Journal of Sustainability Science and Management
Volume 17 Number 7, July 2022: 28-45
eISSN: 2672-7226

COASTAL PROTECTION BY A STEPPED CONCRETE REVETMENT IN THAILAND

SARINYA SANITWONG-NA-AYUTTHAYA[1], CHERDVONG SAENGSUPAVANICH[1]*, EFFI HELMY ARIFFIN[2,3], SUWAT BUAYAM[4], LADDAWAN WIRAMITCHAI[4], KAMONPOL KAYUNHA[4] AND YAOWALUCK CHARUSEIAM[4]

[1]Faculty of International Maritime Studies, Kasetsart University, Sri Racha Campus, Chonburi 20230, Thailand. [2]Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia. [3]Institute of Oceanography and Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia. [4]STS Engineering Consultant, Bangkok 10400, Thailand.

**Corresponding author: cherdvong.sa@ku.th*
Submitted final draft: 8 February 2022 *Accepted: 9 April 2022* http://doi.org/10.46754/jssm.2022.07.003

Abstract: Protecting an eroding coastline is necessary. This study presents how Thailand is undertaking a revetment project by using the Pra-Ae beach as an excellent example where the stepped concrete revetment was successfully implemented and fundamental coastal engineering data was gathered. Public involvement and a surveys involving homes and homeowners of beachside properties were conducted and it provided indispensable recommendations from the revetment project's stakeholders. Existing environmental conditions covering various parameters were assessed. The stepped concrete revetment was carefully designed to protect the coast while promoting the destination and revetment as a good getaway, and relaxation spot in a bid to enhance tourism. As the result, the authors were able to study the design of every revetment component. The parapet elevation was +4.2 m from the mean sea level and designed to be a sitting place for tourists to watch sunset. The overtopping discharge was 0.138 cu.m./s/m. The revetment crest was designed for secondary utilisation in activities such as walking and cycling. In this manner, the stepped concrete revetment at the Pra-Ae beach successfully prevents the erosion of the beach and coastline and promotes tourism. This case study affirms the fact that, when carefully and accurately designed, the revetment will not only protect the beach, but also promote local communitywell-being. The belief that the revetment would do more harm than good to the environment and the community is evidemtly not true.

Keywords: Coastal erosion, stepped concrete revetment, public participation, Pra-Ae beach, integrated coastal management.

Introduction

Coastal erosion is one of the major problems facing coastal towns and cities worldwide (Ahmed *et al*., 2021; Bacopoulos & Clark, 2021; Setyawan, 2021; Uda, 2022). The erosion of the coastline has various causes such as global warming that causes sea levels to rise (Palamakumbure *et al*., 2020, Paprotny *et al*., 2021), following a reduction of riverine and other land-based sediments (Marchesiello *et al*., 2019; Bidorn *et al*., 2021).

The issue is compounded by changes in the use of the land (Saengsupavanich, 2013; Bidorn *et al.,* 2021), the negative impacts of coastal structures such as jetties and breakwaters (Saengsupavanich, 2019; Saengsupavanich, 2020) and the natural occurrence of high waves during monsoons (Ismail *et al*., 2020; Shariful *et al*., 2020) among other factors that include anthropogenic activities that disturb the equilibrium of the coastal sediment (Kamphuis, 2010; Ratnayake *et al*., 2020; Gunasinghe *et al*., 2021).

Managing coastal erosion is not an easy task as many factors are involved. To develop sustainable coastal protections, engineering designs must incorporate environmental and social considerations (Ratnayake *et al*., 2019).

Coastal protection can be divided into two categories either hard or soft options. The hard options implement engineering structures such as revetments and breakwaters (Saengsupavanich *et al*., 2009; Ariffin *et al*., 2020; Rattharangsri *et al*., 2020; Zulfakar *et al*., 2020) while the soft approach relies on non-structural methods such as retreat, setback, mangrove reforestation, bamboo fences (Saengsupavanich, 2013) and even ecologically-friendly structures including reef balls and oyster reefs (Fivash *et al.,* 2021). Both the hard and the soft coastal management approaches have advantages and disadvantages, which are widely discussed in the available literature (Pranzini, 2018; Ariffin *et al*., 2020) and such debates are not the objective of this study.

Additionally, there are a few articles that have considered the negative effects of engineering and installing coastal protections (Aguilera *et al*., 2016; Griggs & Patsch, 2019; Suzuki *et al*., 2021). On the other hand, we intend to present a contrast case study to argue that, if properly designed and implemented, the engineering structures can have numerous positive consequences. This article aims to elaborate on how the Public Works and Town and Country Planning Department (DPT) Ministry in Thailand, successfully managed the coastal erosion at Pra-Ae beach, Koa Lanta, Krabi province by installing a stepped concrete revetment.

The approach used to great success involved the public, environmental evaluations and careful engineering designs. This case study may be used as a guide by other international coastal managers if they consider that Thailand's approach to be sustainable and suitable for adoption in their area. Other coastal protection projects can use this article as a baseline to improve the implementation of their coastal protections.

Thailand's Coastal Status and Responsible Governmental Departments

Thailand is a tropical country with diverse coastal resources. There are 23 shore-connected provinces. Its shoreline is approximately 3,151.13 km, consisting of 1,631 km of sandy coasts, 326 km of rocky coasts, 1,020 km of muddy coasts and the rest are other coastal features such as inlets and estuaries (Marine and Coastal Resources Department, 2017).

In 2017, approximately 704.44 km of Thailand's shoreline experienced erosion (Marine and Coastal Resources Department, undated). In 2021, there were three government departments in Thailand responsible for coastal protection:

(a) Public Works, Town and Country Planning Department (DPT)

(b) Department of Marine and Coastal Resources

(c) Marine Department

Over the last five years, the DPT has been very enthusiastic about defending its eroding coasts with revetments, having armored more than 45.7 km of the eroded shoreline. Being under the Interior Ministry, the DPT is responsible for public works such as building designs and construction controls, town and rural developments, formulating and supervising land use policies and national infrastructure. The DPT has the mandate of the government, the people and a civic duty to ensure the well-being of coastal communities.

The Study Area

Krabi is one of many shore-faced provinces in Thailand that suffers from coastal erosion. The province has a total coastline covering 203.79 km.

Pra-Ae beach (Figure 1) located in Saladan subdistrict of the Koh Lanta district is an area with great potential for development. It is a popular tourist destination for both Thais and foreign visitors, especially from May to November. However, the beach experiences chronic erosion from high waves in the monsoon season. The high waves attack the shoreline ceaselessly and the local government has had to recover the beach every year, wasting its limited annual budget.

Resorts, restaurants, walking tracks and other infrastructure is often destroyed by the waves and the erosion hampers beach utilisation

Figure 1: The study area, the Pra-Ae beach

and impedes sustainable beach development projects.

The Pra-Ae beach faces Andaman Sea and is open to monsoon waves every year from May to October. The annual wave climate synthesised by JONSWAP (which stands for Joint North Sea Wave Project) method (Kamphuis, 2010) revealed that the dominant wave direction is from the west and hits the Pra-Ae beach perpendicularly. The total calm period (having a significant wave height of less than 0.21 m) is 90.83% (Figure 2).

The authors applied a Weibull distribution to predict the extreme wave characteristics. The 50-year return period of the waves would have a significant wave height of 5.19 m and a spectral peak wave period of 11.81 s (Table 1). Long-term tidal statistics from the Marine Department indicates that the tidal range (mean high water to mean low water) at the Krabi station located near the Pra-Ae beach is 2.04 m. The highest water elevation was +2.11 m above the national mean sea level (MSL) (Table 2).

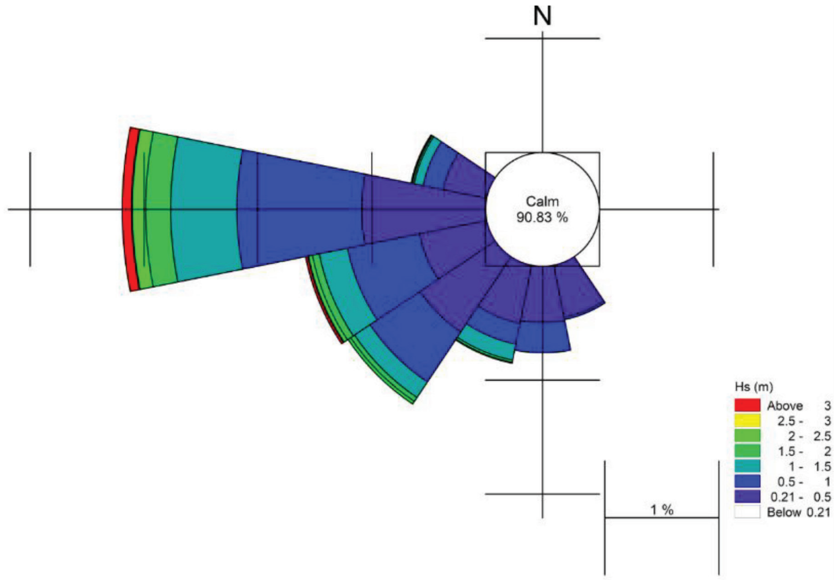

Figure 2: Annual wave rose at the Pra-Ae coast

Table 1: Long-term water characteristics

Return Period (year)	Significant Wave Height (m)	Spectral Peak Wave Period (s)
5	3.91	10.23
10	4.29	10.72
15	4.51	11.00
20	4.67	11.20
25	4.80	11.35
50	5.19	11.81

Table 2: Long-term water level statistics at Krabi station

	Water Level (m. MSL)
Mean high water spring	1.35
Mean high water	0.98
Mean high water neap	0.57
Local mean sea level	-0.02
Mean low water neap	-0.64
Mean low water	-1.06
Mean low water spring	-1.44
Highest high water	2.11
Lowest low water	-2.10

Materials and Methods

Public Involvements during the Revetment Design

Public participation is an important step for the success of integrated coastal erosion management. It has a vital role in sharing information with local communities, raising their awareness and reducing the negative impact of the project implementation. Every coastal protection project implemented by the DPT allows local communities and other interested parties, including non-government organisations and people living in other areas, to participate in the project and has a forum for them to express their opinions.

Two public meetings were held on site to allow stakeholders and interested individuals to participate in the period under review by this study. The first public meeting was held on 12 November 2015 and aimed to:

(a) Raise the participants' awareness of the situation and erosion levels at the Pra-Ae beach

(b) Propose alternatives to defend the coastline with detailed elaborations about their benefits and possible impacts

(c) Explain a scope of the Initial Environmental Examination (IEE)

(d) Gather concerns from the meeting attendees

(e) Allow the participants to vote for a type of revetment that they considered appropriate for the Pra-Ae beach (Figure 3)

The revetment options introduced in the first public meeting included a geobag revetment, a rock revetment, a gabion revetment, a concrete seawall and a stepped concrete revetment. Voting scores were collected and later analyzed by the Multi-Criteria Analysis (MCA) to select the type of structure that was most suitable to the area which had the fewest negative impacts. The criteria used in the MCA, their definitions, and their weights of importance are presented in Table 3 (Saengsupavanich, 2017).

The second public meeting was held to present the engineering and architectural design results. Participants were allowed to suggest further improvements. Another key objective in the second meeting was to present the initial environmental examination (IEE) results as well as finalise the associated environmental mitigation measures. The meeting attendees were allowed to criticise the mitigation measures and add more intense measures if they considered the prepared measures as being insufficient or not good enough.

Figure 3: The first public meeting on 12 November 2015

Table 3: Criteria for revetment selection

Criteria		Weights (%)
Beach protection	Structures must stabilize shoreline from waves and storms. The effective structures should also be able to limit wave overtopping.	15.18
Constructability	Some structures are difficult to construct and involve a lot of construction processes. The ones that can be installed easily and fast are preferred.	7.14
Maintenance	Structures that require less maintenance are better than the ones that must be continuously repaired.	10.71
Flexibility	In a case when a structure fails, it should be able to slow down the erosion until the budget for the repairment arrives.	9.82
Accordance with society	Coastal protection structures must not only protect the coast but also enhance local livelihood. Occupations of local inhabitants are one of the key factors.	14.29
Environmental impacts	An appropriate coastal protection structure should negatively affect the environment as little as possible.	16.07
Stakeholder acceptance	In the questionnaire distributed during the first public meeting, the attendance was requested to vote for the structure considered appropriate. The most voted structure received the highest score.	18.75
Construction cost	The cost of construction is a financial consideration.	8.04
	Total	**100**

Household Survey

The questionnaire survey was undertaken after the first public meeting. The people living in the 1-km radius of the revetment were selected for interviews. There were 2,473 households. To achieve a 0.05 degree of error, 355 households were sampled. Opinions about the revetments to be constructed as well as any related concerns were collected. The result of the household questionnaire helped the authors to design the revetment to suit local community's needs. Moreover, the authors were able to carefully prescribe environmental mitigation measures based on the received interviews.

Environmental Study

A revetment may have both negative and positive impacts on the environment. During the construction phase, many construction activities may deteriorate the environmental quality. Unlike a pier of a port in Thailand (Saengsupavanich, 2011), there is no legal requirement that the revetment must undertake an Initial Environmental Examination (IEE) or an Environmental Impact Assessment (EIA) in Thailand, collecting environmental parameters is very useful for setting up the appropriate mitigation measures during the construction of the revetment. The reports can also be used as baseline data when monitoring the long-term impact of the revetment. Thus, the DPT has carried out the IEE for its revetment projects.

The IEE requires information on the existing environmental conditions. There are no legal regulations covering what environmental parameters must be collected. No compulsory durations of the environmental samplings are available. The IEE undertaken by this study was based on the authors' experience and judgement, as long as the collected information was adequate to draw suitable environmental measures.

In this study, the current environmental status of: (a) Water quality, (b) Sediment and benthos, (c) Nuisance noise levels, (d)

Phytoplankton and zooplankton and (e) Air quality was collected by standard methods (Figure 4).

The water quality, planktons and benthos were sampled at three stations (at the beginning location of the revetment, the middle of the revetment and the ending location of the revetment). This collected information was vital as it considered the species richness and indicated whether there was any rare marine species in the vicinity. The air quality and noise levels were measured at one station for three consecutive days at the appropriate location near the revetment.

The Wave Propagation Study

The engineering study and design of coastal defenses at the Pra-Ae beach required a lot of information such as wind data, wave climate, extreme water level, sediment characteristics, soil foundation strength, beach profile and bathymetric map. The extreme wave climate was analysed in Table 1. The 50-year return period wave had the offshore significant wave height of 5.19 m and the spectral peak wave period of 11.81 s. The design water level was estimated by adding up the mean high water spring level with wave setup and wind setup.

Following the formula outlined by Kamphuis (2010), the wind setup was estimated to be 0.74 m. The wave setup, resulted from wave breaking, was approximated by applying the Goda (2008)'s formula to be 0.56 m. The design water level was therefore +2.50 m MSL.

After obtaining the extreme wave height and direction as well as the design water level, the study investigated wave propagation towards the shore by applying a numerical software package Mike21 PMS (PMS stands for parabolic mild slope), which has been widely used in many coastal engineering studies (Prukpitikul *et al*., 2019). It is based on a parabolic approximation to the elliptic mild slope equation, and can simulate refraction, diffraction and reflection of linear time harmonic waves on a gently sloping bottom. The simulation result of the Mike21 PMS would reveal the wave height at the revetment's toe, which would be used for additional calculations when designing the revetment.

The Revetment Designs

The revetment components were designed based on careful consideration of wave overtopping discharge. As the Pra-Ae beach attracts a lot of visitors, the revetment should not only effectively protect the beach but also enhance

Figure 4: Environmental samplings (a) water quality, (b) sediment, (c) noise level and (d) air quality

beach utilization as well as promote scenic beauty. Great caution was exercised when determining the revetment's front slope. If the front slope was too steep, wave reflection would happen, leading to narrower beach berm. Thus, the revetment's front slope was set to be 1:2 (vertical:horizontal) in order to allow the sand to climb up the revetment.

A proper revetment crest had to be designed to limit overtopping discharge within an acceptable range. The revetment crest was installed with a parapet to further reduce the overtopping discharge and increase its utilisation as a shorefront seat. The step's height was designed to allow easy walking up and down the beach while effectively reducing the wave run-up. Revetment toe was buried deeper than the expected scour depth. A concrete panel was inserted between each pair of piles to prevent sand migration beneath the revetment.

Geotextile sandbags were installed in front of the toe to reduce direct wave impact against the concrete panel. Empirical equations applied during the design of each revetment's components can be found in Table 4.

Results

The coastal protection project at the Pra-Ae beach was successful not only because of the correct applications of engineering formula and design, but the intensive public involvement in the entire process. This section presents the results of the public involvement, the environmental studies, as well as the finalised revetment configuration.

Public Participations and the Household Survey

The first public meeting was held on 12 November 2015 with 63 participants from different groups of stakeholders, including local inhabitants, local governmental departments, non-governmental organizations, news reporters and interested individuals.

The majority of the attendees (94.2%) agreed with the coastal protection project. During the meeting, the stepped concrete revetment was preferred by the majority of the attendees. Some 77.1% of the participants in the meeting agreed that the stepped concrete revetment was the most appropriate option to protect the Pra-Ae beach while 22.9% of the attendees supported the concrete seawall and 5.7% of the meeting participants selected the geobag revetment. These types of revetments were later analysed by the Multi-Criteria Analysis (MCA), using the criteria in Table 3. As the results, the stepped concrete revetment was selected as the most appropriate type of revetment.

After the first public meeting, a household survey was carried out from 13 to 16 July 2016 involving a total of 355 respondents. Most of the interviewees (330 individuals) supported the revetment implementation while 13 respondents were concerned about corruption and 12 interviewees either disagreed or did not want to choose.

After the detailed design of the stepped concrete revetment was completed, the second public meeting was held on 11 August 2016 with 61 participants from different groups of stakeholders. 72% of the meeting attendants were satisfied with the design, foreseeing

Table 4: Design formula for each revetment element

Revetment Element	Formula Applied
Crest width and protection	Pilarczyk (1998)
Parapet	Doorslaer *et al.* (2015)
Overtopping discharge	Van der Meer (1998)
Toe protection	Mcconnell (1998)

that the Pra-Ae beach would become a tourist attraction once the construction of the stepped concrete revetment was finished.

16% of the attendees at the meeting were concerned about environmental impact of the project during its construction such as traffic, vibrations, noise, dust and the interruption of sediment transport. Only 12% believed that the stepped revetment would not solve the erosion problem and the construction might affect the surrounding ecosystem.

Environmental Studies

The environmental sampling showed that the air and water quality at the Pra-Ae beach was good (Tables 5 and 6). The maximum of 49 phytoplankton species and 29 zooplankton were found near the beach (Tables 7 and 8). The most common phytoplankton was of Division Bacillariophyta while the most common zooplankton was Phylum Mollusca.

Table 5: Total particulate matter and dust with a size of less than 10 microns during 16 to 19 February 2016

Parameters	Unit	24-hour Average Value		
		16-17 February 2016	17-18 February 2016	18-19 February 2016
Total dust	mg/m^3	0.058	0.051	0.050
Particulate matter less than 10 microns in size	mg/m^3	0.042	0.035	0.040

**Air quality monitoring point E 503781.03, N 840594.65

Table 6: Sea water quality at the Pra-Ae beach on 20 December 2015

Parameters	Unit	Collection Point		
		E 503677.84 N 840219.60	E 503653.36 N 840361.15	E 503633.52 N 840494.10
Temperature	°C	29.0	29.2	29.2
Electrical conductivity	ms/cm	47.7	45.6	48.4
pH	-	8.2	8.4	8.4
Salinity	ppb	29.8	30.1	30.2
Dissolved oxygen	mg/L	6.0	6.1	6.2
Total solid content	mg/L	38,080	36,900	33,430
Ammonia-nitrogen in non-ionic form	µg/L	<10.00	<10.00	<10.00
Nitrate-nitrogen	µg/L	<10.00	<10.00	<10.00
Phosphate-phosphorus	µg/L	<5.00	<5.00	<5.00
All coliform bacteria	MPN/100 ml	13	13	11
Fecal coliform bacteria	CFU/100 ml	<1	<1	<1

Table 7: Phytoplankton abundance

	Unit	Collection Point		
		E 503677.84 N 840219.60	**E 503653.36 N 840361.15**	**E 503633.52 N 840494.10**
Abundance (mean)	cells/m^3	196,973	198,817	175,520
- Division Cyanophyta		16,048	12,442	6,892
- Division Bacillariophyta		68,769	110,823	112,082
- Division Pyrrophyta		112,156	75,552	56,546
Number of species	species	49	35	31
Biodiversity index		2.46	2.62	2.74

Table 8: Zooplankton abundance

	Unit	Collection Point		
		E 503677.84 N 840219.60	**E 503653.36 N 840361.15**	**E 503633.52 N 840494.10**
Abundance (mean)	inds./m^2	103,016	89,308	92,675
- Phylum Annelida		679	415	-
- Phylum Mollusca		14,857	7,476	11,367
Number of species	species	29	18	14
Biodiversity index		2.27	1.73	1.83

Revetment Design

The surveyed bathymetry was utilized as the main input data for Mike21 PMS. The design water level was set at +2.50 m MSL. The offshore significant wave height of 5.19 m and the spectral peak wave period of 11.81 s were inserted at the offshore boundary condition. As the result, it was found that, in extreme cases, the wave propagated to the shore and reached the revetment with the wave height of 2.09 m (Figure 5).

Acquiring the wave height at the toe, the authors were able to estimate the overtopping discharge. To maintain natural scenic beauty, the stepped concrete revetment's crest height elevation was set at +3.7 m MSL, being equal to the existing beach dune's level. Applying all formula in Table 4, the authors were able to design every revetment component.

Without a parapet, overtopping discharge would be greater than 0.2 cu.m./s/m. As a result, the parapet was needed at the crest so that it could further reduce the wave overtopping. The parapet with its elevation of +4.2 m MSL was designed to be a sitting place for tourists watching the sunset (Figure 6).

The overtopping discharge was re-estimated to be 0.138 cu.m./s/m, which indicated that the revetment's crest would be damaged if not properly paved. The crest width of 10.2 m was needed in order to protect the crest. To promote further beach utilisation, the revetment crest was designed to be a walking, cycling and relaxing space. The revetment's toe was buried at the elevation of -3.7 m MSL to prevent scouring.

The revetment at the Pra-Ae beach began construction in April 2018 and was finished in January 2020. The authors visited the Pra-Ae beach after the construction had completed to

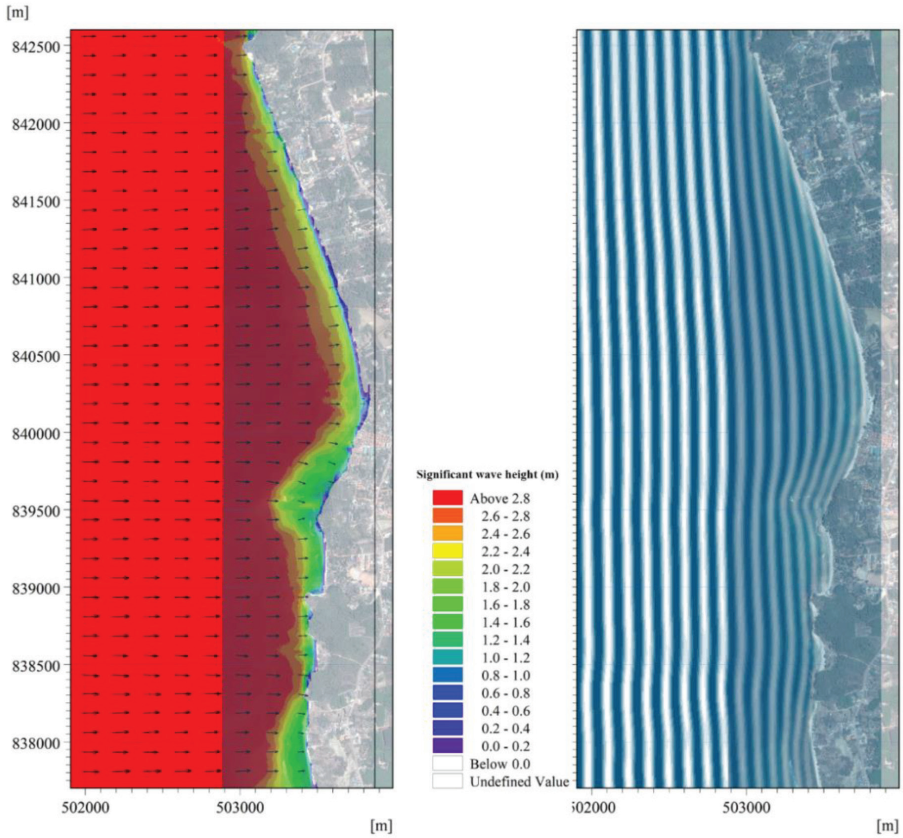

Figure 5: Wave propagation towards the Pra-Ae beach in an extreme case

inspect if the designed revetment has fulfilled its intended function. It was found that the stepped concrete revetment not only prevented erosion, but also attracted local and international tourists. The beach berm was still wide. There was a lot of sand climbing and deposits on the steps (Figure 7). The Pra-Ae beach is now one of the most visited beaches in the Koh Lanta district.

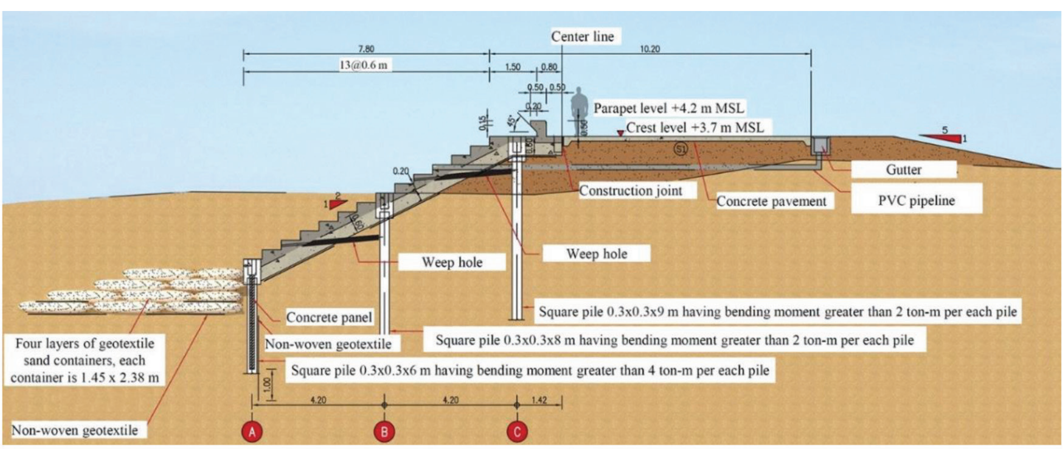

Figure 6: The cross section of the designed revetment

Figure 7: The revetment at the Pra-Ae beach as a new tourist destination

Discussion

Coastal erosion threatens most sea-connected nations. One of the most applied approaches is a coastal revetment. The revetment is not only effective in protecting the coastline, but also promoting local well-being of coastal communities through tourism. This article advocates other similar cases of coastal protection by revetments.

Griggs and Patsch (2019) reports that only 2.5% of California's entire 1,760 km shoreline was armored in 1971 and increased to 13.9% in 2018. The revetment has been applied along the California coast for nearly a century. The erosion affected California's coastal development and infrastructure including both flooding of low-lying areas and erosion of cliffs, bluffs and dunes.

Saengsupavanich (2017) reports an intergrated design of a coastal protection structure in Songkla province in southern Thailand, where the revetment with a blocked surface was carefully designed with architectural improvements for overall aesthetics. In Italy, the erosion increased from approximately 1,000 km in 2005 to roughly 1,400 km in 2015 (Pranzini, 2018). The Italian government implemented hard coastal protection measures including revetments and breakwaters, while walkways have been inserted to allow beachgoers to enjoy a different perspective of the sea and the coast (Pranzini, 2018).

A revetment may partially intercept alongshore sediment transport, consequently creating a downdrift erosion (Saengsupavanich, 2012). In this case, the downdrift erosion induced a positive outcome at an adjacent creek which was frequently clogged (Figure 8). From a shoreline change simulation by a software package called LITPACK, it was found that the Pra-Ae beach would have been eroded as much as 20 m in 25 years if no protection was done (Figure 8). Although the predicted erosion rate was not high, the Pra-Ae beach was a very famous tourist destination that deserved urgent protection. The downdrift erosion actually promoted creek water circulation, improving water quality inside the creek and reducing a risk of inland flooding.

Human intervention in aquatic ecosystems inevitably has both positive and negative impacts on the environment (Dubois *et al*.,

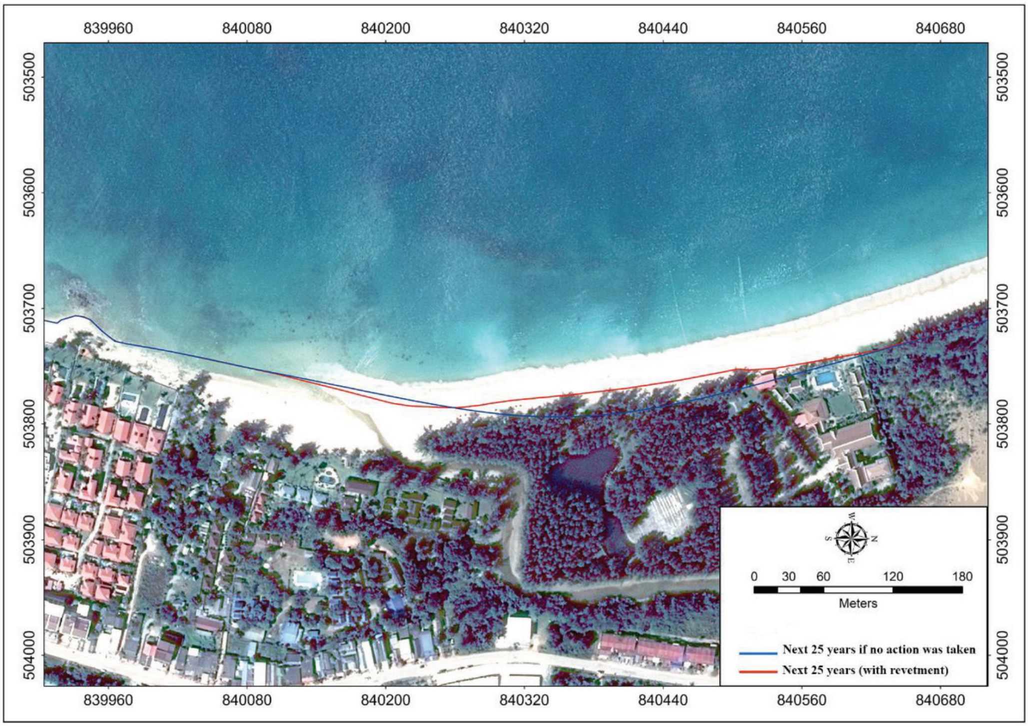

Figure 8: Shoreline prediction simulations

2018; Senanayake *et al*., 2021). Some impacts are immediate and some are long-term. One of the consequences of the construction of the revetment is the loss of a fronting beach because of wave interaction with a structure (Griggs & Patsch, 2019). The authors undertook a beach survey in December 2021 to evaluate the change in beach berm elevation. It was found that the beach in front of the revetment was slighltly eroded. In other words, the fronting beach was scoured by a magnitude of approximately 0.40 m (Figure 9). However, this beach steepening should not be considered significant, compared to other benefits that accrue due to an erosion-safe beach.

If we are overly concerned with the fronting beach slope and let the erosion continue, there will be no beach dunes, no coastal infrastructures, no coastal tourism and no coastal inhabitants. A long-term environmental monitoring programme, covering physical, environmental and socio-economic aspects is necessary (Ratnayake *et al*., 2018). A decision maker must carefully consider if the benefits generated from the revetment outweighs the undesirable side-effects.

It is undeniable that coastal revetments have more negative impact, including visual impacts, restrictions on beach access and loss of the beach width (Griggs & Patsch, 2019). However, when properly designed, the revetment can not only protect the coastline but can also promote natural vegetation as well as increase beach beauty. It can even promote tourism activities and become a resting place for both local people and visitors, as is evident from the many revetment projects designed by the authors (Figure 10).

If the revetment's toe and front slope are accurately determined to minimise the reflected waves, the beach berm in front of the revetment will not become steeper. The sand will climb up the steps. The people will be able to utilise the revetment's steps for picnicking (Figure 5).

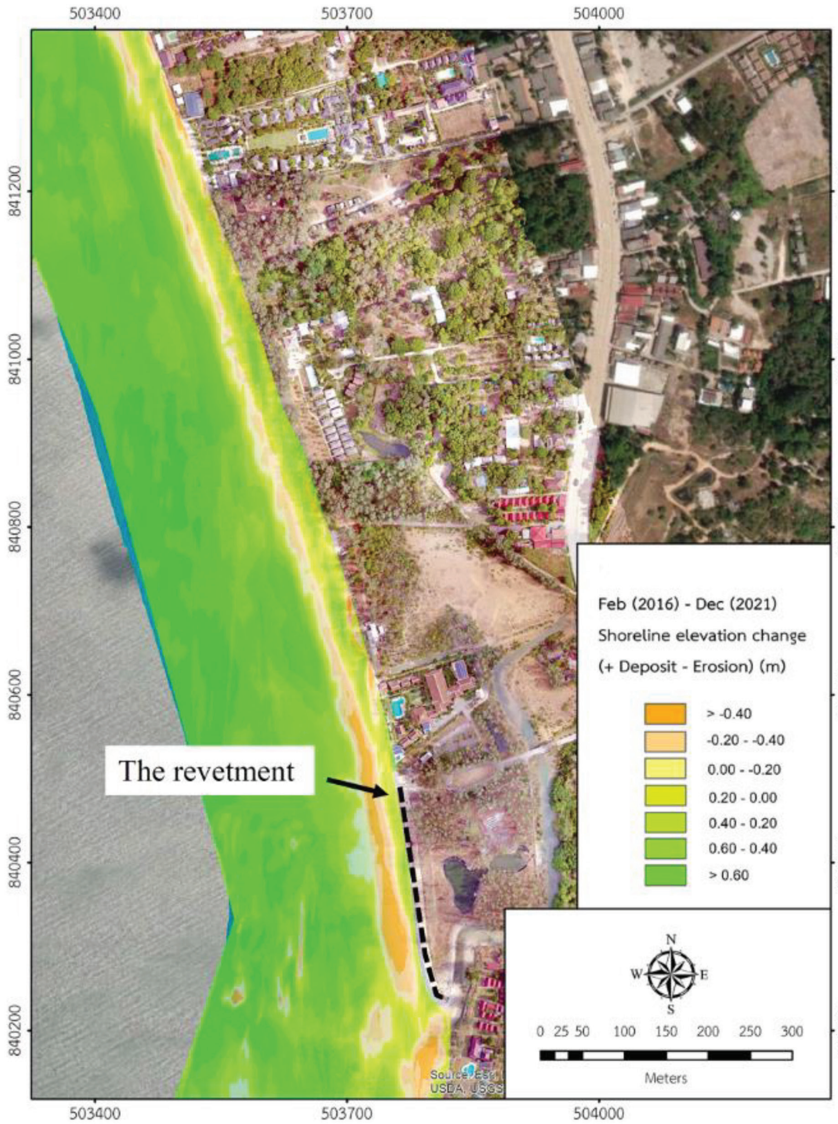

Figure 9: Difference in beach elevation between February 2016 and December 2021

The crest parapet will become a front-row seat to watch beach volleyball. This case study at the Pra-Ae beach proves the fact that, when carefully and theoretically accurately designed, the revetment will have multiple benefits. Not only for protecting the beach but the revetment can be a great socio-economic promoter for local community's well-being.

Conclusion

A stepped concrete revetment is one of the most effective measures in preventing coastal erosion. Benefits from the stepped revetment are multifold. The waves will be dissipated by the steps while the overtopping discharge is reduced by the crest parapet.

Figure 10: Stepped revetments in Thailand, designed by the authors: (a) The Laem Sadet beach, Chanthaburi province, Thailand, (b) The wide beach berm in front of the revetment at the Laem Sadet beach, Chanthaburi province, Thailand, (c) The Khaem Nu beach, Chanthaburi province, Thailand and (d) The stepped revetment at the Khaem Nu beach, Chanthaburi province, Thailand as a new tourist destination

Tourism activities are enhanced. Local inhabitants' livelihood are promoted. On the other hand, if poorly implemented, the revetment project can be catrastrophic. If the stakeholders do not agree and have a chance to involve, the revetment will not be successful. Moreover, if environmental studies and related measures are not available, the revetment will cause many negative externalities. This study demonstrates where the stepped concrete revetment has been successfully implemented in Thailand.

Acknowledgements

The authors would like to thank the of Public Works, Town and Country Planning Department for protecting Thailand's coastline and assisting with this study.

References

Aguilera, M. A., Broitman, B. R., & Thiel, M. (2016). Artificial breakwaters as garbage bins: Structural complexity enhances anthropogenic litter accumulation in marine intertidal habitats. *Environmental Pollution, 214*, 737-747.

Ahmed, N., Howlader, N., Hoque, M. A., & Pradhan, B. (2021). Coastal erosion vulnerability assessment along the Eastern Coast of Bangladesh using geospatial techniques. *Ocean and Coastal Management*, *199*, 105408.

Ariffin, E. H., Zulfakar, Zufayri, M. S., Redzuan, N. S., Mathew, M. J., Akhir, M. F., Baharim, N. B., & Mokhtar, N. A. (2020). Evaluating the effects of beach nourishment on littoral morphodynamics at Kuala Nerus, Terengganu (Malaysia). *Journal of Sustainability Science and Management*, *15*(5), 29-42.

Bacopoulos, P., & Clark, R. R. (2021). Coastal erosion and structural damage due to four consecutive-year major hurricanes: Beach projects afford resilience and coastal protection. *Ocean and Coastal Management, 209*, 105643.

Bidorn, B., Sok, K., Bidorn, K., & Burnett, W. C. (2021). An analysis of the factors responsible for the shoreline retreat of the Chao Phraya Delta (Thailand). *Science of the Total Environment*, *769*, 145253.

Department of Marine and Coastal Resources. (2017). *Marine and coastal resources situation report and coastal erosion of Thailand 2017* (in Thai). https://www.dmcr.go.th/detailLib/4050 (accessed July 2021).

Department of Marine and Coastal Resources. (undated). *Criteria for preparing a plan / project to prevent and solve the problem of coastal erosion* (in Thailand). https://www.dmcr.go.th/detailLib/4936 (accessed Aug 2021).

Doorslaer, K. V., Rouck, J. D., Audenaert, S., &Duquet, V. (2015). Crest modifications to reduce wave overtopping of non-breaking waves over a smooth dike slope. *Coastal Engineering, 105*, 69-88.

Dubois, N., Saulnier-Talbot, E., Mills, K., Gell, P., Battarbee, R., Bennion, H., Chawchai, S., Dong, X., Francus, P., Flower, R., Gomes, D. F., Gregory-Eaves, I., Humane, S., Kattel, G., Jenny, J., Langdon, P., Massaferro, J., McGowan, S., Mikomägi, A., Ngoc, N. T. M., Ratnayake, A. S., Reid, M., Rose, N., Saros, J., Schillereff, D., Tolotti, M., & Valero-Garcés, B. (2018). First human impacts and responses of aquatic systems: A review of palaeolimnological records from around the world. *The Anthropocene Review*, *5*(1), 28-68.

Fivash, G. S., Stüben, D., Bachmann, M., Walles, B., van Belzen, J., Didderen, K., Temmink, R. J. M., Lengkeek, W., van der Heide, T., & Bouma, T. J. (2021). Can we enhance ecosystem-based coastal defense by connecting oysters to marsh edges? Analyzing the limits of oyster reef establishment. *Ecological Engineering, 165*, 106221.

Goda, Y. (2008). Wave setup and longshore current induced by directional spectral waves: Prediction formulas based on numerical computation results. *Coastal Engineering Journal, 50*, 397-440.

Griggs, G., & Patsch, K. (2019). The protection/hardening of California's coast: Times are changing. *Journal of Coastal Research*, *35*, 1051-1061.

Gunasinghe, G. P., Ruhunage, L., Ratnayake, N. P., Ratnayake, A. S., Samaradivakara, G. V. I., & Jayaratne, R. (2021). Influence of manmade effects on geomorphology, bathymetry and coastal dynamics in a monsoon-affected river outlet in Southwest Coast of Sri Lanka. *Environmental Earth Sciences*, *80*, 238.

Ismail, N. I., Ariffin, E. H., Yaacob, R., Lokman, M. H., & Baharim, N. B. (2020). The impact of seasonal monsoons on the morphology of beaches protected by barrier islands in Setiu, Terengganu, Malaysia. *Journal of Sustainability Science and Management, 15*, 1-10.

Kamphuis, J. W. (2010). *Introduction to Coastal Engineering and Management* (2nd ed). Singapore: World Scientific.

Marchesiello, P., Nguyen, N. M., Gratiot, N., Loisel, H., Anthony, E. J., Dinh, C. S., Nguyen, T., Almar, R., & Kestenare, E. (2019). Erosion of the coastal Mekong delta: Assessing natural against man induced processes. *Continental Shelf Research, 181*, 72-89.

Mcconnell, K. (1998). *Revetment Systems against Wave Attack - A Design Manual*. Great Britain: Redwood Books.

Palamakumbure, L., Ratnayake, A. S., Premasiri, H. M. R., Ratnayake, N. P., Katupotha, J., Dushyantha, N., Weththasinghe, S., & Weerakoon, W. A. P. (2020). Sea-level inundation and risk assessment along the south and southwest coasts of Sri Lanka. *Geoenvironmental Disasters*, *7*, 17.

Paprotny, D., Terefenko, P., Giza, A., Czapliński, P., & Vousdoukas, M. I. (2021). Future losses of ecosystem services due to coastal erosion in Europe. *Science of the Total Environment*, *760*, 144310.

Pilarczyk, K. W. (1998). *Dikes and Revetments: Design, Maintenance and Safety Assessment*. Netherlands: A. A. Balkema.

Pranzini, E. (2018). Shore protection in Italy: From hard to soft engineering … and back. *Ocean and Coastal Management, 156*, 43-57.

Prukpitikul, S., Kaewpoo, N., & Ariffin, E. H. (2019). An evaluation of a new offshore breakwater at Sattahip Port, Thailand. *Maritime Technology and Research*, *1*, 15-22.

Ratnayake, A. S., Ratnayake, N. P., Sampei, Y., Vijitha, A. V. P., & Jayamali, S. D. (2018). Seasonal and tidal influence for water quality changes in coastal Bolgoda Lake system, Sri Lanka. *Journal of Coastal Conservation*, *22*, 1191-1199.

Ratnayake, N. P., Ratnayake, A. S., Keegle, P. V., Arachchi, M. A. K. M. M., & Premasiri, H. M. R. (2018). An analysis of beach profile changes subsequent to the Colombo Harbor Expansion Project, Sri Lanka. *Environmental Earth Sciences*, *77*, 24.

Ratnayake, N. P., Ratnayake, A. S., Azoor, R. M., Weththasinghe, S. M., Seneviratne, I. D., Senarathne, N., Premasiri, R., & Dushyantha, N. (2019). Erosion processes driven by monsoon events after a beach nourishment and breakwater construction at Uswetakeiyawa Beach, Sri Lanka. *SN Applied Sciences*, *1*, 52.

Rattharangsri, T., Ariffin, E. H., Awang, N. A., & Hongshuai, Q. (2020). Roughness coefficient of polyurethane-bonded revetment. *Maritime Technology and Research, 2*, 19-32.

Saengsupavanich, C. (2011). A current environmental impact assessment of a port in Thailand: Marine physical aspects. *Ocean and Coastal Management, 54*(2), 101-109.

Saengsupavanich, C. (2012). Assessing and mitigating impacts of shore revetment on neighboring coastline. 2012 International Conference on Environment Science and Engineering IPCBEE Vol.3 2(2012), 24-28. http://ipcbee.com/vol32/005-ICESE2012-D020.pdf

Saengsupavanich, C. (2013). Erosion protection options of a muddy coastline in Thailand: Stakeholders' shared responsibilities. *Ocean and Coastal Management, 83*, 81-90.

Saengsupavanich, C. (2017). Coastal revetment design process in Thailand. *WIT Transactions on the Built Environment*, *170*, 33-44.

Saengsupavanich, C. (2019). Willingness to restore jetty-created erosion at a famous tourism beach. *Ocean and Coastal Management*, *178*, 104817.

Saengsupavanich, C. (2020). Deconstructing a jetty to rectify the downdrift erosion. *Journal of Sustainability Science and Management, 15*, 79-88.

Saengsupavanich, C., Chonwattana, S., & Naimsampao, T. (2009). Coastal erosion through integrated management: A case of Southern Thailand. *Ocean and Coastal Management, 52*, 307-316.

Senanayake, N. D. M., Ratnayake, A. S., Wijesinghe, U. M. P., & Ratnayake, N. P. (2021). Geochemistry and sedimentology of tropical mangrove sediments along the southwest coast of Sri Lanka: Fingerprints for development history of wetlands. *Regional Studies in Marine Science*, *46*, 101884.

Setyawan, W. B. (2021). Adaptation strategy to coastal erosion by rural communities: A lessons learn from Ujunggebang village, Indramayu, West Java, Indonesia. *Maritime Technology and Research*, *4*(2), 252846.

Shariful, F., Sedrati, M., Ariffin, E. H., Md Shubri, S., & Akhir, M. F. (2020). Impact of 2019 tropical storm (Pabuk) on beach morphology, Terengganu coast (Malaysia). *Journal of Coastal Research*, *95*(Special Issue), 346-350.

Suzuki, H., Aoki, T., Inomata, E., Agatsuma, Y., & Aoki, M. N. (2021). Effect of breakwater restoration work following the subsidence caused by the 2011 Tohoku Earthquake on the subtidal kelp population. *Phycological Research*, *69*, 3-11.

Uda, T. (2022). Fundamental issues in Japan's coastal management system for the prevention of beach erosion. *Maritime Technology and Research*, *4*(1), 251788.

Van de Meer, J. W. (1998). Wave run-up and overtopping. In K. W., Pilarczyk (Ed.), *Dikes and Revetments.* Netherlands: A. A. balkema.

Zulfakar, M. S. Z., Akhir, M. F., Ariffin, E. H., Awang, N. A., Yaakob, M. A. M., Chong, W. S., & Muslim, A. M. (2020). The effect of coastal protections on the shoreline evolution at Kuala Nerus, Terengganu (Malaysia). *Journal of Sustainability Science and Management*, *15*(3), 71-85.