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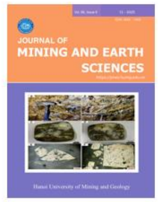

Numerical analysis of stability of sea dikes: a case study at An Bien - An Minh coastline

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ABSTRACT

In response to increasing coastal hazards driven by climate change and sea level rise, this study investigates severe shoreline erosion and instability of the An Bien - An Minh sea dike system in An Giang Province, Vietnam, located in the western Mekong Delta. The research aims to evaluate the existing geological, geotechnical, and hydrodynamic conditions of the study area and to assess their combined influence on the stability and structural performance of the sea dike system. Field investigations and monitoring programs were conducted to collect data on wave characteristics, coastal currents, sediment conditions, and subsurface soil properties. These datasets were integrated into a numerical modeling framework using PLAXIS 3D based on the finite element method to analyze soil-structure interaction, deformation behavior, and stability of the dike system under representative design loading conditions. The numerical analysis focused on stress distribution, displacement patterns, and potential failure mechanisms associated with soft soil foundations and wave-induced loading. Based on the modeling results, an integrated coastal protection solution is proposed, combining offshore wave attenuation structures, reinforced concrete revetments, and mangrove forest restoration. Simulation results demonstrate that the proposed measures significantly reduce wave energy transmitted to the dike toe, mitigate shoreline erosion, and enhance the overall stability and resilience of the sea dike system. In addition to technical effectiveness, the integrated solution supports environmental sustainability by promoting ecosystem-based coastal protection and reducing long-term maintenance requirements. The findings provide a robust scientific basis for climate-resilient coastal infrastructure planning and management in the Mekong Delta and offer practical guidance for the design and upgrading of sea dike systems in other low-lying coastal regions facing similar climate-related challenges.

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1. Introduction

Climate change has emerged as a global challenge, profoundly impacting ecosystems, socio-economic activities, and built infrastructure. Among the most vulnerable regions are coastal zones, which are increasingly exposed to hazards such as sea level rise, shoreline erosion, and saltwater intrusion. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), global mean sea level is projected to rise between 0.43 m and 0.84 m by the end of the 21st century under high-emission scenarios. Sea level rise, combined with the increasing intensity of storms and alterations in nearshore wave and current dynamics, has accelerated coastal erosion in many parts of the world, threatening the stability and safety of sea dikes, breakwaters, and other coastal infrastructure (D'Alessandro & Frega, 2009; Hsu & Evans, 1989).

Coastal erosion is a complex process influenced by multiple natural and anthropogenic factors. Its characteristics depend on various factors and have been investigated through diverse approaches. Al-Fatlawi and Al-Mamoori (2023) applied remote sensing techniques to analyze the spatiotemporal changes of the Iraqi coastline, identifying areas subject to erosion and accretion. Their findings demonstrate the effectiveness of satellite imagery in monitoring shoreline dynamics. Al-Mamoori and Al-Fatlawi (2022) conducted a comprehensive review of recent geological and engineering studies concerning coastal stability in Iraq, highlighting the growing erosion risk and the critical need for integrated coastal zone management strategies. Khalladi and El Blidi (2021) examined shoreline changes in Essaouira Bay, identifying zones of erosion and deposition which they attributed primarily to human activities and climate change.

In response to these risks, many countries have intensified research and implementation of engineering solutions to stabilize coastal zones and protect sea dikes and nearby communities. Proposed measures include the construction of breakwaters, caisson-type dikes, reinforced dike slopes using soil anchors, wave-resisting walls incorporating energy-absorbing materials, eco-soft dikes, and environmentally friendly infrastructure such as mangrove reforestation and the use of sustainable geotechnical materials. The selection and design of these interventions must be adapted to the specific topographical, geological, hydrodynamic, and socio-economic conditions of each site (Dean & Dalrymple, 2002; Ranasinghe & Turner, 2006).

The coastal region of Vietnam, stretching from the north to the south, is densely populated and supports critical infrastructure as well as diverse and ecologically important ecosystems. However, these areas are also severely affected by climate change and human activities. Over the past two decades, significant issues such as coastal erosion, sea dike settlement, and the degradation of mangrove ecosystems have been reported in provinces such as Ca Mau, Bac Lieu, Soc Trang, and Tra Vinh, and Kien Giang (Nguyen, 2014a; Hoang, 2012). Quartel et al. (2007) and Do et al. (2017) have shown that coastal erosion in the Mekong Delta is intricately linked to reduced sediment supply from upstream, excessive sand mining, and altered hydrodynamic and oceanographic conditions in estuarine and nearshore areas. Luom et al. (2024) discussed the status of mangrove forests and coastal erosion, as well as sea dike systems in Kien Giang and Ca Mau. Their findings indicate that erosion severity in the Ha Tien mangrove zone varies with vegetation density and environmental factors.

Among the most severely affected areas is the An Bien - An Minh coastal region in An Giang Province. This region is currently facing intense shoreline erosion, dike foundation settlement, degradation of protective mangrove forests, and deep inland saltwater intrusion. These phenomena collectively pose substantial risks to local livelihoods and the safety of the western sea dike system. Notably, many segments of the existing dikes, mostly constructed prior to 2000, lack uniform structural integrity. These structures often do not incorporate suitable reinforcement techniques or adequate drainage systems. Meanwhile, continued marine encroachment and the intensification of tidal energy have reduced dike slope stability, particularly in areas underlain by soft soils.

Practical experience shows that ensuring the long-term stability of the sea dike system in An Bien - An Minh requires a combination of traditional and modern engineering approaches, integrating hard and soft solutions. Recent studies in Vietnam have suggested the adoption of hybrid solutions such as mangrove reforestation in combination with eco-soft dikes using melaleuca piles, geotextile mats, or anchored retaining wall systems (Pham et al., 2019). However, such solutions must be based on thorough analysis of geological, topographic, geomorphological, and near-shore hydrodynamic conditions, as well as the socio-economic effectiveness of each alternative.

Based on these practical challenges, this study aims to assess the natural conditions, status of sea dikes, and associated instability risks in the An Bien - An Minh area. Accordingly, suitable engineering solutions are proposed to enhance the resilience and stability of the coastal dike system in the context of climate change. The research findings are intended to provide a scientific basis for effective and sustainable design, upgrading, and management of coastal protection infrastructure in the Mekong Delta's priority areas.

2. Study area and methods

2.1. Study area

The study area is located along the An Minh - An Bien coastal line, situated in An Giang Province, a region representing typical low-lying coastal wetland zones in the Mekong Delta. The topography consists predominantly of alluvial plains, with elevation ranging from -1.50 m to +0.50 m relative to mean sea level. This area is subjected to intensive marine dynamics, including tidal fluctuations, wave actions, and littoral currents, while concurrently experiencing rapid coastal infrastructure development.

Significant morphological changes in the shoreline have been observed since 2009 due to combined influences of wave energy, seasonal monsoons, and sediment transport processes. In particular, coastal erosion dominates much of the shoreline, severely impacting coastal forests and threatening the integrity of the existing 70-kilometer sea dike system.

2.2. Methods

2.2.1. Numerical modeling approach and software

The research methodology of this study employs a numerical approach based on the Finite Element Method (FEM) to analyze the complex stability and stress-deformation behavior of the sea dike system. The analysis was conducted using Plaxis 3D Foundation, a specialized software package for simulating geotechnical problems involving advanced soil constitutive models and complex boundary conditions.

Plaxis 3D solves the governing equations by discretizing the soil mass and structures into a finite number of elements. The core mechanism utilizes elasto-plastic constitutive models to accurately capture the non-linear, stress-dependent stiffness and plastic yielding of the soft subsoil under varying stress paths. This methodology allows for a robust assessment of Soil-Structure Interaction (SSI) between the existing dike, the proposed coastal protection measures, and the highly compressible foundation.

2.2.2. Data acquisition and sourcing

The model input was compiled from a combination of primary and secondary data sources.

a. Data sourcing and citation

All primary input datasets, including geotechnical bore log records and hydrodynamic monitoring results, were obtained from site-specific investigations commissioned for the project. Crucially, all parameters or environmental indices that were adopted or derived from existing literature or regional studies (e.g., regional wave climate trends or correlated soil parameters) are explicitly and fully cited immediately in the main text or in Table footnotes to ensure data transparency.

b. Design environmental parameters

The stability analysis was performed under design hydrodynamic loading conditions derived from oceanographic data measured at a coastal monitoring station located along the An Bien - An Minh shoreline, An Giang Province, Vietnam. The monitoring station is situated in the nearshore zone directly exposed to dominant wave and current conditions influencing the western sea dike system.

Wave data were recorded as continuous time-series measurements during the monitoring period from 06 July 2019 to 09 July 2019, which corresponds to representative energetic conditions of the southwest monsoon season. The recorded parameters include significant wave height (H1/3), maximum wave height (Hmax), minimum wave height, and average wave height.

The wave monitoring instrument was deployed at a water depth of approximately 6-7 m relative to mean sea level. The sensor was installed near the seabed to capture wave characteristics representative of nearshore hydrodynamic conditions governing coastal erosion processes and sea dike stability.

From the recorded time series, key statistical wave parameters were derived and are summarized in Table 1. The temporal variation of wave height and wave period distribution is illustrated in Figures 1 and 2, respectively. These oceanographic data provide the basis for defining design wave conditions and evaluating the performance of the proposed coastal protection measures.

Table 1. Wave height characteristics at the study site.

Characteristic	Wave Height [m]	
	H1/3	Hmax
Maximum	1.40	1.53
Minimum	0.05	0.10
Average	0.38	0.53

2.3. Geotechnical input and model layout

In conjunction with wave monitoring, a series of boreholes were strategically drilled along the coastal mudflats to characterize subsurface geotechnical conditions. The borehole locations are shown in Figure 3.

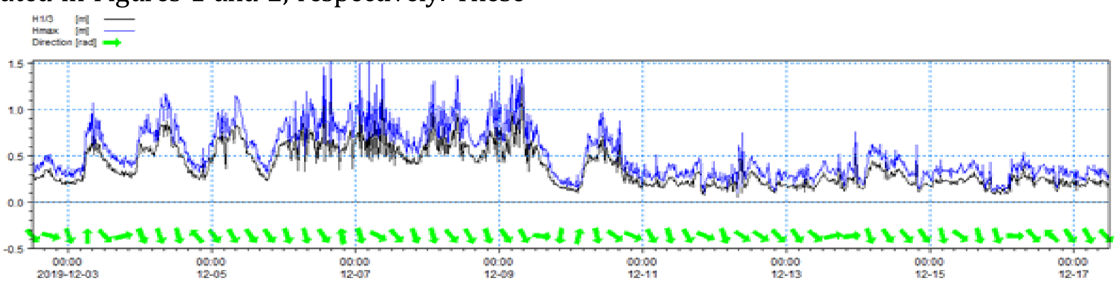


Figure 1. Wave height variations of H1/3 and Hmax at the monitoring station".

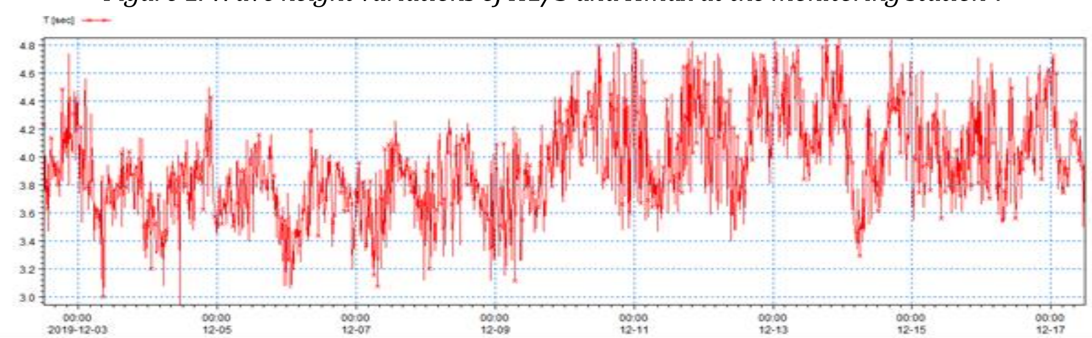


Figure 2. Wave period distribution (T1/3) at the monitoring station

Figure 3. Borehole locations for geotechnical investigation in An Minh - An Bien coastal line.

Soil samples retrieved from the boreholes were subjected to laboratory testing to determine fundamental physical and mechanical properties, including natural moisture content, Atterberg limits, bulk density, elastic modulus, internal friction angle, and cohesion. These geotechnical parameters serve as critical input data for subsequent geotechnical modeling and stability assessment of coastal protection structures. The physico - mechanical properties of soil are shown in Table 2a,2b.

Table 2a. Input parameters used in the Plaxis 3D model.

Parameters	Layer 2	Rock Reinforce (The rubble stone layer)
Model	Soft soil	Mohr-Coulomb (MC)
Behavior	Undrained	Drained
Thick, m	13	
Unit weight, γ(kN/m^3)	14.7	20.00
Saturated unit weight, γbh (kN/m^3)	15.0	22.00
Compression index, Cc	0.697	
Swell index, Cs	0.115	
Void ratio, e0	1.096	
Deformation modulus	1260	50000
Poisson's ratio	0.3	0.26
Cohesion, cref' (kN/m^2)	16.1	1.00
Internal friction angle, φ', degree	11.5	35.00
Dilatancy angle	0.00	5
Permeability coefficient, k(m/day)	5.61E-03	1
ky(m/day)	0.0056	0.0864
kx(m/day)	0.0019	0.0288

Table 2b. Input parameters used in the Plaxis 3D model (Continue).

Parameters	Layer 3
Model	Hardening Soil (HS)
Behavior	Undrained
Thick, m	10
Unit weight, γ(kN/m^3)	17.7
Saturated unit weight, γ_{bh} (kN/m^3)	18.0
Deformation modulus, E_{50}^{ref},kN/m^2	3489.834
Oedometer stiffness , E_{oed}^{ref}, kN/m^2	2791.867
Triaxial secant stiffness, E_{ur}^{ref} , kN/m^2	9480.000
Power, m	0.500
Compression index, Cc	0.166
Swell index, C_s	0.044
Void ratio, e_0	1.015
Cohesion, c_{ref}' (kN/m^2)	16.1
Internal friction angle, φ', degree	10.2
Dilatancy angle	0.00
k_y(m/day)	0.0010
k_x(m/day)	0.0003

3. Results and discussions

3.1. Coastal erosion trends and geotechnical context

+ Impacts and trends of coastal erosion

Under the influence of marine wave dynamics, the shoreline of An Bien and An Minh coastal line (located in the western coastal region of An Giang Province) has experienced significant morphological changes since 2009. The coastal mudflats in this area undergo seasonal variations influenced by weather patterns and discharge flows from inland drainage channels. Although certain sections show signs of mild accretion, coastal erosion remains the dominant process.

The total length of eroded coastline in An Bien area is estimated at approximately 20 kilometers, with the retreat of coastal protection forests reaching up to 20 meters per year in some areas. This erosion intrudes deep inland and poses a direct threat to the existing sea dike system. A multi-year shoreline change analysis (Figure 4) reveals that the average erosion rate ranges from 1÷10 meters per year.

Erosion tends to intensify during the southwest monsoon season (July to September), when recorded wave heights range from 1.4÷1.5 meters. As waves break over shallow nearshore waters, they generate strong longshore currents and disturb the surface structure, displacing large volumes of silt and sand both laterally and perpendicularly to the shoreline. This dynamic is identified as a primary driver of severe erosion in the region. Wave data and directional wave field distributions are illustrated in Figure 5 and 6.

In addition to shoreline retreat, coastal mangrove forests in the study area have also been severely eroded (Figure 7). The degradation of these protective forests has diminished their natural wave attenuation capacity, increasing the vulnerability of the coastal dike system to overtopping and structural failure.

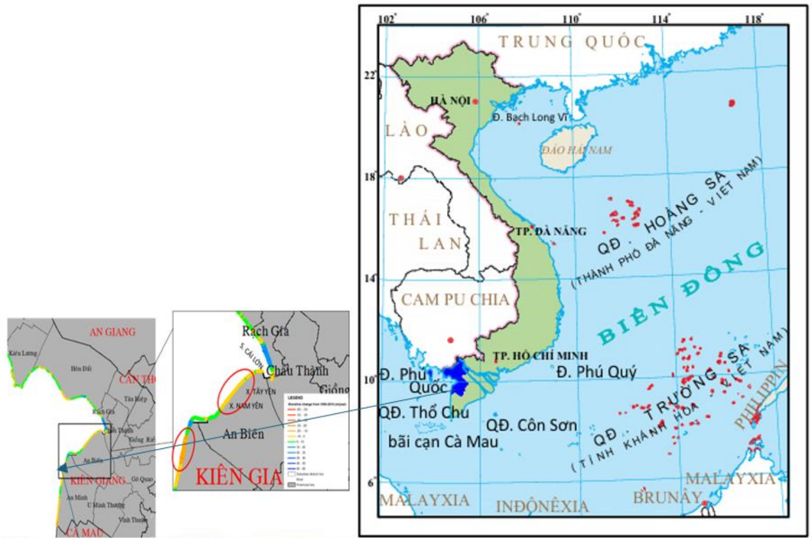


Figure 4. Shoreline erosion trends in An Bien - An Minh coastal area.

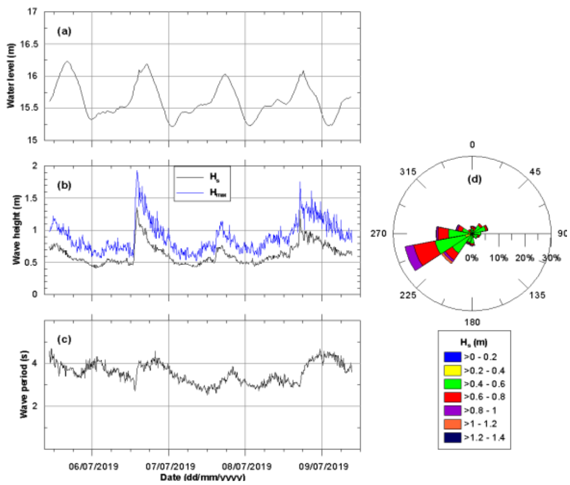


Figure 5. Wave monitoring data at An Bien - An Minh coast from 06/07/2019÷09/07/2019 (Nguyen, 2014b).

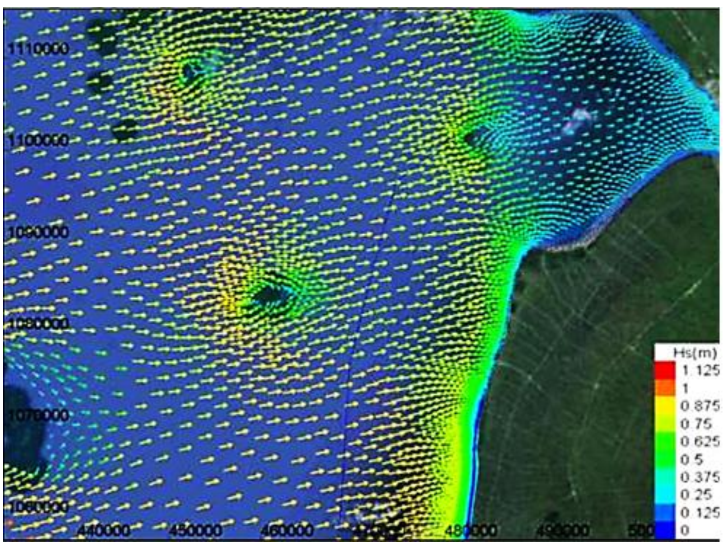


Figure 6. Wave field conditions during the southwest monsoon season (Nguyen, 2014b).

Figure 7. Erosion impacts on coastal protection mangroves (Nguyen, 2014b).

The An Bien - An Minh Sea dike, approximately 70 kilometers in length, with a crest elevation ranging from +2.00÷+2.50 meters and a crown width of 6 meters, has been largely completed in terms of earth embankment construction. However, associated hydraulic structures such as sluice gates and saltwater intrusion control systems remain incomplete. As a result, local authorities have had to construct temporary dams annually, incurring substantial costs and posing operational challenges. Without timely and effective shoreline protection measures, an estimated 10 kilometers of this sea dike may face a high risk of structural failure due to ongoing erosion. Constructed primarily from earth materials and lacking natural wave-breaking forest cover, the embankment is increasingly susceptible to breaching under continued wave attack.

+ Impacts of climate change on coastal dike erosion

Climate change has significantly increased the frequency and intensity of extreme hydro-meteorological events such as heavy rainfall, thunderstorms, squalls, storm surges, and saltwater intrusion. The Mekong Delta (MD), characterized by low-lying terrain, a dense network of rivers and canals, and complex hydrology, is among the most vulnerable regions in Vietnam. According to the Ministry of Natural Resources and Environment (MONRE, 2016), the mean sea level at Ganh Hao station has been rising at a rate of 1.6 cm/year, while Doc river station has recorded an increase of 1.3 cm/year (Table 3).

Table 3. Trends in mean sea level rise from observed data at coastal monitoring stations in southern Vietnam (MONRE, 2016).

No	Station	Monitoring Period	Period Rate of Change (mm/year)	Correlation Index	Evaluation
1	PhuQuy	1986÷2014	5.58	0.9	Rising
2	Vung Tau	1978÷2014	3.19	0.6	Rising
3	Con Dao	1986÷2014	4.79	0.86	Rising
4	Tho Chu	1995÷2014	5.28	0.79	Rising
5	Phu Quoc	1986÷2014	3.4	0.76	Rising

Applying the Brunn rule (Brunn, 1954, 1982), a sea level rise of 2÷4 mm can result in a landward shoreline retreat of 0.1÷0.4 m. Rosati et al. (2013) refined this relationship, estimating that a sea level rise of 0.5 m could induce a shoreline recession of at least 30 meters. Based on observed sea level rise data at monitoring stations in the Mekong Delta between 1981 and 2018, estimated sea level increases of 18.7÷56.7 cm may cause shoreline erosion ranging from 11÷34 meters, with an average annual rate of 0.6 m/year.

In addition, a national-level study conducted by the Vietnam Academy for Water Resources projected that under a sea level rise scenario of 0.3 m by 2050, the average wave height along the western coast of An Giang may increase by approximately 0.15 m - a critical factor expected to exacerbate coastal erosion in the future.

Extreme weather events in the western sea area - such as thunderstorms, strong winds (force 5÷6), gusts (force 7÷8), and wave heights of 2÷4 meters - have been increasingly recorded in recent years, notably in July and August of 2019. The combined effects of storm surges and high waves during these periods caused settlement and damage to multiple coastal protection structures and segments of the sea dike.

In summary, climate change is contributing to the worsening of coastal erosion through various mechanisms, including sea level rise, increased wave energy, and altered littoral current regimes. These developments are anticipated to become increasingly complex and difficult to manage in the future without timely and effective adaptation measures.

3.2. Analysis of coastal dike protection solution

Coastal erosion in the An Bien - An Minh area is driven by a combination of strong hydrodynamic forces, weak soft-soil foundations, and the degradation of natural protective mangrove belts. These factors collectively reduce the stability of the sea dike system and increase the risk of structural failure. Therefore, ensuring long-term safety requires an integrated protection strategy rather than relying on any single measure. This section analyzes a combined solution that includes offshore breakwaters for wave attenuation, mangrove restoration for ecological buffering, and reinforced concrete revetments to prevent direct seawater interaction with the dike body. By integrating hard structural engineering with soft, nature-based measures, the proposed approach aims to simultaneously reduce incoming wave energy, stabilize shoreline morphology, and enhance the structural resilience of the earthen dike. The effectiveness of each component and their synergistic contributions to overall dike stability are evaluated in the following subsections.

3.2.1. Response analysis of the Integrated Dike-Breakwater System

+ Selection criteria for breakwater systems

The use of mangrove belts as natural wave attenuators has proven effective in reducing wave height, limiting shoreline and dike erosion, and preserving coastal ecosystems. When correctly designed, mangroves not only dampen wave energy but also promote sediment deposition and mudflat expansion, contributing to long-term dike stability. The wave attenuation performance of mangroves depends on species composition, density, belt width, and local conditions such as salinity, geomorphology, soil type, and tidal regime.

Species selection must consider ecological conditions. In newly formed mudflats frequently inundated with salinity ≥ 3 ‰, Rhizophora mucronata, Avicennia marina, or Sonneratiaapetala are recommended. In stabilized zones with moderate tidal inundation, Avicennia alba or Bruguiera gymnorhiza are suitable. In low-salinity (< 1.5) estuarine areas, Nypa fruticans, Cocos nucifera, or Lumnitzera racemosa are advisable. For areas with minimal tidal influence, Xylocarpus granatum may further enhance ecological and wave attenuation benefits.

Wave attenuation efficiency is quantified by the coefficient Kt, calculated as the ratio between wave height at the dike toe (H_d) and wave height measured seaward of the mangrove belt (H_0). According to TCVN 10405:2020, Kt ≤ 0.3 is required for adequate dike protection. This effectiveness depends on belt width, tree density, and trunk diameter. In areas with challenging hydrodynamics, supplemental structural interventions (e.g., geotextile mattresses, bio-engineered revetments, rock gabions) may be necessary.

Current mangrove belt density at An Minh and An Bien is approximately 1,500÷3,000 trees/ha, with ~75÷80% canopy cover - indicating low-standing density. Based on TCVN 10405:2020 correlations, a minimum belt width of ≥ 300 m is required to achieve Kt ≤ 0.3, which is impractical given erosion rates and aquaculture pressures. Thus, besides mangrove restoration, integrated bio-engineered and structural solutions are essential to achieve sustainable dike resilience under climate change and future sea-level rise

+ Calculation of offshore breakwater design

The design of the offshore breakwater in this study follows the Vietnamese Standard TCVN 9901:2023 on sea dike engineering. The key geometric parameters governing the layout of the breakwater are determined as follows:

Distance from the shoreline to the breakwater:

$$X = (1 \div 1.5)\, L_{S,0} \qquad (1)$$

Length of each breakwater section:

$$L = (1.5 \div 3.0)X \qquad (2)$$

Separation between breakwaters:

$$G = (1/5 \div 1/3)\ (or\ 2 \,.\, L_s\ ) \qquad (3)$$

Position from mangrove belt to breakwater line:

$$L_x = (1 \div 1.5).L_o \qquad (4)$$

Where L_0 is the deep-water wavelength.

For typical deep-water wave conditions in Nam Yên commune (An Bien area): Deep-water wave height, H_o = 4.65 m

Wave period ,T = 7.90 s

Wavelength: L= 97 m

Thus, L_x = (97 ÷ 146) m

TCVN 12261:2018 requires periodic gaps in breakwaters to allow ecological exchange, sediment transport, and small vessel passage.

Crest elevation Zđ is computed in accordance with the Vietnamese Standard TCVN 9901:2023 (Sea dikes - Design requirements):

$$Z_đ = Z_{tk} + 0.5H_s + H_L \tag{5}$$

where this formulation and safety allowance are consistent with the requirements of TCVN 9901:2023 for crest elevation determination of sea dike and associated coastal protection structures.

Z_{tk} - Design water level, +1.10 m;

Hs - Design wave height, 0.76 m;

It should be noted that the design wave height Hs = 0.76 m does not correspond to the offshore significant wave height measured at the monitoring station. Instead, Hs represents the effective design wave height at the structure location under the most unfavorable monsoon wind conditions. This value was adopted from previous detailed coastal engineering analyses conducted for the An Bien - An Minh coastal area, in which wave transformation processes from deep water to the nearshore zone were considered, including wave attenuation due to shallow-water effects, seabed friction, and natural and structural wave-dissipating elements.

Therefore, the design wave height Hs = 0.76 m differs from the offshore significant wave height (H1/3 = 1.40 m, Table 1) and is consistent with standard engineering practice for nearshore coastal structures, where reduced wave heights acting directly on the structure are used for stability and structural design calculations.

H_L - Immediate settlement, 0.12 m.

Thus, $Z_đ$ = 1.10 + 0.76/2 + 0.12 = 1.59 m

Wave height transmitted behind the breakwater:

$$H_{s,t} = K_t.H_{s,i} \tag{6}$$

Since the requirement is $H_{s,t}$ = 0.4 m, it follows that:

$$K_t.H_{s,i} = 0.4 \rightarrow Kt = 0.4/Hs,i \tag{7}$$

By replacing $H_{s,i}$ with H_i (the design wave height).

$$K_t = 0.4/Hi \tag{8}$$

As R_c represents the freeboard height above the design water level, it is selected as:

$$R_c = 0.5H_i \tag{9}$$

The wave transmission coefficient for the proposed rubble-mound breakwater was calculated using the empirical formula by Kees d'Angremond (1996), expressed as:

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.5\xi}\right) \tag{10}$$

where: Rc - freeboard height of the breakwater above the design water level (m); B - crest width of the breakwater (m); H_i - incident wave height was under monsoon conditions (m); ζ - wave breaking parameter; C - Permeability factor of the breakwater slope, C = 0.64 for permeable structures.

Given a design wave height H_i = 0.76 m, the extreme wave height is determined as H_{max}= 1.6×Hi = 1.22 m. For vertical-slope breakwaters, the breaking parameter ξ→0, simplifying the equation to:

$$K_t = -0.4\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31} \tag{11}$$

Preliminary selection of crest widths B and freeboard heights R_c were made based on calculated crest elevations. Wave reduction efficiency behind the structure was then evaluated for each configuration, as summarized in Table 4.

Table 4. Summary of wave reduction performance based on crest elevation and crest width.

B,m	Z_{tk}, m	Z_d, m	R_c, m	H_i, m	K_t	H, m	Result
1.60m	0.75	1.10	0.35	1.22	0.47	0.58	FAIL
2.10m	0.75	1.10	0.35	1.22	0.43	0.52	FAIL
2.60m	0.75	1.10	0.35	1.22	0.39	0.48	FAIL
3.10m	0.75	1.10	0.35	1.22	0.36	0.44	FAIL
1.60m	0.75	1.50	0.75	1.22	0.34	0.42	FAIL
2.10m	0.75	1.50	0.75	1.22	0.29	0.36	PASS
2.60m	0.75	1.50	0.75	1.22	0.26	0.32	PASS
3.10m	0.75	1.50	0.75	1.22	0.23	0.28	PASS

Technically, wave attenuation behind the structure is primarily influenced by the freeboard height (R_c) and crest width (B). Increasing R_c yields a more significant reduction in transmitted wave height compared to increasing B. From a technical perspective, increasing the crest elevation results in a more significant reduction in transmitted wave height compared to increasing the crest width.. Based on evaluations with two crest elevations (+1.10 m and +1.50 m) and four crest widths, the configuration with Zd = +1.50 m (operating level Zoper = +1.60 m) and B = 2.10 m is identified as the most technically appropriate solution in terms of wave attenuation performance and structural safety.

Considering the wave climate at An Minh - An Bien area, the optimal offshore breakwater should be positioned at 97 - 146 m from the shoreline. The minimum crest elevation should be Z ≥ +1.60 m, and the crest width should be B ≥ 2.10 m. Gaps of approximately 10 m should be introduced every 200÷250 m along the breakwater to enhance sediment and ecological exchange, as well as to facilitate the passage of small boats when necessary.

The numerical modeling confirms that the offshore breakwater is the pivotal component of the proposed integrated solution.

The proposed breakwater structure for the region is illustrated in Figure 8. It comprises PHC piles (D300) with a length of 9 m, connected by reinforced concrete beams (40×60 cm). The interior is filled with rubble stones (40×40 cm). To prevent excessive settlement, anti-settlement piles are recommended beneath the rock fill. Additionally, toe protection using large stones is placed seaward to prevent scouring and enhance structural stability.

The Plaxis 3D software was used to simulate the RC pile-beam structural system, as shown in Figure 9. The input parameters for the numerical model are summarized in Table 2a,2b, Table 5.

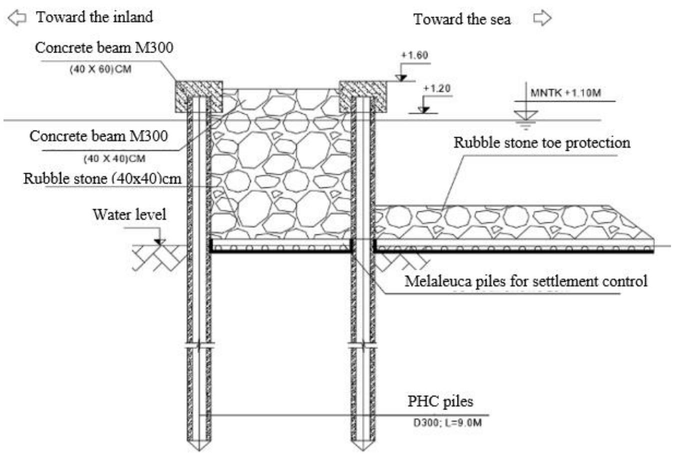


Figure 8. Proposed breakwater structure for An Bien - An Minh area.

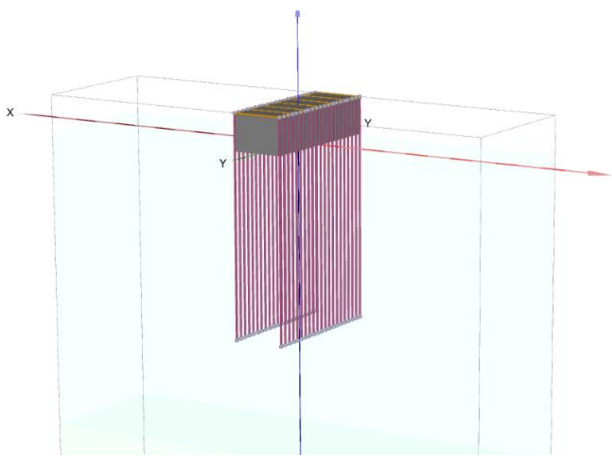


Figure 9. Structural model of reinforced concrete pile-beam system.

Table 5. Input parameters of the RC pile-beam structural system used in the Plaxis 3D model.

Properties	Concrete beam	Embedded beam (RC pile)
Stiffness	$30x10^6$ KN/m^2	$30x10^6$ KN/m^2
Axial skin resistance, Tmax		$1x10^{12}$ KN/m
Base resistance		0 KN

Layer 3 is simulated using the Hardening Soil (HS) model. Deformation modulus is E_{50}^{ref}. The reference secant stiffness in drained triaxial loading is set equal to the reference oedometer stiffness ($E_{50}^{ref}=E_{oed}^{ref}$). The reference unloading/reloading stiffness is taken as three times the triaxial secant stiffness ($E_{ur}^{ref} = 3E_{50}^{ref}$).

Regarding the selection of the constitutive soil model, the Soft Soil model was adopted for Layer 2 to represent the behavior of very soft, normally consolidated to lightly overconsolidated clay with high compressibility, which is typical of the An Bien - An Minh coastal zone. This soil layer is characterized by high water content, large void ratio, and significant primary consolidation under relatively low stress levels. Compared to simpler models such as Mohr-Coulomb, the Soft Soil model is more suitable because it explicitly accounts for stress-dependent stiffness and volumetric compression governed by the compression index (Cc) and swelling index (Cs), which are critical parameters for soft coastal deposits.

The Hardening Soil model was used for the underlying stiffer soil layer (Layer 3) to capture its nonlinear stress-strain behavior under loading and unloading conditions. This combined modeling approach allows a more realistic representation of the stratified soft soil foundation and its interaction with coastal protection structures.

Although a detailed parametric sensitivity analysis was not conducted in this study, the numerical results indicate that the computed maximum displacement of 2.36 cm is primarily controlled by the compressibility parameters (Cc, Cs) and the reference stiffness modulus of the soft soil layer. Reasonable variations in these low-strength soil parameters are expected to influence the magnitude of displacement; however, the overall deformation pattern and stability assessment remain unchanged. Importantly, the predicted displacement values remain within acceptable limits specified by current design standards, indicating that the proposed solution is not overly sensitive to moderate uncertainties in soft soil properties.

The analysis was carried out in four main steps. First, the initial stress state of the subsoil was analyzed to determine the natural stress distribution before any construction activity (Figure 10). Second, the construction process of the revetment was simulated to evaluate its impact on the stress redistribution and deformation within the soil-structure interaction system (Figure 11). Third, the structure was modeled under design wave loading conditions, reflecting the actual service stage during operation (Figure 12). Finally, a global stability analysis was conducted to assess the overall safety, deformation behavior, and internal forces within the structural system.

In the Plaxis 3D model, the design wave loading was applied in the form of an equivalent

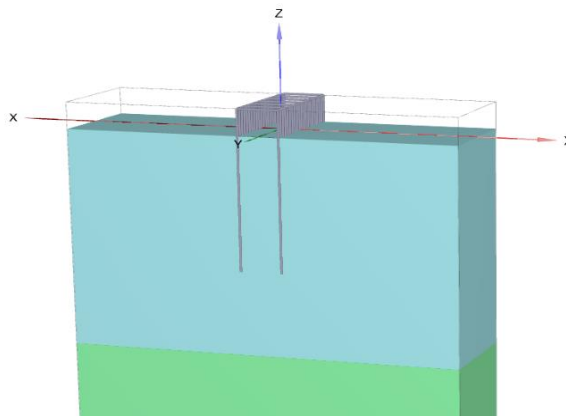


Figure 10. Initial stress state analysis of the foundation soil.

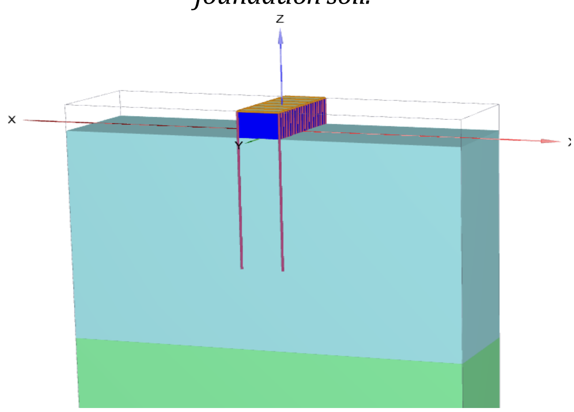


Figure 11. Simulation of the revetment construction process.

static pressure acting on the seaward face of the revetment slab.

The magnitude of the wave pressure was derived from the design wave height Hs and corresponding water level, following standard coastal engineering practice for quasi-static representation of wave action in geotechnical numerical analysis.

The wave pressure was assumed to vary linearly with depth, with the maximum pressure applied at the still water level and decreasing toward the toe of the revetment. This pressure distribution was imposed as a surface load on the exposed slab elements in the direction normal to the slope. The load was applied under drained conditions, allowing pore water pressure dissipation through the drainage layer and toe drains incorporated in the model.

This approach provides a simplified but conservative representation of the hydrodynamic loading effects on the revetment system and is commonly adopted in finite element analyses when fully dynamic wave modeling is beyond the scope of the study.

The simulation results indicate that the maximum total displacement of the coastal revetment system under the design wave loading reaches 2.36 cm (Figure 13). The maximum vertical displacement of the D300 reinforced concrete piles is 1.8 cm, while the maximum horizontal displacement is 1.4 cm, as illustrated in Figure 14 and 15, respectively.

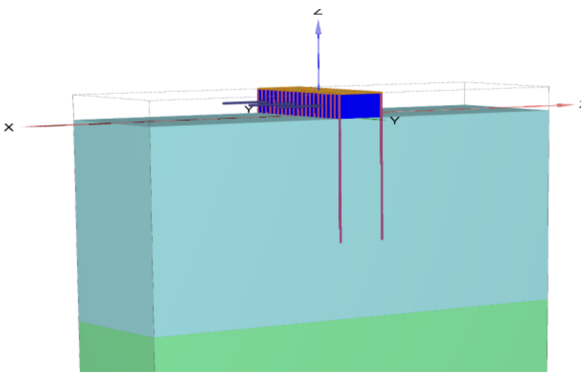


Figure 12. Revetment under the action of the design wave pressure.

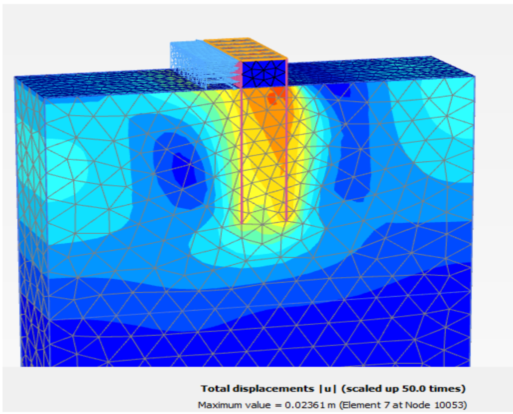


Figure 13. Total displacement of the revetment system under design wave

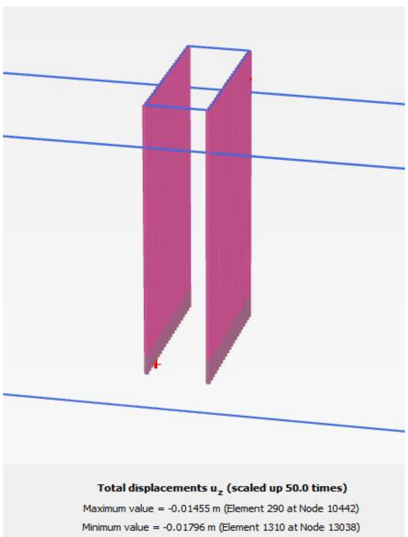


Figure 14. Vertical displacement diagram of the pile subjected to wave loading.

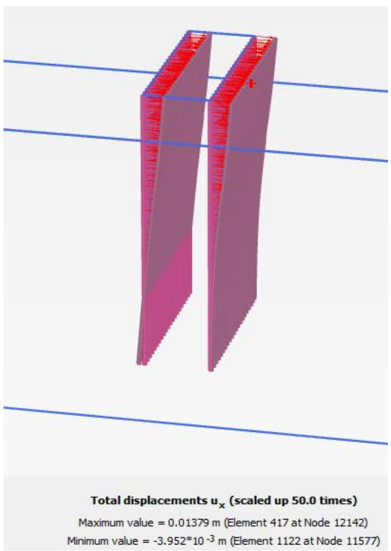


Figure 15. Horizontal displacement diagram of the pile subjected to wave loading.

In addition, the internal force diagrams of the piles, including bending moment and shear force, are presented in Figure 16 and 17. The computed internal force values are within the allowable structural capacity of the PHC D300 piles, ensuring the safe structural performance of the revetment system under the applied design wave loads.

3.2.2 Analysis of the reinforced concrete revetment solution for dike body protection

Although the reinforced concrete revetment provides an effective barrier against seawater intrusion into the earthen dike body, it should be noted that the concept of placing a concrete cover layer on the dike slope is not entirely new. Therefore, for comparison, a brief assessment of the breakwater-dike structure is presented to highlight its potential advantages and inherent limitations relative to conventional revetment solutions. In terms of performance, the breakwater dike is capable of dissipating wave energy more effectively before waves reach the main dike, thereby reducing hydrodynamic pressure on the slope and enhancing overall stability during extreme storm conditions. By attenuating wave forces offshore, this structural form may also lower the design demands on the revetment materials of the landward dike.

However, breakwater dikes also exhibit several disadvantages. They generally require more complex hydraulic and geotechnical analyses and careful consideration of their influence on local sediment transport and nearshore morphology.Inappropriate alignment or structural configuration may lead to localized scour or undesired sediment deposition. In addition, the maintenance of armor units or outer layers is relatively demanding under severe marine conditions.

Given these trade-offs, and considering the very soft, organic-rich foundation soils typical of the An Bien - An Minh coastal zone, the present study focuses on evaluating the reinforced concrete revetment solution. Nevertheless, the computed responses of the proposed design should be rigorously checked against the permissible limits specified in current standards to verify its engineering feasibility and ensure long-term performance under design hydraulic conditions.

The coastal dike system in An Bien - An Minh area is primarily constructed on soft soil with high organic matter content (layer 1), characterized by

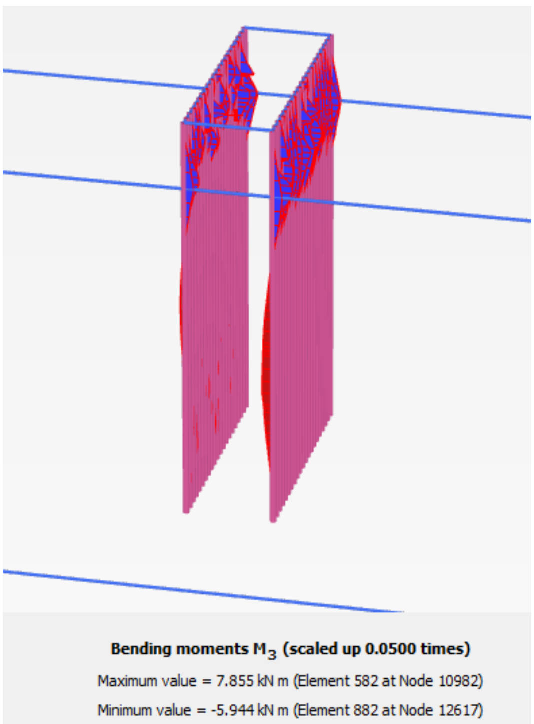


Figure 16. Bending moment diagram of the pile under wave loading.

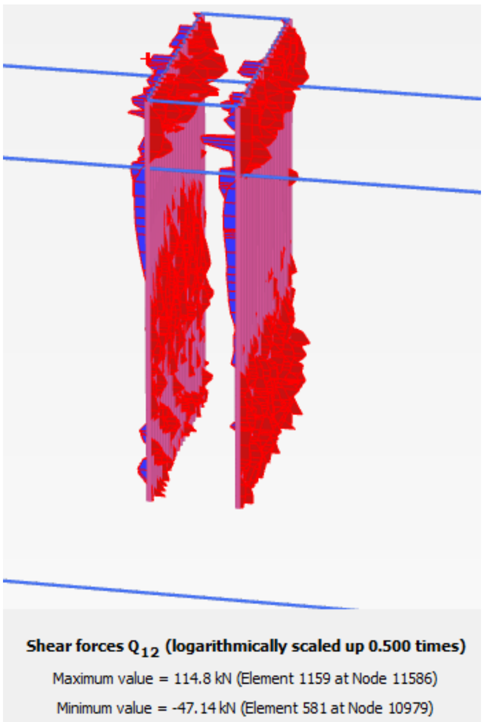


Figure 17. Shear force diagram of the pile under wave loading.

low bearing capacity and a high susceptibility to erosion under direct exposure to seawater and wave action. Current reinforcement solutions, such as the use of rubble stones, precast concrete elements, or stone revetments, have been implemented in several sections. However, practical observations reveal that these methods have not been highly effective; certain areas still exhibit signs of erosion and localized damage. The main reason is that such approaches fail to address the core issue: the direct interaction between seawater and the earthen dike body has not been effectively prevented.

Based on the analysis of these limitations, a solution is proposed to fully cover the seaward face of the dike with a reinforced concrete slab combined with a geotextile layer, in order to completely isolate the dike body from the marine environment. Specifically, a 10 cm thick reinforced concrete slab is cast on the dike slope, reinforced with D10 steel bars arranged in a 20 × 20 cm grid. The concrete is divided into 5 m long sections with expansion joints to minimize cracking due to shrinkage and thermal fluctuation. Beneath the concrete, a geotextile layer serves both as a seepage barrier and a protective layer for the weak subsoil. The geotextile is isotropic and has an axial stiffness (EA_1) of 1.0×10^8 kN/m. Additionally, a drainage system consisting of weep holes and concrete toe drains is incorporated to release any water accumulated within the dike body, thereby enhancing long-term stability. For segments exposed to high wave forces, crest walls can be installed to increase elevation and prevent overtopping. The cross-section of the dike body is illustrated in Figure 18. The calculation steps are presented in Figure 19. The computational results are presented in Figure 20.

The design verification focuses on two critical aspects: External Stability (safety of the slab on the slope) and Internal Forces (structural strength of the slab)

3.3. Stability analysis of the reinforced concrete revetment system

In coastal engineering practice, the performance of revetment systems must be evaluated by first assessing their external stability under hydrodynamic loading before considering internal structural strength. Primary failure modes such as toe scour, undermining, sliding, and uplift govern the overall safety of slope protection systems. If these external stability conditions are not satisfied, structural failure may occur

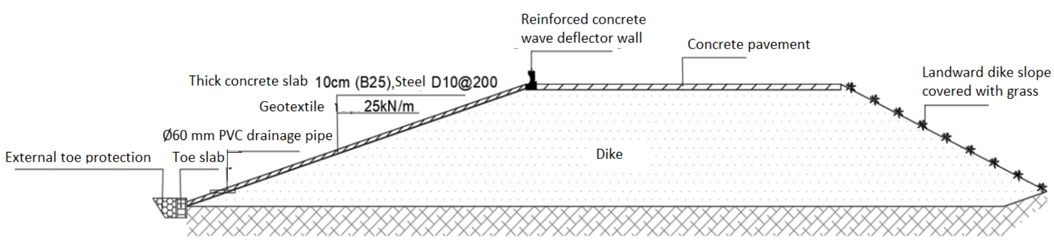
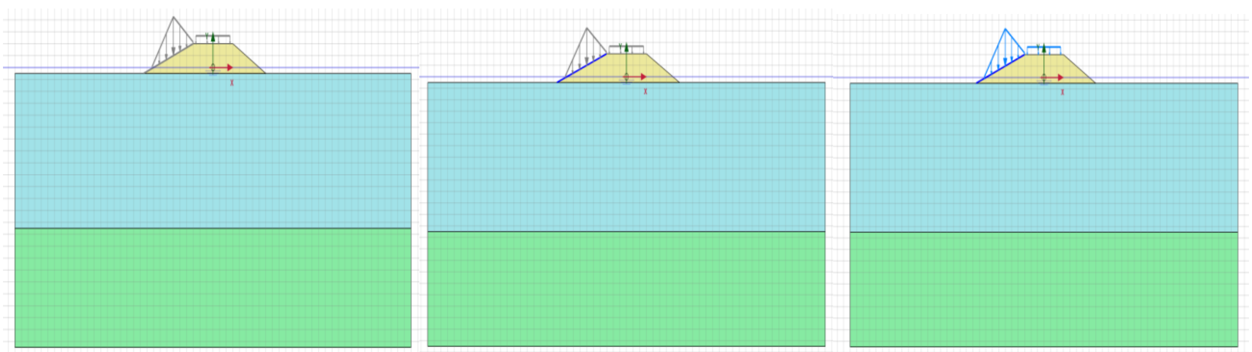


Figure 18. Seawall covering solution using reinforced concrete slabs



(a) Step 1: Analyze the initial condition. *(b) Step 2: Construct the protective concrete slab and underlying geotextile layer.* *(c) Step 3: Compute wave pressure acting on the dike face (as defined in Section 3).*

Figure 19. Calculation steps for internal forces in the concrete slab.

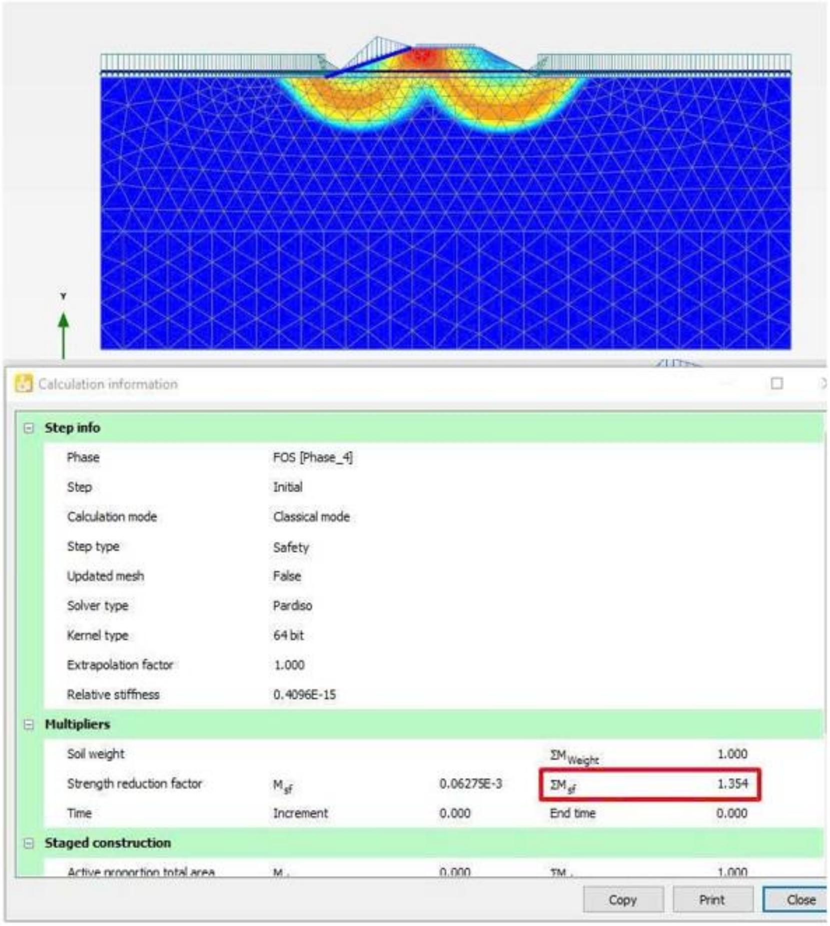


Figure 20. Sliding stability check.

regardless of the material strength of the revetment slab.

Accordingly, the analysis of the proposed reinforced concrete revetment system is structured to prioritize: (i) stability of the revetment toe against wave-induced scour and undermining, (ii) stability of the slab against sliding and uplift due to wave downrush and pore water pressure, and only subsequently (iii) verification of internal forces in the reinforced concrete slab.

3.3.1. External stability verification of the reinforced concrete revetment

The overall stability of the reinforced concrete (RC) slab revetment was evaluated under design hydrodynamic loading conditions, including wave pressure and self-weight, in full compliance with the current Vietnamese Standard TCVN 9901:2023 (Sea dikes - Design requirements). In accordance with coastal engineering practice, the assessment prioritizes external stability criteria governing the ability of the revetment system to remain stationary under wave action before considering internal material strength.

+ Stability of the revetment toe against scour and undermining

The stability of the revetment toe is a primary controlling factor for the safety of the entire slope protection system. Concentrated wave-induced flow and return currents may cause localized scour and undermining at the toe, which can lead to progressive loss of support and eventual collapse of the overlying slab regardless of its structural strength.

In the proposed configuration, toe stability is ensured through the combined effect of offshore breakwaters, which significantly reduce incident wave energy, and the provision of a reinforced concrete toe beam integrated with an effective drainage system. These measures limit near-bed flow velocities and prevent erosion of the foundation soil at the toe. Consequently, the toe remains stable under the design wave conditions considered in this study.

+ Sliding and uplift stability of the revetment slab

Following verification of toe stability, the reinforced concrete slab was assessed for stability against sliding and uplift under wave downrush and pore water pressure. Sliding is the dominant external failure mode for revetment slabs placed on sloping embankments. The factor of safety against sliding (Fs) was calculated as the ratio of total stabilizing forces (self-weight, friction, and adhesion) to the total driving forces (downslope component of gravity and wave-induced forces acting parallel to the slope).

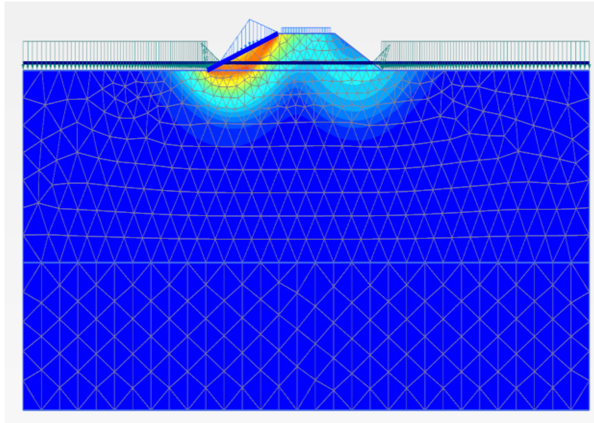
The analysis indicates that Fs = 1.354, which exceeds the minimum required safety factor (Fs,min = 1.30) specified in TCVN 9901:2023 for permanent sea dike protection structures. Therefore, the revetment slab is considered stable against sliding failure.

Potential uplift or breakout caused by excess pore water pressure beneath the slab during wave run-up and drawdown is effectively mitigated by the design. The combined use of a geotextile layer and a network of weep holes and toe drains allows rapid dissipation of pore water pressure, preventing the accumulation of hydrostatic or hydrodynamic uplift forces that could compromise slab stability.

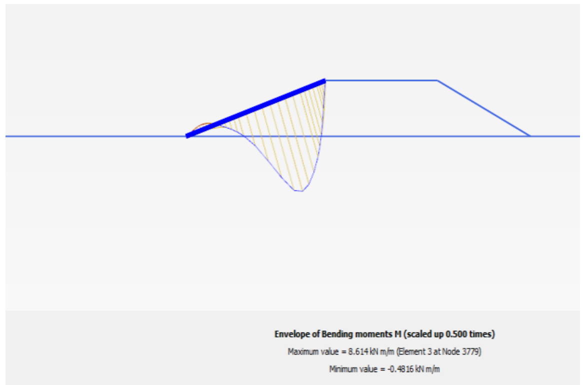
3.3.2. Internal force verification of the reinforced concrete slab

After confirming that the revetment system is externally stable and remains stationary under hydrodynamic loading, the internal forces induced in the reinforced concrete slab were analyzed to verify its structural capacity. The numerical results under design wave loading are presented in Figure 21, including the strain field, deformation mesh, maximum bending moment, and maximum shear force.

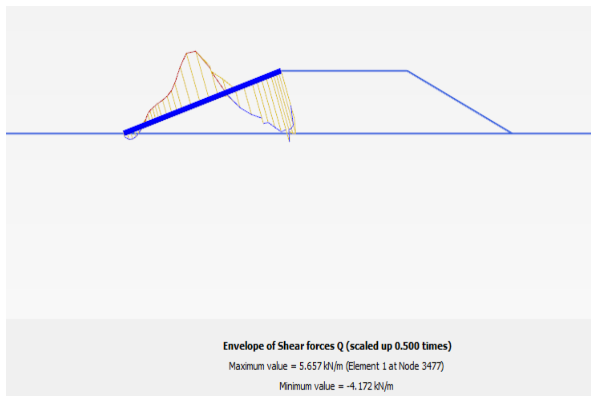
The analysis shows that the maximum bending moment induced by wave loading is 8.6 kNm/m, while the maximum shear force is 5.6 kN/m. Based on these internal force values, the reinforced concrete slab was designed in accordance with ACI 318, ensuring adequate load-bearing capacity, crack control, and long-term durability in a corrosive marine environment. The D10 steel reinforcement arranged in a 20 × 20 cm mesh satisfies the requirements for bending, shear resistance, and crack limitation.



(a) Strain field and deformation mesh.



(b) Bending moment in reinforced concrete (RC) Mmax = 8.6 kNm/m.



(c) Shear force in the concrete slab Qmax =5.6 kN/m.

Figure 21. Computed internal forces in the concrete slab.

Compared with previous studies-such as the gabion-based revetment systems proposed by Nguyen & Tran (2018) and the wave barrier wall solution suggested by Le (2020)-the proposed reinforced concrete slab combined with a geotextile layer provides superior isolation of the earthen dike body from direct seawater interaction, which is the critical factor governing long-term stability. In addition, the geotextile layer contributes to stress redistribution and mitigation of localized settlement, advantages that are difficult to achieve using stone or precast concrete elements alone. These findings are consistent with the conclusions of Wubshet et al. (2022) regarding the effectiveness of hard surface protection combined with impermeable barriers for earthen embankments founded on soft soils.

In summary, once external stability is ensured, the proposed revetment solution demonstrates sufficient structural capacity and reliability, meeting key criteria for long-term stability and applicability to coastal dike systems under similar geological and hydrodynamic conditions, such as those found in the southwestern Mekong Delta. Future studies should focus on pilot-scale implementation and long-term field monitoring of deformation, pore water pressure, and seepage behavior to further validate and optimize the proposed design.

4. Conclusions

This study has demonstrated that the An Bien - An Minh coastal zone is currently facing a high risk of sea-dike instability, primarily driven by the combined effects of soft ground conditions, wave-induced erosion, and the intensifying impacts of climate change. Results from both field investigations and numerical simulations indicate that ground displacement and structural deformations may potentially exceed allowable limits in the absence of integrated protective interventions. Notably, simulations conducted using Plaxis 3D revealed that the total displacement of the revetment system could reach up to 2.36 cm, while the displacement of reinforced concrete piles may approach 1.8 cm. However, these values remain within acceptable safety thresholds, provided that appropriate design measures are implemented.

Based on these findings, the research proposes a comprehensive set of countermeasures:

(1) Covering the dike crest with reinforced concrete combined with geotextile layers to prevent seawater intrusion into the dike body;

(2) Construction of offshore breakwaters with optimized geometry and elevation to dissipate wave energy before it impacts the dike toe;

(3) Restoration and expansion of mangrove forests to form a natural ecological buffer zone that mitigates wave action and promotes shoreline stability. The proposed solution is technically feasible and satisfies key requirements for stability, durability, and applicability to coastal dike systems under similar geological and hydraulic conditions.

The outcomes of this research serve as a crucial scientific foundation for the planning, upgrading, and sustainable management of sea dike systems in the Southwestern coastal region of Vietnam. Moreover, the integrated approach combining numerical modeling and empirical field assessment can be replicated in other coastal areas with similar geotechnical and environmental conditions across the Mekong Delta and along the Vietnamese coastline. Pilot-scale implementation and long-term monitoring are necessary to validate the effectiveness and practicality of the proposed solutions prior to large-scale deployment.

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Contributions of authors

Tai Tien Nguyen - proposes ideas and contributes to the manuscript; Son Truong Bui, Nu Thi Nguyen, Duong Thanh Nguyen - constructs the manuscript and contributes to the material analyses. The authors declare no conflict of interest.

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