operation is not dependent on a particular season, since the sill can be put in place through the land-based pumping of a slurry mixture. The third component of this mitigation plan involves the installation of a 2.0 km long submerged artificial reef designed to diminish the wave energy reaching the beach. This reduction in wave energy will facilitate the natural process of beach building over time. The artificial reef will consist of concrete blocks, similar to tetrapods, positioned along a 15 meter width and extending to a height of 3.0 meters, following the 4.5 meter depth contour.

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