Holistic coastal protection strategies with nature-based solution for climate change adaptation in deltaic coast

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Abstract

River deltas are the most dynamic landforms on earth and have become more prone to disasters due to climate change and rising sea levels. Sea level rise and other coastal hazards, such as coastal erosion, salinity intrusion, and storm surges, affect delta ecosystems and the livelihoods of people depending on them. Many people live in deltas, with several of them experiencing a growing population, which requires a sustainable and integrated approach to balance various and often competing interests, notably ecosystem conservation, biological and cultural diversity, agricultural productivity and other social and economic benefits to support livelihoods. This study proposed the coastal protection strategies for the Mekong delta, including nature-based solutions and permeable breakwaters. Although single coastal protection defences are currently the prevailing practices in the region, their success is limited to slowing down the erosion rate. Due to the complexity of the hydrodynamic and morphological regimes and the characteristic of the mangrove mud coast, one single line of defence is neither sustainable nor successful. Accordingly, this study proposes holistic coastal protection strategies for mangrove muddy coasts under climate change, namely multiple lines of defences incorporating first nature-based solutions and green infrastructure. Second, advanced perforated hollow triangle breakwaters are introduced based on principles of environmental exchange and conservation, such as previously applied to the coastline of Tien Giang province. These breakwaters have shown benefits for wave reduction, as well as for stimulating sedimentation and for restoring mangrove ecosystems. Lastly, holistic coastal protection strategies are proposed for the entire coast of the Mekong delta, with comprehensive coastal protection solutions presented for the Ben Tre provinces.

Keywords: Coastal protection strategies, multiple line defence, nature-based solutions, perforated hollow breakwaters, coastal Mekong Delta.

1. Introduction

The International Union for Conservation of Nature (IUCN) defines nature-based solutions as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2019; Oral et al. 2020). Accordingly, in recent years, there has been a change of approach toward development that ensures human well-being and the preservation of nature, notably the implementation of green infrastructure projects (Romero et al., 2012; Silva et al., 2017; Schoonees et al., 2019) (Figure 1). Worldwide, building with nature is a new approach to designing and developing nature-based solutions for water-related infrastructures, such as coastal protection constructions to restore coastal and marine ecosystems to create living shorelines (Waterman, 1995; 2008; 2010; De Vriend et al., 2015). The multiple lines of defence solution are highly proposed to manage the coast profitably and effectively sustain the ecosystems and coastal habitat restoration, providing food and habitat for flora and fauna and the people inhabiting these regions. The solution goes step by step to complete more optimal solutions, such as hybrid alternatives and adaptive solutions in the future (see Table 1).

The concept of "multiple lines of defence" was first introduced by the Pontchartrain Conservancy (PC) against hurricanes in southeast Louisiana after the occurrence of Hurricane Katrina and Rita in 2005 (Lopez et al., 2005). There are two critical elements of managing and sustaining the coast, including (1) preventing storm surges or reducing storm damage (Lines of Defense) and (2) sustaining the wetland habitat goals (Target Habitat Types; Lopez, 2009). This concept is a methodology to design flood control and wetland restoration in coastal Louisiana to sustain the ecology and economy of the state's coastal areas. This method is in line with coastal green infrastructure (IUCN 2020, 2021; Chávez et al., 2021) and potentially be applied in other coastal areas worldwide to bring multiple benefits in terms of economic development and ecosystem rehabilitation (Narayan et al., 2016; Ellison et al., 2020).

MLD and the concept term of "Room for the coast" for coastal Mekong Delta were proposed by Le Xuan et al. (2022b) to introduce the different coastal protection solutions for reducing the incoming waves, stimulating sedimentation and mangroves restoration. There are several coastal areas applied this solution that bring effective and positive consequences. This solution is more friendly with environment according to the classification of Schoonees et al. (2019).

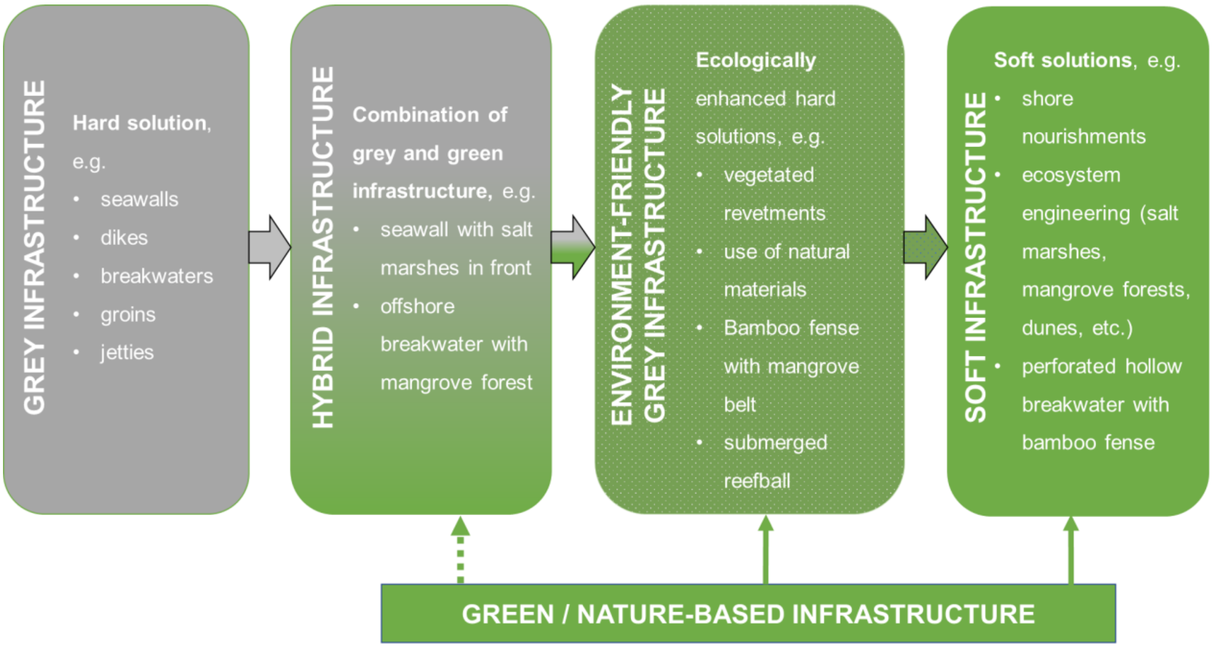

Figure 1. The current trend of switching from hard engineering solutions to soft infrastructure solutions (Adapted from Schoonees et al., 2019)

Table 1. Types of coastal green infrastructure (Chávez et al., 2021)

Types	Definition	Example
Type 1 Nature reclamation	Habitat conservation and restoration are viable and may be accompanied by other measures to increase ecosystem's ecological health and resilience.	Coastal dune restoration
Type 2 Engineered ecosystems	Ecosystems are rehabilitated to recover critical services without reaching the complexity level of natural systems. Natural processes are allowed	Action to allow windows of opportunities for

	to modify ecosystems to a certain degree to return the system to a more natural form.	flora and fauna recovery
Type 3 Ecologically enhanced engineering	Traditional hard and/or soft engineering measures are modified to change physical processes, perhaps indirectly producing certain benefits from the natural processes that are maintained or adapted in imitation of natural ecosystems.	Beach nourishments, artificial coral reefs.
Type 4 De-engineering/ Relocation	De-engineering means that hard and/or soft coastal structures are removed to recover the system and move towards more natural functioning. These actions are often accompanied by the relocation of human interests to more convenient sites and conditions.	Removal of coastal defence structures, retreat of tourist infrastructure (e.g., restaurants)

Multiple lines defence solution has been applied in the US and the Netherlands because of its advantage over a single solution, which cannot solve a multi-target problem in the dynamic area of socio-economic activities such as coastal lands. A single hard engineering structure is very costly and cannot protect hinterland when construction breakdown (Geography Revision, 2021). How safe a coastal area does depend entirely on offshore constructions. Furthermore, instead of taller sea dikes, heavier breakwaters or large riprap to resist strong wave attack and high flows on the coast has been involved in multiple lines of defence strategy with lower cost but stronger resilience (Sutton-Grier et al., 2015). In addition, when the sea level rises due to climate change and land subsidence, investment in upgrading hard structures becomes costly and requires extensive labour forces to optimise structural design, especially upgrading the existing constructions under adverse weather and strong wind, wave conditions (Hinkel et al., 2014; Vousdoukas et al., 2020). Finally, the tidal hydrodynamics, wave-induced and storm surges, and coastal flooding will be more frequent and strongly impact the construction, causing damage and failure of protection function, reducing the construction life (Idier et al., 2017, 2019; Kirezci et al., 2020). Therefore, it is necessary to have a holistic solution to protect coastal areas and expand mangrove forests to construct green belts, restore habitats and enhance biodiversity to ensure sustainable livelihoods for local communities as an Integrated Coastal Zone Management program. The multiple lines of defence strategy is an innovative coastal development, emphasising hard and soft solutions to provide long-term sustainable solutions for restoring coastlines, habitats, and land reclamation.

The Vietnamese Mekong Delta (VMD) has recently faced many severe problems (Figure 2). The historical drought and salinity intrusion event during the dry season in 2020 that spread over 40,577 km^2, affecting 29,700 hectares of rice fields across the delta, is amongst the worst (Le Xuan et al., 2022a). Also, land subsidence was found to be between 0.1 and 81 cm over ten years, and sea-level rise between 2-3 mm/year to climate change (Minderhoud et al., 2017). Moreover, coastal erosion observed along the coastal strip in the last 30 years constitutes another threat to VMD. Every year, 300-500 hectares of land lost, infrastructure damage, and mangrove degradation. The result of surveys and research by the Southern Institute of Water Resources Research (SIWRR) in 2022 illustrates severe coastal erosion that happened around 282/744 km of coastline with an erosion rate of 1-40m/year (Figure 2).

Figure 2. Coastal erosion in Mekong Delta

Therefore, the general approach must recreate the natural coastal protection system. A regional coastal protection strategy is considered to be more effective than using a single coastal protection element. Furthermore, this approach will facilitate the realisation of parallel socio-economic and environmental benefits. In general, coastal planning and management should follow natural development and include appropriate soft and hard protection measures. Regarding limited financial resources, it is necessary to prioritise and optimise the design. To provide an overall solution for each area, it is essential to consider the hydrodynamic, geological, and morphological conditions in that area and, simultaneously, the need for urgent protection. The main parameters required for the proposed design process are (i) water level (normal tidal fluctuations but also extreme water levels) and (ii) wave parameters (significant wave height), wave period), (iii) soil characteristics, and (iv) shoreline shape and shore depth. The solutions to prevent erosion and protect the coast are usually divided into hard construction solutions and soft solutions. The hard solutions include sea embankment, breakwater, dike, and soft solutions include beach nourishment, mangrove planting, and sand dunes. The overall solution against coastal erosion needs to be a combination of many of the above resolutions and, depending on the specific conditions of each area, choose the appropriate combination of solutions.

2. Comprehensive protection strategies for muddy plat delta

"*The Multiple Lines of Defense Strategy (MLDS) identifies a system to reduce flooding for coastal communities through natural landscape features found in a healthy estuary and engineered structural features such as levees and floodgates*" (https://www.crcl.org/mlods). Initially, this new trend was applied to the lowland coast to combine many components for shoreline protection and ecosystem restoration in the United States of America, such as in Louisiana in 2006 and the North Atlantic region in 2015. This strategy is based on "Building with nature" or "Green Infrastructure", as introduced in the introduction. The general approach is to restore the natural coastal protection system. The coastal protection strategy is considered based on the characteristics of individual regions, and multiple solutions are more effective than using a single coastal protection solution. Moreover, this approach will promote the realisation of parallel socio-economic growth and environmental benefits.

To protect the coast from erosion and restore America's coastal ecosystems, the "Living shoreline" project was proposed (New Jersey Resilient Coastlines Initiative, 2016). The main principle is transforming from a grey to a green-softer technique for coastal protection (Figure 3). This project's approach combines many possible natural components to create effective buffer zones for reducing wave energy, combating erosion, and establishing favourable habitats for developing flora and fauna systems. Popular organic structures and materials are used to create the "Living shoreline", such as mud, silt, mangroves, aquatic plants, rocks, artificial reefs, and eco-friendly local materials. These components are arranged according to the function of a multi-layered system to protect the coast.

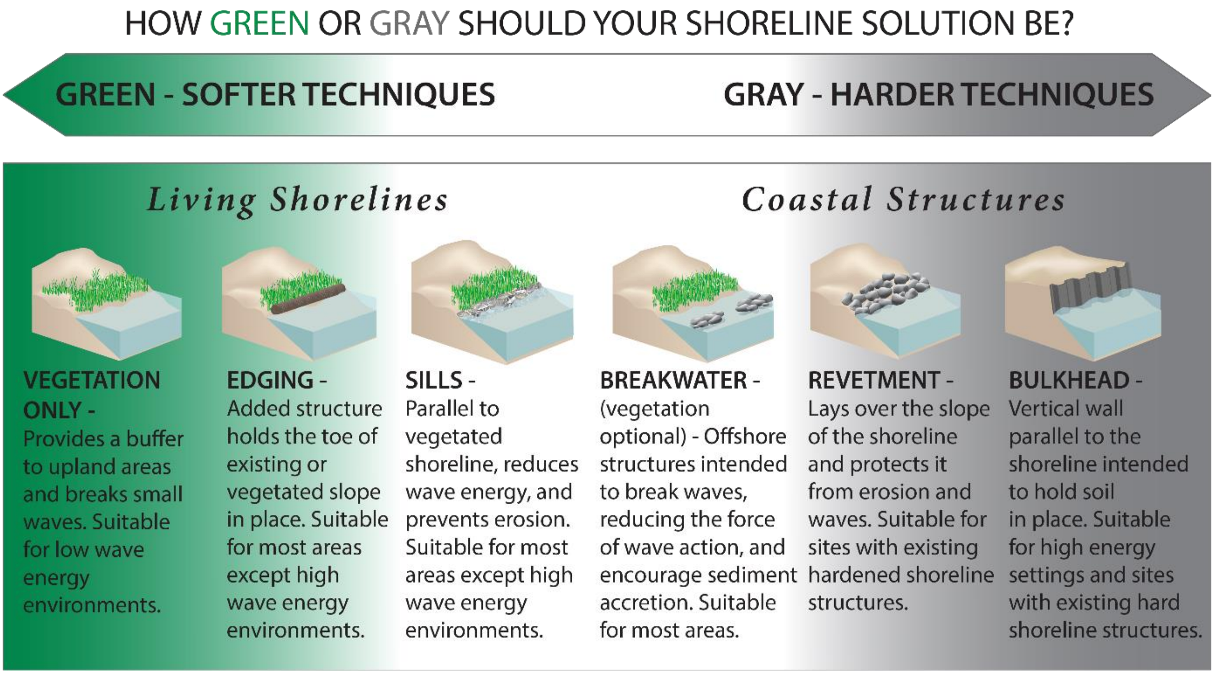

Figure 3. The transformation from a grey technique to a green-softer approach for coastal protection (*Source: https://www.habitatblueprint.noaa.gov/living-shorelines/)*

2.1. Why do we need multiple lines of defence?

Le Xuan et al. (2022b) had proposed a holistic solution for adequate future protection of the VMD coast, emphasising both hard and soft solutions to provide long-term sustainable solutions for restoring coastlines, habitats and land reclamation. To evaluate the role of multi-layer protection, we investigate the elevation of sea dyke in different conditions to answer why the VMD needs multiple lines of defence.

The elevation of sea dikes, the last defence line, can be determined using the following equation:

$$Z_d = Z_{tp} + R_u + a$$

where Z_d is the crest elevation of the sea dike, Z_{tp} is the design water level, R_u is the height of the runup waves, which depends on the slope of the inclined exposed face of the sea dike, and *a* is a safety value added to consider future sea level rise.

This is an example of calculating the crest elevation of a sea dike in the East Sea Sea in three cases consisting of the sea dike only, the sea dikes with breakwaters and the sea dikes with breakwaters and mangrove forests with a thickness of 150 m (Phan et al., 2015).

a) Crest elevation of sea dike without breakwater and mangroves

$$Zd = 2.5 + 3.5 + 0.4 = 6.4 \text{ m}$$

b) Crest elevation of sea dike with breakwater

$$Zd = 2.5 + 1.8 + 0.4 = 4.7 \text{ m}$$

c) Crest elevation of sea dike with breakwater and mangroves

$$Zd = 2.5 + 1.1 + 0.4 = 4.0 \text{ m}$$

Without breakwaters and mangroves forest, the crest elevation of the sea dike is 6.4 m, while it decreases to 4.0 m in the presence of mangrove forests and through reinforcement by breakwaters offshore. The wave runup height reduces significantly from 3.5 m to 1.1 m in the case of 150m mangroves. Off shore breakwaters can reduce 60-75 % of wave energy (Le Xuan et al., 2022). Therefore, the wave height attacked to the mangrove forest also reduces significantly.

The role of mangrove forests and breakwaters is crucial for reducing the required height of the sea dike and, thus, the construction cost. If we focus only on upgrading sea dikes and constructing breakwaters, the cost of the system is substantially high. However, uncertainties and high risks are still associated with extreme weather conditions and severe sea states. Moreover, high sea dikes will lead to appropriate the massive land and loss of coastal landscape, affecting the environment and surrounding areas.

Meanwhile, taking advantage of existing mangroves or preserving and expanding mangroves has the effect of reducing waves, protecting the sea-dyke, enhancing biodiversity, maintaining habitat for flora and fauna and sea birds, and creating a clean ecological environment for marine tourism. Besides, mangroves are an excellent biosphere reserve for carbon sequestration and exchange (Kauffman et al., 2011; Alongi & Mukhopadhyay, 2015); they act as a wastewater filter system for groundwater recharge (Robertson & Phillips, 1995; Wong et al., 1997; Ouyang & Guo, 2016). Finally, mangrove forests on the VMD coast are a precious resource, a long-standing home, and a place to provide food for residents of the western provinces for generations (Phung, 2012).

It is noted that the protection of mangrove belts is effective in case of a thickness of a minimum of 150 m and can effectively reduce wave energy by 50%. The wider protective mangrove belt (about 500 m) is ideal and achieves an optimal level of wave reduction up to 90% for the typical wave spectrum around the VMD coast (Alongi, 2009; Besset et al., 2019).

Figure 4 illustrates the complete system of multiple lines of defence solution for VMD, including main components such as offshore perforated hollow breakwater, bamboo/coconut or melaleuca fences, mangrove forest and sea dike. Offshore breakwater is the main barrier to reducing the strong incoming wave and allowing sediment to pass through. Bamboo/melaleuca T fences work as permeable dams to rapidly trap the sediment, reduce the horizontal velocity significantly for vertical settling of fine sediment, and help mangrove seedlings take root into the soil in a calm water environment. Moreover, seed pods germinate on the tree, ready to take root when they drop under calm water and proper sediment ground within the sedimentation basin. Mature mangroves are effective defence lines to dissipate remaining wave energy to protect the sea dike behind (Figure 4). Besides, mangroves also bring enormous economic and environmental benefits such as supplying timber and charcoal, a habitat for flora and fauna, a biosphere reserve for carbon sequestration and exchange, a wastewater filter system for aquifers and a clean ecological environment for tourism. The sea dyke is the last defence line to protect the saltwater overflow into the farmland, assets and house in villages.

1. Wind farm
2. Porous Breakwater
3. Bamboo/Melaleuca fences and seedling
4. Mature mangroves forest
5. Sea dyke
6. Evacuation Road
7. Drainage channel
8. Farmland

Figure 4. Proposed multiple lines of defence for the VMD coast

3. Introduction of new offshore breakwaters

To establish the different components of the MLD, the offshore breakwater is an important component to reduce the incoming wave energy and create conditions for the sand and mud for depositing sedimentation basin behind the breakwater. Therefore, Southern Institute of Water Resources Research had developed the perforated hollow breakwater since 2019 to achieve this objective.

Perforated hollow triangle breakwater (TC1) has a cross-section of the letter A, a long structure monad 2.5 m, height is 2.6 m, foot width is 3.12 m arranged with serrated edges to increase the contact area of the structure and the foundation, increase bottom friction to help stabilise the dike (Le Xuan et al., 2022a) (Figure 5). Each structure is arranged with an interlock to create a connection when assembled to increase the stability of the dike. TC2 structure has a truncated pyramid shape, and each structure monad long is 3.6 m, height 2.5 m, foot width 3.8 m extended to 4 directions, with the base face type bevelled outward has the effect of increasing the weight of the base to help stabilise the structure, at the same time, evenly distribute the load of the member transmitted to the foundation, reducing the cost of foundation treatment and reducing the erosion of the base of the structure. When installing, the components are placed on the foundation made of melaleuca poles and crushed stone to distribute the load to the foundation, reducing settlement evenly. The front and behind of the dyke are reinforced with pit rock to prevent foot erosion and, at the same time, increase the stability of the construction.

The advantage of the perforated hollow structure wave reduction dike is to reduce the wave impact on the coast, dissipates wave energy thanks to the surface porosity of the structure, and reduces reflected waves and pressure on the structure body (Le Xuan et al. 2022a). The design has a hollow structure and holes in the surface that allow the sand from the outside to transport through the dike body, creating an accumulation at the back and shielding young plants from growing and developing. On the other hand, this structure hinders the movement of plants and animals underwater, favouring environmental exchange in front and behind the dike. After the construction causes accretion, create a dump. This structure can be reused and relocated to a new location to cause accretion.

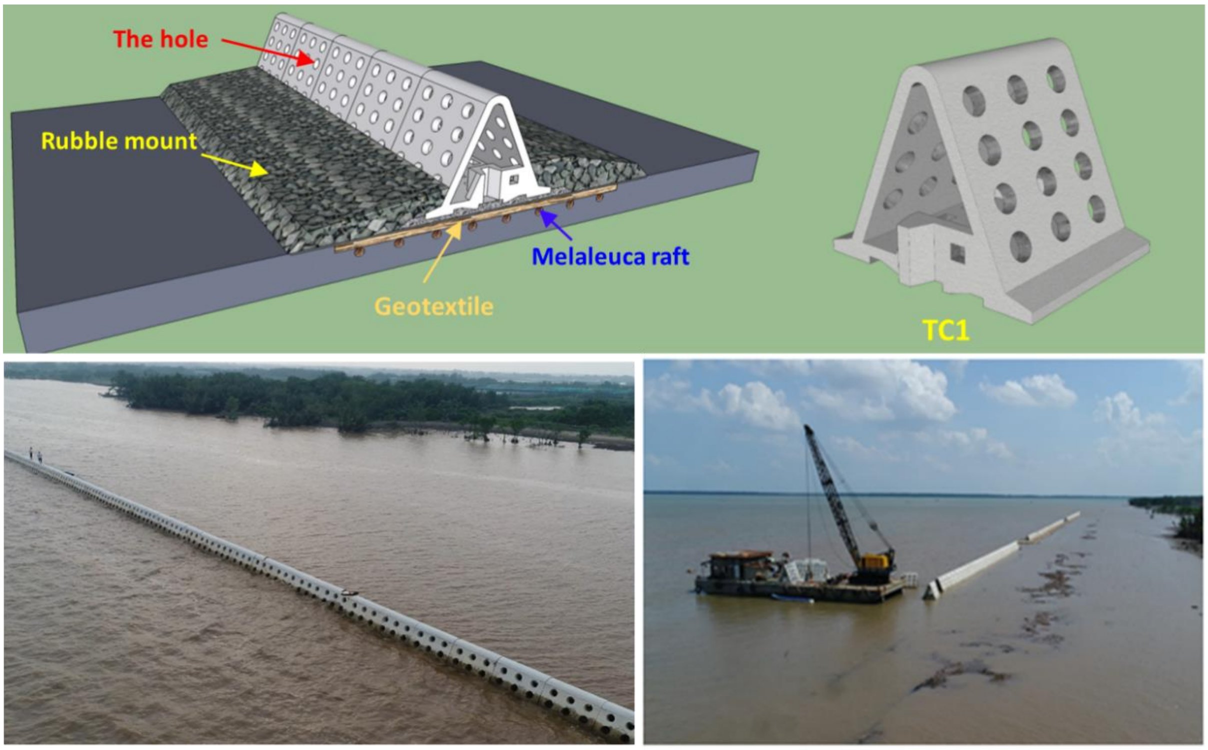

Figure 5. The construction TC1 breakwater and the installation of the breakwater route

3.1. Field construction and functional effectiveness

Components are mass-produced in the factory from high-grade concrete (M40-M60 Mpa) using special formwork made of steel should ensure dimensional accuracy and product quality. At the same time, it makes the construction process simple and quick (The structure is moved to the construction site by barge and then installed by a 35–50-ton crane mounted on the deck). This is meaningful because marine works can only be constructed during the calm sea season (Figure 6).

The technology of the perforated hollow structure wave reduction dike proposed by scientists from the Southern Institute of Water Resources Research - Viet Nam Academy for Water Resources has been approved by the Investment Project Management Board for the construction of agricultural and rural development works under the Department of Agriculture and Rural Development of Tien Giang has selected as the solution to protect the Con Cong and Tan Thanh coasts with the length of the construction route of 1600m, 1500m, respectively. Now TC1 structure continues to apply for coastal protection from the Tan Thanh culvert to the north of the Tan Thanh tourist area, with the length of the construction route 1442m. Construction is underway from May 2021.

Figure 6. The prefabricated components of TC1 (a) and TC2 (b) in the factory and installation on the construction field in Con Cong (c, d), Tien Giang 2020

The line of Con Cong coastal protection works, Phu Tan commune, Tan Phu Dong district was built from urgent capital to deal with riverbank and coastal erosion supported by the Government for the Mekong Delta provinces. The total length of the protection dike line is 1600m, the number of built wave-reducing dikes is 10, length of each dike is 135 m. The construction route was built in April 2019, completed, and used in December 2019.

3.2. Effectiveness of wave reduction and stimulating sedimentation

The results of field measurements show that the wave reduction efficiency of Con Cong coastal protection construction is 60-70%, and the wave height behind the breakwater is less than 0.3m (see Figure 7).

The field survey results show that, after two years of being put into use, the wave-reducing dyke protecting the Con Cong coast is stable, with evidence of adequate protection against erosion. The beach behind the dyke shows sand deposits with a thickness of about 1m, and there is no sign of foot erosion in front of the construction; sand accretion occurs behind the dyke, and near the shore where the current is more substantial, the sapling grows, this is an excellent sign to restore mangroves and coastal vegetation (see Figure 7). For Tan Thanh coastal protection works, after one year of being put into use, the average sedimentation thickness is about 0.3 - 0.5m.

Figure 7. The sedimentation process (left) and the regeneration of apple mangrove (*Sonneratia caseolaris*) behind the breakwater (right) in coastal Con Cong, Tien Giang 2020-2022

4. Proposed holistic coastal protection strategies for Mekong Delta

Figure 8 shows the recommended coastal protection strategies along the study area. The revetment for sea dike construction and offshore breakwater for reducing the incoming wave energy and planting mangroves in the sedimentation zone for the coastal sections in Tien Giang and Bac Lieu, Soc Trang, is encouraged. For the coastline of Ca Mau in the East Sea, we propose (Figure 8) the construction of an offshore breakwater without mangrove planting because there are mangrove forests in Ngoc Hien and Nam Can district already exist (Figure 8). Therefore, an offshore breakwater that can prevent coastal erosion, ensure ecosystem benefits, and protect the mangrove belt is highly recommended. The solution of constructing revetment combined with beach nourishment is recommended for several coastal sections in Ben Tre and Tra Vinh provinces. For the coastline in Tran Van Thoi district, Ca Mau in the West Sea, the offshore breakwater and beach nourishment are recommended to enrich the sedimentation zone for mangrove restoration. In the last section in Kien Giang (Figure 8), the offshore breakwater for eliminating coastal erosion and planting mangroves to protect the hinterland area is encouraged.

Figure 8. Proposal for different coastal protection strategies along the coast (Le Xuan et al. 2022b)

Based on a wide range of factors, including sea states (wave and tide parameters), hydrodynamic regimes, social and cultural conditions, sediment characteristics, ecosystem, environmental conservation, wildlife refuge, local policy, governance, indigenous people's perception of coastal protection, local livelihood, state funding, technical expertise, storm characteristics and the state economy the coastal protection strategies are taken. These are the critical factors in deciding any coastal protection strategy in every coastal area. Gathering all this information from different coastal regions needs a detailed feasibility study to determine the length of recommended protection works. It is also difficult to show that the recommended coastal protection works as an end solution for minimising coastal erosion. Therefore, this study primarily outlined the main principle of coastal protection works in the deltaic coast of VMD that can be decided at any place based on the circumstances. Depending on numerous factors, coastal managers have these coastal protection options or alternatives to evaluate any coastal erosion problem. In addition, five types of MLD are proposed to apply to different climate change circumstances and coastal erosion circumstances on the deltaic coast. These can also be employed as helpful guidelines in policy making.

Located in an area greatly affected by changes in sediment and flow of estuaries: Cua Dai, Ham Luong, Co Chien, and Cung Hau, the shoreline of Ben Tre province, with a length of about 65km, has alternating erosion (Figure 9). Interstitial and sandbars are forming south, so the shoreline changes in this area have strong fluctuations. The bank of Thua Duc commune and the part of Ham Luong river mouth in Thanh Hai commune are two areas strongly affected by sea waves causing severe erosion, so it is necessary to have hard construction solutions to protect the area. This area. The banks of Thoi Thuan and Bao Thuan communes have development of sandbanks with a tendency to develop from north to south, causing accretion in the Ba Lai estuary area, so the soft solution is to use bamboo fences, and plant flooded forests. It is highly feasible to use saline water for the tail section of the sandbar and the alluvial area at the estuary.

Besides, the sea dike is located deep inside; outside are mangrove forests, aquaculture, and agricultural areas, so protecting the coast from erosion is most important. The explanation for selecting a comprehensive solution to protect the coast of Ben Tre is based on an analysis of causes and the current status of erosion. On that basis, the overall solution to protect the Ben Tre sea dike (Figure 9) is proposed, including the following types of solutions:

Type 1: is a wave-reducing construction that causes accretion to protect the unforested coastal sections and the mangroves that are threatened by waves and coastal currents, making the remaining mangrove strip. It is gradually narrowing. The total applicable length is about 20 km. The hard solutions are breakwaters to stabilise the beach, causing sedimentation to create the beach. The combined solutions are "soft" structures made of local materials (melaleuca poles or bamboo poles). These "soft" solutions aim to deposit fine, nutrient-rich silt particles so that mangroves can be restored. After stabilising alluvial ground, mangroves are planted inside the dike to reduce waves.

Type 2: Newly built revetment for surface erosion sections.

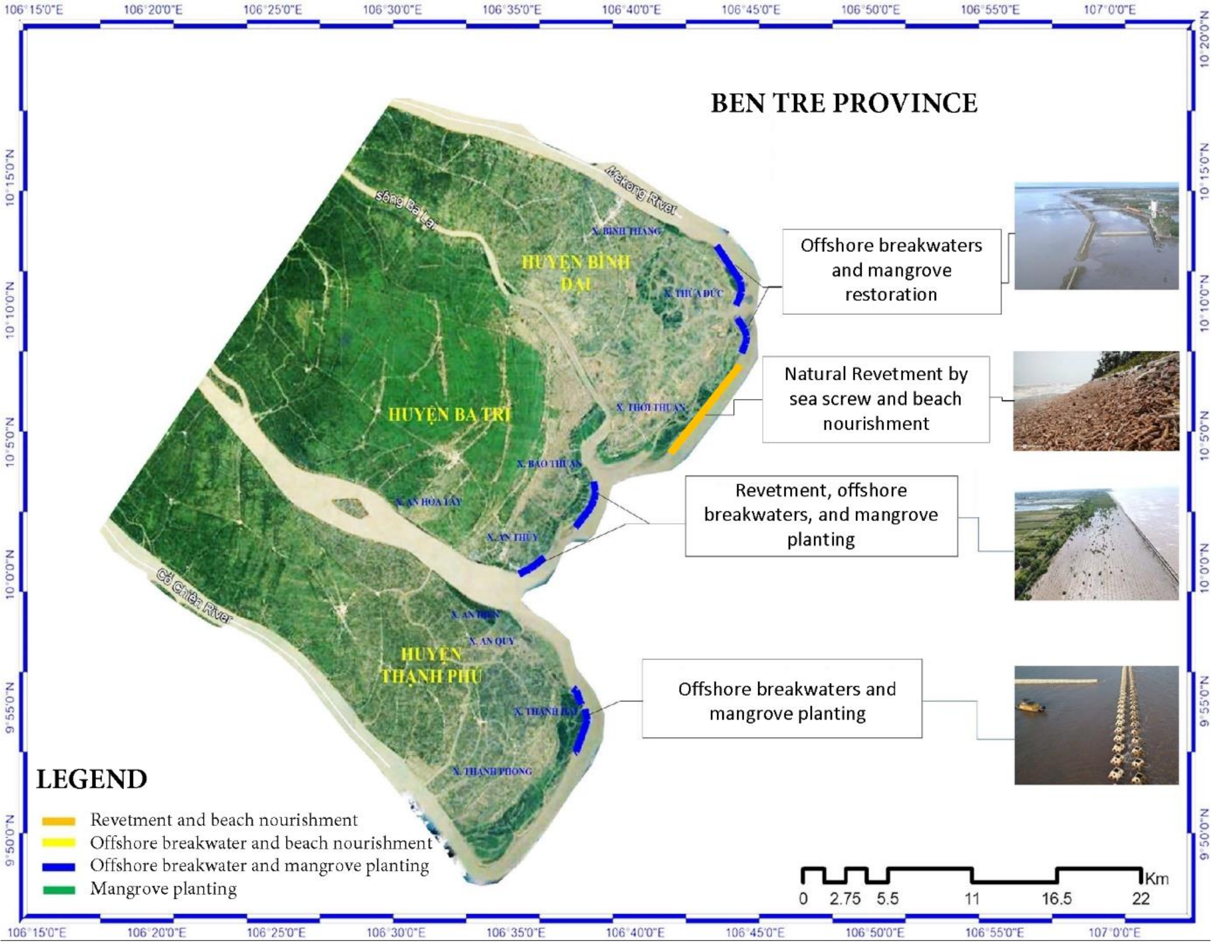

Figure 9. A typical example of coastal protection solutions for Ben Tre province is based on a MLD approach.

5. Conclusions and remarks

MLD coastal protection solutions and overall solutions for the entire coast of the Mekong Delta have been introduced and presented on the basis of research, summarizing from actual works and coastal protection trends of the world for the lowlands. This is a promising solution that can be applied and adapted to each specific area.

This research has provided an overall coastal protection solution for the Mekong Delta with many combined solutions that both meet the goal of coastal protection and are environmentally, friendly and suitable for the deltaic region. This paper also introduces the detailed planning of coastal protection solutions for a typical area on the coast of Ben Tre with a combination of many different solutions. This study also introduces a type of hollow structure wave-reducing dyke TC1, TC2 which is researched and developed to protect the coast of the Mekong Delta - Vietnam based on detailed studies and practical applications.

Within the state-level project cluster's framework for researching and proposing solutions to prevent coastal erosion in the Mekong Delta, we have conducted theoretical research combined with a mathematical model, physical model of stability, wave-reducing efficiency, and construction layout of hollow structure TC1 and TC2. The structure has been practically applied to protect the coasts of Con Cong and Tan Thanh in Tien Giang province. The construction has been used regularly, initially ensuring the task of reducing waves and causing accretion. Field measurements show that the wave reduction efficiency reaches 60÷70%, mudflats deposition from 40÷100 cm. This is a new technology; it has been in use for more than 3 years now showing the clear effectiveness of mangrove restoration in Tien Giang province.

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