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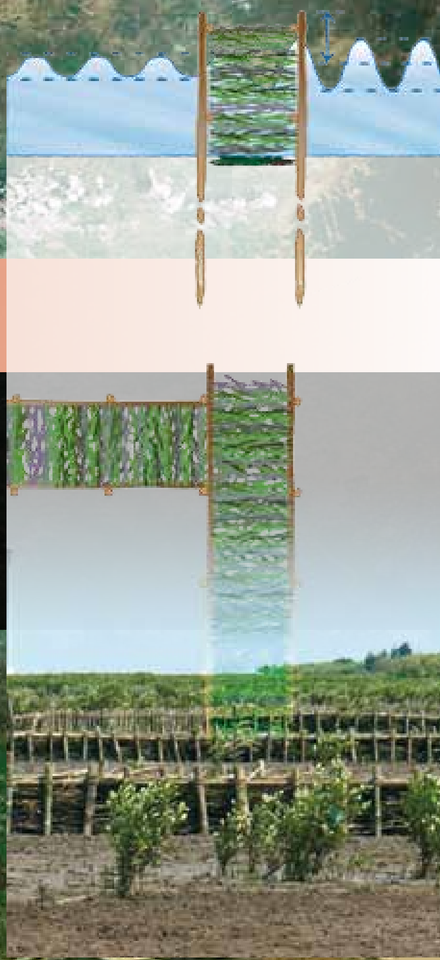

Thorsten Albers - Dinh Cong San - Klaus Schmitt

Shoreline Management Guidelines

Coastal Protection in the Lower Mekong Delta

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Shoreline Management Guidelines

Coastal Protection in the Lower Mekong Delta

Thorsten Albers, Dinh Cong San and Klaus Schmitt

October 2013

FOREWORD

"Deltas are links between continents, coasts, seas, and cultures and are dynamic, highly productive areas in terms of marine life, wildlife, and human development. Their very character also makes deltas vulnerable to sea level rise, subsidence and the effects of climate change, challenges that threaten their ultimate survival. …Increased demands for hydropower and flood protection and highly probable acceleration of sea-level rise, changes in river flows and intensification of storms as a result of climate change will create an emergency of planetary proportions during the 21st century. Elevated international recognition and much more robust governance, research, action and the scientific and technical capacity to support it, are required to ensure social and environmental resilience." (Communiqué of Cooperation, DELTAS 2013 Viet Nam: World Delta Dialogues II, May 2013, Ho Chi Minh City, Viet Nam).

One of the challenges the Mekong Delta in Viet Nam is facing is erosion. Because the Delta is densely populated and plays an important role for the economy of Viet Nam many different attempts have been made to protect the coast from erosion and the land from flooding. Despite these attempts, erosion is still destroying mangrove forests and is endangering the dyke and thus people and infrastructure behind the dyke. Therefore, a new approach to coastal protection has been piloted along the coast of Soc Trang and Bac Lieu Provinces, namely an area coastal protection strategy which uses floodplain management as a sustainable and effective way of erosion and flood protection. The design and construction of the structural protection measures is based on numeric modelling which simulates hydrodynamics and shoreline development as well as physical modelling to ensure effectiveness and avoid negative effects such as downdrift erosion as far as possible.

Chapter 5 of the shoreline management guidelines provides a comprehensive overview of the different elements of erosion and flood protection and gives examples of their application in the Lower Mekong Delta. This chapter is written for planners and decision-makers who should use the guidelines for the selection of site specific and appropriate erosion protection measures. In addition, the other chapters provide a basic overview of coastal engineering, shoreline and coastal management strategies and coastal design.

Dr. Klaus Schmitt

Chief Technical Advisor,
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Acronyms

ADB	Asian Development Bank
ADCP	Acoustic Doppler Current Profiler
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
BP	Before Present
BWK	Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau e.V.
CEM	Coastal Engineering Manual by the US Army Corps of Engineers
DGPS	Differential Global Positioning System
DSS	Decision Support System
EAK	Empfehlungen des Ausschusses für Küstenschutzwerke – Empfehlungen für Küstenschutzwerke
GIZ	Gesellschaft für Internationale Zusammenarbeit GmbH
GPS	Global Positioning System
HD	Hydrodynamic
ICAM	Integrated Coastal Area Management
IPCC	Intergovernmental Panel on Climate Change
LAT	Lowest Astronomical Tide
LIDAR	Light Detecting and Ranging
MARD	Ministry of Agriculture and Rural Development
MHW	Mean High Water
MLW	Mean Low Water
MoNRE	Ministry of Natural Resources and Environment
MRC	Mekong River Commission
NGI	Norwegian Geotechnical Institute
RTK	Real Time Kinematics
SIWRR	Southern Institute for Water Resources Research
2D	Two-Dimensional
3D	Three-Dimensional

Abbreviations

etc.	Et cetera
e.g.	For example
i.e.	That is
N	North
NE	Northeast
NW	Northwest
S	South
SE	Southeast
SW	Southwest
W	West

Symbols

a	Wave amplitude [m]
d	Mean height of Geotube [m]
D_{N50}	Mean diameter of armour stone [m]
$d_{50,p}$	Mean diameter of sand in prototype [m]
$d_{50,m}$	Mean diameter of sand in model [m]
e	Limit of tolerable erosion [m]
F	Force [N]
H	Wave height [m]
H_S	Significant wave height [m]
H_T	Height of transmitted wave [m]
K_D	Stability coefficient
K_T	Transmission coefficient
L	Wave length [m]
l	General length parameter
L_B	Length of a breakwater [m]
l_n	Length of groin [m]
L_0	Length of a gap between breakwaters [m]
N	Number of waves during the design storm event
n	Pore content
P	Porosity of armour layer
R_C	Freeboard [m]
S	Degree of damage of armour layer
s_N	Distance between cross-shore groins [m]
T	Wave period [s]
T_m	Mean wave period [s]
T_P	Peak wave period [s]
W_{50}	Weight of a single armour stone [N]
x	Length parameter; distance of a breakwater to the shoreline [m]
y	General length parameter

Greek symbols

α	Angle of approaching waves at breaker line [°]
β	Beta
θ	Voids ratio
θ_m	Mean wave direction [°]
γ_S	Specific weight of armour stone material [N/m³]
γ_W	Specific weight of water [N/m³]
Θ	Slope (of revetment) [°]
ξ	Irribaren number (surf similarity)
ρ	Bulk density (of mud) [g/cm³]
ρ_d	Dry density (of mud) [g/cm³]
ρ_s	Density of sediments [kg/m³]
ρ_w	Density of water [kg/m³]
Δ	Ratio of densities (of water and sediments)
ε	Deformation [m]
μ	Scale factor (for physical models)

Units

cm, cm^3	Centimetre, cubic centimetre
g	Gramme
ha	Hectare
Hz	Hertz
kg	Kilogramme
km, km^2	Kilometre, square kilometre
kN	Kilonewton
l	Litre
m, m^2, m^3	Metre, square metre, cubic metre
min	Minute
s	Second
USD	United States Dollar
°	Degrees

Mathematical function

sin	Sinus
tan	Tangent
cot	Cotangent

EXECUTIVE SUMMARY

The highly dynamic coastline of the Lower Mekong Delta is influenced by waves, tidal currents, changing sediment loads from the Mekong, and further factors such as storm surges. In addition, anthropogenic impacts through dyking and drainage, agriculture, aquaculture and fishery have influenced the present course and form of the shoreline.

Forecasts concerning future developments in coastal areas of the Mekong Delta contain large uncertainties due to complex morphodynamic and hydrodynamic processes. Furthermore, global climate change will have a major influence on the Lower Mekong Delta, e.g. through an increased frequency and intensity of storm surges and changing sediment transport conditions and erosion patterns. The magnitude of the changes, however, is not clear.

Anthropogenic use of the coastal areas in the Lower Mekong Delta requires engineering measures. In most cases, natural dynamics of the coastline have to be controlled. Coastal protection measures – subdivided into measures of erosion protection, flood protection and drainage of the hinterland – are essential to meet the requirements of an increasing development pressure. Every intervention in the coastal system causes reactions. Negative impacts must be minimised as much as possible. Thus, all measures must be carefully planned and based on a sound understanding of coastal processes. The large range of interests in coastal areas makes the management of shorelines and the design of coastal engineering measures a very sophisticated procedure.

Cooperation among experts from the fields of coastal morphology, coastal engineering, landscape architecture and planning, and environmental management is essential for successful coastal management and adaptation to climate change. Although coastal management is interdisciplinary, in the end, the basis for all decisions is an engineering one.

Coastal engineering and management are disciplines for which only a few codes of practice or design manuals are available. Some standard procedures exist, but any application of standard procedures is limited, because solutions are generally site-specific.

Before implementing coastal protection measure, a detailed description of the status quo and the formulation of the explicit problem are essential for developing a successful design. The applied coastal protection measure must be chosen according to the site-specific situation.

Within the design process, the decision-makers should be provided with the necessary information about the impacts of the planned measures. Numerical models and modern measurement and monitoring techniques generate huge amounts of data. The analysis and evaluation of all these data as well as the preparation of relevant information and the dialogue with the decision-makers needs to be done by experts. Computer-based decision support systems (DSS) allow for interdisciplinary analysis and effective application of these data and hence result in improved decision-making. However, maintenance of the DSS and sufficient training of personnel is essential to assure the sustainable benefit of such a system.

In coastal engineering, the application of only one coastal protection element is technically difficult and cost-intensive – in construction and maintenance. The dyke is the main flood protection element in the Lower Mekong Delta, but if it is the only element without any floodplains, its construction must be strong and high. Wide-ranging implementation of such a dyke system is not appropriate, especially in light of future scenarios with an increased frequency and intensity of extreme events. Deciding factors include limited funding, but also technical boundary conditions such as the limited underground load-bearing capacity. This must be considered when the general coastal protection strategy is defined. Due to existing land use and infrastructure, in most cases the strategy of defence will be applied. As a result, different coastal protection elements should be combined into a coastal protection system.

Coastal floodplains, consisting either of marsh or a mangrove belt, are an important stabilising element of the coastal protection system. They protect against coastal erosion and flooding. The higher the floodplain, the greater the wave dissipation on the floodplain and tidal flats. As a result, the wave load on the dyke is significantly decreased. In the presence of mangroves, the effect of wave reduction is even larger. Thus an area coastal protection system including floodplains vegetated with mangroves and a sound dyke construction is the most sustainable coastal protection system for low-lying areas.

In many cases, the mangrove belt at the coast has been severely damaged by cutting of mangroves, pollution or modification of the hydrology. In these cases, the re-establishment of floodplains including the mangrove belt has to be carried out. The construction of T-shaped bamboo fences, as done in Soc Trang Province and Bac Lieu Province, is an effective measure to do this. Due to materials used, this measure is sustainable and cost-efficient. The principle of the measure can be adapted and transferred to different coastal sections, but it is important to know the hydrodynamic and morphodynamic boundary conditions. As for all projects dealing with coastal morphology, it is essential to acquire and analyse available relevant data to initiate the design of a measure.

In the context of coastal engineering activities, hydrodynamic and morphodynamic studies have to be carried out to provide a comprehensive basis for decision-making. Such studies can be divided into the collection of existing data, field measurements and surveys, numerical modelling and physical modelling. Depending on the location, the available information and the planned activities, one or more different study types can be applied over the course of the design of a measure.

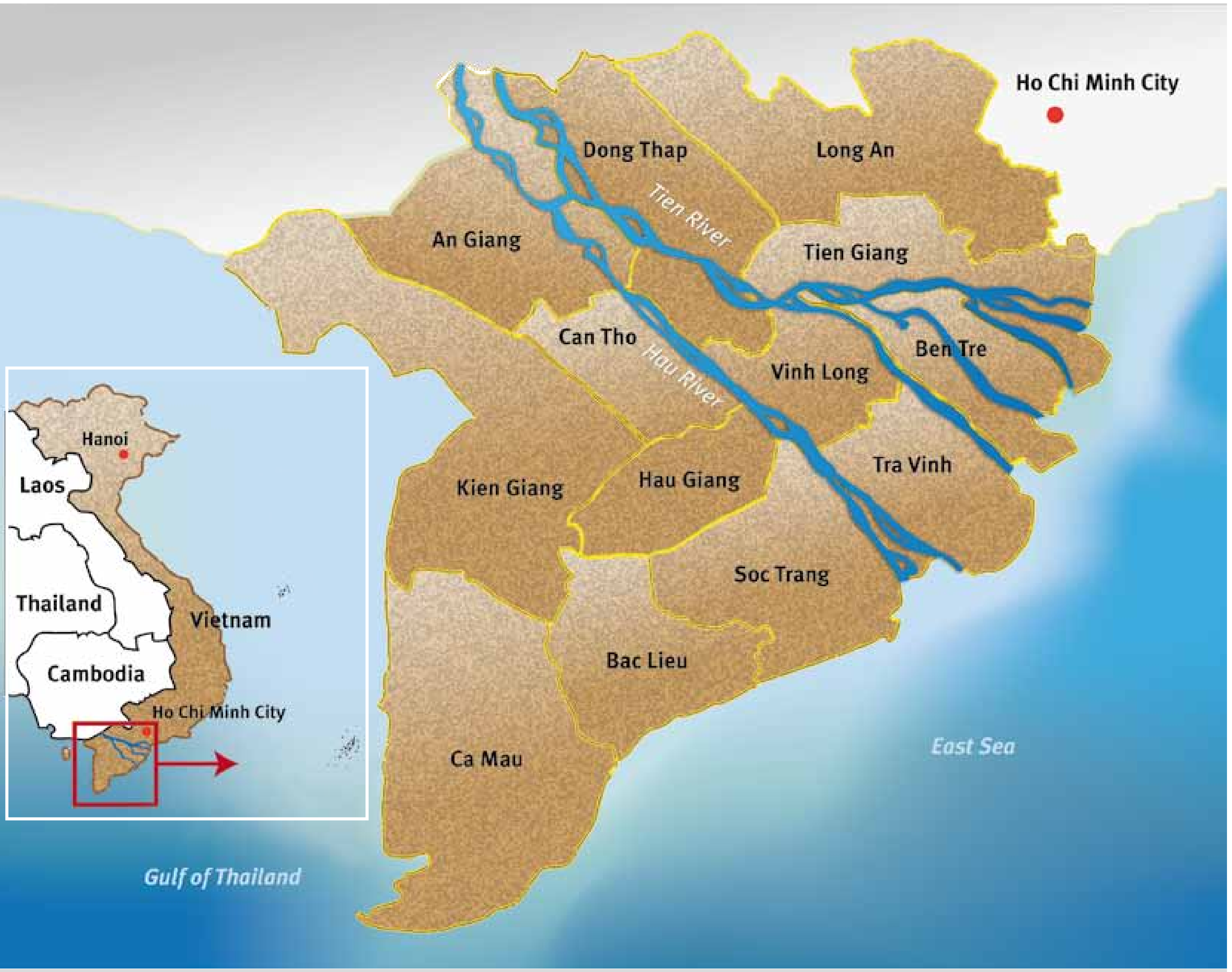
For many coastal sections, the available data are not sufficient to carry out a comprehensive design of coastal protection measures. In these cases, field measurements have to be carried out to understand the hydrodynamic and morphodynamic boundary conditions. Field measurements are complex and time-consuming, and require comprehensive and sophisticated analysis of the data, but normally cannot be completely replaced by numerical modelling.

The application of numerical models in coastal engineering has increased during the last three decades. Numerical models are only useful when applied in combination with qualified engineering assessments. They provide information about causes of present problems and consequences of different measures planned, but require sound input data, a sophisticated interpretation of the simulation results and comprehensive understanding of the physical processes.

When planning shoreline management measures, it is very important to understand and quantify sediment transport and hydrodynamic processes. Although physical modelling is cost-intensive and requires sufficient laboratory equipment and experienced staff, it is an appropriate method to study these processes. Thus, physical modelling should be taken into consideration in addition to field measurements and numerical modelling. It can help to develop and improve the numerical models.

During the creation of coastal protection measures, the person in charge of the coordination and supervision of the activities should be experienced and skilled, and be present at the site on a regular basis. A detailed documentation and monitoring of the construction are essential to gain information for future constructions. To be able to assess the effectiveness of the coastal protection structures, a comprehensive monitoring programme is essential. However, monitoring should already start before the installation of further structures. It helps to draw conclusions about the structure itself, its wave damping effect and its effects on the surrounding sediments.

1 INTRODUCTION



The Vietnamese coastline extends for about 3,260 km without island coastlines and includes two large river deltas formed by Holocene alluvial deposits: the Song Hong (Red River) Delta in the north and the Cuu Long (Mekong Delta) in the south. Thus, coastal engineering and coastal management are very important disciplines for Viet Nam.

Tides, storm surges, changing sediment loads from the large rivers and many other factors have led to a permanent reshaping of the coastline. In addition, anthropogenic impacts through dyking and drainage, the fishery and shipping industry, and coastal development as well as the creation of recreational areas have influenced the present form of the coastline. Natural changes and anthropogenic impacts have influenced the ecological as well as the morphodynamic development, and many factors have interacting effects (Gätje & Reise, 1998).

The large number of forces that affect the shoreline makes forecasts concerning future developments very complex. Furthermore, a clear approach for solving conflicts about the use of coastal resources, conflicts which have arisen particularly in the recent decades, is still missing (BMU, 2006). The impacts of climate change in future decades are also not clear, but most likely the frequency and intensity of storm surges will increase. Morphodynamic processes including sedimentation and erosion will change in parallel with changes in the currents and sediment transport conditions (Woth et al., 2006; IPCC, 2007).

The natural dynamics of the coastline have to be controlled using adequate measures, if, for example the availability of the navigation channels or the functionality of coastal protection is to be maintained. The mouths of large estuaries and tidal flat areas in particular are subject to large morphologic developments despite detached coastal engineering measures. Every intervention in the coastal system causes reactions, and in many cases coastal engineering measures had negative consequences because the initial problem was just shifted along the coastline. Thus, all measures must be planned carefully and based on a sound understanding of coastal processes (Albers, 2012).

These guidelines provide a foundation to understand the general principles of coastal engineering, generate a knowledge base for shoreline management and support decision-makers in the process of coastal design. The guidelines have a clear reference to the lower Mekong Delta.

The Mekong River originates in Tibet and flows through China, Myanmar, Laos, Thailand, Cambodia and Viet Nam before it discharges into the Vietnamese East Sea (South China Sea). The Mekong as it reaches the Delta branches into nine arms (Cuu Long; nine dragons) and a dense canal network. In Viet Nam, the Mekong River separates into two large branches, the Tien River and the Hau River. The Tien River branches into six tributaries and the Hau River into three tributaries. Together they form what are called the "Nine Dragons" in the Vietnamese language (Figure 1).

The area that is referred to as the Mekong Delta is located downstream of Kompong Cham, Cambodia. The size of the catchment area of the Mekong River Basin in Viet Nam is 65,000 km² and the delta has four million hectares of cultivated land for nearly 18 million Vietnamese inhabitants, which is about 22% of the country's entire population (Tuan et al., 2007).

The Mekong Delta plays an important role as the 'rice bowl' for the whole of Viet Nam. Rapid expansion of shrimp farming in the Mekong Delta has contributed to economic growth and poverty reduction, but has been accompanied by rising concerns over environmental and social impacts (Phan & Hoang, 1993; de Graaf & Xuan, 1998; Páez-Osuna, 2001; Primavera, 2006). The lack of an integrated approach to sustainable management, utilisation and protection of the coastal zone and economic interests in shrimp farming have led to the unsustainable use of natural resources, thus threatening the protection function of the mangrove forest belt and, in turn, reducing income for local communities (Schmitt et al., 2013). The coastal zone is also affected by the impacts of climate change (IPCC, 2007; Carew-Reid, 2007; MoNRE, 2009; MRC, 2009). Climate change is predicted to cause an increased intensity and frequency of storms, floods and droughts, increased saline intrusion, higher rainfall during the rainy season and rising sea levels.

Figure 1: Map of the Mekong Delta (opposite page)

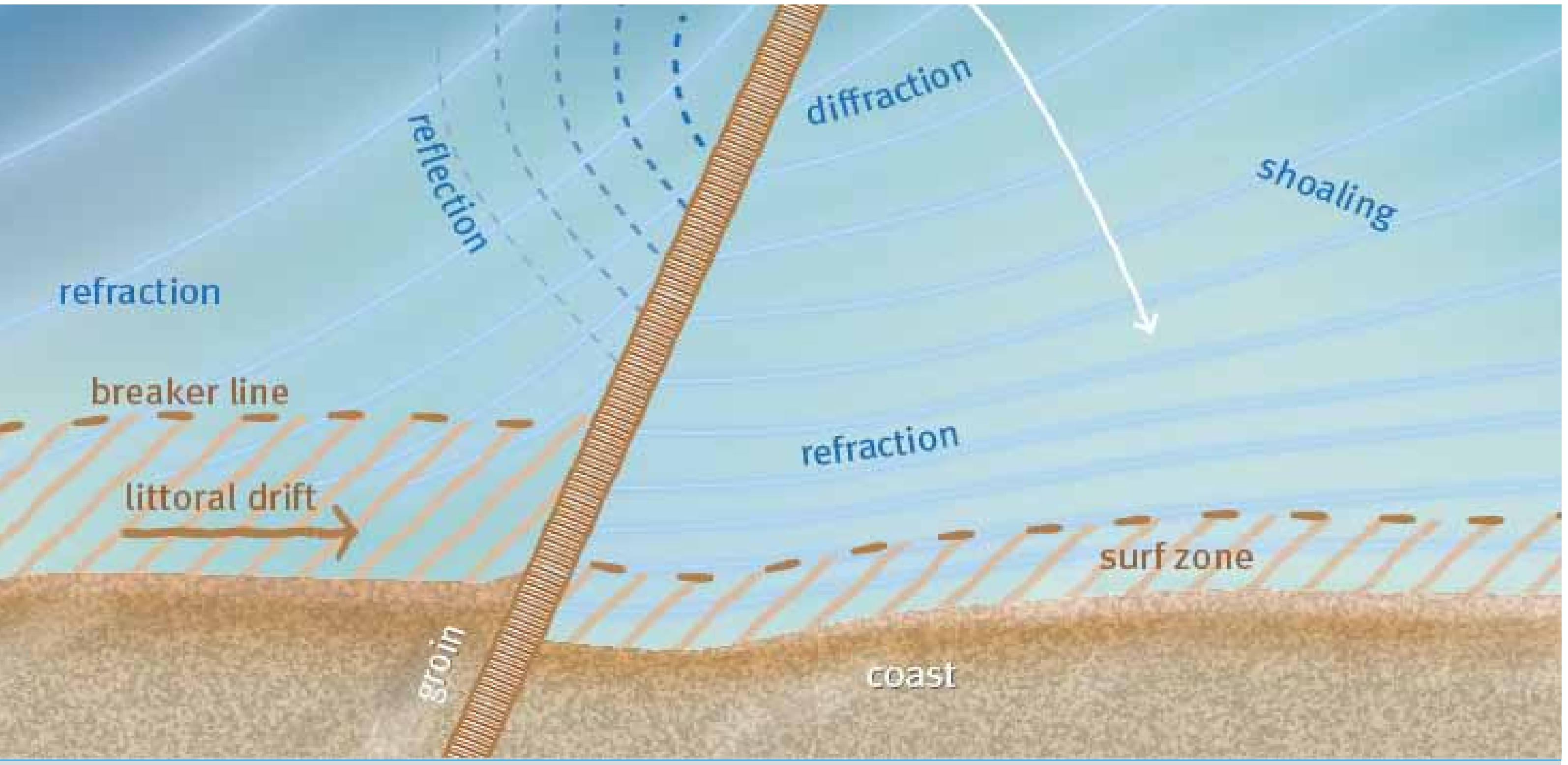
The thirteen provinces in the Mekong Delta have a combined coastline stretching for approximately 600 km along the Vietnamese East Sea (South China Sea) and the West Sea (Gulf of Thailand). The greater part of the delta is influenced by tides, e.g. through saline intrusion in the river branches. According to the classification of Davis & Hayes (1984) the coasts of the delta are a mixed-energy (tide-dominated) environment affected by the discharge regime of the Mekong River and its sediment load, the tidal regime of the Vietnamese East Sea and the Gulf of Thailand as well as coastal long-shore currents driven by prevailing monsoon winds and the corresponding wave conditions (Delta Alliance, 2011). The east coast from north of Ben Tre Province to the Cape Ca Mau is influenced by the irregular semi-diurnal tide of the East Sea with a tidal amplitude of 3.0 - 3.5 m. From the Cape Ca Mau to Kien Giang along the west coast, the tides are irregular diurnal with a tidal range of approximately 0.8 - 1.2 m (Delta Alliance, 2011).

The entire coastline is characterised by a dynamic process of accretion and erosion. In some areas, loss of land of up to 30 m per year due to erosion has been recorded, while in other areas land created through accretion can reach up to 64 m per year (Pham et al., 2009; Joffre, 2010; Pham et al., 2011).

Along such a dynamic coastline, a narrow mangrove forest belt is often not sufficient to protect the coast and the earth sea dyke from erosion. In such a setting, mangrove management cannot be done effectively through a sectoral approach; it must be part of an integrated coastal area management (ICAM) approach including climate change adaptation measures. ICAM requires risk management of the coastal zone as a whole – not only of isolated erosion sites – by considering different options depending on site-specific conditions and by putting in place risk spreading strategies over space and time to address uncertainties, such as dealing with predicted negative impacts of climate change.

For a sustainable and holistic management and design of coastal protection in a complex environment, it is essential to understand hydrodynamic and morphodynamic processes in the coastal zone. Driving forces, such as waves and tides therefore also have to be known. The introduction to these Guidelines (Chapter 1) contains general aspects and some facts about the Lower Mekong Delta, and is followed by a comprehensive description of coastal hydrodynamic and morphodynamic processes in Chapter 2. The principles of waves, tides and other water level variations and the resulting currents are explained. Basic coastal hydrodynamics and sediment transport processes are presented and the general evolution of shorelines is discussed. In Chapter 3, a general classification of different types of coasts, estuaries and deltas helps to understand site-specific characteristics of different coastal sections. Chapter 4 gives an overview of various anthropogenic and natural causes of coastal erosion and flooding. Thus, Chapters 2-4 provide basic coastal engineering knowledge.

In coastal engineering, there are different elements of erosion protection, flood protection and elements of drainage. They are described in Chapter 5 and examples of application in the Lower Mekong Delta are provided. Chapter 6 gives a brief overview of different shoreline and coastal management strategies and summarises some general aspects of coastal design and Chapter 7 describes the methodology of coastal design including the possible investigation methods. This closes the gap between the identification of a problem and the execution of a coastal engineering measure.



The coastal geomorphology of the Mekong Delta is influenced by waves, tides, the discharge regime of the Mekong, and its sediment load, as well as by the monsoon cycle and the complex interaction among these factors. The monsoon winds have a direct influence on the waves, and sediment load of the Mekong is largest at the end of the rainy season. Waves are able to transport large amounts of energy across the deep water to the coast. When they hit the coast, they can lead to increased sediment transport, severe erosion and consequently to failure of the coastal protection system and flooding of the hinterland. Thus, waves are one of the most important parameters for the coastal morphology and the design of coastal protection. However, there are local differences in the Mekong Delta, especially between the coast of the Vietnamese East Sea in the east and the coast of the Gulf of Thailand in the west of the Mekong Delta.

During the northeast monsoon season between November and March, the main wave direction along the east coast of the Mekong Delta is from the northeast. The highest waves during the year occur from this direction in the winter (Eisma, 2010). Around the Cape Ca Mau, in the Gulf of Thailand, the wave climate is moderate during this period with wave directions ranging from northeast to south-southwest (Ekphisutsuntorn et al., 2010). At the eastern shore of the Gulf of Thailand, monsoon winds are generally dominant, but there is frequent alternation between sea breezes during the day and land breezes at night. During the southwest monsoon season between Mai and September, waves are predominantly approaching the east coast and the west coast of the Mekong Delta from the southwest. The Gulf of Thailand is to some extent sheltered from southwest and northeast winds. Typhoons that approach from the east-southeast and generate high waves and storm surges rarely enter the Gulf of Thailand. These mainly occur from May to December, and are rare from January to May (Eisma, 2010).

The following chapters describe the main driving forces of coastal morphology and the principles of coastal hydrodynamics and sediment transport that lead to shoreline evolution.

2.1 Waves

Wind and variations in the atmospheric pressure are responsible for the generation of waves, wind set-up, and surge, as well as wind-generated currents.

Short waves, with periods less than approximately 20 s, and long waves, with periods between 20s and 40 min, can be distinguished. Waves with larger periods, such as tidal oscillation, are referred to as water-level variations. For the coastal morphology and the design of coastal protection, short waves are one of the most important parameters.

In nature, waves can be viewed as a wave field consisting of a large number of single waves each characterised by a wave height, wave period, wave length and propagation direction (Figure 2). Wave fields with many different wave periods and heights are called irregular, and wave fields with many wave directions are called directional. The wave conditions vary from site to site depending on the wave climate and the type of water area (The Open University, 2006).

2.1.1 Types of waves

Short waves can be divided into wind waves and swell waves (Mangor, 2004):

- Wind waves: These are waves generated and influenced by the local wind field. Wind waves are normally relatively steep (high and short) and are often both irregular and directional. Wind waves generate an offshore movement of sediments.
- Swell waves have been generated by wind fields far away and have travelled long distances over deep water away from the wind fields, which generated the waves. Their direction of propagation is thus not necessarily the same as the local wind direction. Swell waves are often relatively long, of moderate height, regular and unidirectional. Swell waves tend to build up the coastal profile.

2.1.2 Wave generation

Wind waves are generated as a result of the application of energy of the wind on the surface of the water. The wave height, wave period and propagation direction depend on:

- The wind field (speed, direction and duration).
- The fetch[1] of the wind field (meteorological fetch) or the fetch of the water area (geographical fetch).
- The water depth over the wave generation area.

Swell waves are, as previously stated, wind waves generated elsewhere but transformed as they propagate away from the generation area. The dissipation processes, such as wave breaking, attenuate the short period much more than the long period components. This process acts as a filter, whereby the resulting long-crested swell will consist of relatively long waves with moderate wave height (The Open University, 2006).

[1] The fetch, often called the fetch length, is the length of water over which a given wind has blown.

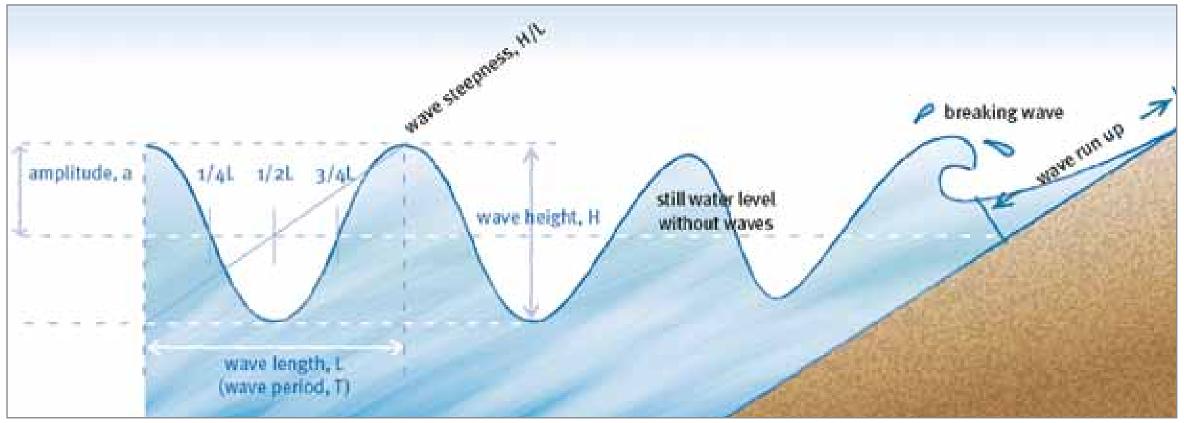


Figure 2: Vertical profile of idealised waves

2.1.3 Wave transformation

When waves approach the coast, they are affected by the seabed through shallow water processes such as refraction, shoaling, bottom friction and wave breaking (Figure 3). If the waves meet major structures or abrupt changes in the coastline, they will be transformed by diffraction. If the waves meet a steep structure, reflection will take place, and if the waves meet a permeable structure, partial transmission will take place (Mangor, 2004).

- Refraction is a change in the direction of the wave propagation. It occurs if a wave front does not approach the depth contour lines parallel in shallow water. Refraction is caused by the fact that the waves propagate more slowly in shallow water than in deep water. As a consequence, the wave fronts tend to approach parallel to the beach.

- Shoaling is the deformation of the waves, which starts when the water depth becomes less than about half of the wave length. Shoaling causes a reduction in the wave propagation velocity as well as shortening and steepening of waves.

- Diffraction occurs when waves hit massive structures such as breakwaters or groins. Physically, the tip of the breakwater then becomes the origin of a new wave. Diffraction is the process by which the waves propagate into the lee zone behind the structures.

- Bottom friction causes energy dissipation and thereby wave height reduction as the water becomes shallower.

- Depth-induced wave breaking of individual waves starts when the wave height becomes greater than a certain fraction of the water depth. As a rule of thumb, the wave height of an individual wave at breaking is often said to be around 80% of the water depth.

- Wave run-up is the maximum level the waves reach on the beach relative to the static water level (see Figure 2). It depends on the beach slope, the significant wave height and the wave period in deep water.

- Wave overtopping takes place when waves meet a submerged reef or structure, but also when waves meet an emerged reef or structure lower than the approximate wave height. During overtopping, two important processes take place: wave transmission and the passing of water over the structure.

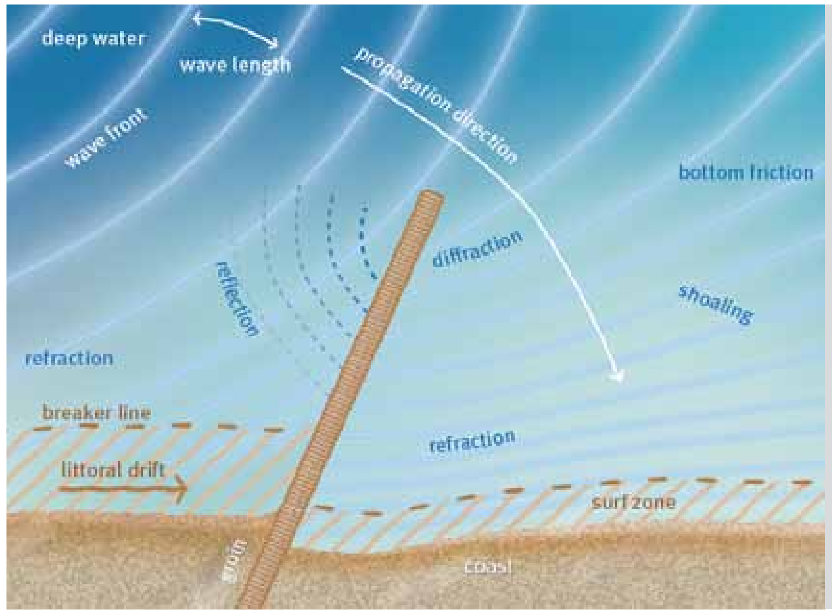


Figure 3: Schematic illustration of nearshore wave processes

2.1.4 Statistical description of wave parameters

Due to the random appearance of natural waves, a statistical description is required. The individual wave heights often follow a Rayleigh-distribution. Statistical wave parameters are calculated based on this distribution. The most commonly used variables in coastal engineering are (CEM, 2002):

- The significant wave height (H_s) is the mean of the highest third of the waves in a time-series of waves representing a certain sea state. This corresponds well with the average height of the highest waves in a wave group.

- The mean wave period (T_m) is the mean of all wave periods in a time-series representing a certain sea state.

- The peak wave period (T_p) is the wave period with the highest energy. The analysis of the distribution of the wave energy as a function of the frequency for a time-series of individual waves is referred to as spectral analysis. The peak period is extracted from the spectra.

- The mean wave direction (θ_m) is defined as the mean of all the individual wave directions in a time-series representing a certain sea state.

These parameters are often calculated from continuous or periodic time-series of the water surface elevations.

2.1.5 Wave climate classification

The dominant wind climate induces a corresponding characteristic wave climate. The monsoon climate is characterised by prevailing seasonal wind directions. In Southeast Asia, the summer monsoon is referred to as the SW-monsoon, and is warm and humid. The winter monsoon, which is referred to as the NE-monsoon, is relatively cool and dry. The east coast of the Mekong Delta is predominantly exposed to waves during the NE-monsoon (Pham, 2011).

Monsoon winds are relatively moderate and persistent for each monsoon season. This means that the corresponding wave climates are also seasonal.

Figure 4 shows wave data from Con Dao Island, 230 km southeast of Ho Chi Minh City. It highlights the two main wave directions, which are induced by the northeast monsoon and southwest monsoon, respectively. In winter, a larger quantity of higher waves from the northeast dominate the wave climate. During summer, the waves approach from the southwest and the appearance of larger waves is reduced. However, strong SW monsoon winds occasionally create waves of up to 3 m in height (Dat & Son, 1998).

These offshore wave conditions are transformed due to shallow water processes when the waves approach the coasts of the Mekong Delta. The corresponding wave heights on the east coast of Ca Mau can be up to 2 m nearshore during the northeast monsoon (ADB, 2011).

Tropical storms are called typhoons near SE-Asia and Australia. They are generated over tropical sea areas where the water temperature is higher than 27°C, and normally form between 5°N and 15°N and between 5°S and 15°S. From there, they progress towards the W-NW in the northern hemisphere and towards the W-SW in the southern hemisphere. An average of 60 cyclones are generated every year. Tropical cyclones are characterised by wind speeds exceeding 32 m/s and they give rise to very high waves, storm surges and cloudbursts. Tropical cyclones occur as single events, peaking during September in the northern hemisphere. They are rare and therefore recording programmes seldom document the resulting waves (Schwartz, 2005).

The Mekong Delta has not been hit regularly by severe typhoons in recent times. However, there have been some significant events. The most catastrophic of these was typhoon Linda (or storm no. 5) on 2 November 1997. It moved across the southern tip of the Ca Mau peninsula before crossing into the Gulf of Thailand. The typhoon killed more than 3,600 people and injured more than 850 (Giang, 2005). It destroyed more than 200,000 homes and caused severe damage across the provinces Soc Trang, Ca Mau, Bac Lieu and Kien Giang. It resulted in flooding, damage to mangrove forests and inundation including associated damage to agricultural production. Housing and infrastructure was also affected by strong winds and flooding. More than 200 km of dykes were breached or destroyed completely (Dillion & Andrews, 1997).

This destruction was accompanied by severe coastal erosion. The population in the Mekong Delta was not prepared for such an extreme event. The lack of storm and flood resilience and sufficient catastrophe management amplified the damage (Truong & Ketelsen, 2008).

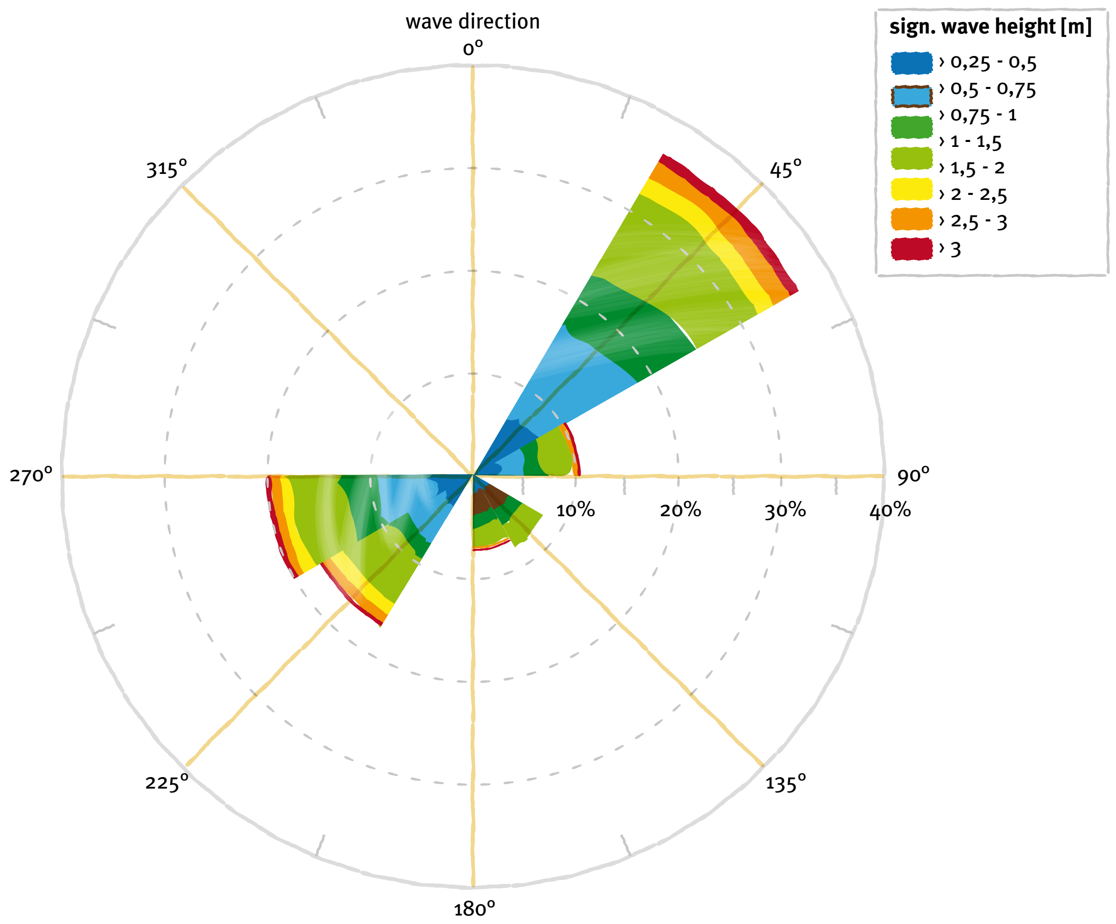
During typhoon Linda, very strong onshore winds of over 140 km/h reached the east coast of Ca Mau. Inland Ca Mau and southern Kien Giang experienced very strong winds that reached speeds of over 70 km/h. The greatest physical effects of Linda on the mainland were on the lightly populated east coast of Ca Mau when the typhoon approached and crossed the coast. This occurred at high tide, and the strong onshore winds and associated low atmospheric pressure led to severe storm surge conditions. The accompanying wave field had a long fetch, which meant that waves of over 3 metres were directed onto the shore (ADB, 2011).

In 2006, typhoon Durian hit the Lower Mekong River Delta, causing huge damage to that area. Data from Tien Giang Province listed 25 sunken ships, 82 ha of ruined rice fields and 416 ha of damaged crops. The most serious losses were recorded in My Tho City, Chau Thanh District with 2 dead and 26 missing persons. 8,977 houses collapsed or were seriously damaged. The storm track was irregular which made an accurate forecast impossible and thus made it also impossible to put appropriate catastrophe precautions in place. When hitting the Delta, the velocity of the typhoon reached 23 m/s (82.8 km/h). Wind directions around the typhoon led to offshore winds on the west coast of the Delta, which limited the formation of storm surge and reduced the occurring wave heights[2,3].

[2] http://vietbao.vn/Xa-hoi/Bao-so-9-Ben-Tre-Tien-Giang-bi-thiet-hai-nang-ne/70070577/157/

[3] http://caimon.org/Tintuc/BaoSo9.htm

Figure 4: Wave rose of Con Dao (Data source: Dat & Son, 1998)



2.2 Water level variations

Variations in water levels can be divided into regular oscillating variations with periods from half days to one year (e.g. tides) and into non-regular variations with recurrence intervals from days up to several years (e.g. storm surges).

Variations in the water levels are important because they generate currents, which lead to transport processes and morphological changes. Flooding is another important aspect of extreme water levels.

2.2.1 Tides

The astronomical tide is generated by the rotation of the earth combined with the varying gravitational impacts of the sun, the moon and the planets on the water. These tidal constituents determine the tide at any given location. The tide is mainly generated in the deep ocean, from where it travels to the coastal waters.

The height of the tidal wave in deep water is normally less than 0.5 m. In shallow coastal waters it is modified by shoaling and friction. In restricted waters, such as the mouths of estuaries, changes of the cross section and reflection lead to tidal ranges that can be up to 15 m. The astronomical tide at a specific location can be predicted using mathematical methods and is usually published in tide tables. Tidal conditions at a location vary mainly according to semi-diurnal and diurnal constituents. If the semi-diurnal constituents dominate at a location, the tide is classified as a semi-diurnal tide, and if the diurnal constituents are predominant, it is classified as a diurnal tide. A semi-diurnal tide has two low waters and two high waters every day, whereas diurnal tides have only one of each every day. Mixed tides are another variant that occurs (Mangor, 2004).

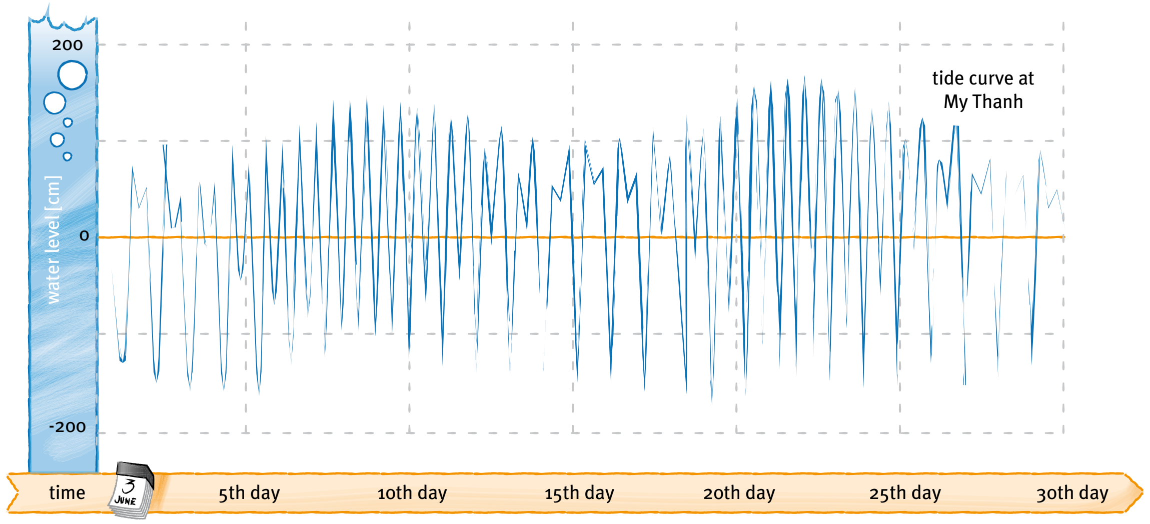
In addition, fortnightly variations must be considered. The tide is higher than normal during the full moon and new moon (spring tide), while it is lower during the quarters (neap tide).

The tide at a specific location can be described with some characteristic values, such as the mean high water (MHW), mean low water (MLW), tidal range (MHW-MLW) or the lowest astronomical tide (LAT). The latter is important for navigation and is displayed, for example, in sea charts. The reference level is of great importance for the correct use of the tidal information (The Open University, 2006).

A location with a tidal range > 1.5 m is defined as a macro tidal regime. The coastal morphology at sites with a macro tidal regime and a relatively mild wave climate is normally mainly influenced by the tide (Mangor, 2004). This regime is often reflected in wide tidal flats and can be found, for example, on the east coast of the Mekong Delta.

The coasts of the Mekong Delta are affected by two tidal regimes: The area stretching from the mounts of the Mekong River to the Cape Ca Mau at the southernmost point of Viet Nam is dominated by semi-diurnal tides. At the mouths of the Hau River (Bassac River), the tidal range is about 3.5 m during spring tide and decreases towards the Cape Ca Mau. The west coast of the Mekong Delta is dominated by diurnal tides, and here, the tidal range is around 1.0 m.

The upper diagram in Figure 5 shows a tide curve recorded at the mount of the My Thanh River on the northeast coast of Soc Trang Province. The semi-diurnal water level variation and fortnightly spring-neap-cycle are clearly visible. The lower diagram in Figure 5 shows the recorded diurnal tide at the mount of the Song Doc River on the southwest coast of Ca Mau Province. The comparison of the two tide curves shows the general difference between the semi-diurnal and the diurnal tides, but also the different ranges of the tide in the East Sea and the Gulf of Thailand (Please note the difference in scale of the water level).



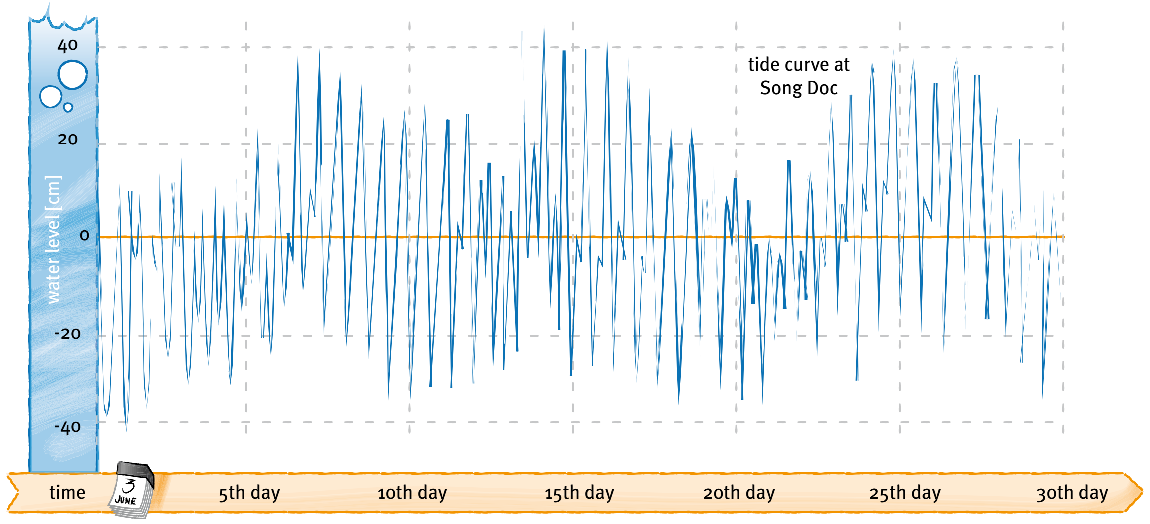


Figure 5: Semi-diurnal tide and spring-neap cycle at the mouth of the My Thanh River (top) and diurnal tide at the mouth of the Song Doc River on the west coast of Ca Mau Province (bottom); Data source: SIWRR

2.2.2 Seasonal variations

In the Mekong Delta, the monsoon cycle, with seasonal variations in the wind and pressure systems and in precipitation levels, leads to seasonal variations in water levels, especially at gauges in the mouths of the Mekong branches with peaks at the end of the rainy season.

2.2.3 Storm surges

The water level also varies as a function of the wind impact and atmospheric pressure variations on the water surface. A storm surge is the result of the combined impact of the wind stress on the water surface, the atmospheric pressure reduction, decrease in water depth at the coast and the horizontal boundaries of the coastal water. The storm surge does not include the effect of the astronomical tide. However, the combined effect of astronomical and meteorological surges is often referred to as a storm surge – the popular expression for an unusually high and destructive water level along a shore (Mangor, 2004).

Strong monsoon winds can lead to higher water elevations in the Mekong Delta. In combination with a spring tide, this produces a storm surge with water levels that are elevated by up to 0.8 - 0.9 m.

Large waves during a storm surge can cause the destruction of exposed infrastructure along the coast. These waves undermine mangroves, penetrate through the thin belts of mangrove forests, and erode exposed earth dykes. Earth dykes that have been exposed by mangrove removal are especially endangered and can breach during an extreme event. The conversion of mangroves into aquaculture ponds has potentially exposed infrastructure to storm surges.

The sea level rise projected by climate models will increase the height of water levels during storm surges by up to 1 m. Water levels of this height combined with waves of 1 - 2 m will lead to overtopping of dykes that are built according to the current recommended dyke standards. Waves will also be able to penetrate further into mangrove forests, and a belt of mangroves of 20 - 30 m will not offer sufficient protection for earth dykes (ADB, 2011).

When winds blow from the southwest, Ngoc Hien District (the peninsula at the tip of Ca Mau Province) is downwind of a considerable fetch and is subject to higher water elevation. The same is the case for strong northeast winds. Ngoc Hien is therefore especially exposed and vulnerable to storm surges from strong monsoon winds coming from both southwest and northeast wind (ADB, 2011).

2.2.4 Sea level rise and subsidence

Sea level rise and subsidence are long-term changes of the water levels and the elevation of the land, respectively.

2.2.4.1 Sea level rise

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, coastal areas in Asia, especially heavily-populated delta regions in Southeast Asia, will be at the greatest risk due to increased flooding from the sea and from the rivers (IPCC, 2007). Rising sea levels will also have a great impact on long-term coastal morphology. The magnitude of this sea level rise is still the subject of international research and discussion, and the Intergovernmental Panel on Climate Change has stated that during the last 100 years the mean sea level has risen between 10 and 25 cm. Coupled ocean-atmospheric climate models forecast a global sea level rise over the course of this century of 18 - 38 cm for a low emission scenario and 26 - 59 cm for a high emission scenario. Of course the estimated sea level rise will vary from region to region. The range of 9 - 88 cm that was indicated in the Third Assessment Report (IPCC, 2001) was corrected because it was possible to decrease uncertainties associated with some parameters.

A statistical downscaling of the climate change modelling has been carried out for the Mekong Delta. This regional downscaling resulted in different sea level rise scenarios depending on the emission scenario. By the end of the 21st century, the sea level from Ca Mau to Kien Giang could rise by up to 72 cm (low emission scenario) or 105 cm (high emission scenario) (IMHEN, 2011).

In 2012, the Ministry of Natural Resources and Environment of Viet Nam published estimated rates of sea level rise based on various emission scenarios. The data regarding sea level rise in the Lower Mekong Delta are presented in Table 1.

Sea level rise will cause increased risks of flooding of low-lying areas and areas protected by sea defences. Therefore, future sea defence projects should take the expected sea level rise into consideration. A projected value of sea level rise should be included over the certain lifetime of the defence system. Another possibility is to monitor the sea level rise and make adjustments to the defence system as required. Under all circumstances, the increasing sea levels call for flexible designs.

A further impact of sea level rise is a changed sediment regime in the lower reaches of the estuaries that will increase the deficit in sand supply to the coast, while also causing a direct increase in the coastal erosion caused by sea level rise.

Wind velocities will increase in parallel to rising sea levels. This means that extreme events such as storm surges during a typhoon will become even more severe. If a typhoon with the same characteristics as Linda were to cross the Ca Mau peninsula at high tide, the projected water surface elevation combined with larger waves will result in severe damage to the sea dykes and fishing villages in estuaries and canal mouths along the entire coast. Ngoc Hien District will be almost completely inundated and very strong currents are predicted to flow through the Grand River resulting in erosion along the southern border of Nam Can District (ADB, 2011).

[4] http://tnmtcaobang.gov.vn/index.php/vi/download/Du-lieu/Kich-ban-bien-doi-khi-hau-nuoc-bien-dang-cho-Viet-Nam-Phan-2-Ban-do-va-bang-bieu-cua-Kich-ban/

Table 1:
Water level rise in the Lower Mekong Delta based on different emissions scenarios (cm) [4]

Scenario	Areas	The timeline of the 21st century								
		2020	2030	2040	2050	2060	2070	2080	2090	2100
Low emission (B1)	Ke Ga – Ca Mau tip	8-9	11-13	17-19	22-26	28-34	34-42	40-50	46-59	51-66
	Ca Mau tip – Kien Giang	9-10	13-15	18-21	24-28	30-37	36-45	43-54	48-63	54-72
Medium emission (B2)	Ke Ga – Ca Mau tip	8-9	12-14	17-20	23-27	30-35	37-44	44-54	51-64	59-75
	Ca Mau tip – Kien Giang	9-10	13-15	19-22	25-30	32-39	39-49	47-59	55-70	62-82
High emission (A1FI)	Ke Ga – Ca Mau tip	8-9	13-14	19-21	26-30	35-41	45-53	56-68	68-83	79-99
	Ca Mau tip – Kien Giang	9-10	14-15	20-23	28-32	38-44	48-57	60-72	72-88	85-105

2.2.4.2 Subsidence

Subsidence of the ground in the coastal area will be experienced as a relative sea level rise and will cause erosion in the upper part of the coastal profile. Subsidence can be a natural phenomenon in deltas consisting of fine sediments, but human activities, such as the extraction of groundwater and/or oil and gas, have also resulted in severe subsidence (Mangor, 2004).

In 2012, an initial survey concerning subsidence due to groundwater extraction in the Lower Mekong Delta was carried out in Ca Mau Province by the Norwegian Geotechnical Institute (NGI). The Ministry of Agriculture and Rural Development (MARD) and the Southern Institute for Water Resources Research (SIWRR) provided data on the extent of groundwater pumping in Ca Mau, where groundwater pumping from deep aquifers is quite extensive. A total of approximately 109,000 wells exist in the investigated area, and the total quantity of groundwater pumped every day ranges up to approximately 373,000 m^3. This results in a large potential for significant subsidence of the ground surface due to ongoing groundwater pumping. Based on the available data, the NGI estimated rates of subsidence in the order of 1.9 to 2.8 cm/year depending on the total pumping rate and the estimated natural recharge (NGI, 2012).

2.3 Currents

The water level variations induced by astronomical tides generate tidal currents. Tidal currents are strongest in straits where the current is forced into a narrow area. The most important tidal currents in relation to coastal morphology are the currents generated in tidal inlets. Typical maximum current velocities in tidal inlets are approximately 1 m/s, whereas tidal current velocities in straits in estuaries can reach speeds as high as approximately 3 m/s (The Open University, 2006).

Water particles under waves in deep water move on almost circular orbitals. At the surface, the orbital diameter corresponds with the wave heights. The diameter decreases exponentially with increasing depths, until a depth of roughly half of the wave length is reached. In shallow water where the water depth is less than half of the wave length, the orbitals become progressively flattened with depth. The almost horizontal orbitals generate currents with velocities (orbital velocities) of the same order as the tidal currents.

Wind generated currents are caused by the direct action of the wind shear stress on the surface of the water. The wind generated currents are normally located in the upper layer of the water body and are therefore not very important for the morphology of the seabed. In very shallow coastal waters and lagoons, the wind-generated current can, however, be of some importance. Wind-generated current speeds are typically less than 5 per cent of the wind speed (Mangor, 2004). During the northeast monsoon, the sea currents in the Vietnamese East Sea are directed to the southwest, whereas during the southwest monsoon, the sea currents on the coast of Viet Nam are directed to the northeast (Hu et al., 2000).

Storm surge currents are generated by the total effect of the wind shear stress and the barometric pressure gradients over the entire area of water affected by a specific storm. This type of current is similar to the tidal currents. The horizontal current velocity follows a logarithmic distribution in the water profile and has the same characteristics as the tidal current. It is strongest at large water depths away from the coastline and in confined areas, such as straits and tidal inlets (Mangor, 2004).

2.4 Coastal morphodynamics

Coastal erosion and accretion are complex processes depending on various influences. Key elements include the sediment transport under the influence of currents and waves, the overall dynamics of beaches in a coastal section, as well as anthropogenic impacts (Prasetya, 2006).

Due to its vectorial character, the sediment transport at the coast can be divided into:

- cross-shore sediment transport (on-/offshore transport) and
- longshore sediment transport.

Coastal cross-shore sediment transport mainly induces short-term morphologic changes, e.g. during storm events. Coastal longshore transport mainly causes long-term morphologic changes of a coastal section.

Sediments are transported when shear stresses, induced by the water movement, are large enough to initiate a movement of single particles. Shear stresses can be caused by currents, by the orbital velocities of waves, or a combination of both.

2.4.1 Longshore sediment transport

Littoral transport is the term used for the sediment transport along a shoreline. The littoral transport is also called longshore sediment transport or littoral drift. Littoral transport is often described under the assumption that the shoreline is nearly straight with nearly parallel depth contours. This assumption is very often valid, especially if the sections of the shore are not too long and if a gradual transition between such sections is assumed (Mangor, 2004).

The longshore current is the dominant current in the nearshore zone, and is generated by the shore-parallel component of the stresses associated with the breaking process for obliquely incoming waves. During storms, the longshore current can reach speeds exceeding 2.5 m/s. When wave fronts approach the shoreline obliquely, refraction tends to turn them so that they are almost parallel to the shoreline. At the same time, when approaching the surf zone, they undergo shoaling, which means that they become steeper and higher. Finally, the waves break, and during the breaking process, the associated turbulence causes some of the seabed sediments to be brought into suspension. These suspended sediments, plus some of the sediments on the seabed, are then carried along the shoreline by the longshore current, which reaches its maximum near the breaker line (see Figure 3). The two transport mechanisms are referred to as suspended transport and bed load transport, respectively. The sum of these is the littoral drift (Figure 6; The Open University, 2006).

The magnitude of the littoral drift depends on the wave height, the wave incidence angle and the grain size of the existing sediments. The littoral drift also depends on the sea current, although to a smaller extent than it depends on the wave conditions. However, the tide as well as sea currents can also have a significant influence on the transport conditions for macro-tidal environments. Positive or negative correlation between the waves and the water-level variations may be of importance for sedimentation patterns near large structures. The magnitude of the longshore current varies in approximate proportion to the square root of the wave height and with sin(2α), with α representing the wave incidence angle at the breaker line. As the position of the breaker line constantly shifts due to the irregularity of natural wave fields, the distribution of the longshore current in a coastal profile varies accordingly (The Open University, 2006).

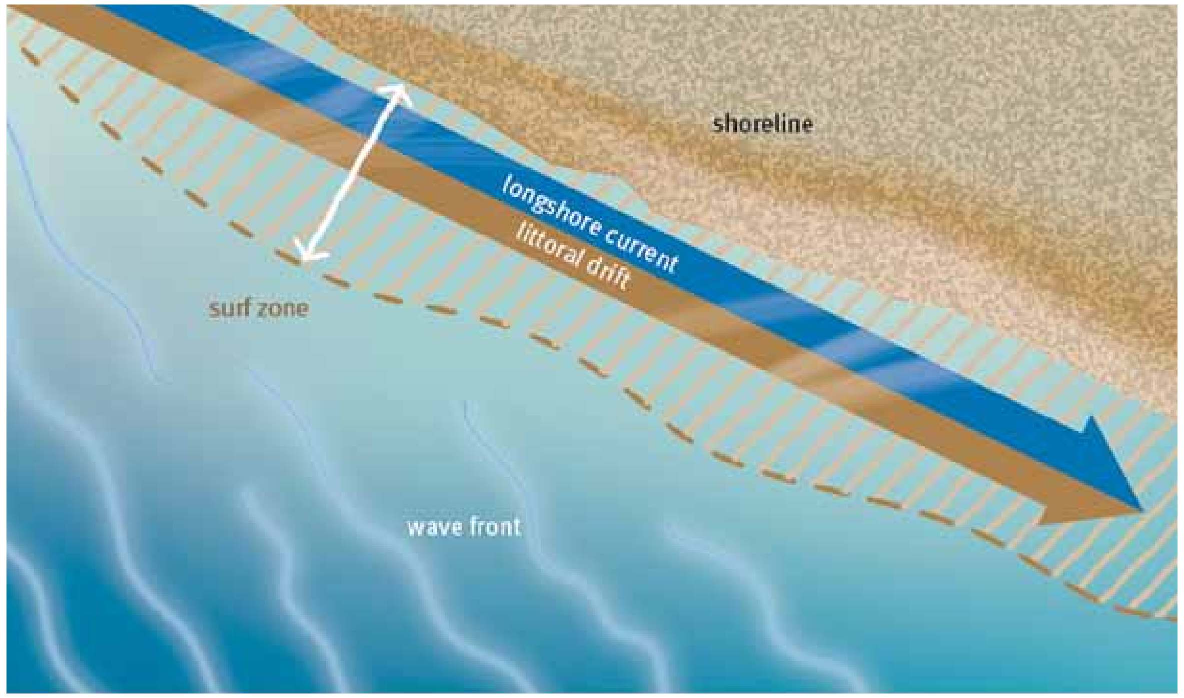


Figure 6:
Model of longshore sediment transport

The fine cohesive sediments, which may be present in the outer part of the profile, will be in suspension over the entire water column and will also tend to spread over the entire coastal profile during strong wave exposure. Any change in the hydrodynamics or bathymetric conditions will 'immediately' result in a corresponding change in the transport capacity and therefore also in the morphology (Mangor, 2004). This results for instance in accumulation of sediments behind breakwaters and fences.

The impacts of morphologic changes of a coast induced by littoral drift depend on the physiographic unit of the coastal section. Open and closed sand systems have to be differentiated (Figure 7). In open systems, exposed areas are a sediment source and eroded sediments are transported in the surf zone along the coastline. At the end of the physiographic unit, the sediments leave the coastal section and accumulation (e.g. sand spits) forms in areas with reduced currents or wave action (CEM, 2002). The southeast coast of the Mekong Delta with its spit at the southern tip of Ca Mau is such an open system. In closed systems, the physiographic unit lies between fixed headlands, such as rocks. Within the closed system, cross-shore and longshore sediment transport lead to an oscillating shoreline, and sediments do not leave the system. Erosion and accumulation are in balance, whereas in an open system erosion overbalances along certain coastal sections.

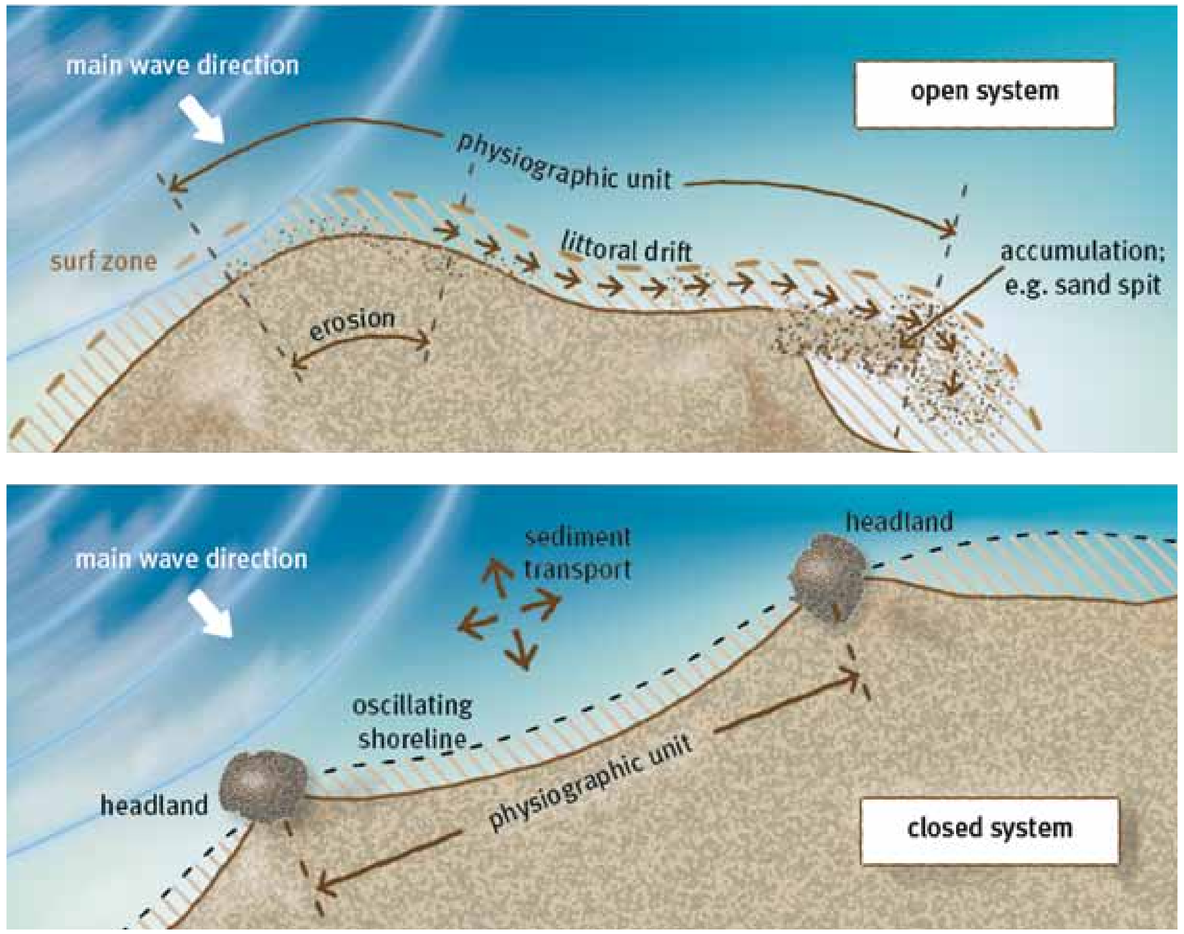


Figure 7: Open and closed sediment transport systems (modified from CEM, 2002)

2.4.2 Cross-shore sediment transport

On a straight coastline, orthogonal approaching waves induce a net transport of water in the direction of the waves. This leads to a backwater in the breaker zone, which is called wave set-up and may be increased during storms by the wind set-up. The gradient of the water level in the breaker zone leads to seaward directed currents, which are in equilibrium with the approaching currents. The landward directed currents run at the surface, while the seaward directed currents run at the bottom. The currents depend on the length, period and height of the waves, on tidal currents and on the bottom friction. If the water level gradient and the wave parameters are constant, a beach profile is formed, which is in equilibrium with the waves and stable as long as the wave conditions do not change (Dean, 1987; Dean, 1991).

On natural coasts, tides and daily as well as seasonally changing wave conditions preclude the formation of an equilibrium profile. The beach profile reacts to every change of the wave parameters with the attempt to form a new equilibrium profile. The result is an oscillating cross-shore sediment transport.

The landward directed transport is induced by long and plane waves (e.g. swell). The seaward directed transport occurs predominantly during short and steep waves and leads to erosion of the beach. Figure 8 shows the schematic changes of a beach profile due to a storm event. If the profile is not in equilibrium due to increasing wave activity, the upper part of the profile will be the first to experience erosion. The material deposits at the lower parts of the profile and leads to a flattening of the profile. As a consequence, the dissipation of the wave energy is distributed over a larger area and the erosion rate is decreased. When the equilibrium profile is reached, the erosion rate becomes nearly zero (CEM, 2002).

The concept of equilibrium profiles is a rather crude representation of the coastal profile conditions since it neither includes nor explains the occurrence of bar formations, etc. However, the concept of the equilibrium profile is a rather practical „tool" for the analysis of coastal conditions and, as already mentioned, for preliminary design considerations.

Correlations between the grain size, equilibrium profile and wave conditions show that it is very important in beach nourishment to use materials as coarse as or coarser than the native material. Otherwise, the nourished sand will immediately be transported offshore in nature's attempt to form a new and flatter equilibrium profile, which fits the finer sand (Mangor, 2004).

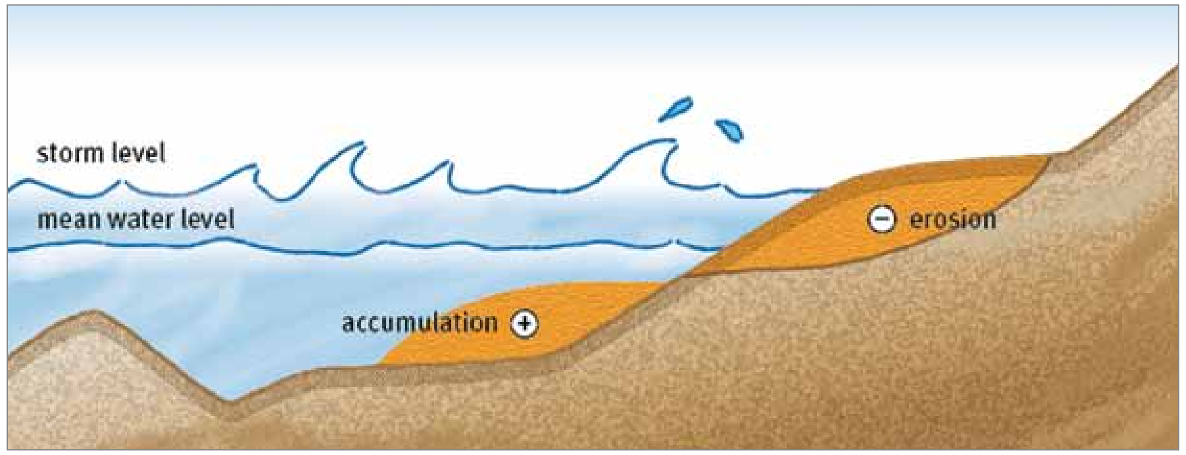


Figure 8: Schematic changes of a beach profile due to a storm event (modified from CEM, 2002)

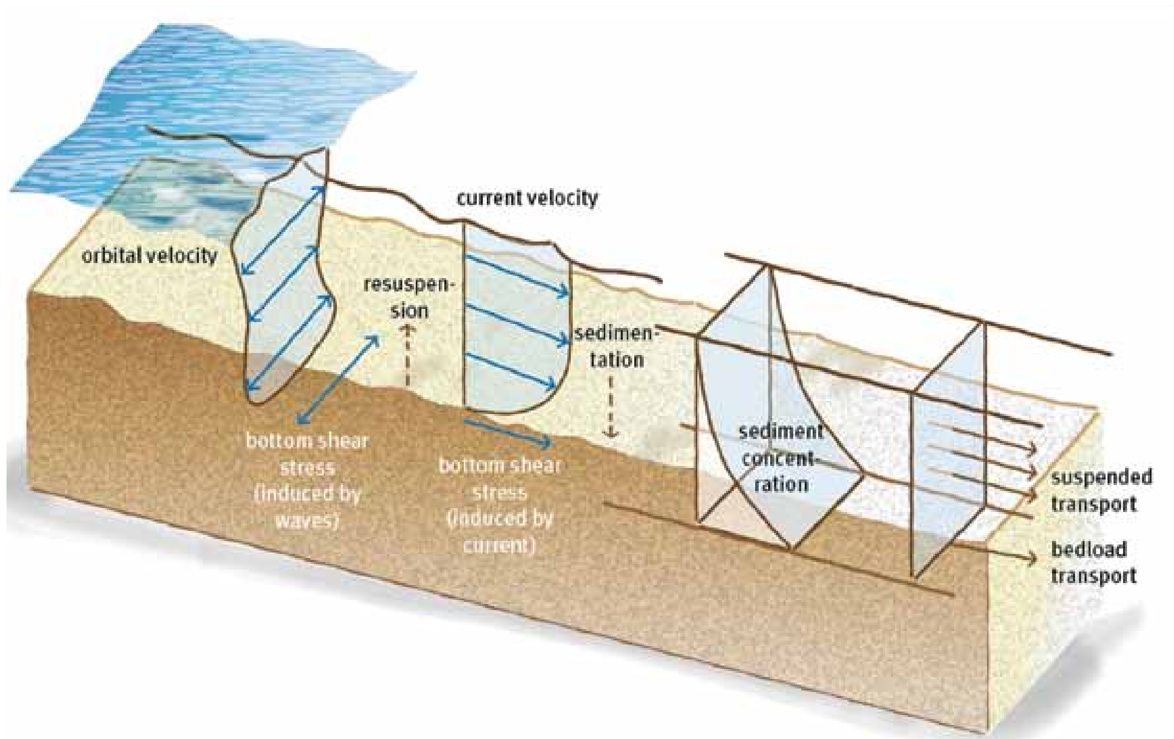


Figure 9: Processes of sediment transport (modified from Soulsby, 1997)

2.4.3 Transport of sediments

The largest fraction of the sediments (more than 90%) is transported in suspension; the rest is transported near the bottom in saltation. Due to the large settling velocity, non-cohesive sediments such as sand are mainly transported as bed load. Fine, cohesive sediments are mainly transported in suspension (Figure 9; Soulsby, 1997).

If the hydrodynamic conditions change, the sand transport will react immediately, while the transport of fine sediments will only react slowly. This is the so-called lag effect (Van Rijn, 1993).

Ports, constructed in environments where the transport of fine sediments takes place, will be exposed to siltation due to the entrainment of water with suspended fine sediments. The siltation is proportional to the water exchange.

Sand can form stable coastal profiles and beaches in a wave-dominated environment, which is not the case with mud. Muddy coastlines are therefore only found in environments that are fairly calm in terms of wave conditions or in environments where there is an abundant supply of fine sediments. Such muddy coastlines are normally vegetated, e.g. in the form of mangroves (in the tropics and sub-tropics) and are normally fronted by very flat slopes or tidal flats. Mixed environments with wave-exposed sand shores or sandy tidal flats alternating with mud-dominated upper tidal flats and deeper muddy areas are seen quite often. Such environments need special consideration in relation to shoreline management projects (Mangor, 2004).

Most of the transport of non-cohesive sediments (sand) takes place in wave-dominated environments. In tidal channels of estuaries and in tidal inlets, the transport of sand is mainly dominated by tidal currents (Soulsby, 1997).

The settling velocity of the transported sediment grains is the major difference between the non-cohesive and the cohesive sediment environments, often referred to as mud. However, another marked difference is the cohesion forces between the single sediment grains, which are characteristic for the cohesive sediments. The settling velocity of sand grains is relatively high whereas the settling velocity of mud particles is relatively low. This implies that the fine sediments are suspended nearly evenly over the entire water column, whereas the suspended sand is only found very close to the seabed (Van Rijn, 2005).

Over the course of a tidal cycle, sediments of tidal flat areas underlie different transport processes. Van Rijn (1993) differentiates among settling, deposition, consolidation and erosion.

Parker (1986) developed a model, which shows the processes and interrelations from mobile sediments to a consolidated bottom. During phases of increased currents and wave activity, sediments are in balance in the water column and are transported by the motion of the water (mobile suspension). If the intensity of the turbulence of the current decreases (e.g. due to structural measures such as fences) and the gravitation force overbalances, the sediments start to settle. Attractive forces of the cohesive particles cause the formation of flocs consisting of several sediment particles. With increasing floc sizes, the settling velocity increases in comparison to single particles. If a certain sediment concentration is exceeded, the flocs hinder themselves and the settling velocity decreases again (hindered settling). The phase of transport, if no horizontal motion is possible anymore, but just a vertical settling with significantly decreased settling velocities, is called stationary suspension.

Currents and the impacts of waves may transport flocs from stationary suspension into mobile suspension again. The own weight of the sediment particles at the bottom densifies the material. The pore water in the hollow spaces between the particles is pushed out during this process. The compaction of the deposited sediments by its own weight with parallel separation of the pore water is called consolidation.

Consolidation can progress as long as currents and waves are not strong enough to erode the deposited material. This occurs during periods around slack water and around tidal low water, when the tidal flats fall dry. Consolidation of cohesive sediments leads to increasing stability against erosion, so that the sediments are not re-suspended even at increasing current velocities and turbulences. The bottom elevation increases to a certain degree, and this phase of increased stability against erosion is called settled mud or settled bed (Migniot et al., 1981).

2.5 General shoreline evolution

Shoreline retreat leads to the loss of land and threatens coastal communities and infrastructure. Therefore, the evolution of shorelines is a major topic and it is important to understand the causes of erosion in order to be able to forecast the long-term development of the shoreline. Based on this, coastal development can be planned and, where necessary, appropriate coastal protection countermeasures can be planned.

The basic reason for most shoreline changes is a gradient in the littoral transport over a coastal section. If a certain section has an increasing transport in the direction of the net transport, this will result in coastal erosion.

During extreme events with large waves, which may come from uncharacteristic directions, combined with high storm surge two aspects have to be considered in relation to shoreline evolution:

- Offshore loss of sand: The profile will not be in equilibrium under storm surge conditions, and offshore transport of sand will cause erosion in the inner part of the coastal profile leading to a retreating shoreline and coastline. The reshaping of the profile towards the equilibrium profile after the storm surge will normally be very slow and not complete. This means that the offshore loss during such events is an important aspect of coastal erosion and has to be taken into account in the design of shoreline management measures. Similarly, a permanent sea level rise will cause permanent coastal erosion.

- Longshore loss off sand: This occurs during an extreme event, when the wave conditions typically differ from the prevailing wave conditions with respect to height, period and direction. The normal wave climate could, for example, be a monsoon climate, whereas the extreme climate could be dominated by typhoons. Even if the extreme conditions are represented in a statistically correct manner in the normal wave climate, the frequency of occurrence will be very small, which means that it will only play a minor role in the sediment budget. However, on the day the extreme event occurs, there will be very large littoral transport rates and gradients, which in turn will cause great changes to the shoreline and coastline.

The above description shows that it is important to study 'normal' as well as extreme events in relation to shoreline evolution and coastal erosion.

The longshore and the cross-shore (on-/offshore) processes are normally analysed separately, although this is not entirely correct, but considering the tools available, it has been the most practicable possibility (Mangor, 2004).

3 COASTAL CLASSIFICATION

The coastal profile mainly depends on the wave conditions, tidal regime, storm surge conditions and type of sediments existing in the area. Furthermore, the directional characteristics of the wave climate, the supply of sediments to the coastal area and geological and biological factors have a formative influence.

3.1 Coastal profiles

This section gives a classification of different coastal profiles that can be found in the Lower Mekong Delta.

3.1.1 Moderately exposed littoral coast

The moderately exposed littoral coast is characterised by a narrow beach. The coast can consist of small dunes or cliffs. This type of coastal profile normally exists in connection with coastlines facing relatively small bodies of water with typical dimensions from 10 to 100 km. Storm wave climates have significant wave heights (H_s) between 1 and 3 m and the tidal regime is micro-tidal to moderate. The gross littoral transport is relatively small, on the order of 10,000 to 50,000 m^3 per year, and the littoral zone is relatively narrow, typically 50 to 300 m (Mangor, 2004).

3.1.2 Protected or marshy coasts

Protected coasts can be found in connection with coastlines bordering small bodies of water such as estuaries and lagoons with typical dimensions of less than 10 km. They are characterised by a narrow beach or very often by the complete lack of a sandy beach. The coast is often covered with vegetation right out to the beach (Figure 10).

Protected coasts can occur under micro to moderate tidal regimes and up to macro storm surge regimes. On such coasts, the littoral transport is less than 5,000 m^3 per year and there is hardly any littoral zone (Mangor, 2004). Protected coasts normally do not erode, but can be exposed to flooding, and are normally of poor recreational value (Schwartz, 2005).

3.1.3 Tidal flat coast

Tidal flat coasts are characterised by a very wide and flat foreshore, the so-called tidal flats. This type of coastal profile develops when tidal processes dominate over wave processes (Figure 11).

The width and character of the hinterland of tidal flat coasts mainly depends on the storm surge conditions and the general geology and morphology of the area. Low-lying coasts are exposed to regular flooding during storm surges. In this case, sea defences such as dykes have often been constructed to protect the hinterland.

Figure 10: Protected coast at Ha Tien in Kien Giang Province (Photo: GIZ Kien Giang)

Tidal flat coasts are most frequently found in connection with moderately exposed to protected conditions combined with non-tropical climates. Under tropical conditions, the tidal flats are often vegetated by mangroves, which change the character of the tidal flat (see below).

Under protected conditions, e.g. in estuaries, the tidal flat often consists of fine sand and mud. Under more exposed conditions, the tidal flat will mainly consist of fine to medium sand, but many variations of tidal flat coasts exist. The specific characteristics very much depend on the type and amount of sediments supplied from nearby rivers.

Sediment transport processes on tidal flats are influenced by both tidal currents and waves. The presence of non-cohesive as well as cohesive sediments makes the description of the relevant longshore and cross-shore transport processes very complex (Schwartz, 2005).

Tidal flat coasts are seldom used for traditional beach recreation, as they provide no attractive beaches, but they often constitute important habitats (Mangor, 2004).

3.1.4 Monsoon coast or swell coast

Monsoon coasts and swell coasts are characterised by continuous wave exposure. Average wave heights are typically in the order of H_s=1-2m and extreme waves less than approximately H_s=3m. These coastal conditions often occur in environments with an abundant supply of sand and fine sediment from tropical rivers. The combination of available mixed sediments and a fairly constant wave climate results in a very pronounced sorting of the sediments. This results in the formation of a narrow sandy beach and a sandy shoreface out to a water depth of 3 to 4 m. The width of the shoreface is often less than 200 to 300 m (Mangor, 2004).

The beach material often consists of well-sorted medium sand. Beyond this sandy shoreface, the bed material often shifts abruptly to silt or mud and the slope of the profile becomes considerably gentler. The fine offshore bed material is only brought in suspension and transported during the rougher part of the monsoon period. Under these conditions, there is considerable transport of fine material on top of the littoral transport of sand. Figure 12 shows an example of a monsoon coast near the mouth of the Dinh An River in the northeast of Soc Trang Province.

The monsoon wave climate is seasonal, while this is seldom the case for swell climates. The monsoon coasts are normally only used for recreation in the calm period as the waves are too rough in the monsoon period. Furthermore, the water is often turbid during much of the monsoon period (Schwartz, 2005).

If there is no supply of sand to the coast, monsoon and swell coastlines are often exposed to erosion. Other typical problems are sedimentation in ports and the closure of river mouths due to the seasonal pattern of precipitation and wave conditions.

Figure 11: Tidal flat coast in Soc Trang (Photo: Schmitt)

Figure 12: Coast near the mouth of the Dinh An River in Soc Trang Province (Photo: Albers)

3.1.5 Muddy coast with mangrove vegetation

This type of coast is characterised by a muddy shoreface, sometimes in the form of muddy tidal flats and the lack of a sandy shore. The area exposed to the tidal variation, or a part of it, is vegetated by mangroves (Figure 13).

Muddy coasts with mangrove vegetation occur in tropical climates where rivers supply abundant fine material to the coastal zone. Normally the wave exposure is low to moderate and the tidal regime can be any type.

The hinterland often consists of low-lying wetland exposed to flooding. Dykes are often built in such areas.

Mangrove forests constitute an important part of such a profile, both biologically and with respect to the stability of the coastal profile. Cutting of the mangrove forests causes very severe problems for such a coast as it decreases the bio-diversity and causes erosion and flooding (Figure 14).

Figure 13: Mangrove vegetation on the coast of Soc Trang Province (left: Trung Binh Commune in Tran De District, right: Lai Hoa Commune in Vinh Chau District); (Photos: Schmitt)

Figure 14: Eroding mangrove forest belt on the coast of Soc Trang Province (Vinh Tan Commune); (Photo: Albers)

3.2 Estuaries

By definition, an estuary is the part of a river that is influenced by tides. Thus, the upper limit is generally considered to be the furthest point at which a tidal range can be detected. Estuaries are characterised by strong salinity gradients (and hence gradients of water density), and an estuarine turbidity maximum due to large suspended sediment concentrations. Most estuaries have meandering courses and numerous tributaries. They can usually be divided into three sections: a lower (or marine) estuary, in free connection with the open sea; a middle estuary, where most of the mixing between seawater and river water takes place; and an upper (or fluvial) estuary, dominated by freshwater influences but nevertheless subjected to daily tidal rise and fall (The Open University, 2006).

Estuaries transport varying amounts of sediments and discharge them into coastal waters. Waves and tidal currents have to be sufficiently strong to disperse the sediments. An estuary is less likely to develop where sediment discharge is too high and waves and currents are not strong enough to disperse the sediments. In that case, a delta may grow seawards from the river mouth instead.

Estuaries have a global significance for continental shelf and oceanic processes because of the exchange of water and sediment with coastal seas. Estuaries act as a sort of filter for sediment input to the oceans. Suspended sediment concentrations are generally high and the sediments are often richly organic (Schwartz, 2005).

Intertidal flats, at the boundary area of the tidal channels of the estuary, are alternately covered and uncovered by the rise and fall of the tides. There is a progression in grain size from mud-dominated sediments at the high tide level to sand-dominated sediments at the low tide level. Intertidal flats typically have very low gradients, usually on the order of 1:1,000. In tropical and equatorial regions, intertidal flats and shores of estuaries are commonly colonised by mangrove trees (Figure 15). The aerial root system of the mangroves traps the mud (see Figure 13). Mangrove swamps, rather than salt-marshes, dominate the zone around the high water level in such regions (Mangor, 2004).

Figure 15: Tributary of the Bassac River in Soc Trang Province (Photo: Schmitt)

3.3 Deltas

Hydrodynamics and morphodynamics are similar in both estuaries and deltas. The discharge from rivers with deltas is large enough to transport the sediment load to the river mouth or beyond. If the rate of sediment supply exceeds the rate of sediment dispersal by waves and tidal currents, a coastal accumulation of sediments forms a delta, typically extending seawards from the river mouth. In estuaries without deltas, the discharge is not sufficient to transport sediments to the river mouth. Sediments therefore accumulate in the estuary and no delta is formed. In some cases, the sediment load in the estuary may not be sufficient to form a delta.

Deltas are usually fed by rivers with extensive catchment areas and many tributaries supplying both water and sediment. Water supply and sediment discharge are determined by precipitation and erosion within the catchment areas and themselves depend on the climate, local geology, relief and land use.

There is a wide variety of delta types, depending on the relative influences of river flow, wave action and tidal currents. Where the river discharges into deep water and/or where there is a significant tidal range, the river mouth tends to resemble a large and rather complicated estuary, with islands and interlinked channels.

Delta complexes can be hundreds of kilometres across. They commonly consist of an extensive lowland area just above sea-level (the delta plain), crossed by a network of active and abandoned channels (Figure 16). The raised banks of the channels are called levies, and are separated by either vegetated or shallow-water (wetland) areas. The numerous channels or distributaries range in width from a few tens or hundreds of metres to several kilometres.

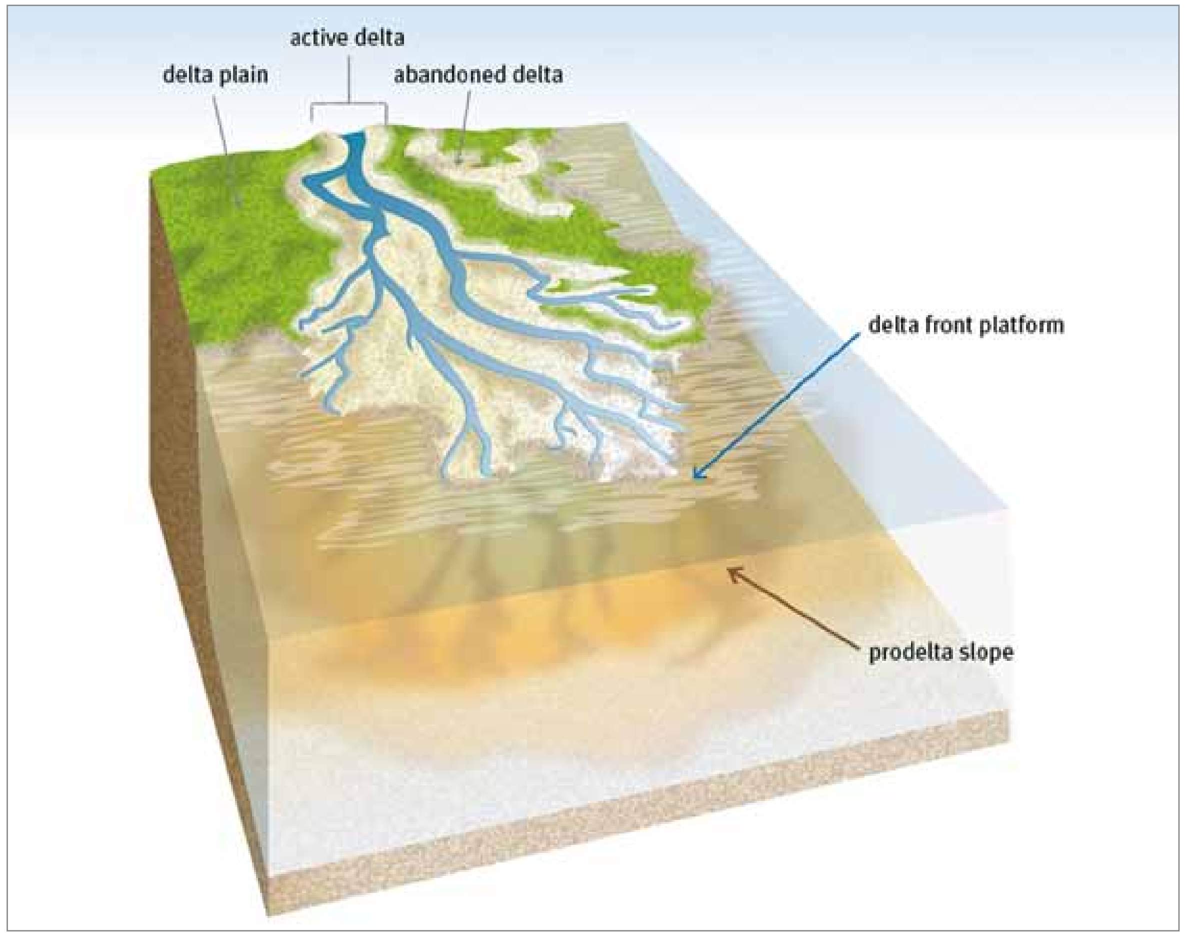


Figure 16: Perspective view of a delta showing the principal components (modified from The Open University, 2006)

Deltas are highly dynamic systems, which can influence large areas of the continental shelf. The delta front lies seawards of the delta plain, and comprises the shoreline and the offshore part of the delta just below sea level, where the fluvial bedload is deposited and where the sediments consist mainly of different types of sand. The deeper offshore zone is the prodelta, which receives much of the silt and clay transported seawards in suspension and deposited in layers that are gently inclined seawards.

Most of the world's major deltas form extensive wetlands of high biological productivity and fertility. Many large deltas are also regions of active crustal subsidence as a result of isostatic adjustments in response to loading by the great mass of sediments deposited on the deltas. In many parts of the world, their thick sediment accumulations are important as a source and reservoir for deposits of oil, gas and coal. Subsidence in deltaic regions results not only from loading by the accumulation of successive layers of sediment, but also from compaction of those sediments. Since the lowland plains of deltas remain close to sea-level, rates of sediment deposition and of subsidence must remain broadly in balance (The Open University, 2006).

Where the tidal range is small (less than approximately 0.5 m), the delta is dominated by the river discharge. Mixing processes and sedimentation mostly take place seaward of the mouths.

Tide-dominated deltas occur where the tidal range is large (>4 m). Although net sediment transport is seawards, there is also some landward movement of sediment during ebb tide. In tide-dominated deltas, sediments transported by river flow and deposited near the mouths are rapidly reworked by tidal currents into a series of linear subaqueous ridges.

If wave energy at the coast is sufficiently high, a wave dominated delta can occur. In such situations, the river flow and, temporarily, the ebb current are moving seawards against the direction of wave propagation so that wave speed and wavelength decrease and wave height increases. As a result of these changes, waves approaching the river mouth are liable to break earlier in deeper water than they would normally. The strong mixing of seawater with river water in this zone leads to rapid deposition of sediments. The shorelines of wave-dominated deltas are characterised by straight, sandy beaches.

Many deltas are subject to interference from human activities, such as damming of rivers upstream, agricultural activity, or hydrocarbon exploitation on the delta plain. Substantial areas of the delta plain were reclaimed for housing areas, new channels were dug and existing channels deepened to make navigation easier. As a result of these measures, since the early years of the last century, the rate of subsidence has exceeded the rate of sediment deposition. The elevation of delta plains is close to the sea-level and thus deltas are very vulnerable to flooding, especially from storm surges, which can lead to enormous loss of life among the agrarian communities living on them. The probability of severe flooding increases almost annually, due to human activities in the delta region. Subsidence can become larger than the sedimentation rate and the sea-level rise increases the frequency and severity of tropical typhoons and storm surges.

3.4 Geology of Viet Nam's south coast

The Mekong Delta is comprised of vast low-lying areas with an elevation of 0 - 4 m above mean sea level. It is formed of eroded sediments from the upper basin that were deposited in the lower basin. An extensive network of canals has been constructed in the last 300 years. The structures comprise 7,000 km of main canals, 4,000 km of secondary canals of farms systems, and more than 20,000 km of protection dykes to prevent flooding (Tuan et al., 2007).

Based on the influence of the diverse tidal patterns, the Mekong Delta can be divided into three different hydrological regions (Delta Alliance, 2011):

- The northern plains, including sections of the provinces An Giang and Dong Thap; an area of about 300,000 ha, where the impact of the river floods is dominant.
- An area with combined river flood-tidal impacts; this region is bound by the Cai Lon River – Xeo Chit Channel, Lai Hieu Canal – Mang Thit River and Ben Tre – Cho Gao Canals, with an area of about 1.6 million ha.
- The coastal delta regions with direct influence of the primary tides; this includes the entire coastal region of the East Sea, with an area of about 2.0 million ha.

Viet Nam's south coast consists almost entirely of Quaternary deposits like at the mouths of the Mekong River. Some rocky promontories (granite) can be found at Cape Vung Tau (Eisma, 2010).

At the mouths of the Mekong River, the coast is formed of mudflats with mangrove vegetation. The Mekong River delta consists of large low-lying floodplains protected by dykes. Along the coast, a narrow belt of mangroves and a few sandy spits grade seaward into tidal flats that are between 1 and 3 km wide. In the delta, 10 to 20 m of Holocene deposits overlie late Pleistocene deposits, older bedrock and a filled-in incised river valley (more than 70 m deep), which dates from the last glacial period. Marine deposits prevail in the earliest Holocene deposits (Eisma, 2010).

High resolution seismic profiles, which show differences in clinoform structures and sediment characteristics, allow a division of the subaqueous delta into four zones: Mekong River mouth, east coast of the Ca Mau Peninsular, Cape Ca Mau and west coast of the Ca Mau Peninsular (Xue et al., 2010).

Delta progression became rapid during the high sea level period (6,000 - 5,000 BP) and was influenced by fluctuations in river sediment supply, tectonics with areas of uplift and depression, relative sea level changes, and mangrove vegetation, which promoted sediment accumulation. An increasing wave influence that occurred after the former bight has been filled by the progressing delta body led to a morphological asymmetry in the last 3,000 years. Coastal longshore currents, increased by the northeast monsoon, transported large amounts of sediments to the southwest. A large downdrift area (including the Ca Mau Peninsular) and subaqueous area was formed (Xue et al., 2010). During the past 5,000 years, the delta front has moved seaward by more than 90 km (more than 20 m/year) in the area along the Bassac Channel, decreasing to about 50 km during the same period (about 12 m/year) to the northeast (with an overall average of 17-18 m/year between 5,000 and 3,000 BP and 13-14 m/year after 3,000 BP). The sediment discharge of the river during the past 3,000 years has been about the same as the present sediment discharge (Ta et al., 2002).

At present, much of the river sediment is supplied during periods of high river flow and much sediment is flushed out into the coastal sea. During periods of low river flow, turbidity reaches a maximum in the estuary, where a lot of the supplied sediment is deposited. The sand in the relict beach ridges and dunes dates mainly from the last interglacial period, and has been reshaped several times by wind action. This is probably related to destruction of vegetation during climatic changes in the late Pleistocene (Murray-Wallace et al., 2002).

The sediment brought into the coastal sea by the Mekong largely moves southward under the influence of the northeast monsoon and goes around Cape Ca Mau into the Gulf of Thailand (Xue et al., 2010; Xue et al., 2012). South of the river mouths, the coast down to Mum Bar Bung and the west coast from Mum Bar Bung up to Hon Chong consists of mangrove forests and mudflats, with a short sandy beach west of Ca Mau. Hon Chong is composed of Palaeozoic limestone, and the offshore islands up to the The Chats archipelago consist of Palaeozoic and Mesozoic formations, with steep cliffs forming the coast. The large island of Phu Quoc has sandy beaches between promontories with rocky cliffs (Eisma, 2010).

4 COASTAL EROSION AND FLOODING

Coastal erosion and flooding can have natural or anthropogenic causes. Many impacts, due to natural processes as well as human activities, are permanent and irreversible.

To identify the causes of erosion and flooding in certain coastal areas, the processes and parameters described in Chapter 2 and the coastal classification described in Chapter 3 have to be known.

Erosion in Vinh Tan (Photo: Schmitt)

4.1 Natural causes of coastal erosion

Differences in the wave conditions at certain coastal sections, a curved coastline or special bathymetric conditions can lead to increasing transport rates and therefore to erosion. Storm surge conditions with large waves may lead to offshore loss of sediments due to non-equilibrium in the profile during the storm surge. At coastlines with a very oblique wave approach, there is a tendency for spit formations to occur naturally parallel to the coast.

The loss of material from an area exposed on one or two sides typically happens at the tip of deltas, which do not receive sufficient material from the river. This can be due to natural shifting of the river alignment, but also due to human activities, which will be discussed later.

Sea level rise is also a natural reason for coastal erosion. Worldwide sea level rise is a phenomenon, which has been discussed for decades. A global sea level rise of 0.10 m to 0.25 m has been recorded over the last century, and rising sea levels will cause a shoreline setback. Littoral coasts consisting of fine sediments will be exposed to higher setbacks than coasts consisting of coarser sediments (Mangor, 2004).

There is a natural variation in the supply of sand to a coastline from a river. Droughts in large river basins can result in long periods with decreasing supply of sand to the shoreline, leading to shoreline erosion.

4.2 Human causes of coastal erosion

Although there are many natural causes of coastal erosion, most of the causes affecting coastal communities are due to human intervention in the transport processes along the coastlines and/or reductions in the supply of sand to the shorelines:

- Measures aimed at coastal protection, erosion protection and port engineering
- Removal of coastal vegetation
- Reduction of the sediment supply from the estuaries due to river engineering activities
- Dredging and dumping of sediments

Coastal structures interfering with the littoral transport are the most common cause of coastal erosion. The presence of the structure has a series of effects such as loss of sand to deep water or trapping of sand in entrance channels and outer harbours. Furthermore, trapping of sand on the upstream side of the structure takes sand out of the sediment budget, which causes erosion along adjacent shorelines. This occurs mostly, of course, on the lee side, but large structures may also cause (initial) erosion on the upstream side.

The structures, which may cause this type of erosion, are:

- Groins and similar structures perpendicular to the shore
- Ports
- Inlet jetties at tidal inlets and river mouths
- Detached breakwaters

The accumulation and erosion patterns adjacent to coastal structures depend on the type of coastline (e.g. the wave climate and the orientation of the shoreline), the extent of the structure relative to the width of the surf-zone and the detailed shape of the coastal structure, etc. (CEM, 2002).

Subsidence lowers the surface in a specific region. It is a local or regional phenomenon, and this puts it in contrast with the sea level rise, which is global.

Subsidence can be caused by many different phenomena, natural as well as human. Natural causes include the settling of soft sediments, tectonic activity and different kinds of rebound processes. Human causes of subsidence include the extraction of groundwater, oil or gas in the coastal area. Subsidence acts in the same way as sea level rise in relation to shore erosion, apart from the fact that sea level rise will always be a gradual and slow process, whereas subsidence may occur rapidly depending on the cause of the subsidence (Mangor, 2004).

Figure 17: Flooding at Cu Lao Dung island in October 2011 (Photos: Cu Lao Dung District)

4.3 Natural causes of flooding

Flooding is an even more severe phenomenon along low-lying coasts than coastal erosion. It appears very quickly and often covers huge areas. Coastal flooding causes extensive damage and very often loss of life. These guidelines only consider flooding along open coasts. Flooding in estuaries and delta areas caused by river floods is also very important, but not covered in these guidelines.

Figure 17 shows flooding at Cu Lao Dung Island in the mouth of the Hau River. In October 2011, many dykes breached during high-tide in Cu Lao Dung, Tran De and Vinh Chau districts. The river overflowed the dyke in several sections. More than 2,000 ha of agricultural areas were flooded.

Flooding only occurs in areas where the coast and the coastal hinterland are low relative to extreme water levels. Extreme water levels can be divided into two types:

- Recurring events: The combined effect of tide and storm surge together with the action of waves, which is important, for example when dykes breach during a storm surge. Tsunamis can also cause flooding.
- Long-term trends: Sea level rise and subsidence may give an increased risk of flooding combined with recurring events.

Recurring events will normally occur as the result of combinations of extreme tides, seasonal variations and meteorologically generated storm surge (e.g. by typhoons). The methods used for analysis of the various types of events vary, as they follow different statistical distributions. Depending on the analyses for a given site, the flooding conditions will normally be described in the form of recurrence periods (in years) versus extreme water levels.

Long-term trends will normally not cause flooding by themselves, but they will increase the flood level, or in other words, they will decrease the interval at which the events recur (Kamphuis, 2010).

4.4 Causes of flooding due to human activities

Human activities can increase the risk of flooding or even cause flooding. Regulation or reclamation work in a tidal inlet or an estuary can change the tidal regime and thus the flood levels in the estuary. The construction of dykes decreases the storage capacity in certain areas and very often is followed by increased flood levels along the estuary (Hoa et al., 2007). Extensive cutting of mangrove areas can also change the flood conditions in the hinterland.

Long-term trends in sea level rise and subsidence can also be influenced by human activities. This will increase the risk of flooding in areas prone to naturally recurring flood events. Subsidence due to human interference in coastal areas can be caused by the extraction of groundwater, oil or gas. It may occur on very different time scales (The Open University, 2006).

4.5 Sea defence design considerations

Many low-lying areas, especially in coastal deltas, have been developed for agriculture, infrastructure and habitation due to the fertile soil, good access to the sea and potential economic growth. Because of the regular flooding (that, in turn, creates the fertile soil etc.), coastal defence works were designed, taking into account different parameters such as the lifetime of the structure, the acceptable risk that the sea defence fails within the considered lifetime and the design recurrence period for the design flood level.

If the area exposed to flooding is small or medium in size, and if it is only developed to a small degree, such as rural or farming areas, then a relatively high risk of flooding can be accepted. This consideration is a correlation between the lifetime, the recurrence period and the acceptable risk of failure during the lifetime of the sea defence.

However, if the potential flooded area is large and intensively used for habitation and infrastructure, the acceptable risk of flooding will be very low. In the case that the selected lifetime of the dyke is 100 years, the required design recurrence period will be approximately 10,000 years. More comprehensive procedures for detailed design of sea defences are provided by Kamphuis (2010).

Sea level rise is a worldwide phenomenon, which has to be taken into account in low-lying areas when designing sea defences and planning land utilisation.

5 COASTAL PROTECTION

Coastal protection measures defend the coasts of the mainland and islands against destructive impacts of the sea. Eroding coastlines can be protected by constructions, which absorb the forces of waves and currents. Measures of floodplain management result in a seawards displacement of the hydrodynamic loads, and a reduction of the forces at endangered coastal sections.

5.1 Coastal protection system

Human activities have influenced the natural development of the coastal areas in the Mekong Delta since the beginning of the 18th century (Tuan et al., 2007). Today, the coastal areas of the lower Mekong Delta are therefore cultural landscapes influenced by technical activities. Only a few coastal sections can be considered as natural coastal landforms. The present coastline has been influenced by dyke construction and drainage, while even some parts of the tidal flats were formed by anthropogenic influences. Based on local experiences regarding the protection of the coasts, different coastal protection measures have been developed, which complement each other.

The elements of coastal protection can be classified based on their shape (area, linear, punctiform) or based on their function (erosion protection, flood protection, drainage) as shown in Tables 2 and 3 (Von Lieberman, 1999).

Table 2:
Classification of coastal protection elements according to their shape

Function	Element
Area coastal protection	Beach nourishment, floodplain, island, dune, tidal flat
Linear coastal protection	Dyke, groin, revetment, dune, reef, breakwater
Punctiform coastal protection	Storm surge barrier, sluice, tidal outlet, coastal pumping station

Table 3:
Classification of coastal protection elements according to their function

Function	Element
Elements of erosion protection	Groin, flood plain, beach nourishment, revetment, seawall, breakwater
Elements of flood protection	Dyke, storm surge barrier
Elements of drainage	Sluice gate, tidal outlet, coastal pumping station
Natural coastal protection elements	Island, tidal flats, floodplains

Different elements of coastal protection can be assembled into a coastal protection system as shown in Figure 18. The tidal flats and floodplains (vegetated with mangroves) decrease the incoming tidal and wave energy (for details, see McIvor et al., 2012A) and thus significantly reduce the wave load on the dyke. The summer dyke avoids flooding during a season with a low probability of storm surges and allows for usage of those areas during that time. The main dyke prevents flooding of the hinterland due to extreme events with very high water levels. In the case of such an extreme event, the area between the two dyke lines offers additional retention and also decreases the wave load on the main dyke. This form of coastal protection can be found for example along some parts of the German North Sea coast (without mangroves). It provides maximum protection, but is very cost-intensive and land-consuming.

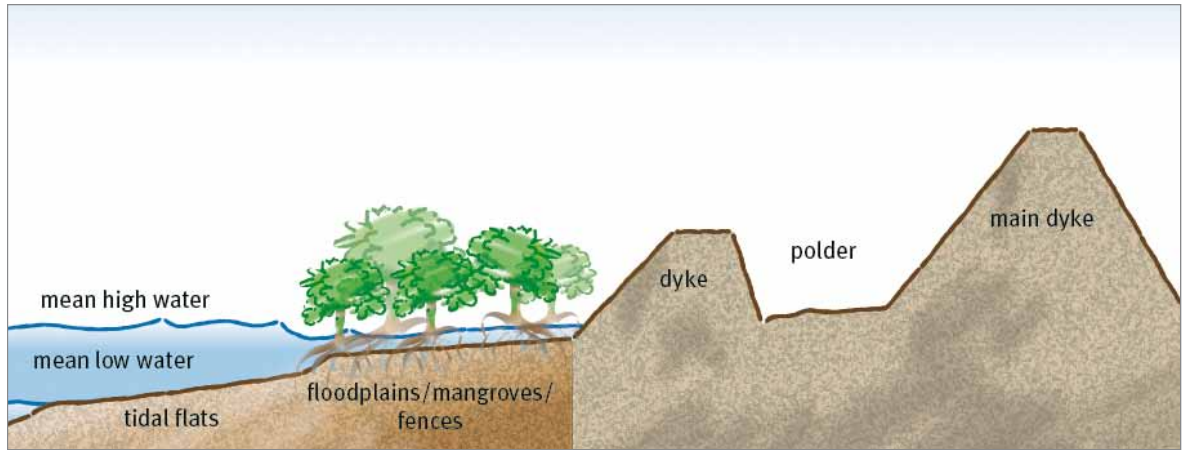


Figure 18: Composition of a coastal protection system

5.2 Elements of erosion protection

The morphology of islands and coastal sections is characterised by nearshore hydrodynamic processes. In addition to tidal currents, waves also have a significant influence on sedimentation and erosion, and therefore on accretion and retreat of the shoreline. Since the middle of the 19th century, extensive protection measures to decrease the wave energy and currents have been installed in many different variants.

Elements of erosion protection can be classified according to their general alignment and dimension. They comprise longshore elements, such as breakwaters and revetments, cross-shore elements, such as groins, and area protection, such as floodplains and nourishments.

5.2.1 Longshore elements

Longshore elements such as seawalls, dykes or revetments protect shorelines or dunes against erosion caused by currents and waves, and do not interrupt or reduce the coastal longshore sediment transport. By combining longshore elements with cross-shore elements such as groins or nourishments, longshore transport can be influenced.

A distinction must be made between the design of permeable and impermeable revetments. Mechanical loads result from the own weight of the structure, hydrostatic load, currents, waves and exceptional loads such as impacts of floating items or boats.

5.2.1.1 Detached breakwaters

A detached breakwater is a structure parallel, or close to parallel, to the coastline, built inside or outside the surf-zone. Detached breakwaters are mainly built with two purposes, either to protect a harbour or marina from wave action, or to protect the coast from erosion. Important parameters that characterise detached breakwaters are their length (L_B) and the distance to the shoreline (x).

Accumulation forms that develop after installation of the breakwater include salients and tombolos (Figure 19):

- Salient: When the dimensionless breakwater length L_{B^*} (breakwater length relative to distance to shoreline) is less than approximately 0.6 to 0.7, a bell-shaped salient in the shoreline will form in the lee of the breakwater. However, parameters other than the breakwater length and distance also influence the accumulation pattern.

- Tombolo: When the dimensionless breakwater length L_{B^*} is greater than approximately 0.9 to 1.0, the sand accumulation behind the breakwater will connect the beach to the breakwater in a tombolo formation. But again, parameters other than the breakwater length and distance influence the accumulation pattern.

If there are several breakwaters in a series, this is referred to as a segmented breakwater, where the length of the gap between the breakwaters is defined as L_0.

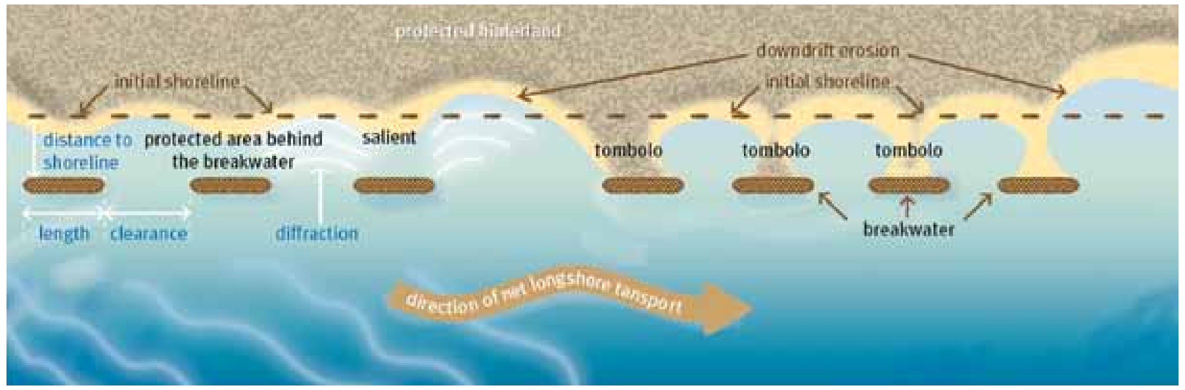


Figure 19: Effects of detached breakwaters

A detached breakwater provides shelter from the waves, causing the littoral transport behind the breakwater to be decreased and the transport pattern adjacent to the breakwater to be modified. These characteristics of a breakwater are utilised in different ways for various types of breakwaters by varying relevant parameters.

Depending on the cross-section of the breakwater, the water depth and the initial wave parameters, only a small part of the wave energy reaches the landward side of the structure. Thus, a protected area is created. The waves passing the breakwater underlie diffraction and their propagation direction changes towards the protected area. The reduced wave motion in the protected area stimulates sedimentation and the shoreline is relocated seaward. Depending on the length of the breakwater, the distance to the shoreline and the wave transmission of the structure, a partial or complete tombolo develops. The transmission coefficient is defined as the ratio between the transmitted wave height and initial wave height. It depends on the crest height as well as the shape and the permeability of the breakwater. The development of tombolos is more likely if the breakwater is built in the surf zone.

A tombolo is a very stable formation, because the course of the new shoreline is almost perpendicular to the diffracted waves. Detached breakwaters that are arranged parallel to the coast allow longshore sediment transport to a certain degree. In the case of a major disturbance of the longshore transport, corresponding countermeasures, such as groins or nourishments, can also be designed. Detached breakwaters are used to protect single, very exposed coastal sections and can be arranged in a chain of several breakwaters with gaps in between, or as one breakwater with a length of between 100 m and 200 m.

Breakwaters differ in terms of position (deep/shallow water), construction type (dumped, vertical, floating) and effectiveness (development of salients or tombolos), and combinations are also possible.

Furthermore, differences in the construction height of the breakwater exist. Some breakwaters are emerged, some are submerged. The most commonly used type of breakwater is the dumped breakwater with a crest height above the mean high water level (CEM, 2002; Kamphuis, 2010; EAK, 2002).

Rubble mound breakwaters (dumped breakwaters) consist of several layers of graded stones (Figure 20). In general, they are constructed as detached breakwaters. The layered arrangement is used to reduce construction costs and to decrease the permeability.

Figure 21 shows a detached rubble mound breakwater at Ha Tien in Kien Giang Province. The view is along the south side of the newly reclaimed land at the southern side of the mouth of the Dong Ho River.

Figure 22 shows a detached breakwater consisting of gabions at the West Sea coast at Vam Kenh Moi (near Da Bac), Ca Mau Province. Gabions are net mesh stone-filled mattresses. They are only recommended at fairly protected locations (see Chapter 5.2.1.2).

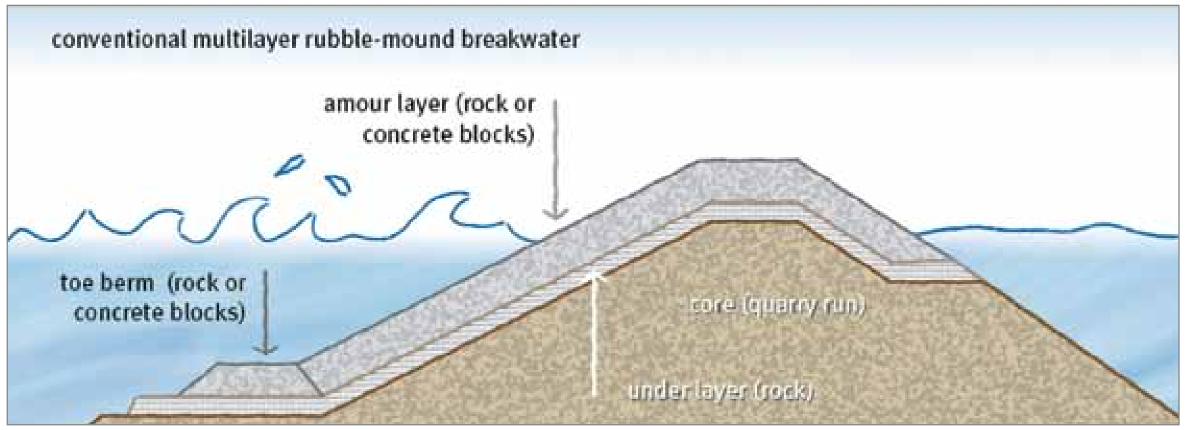


Figure 20: Rubble mound breakwater (modified from CEM, 2002)

Figure 21: Detached rubble mound breakwater at Ha Tien in Kien Giang Province (Photo: Russell)

Figure 22: Detached breakwater consisting of gabions at the West Sea coast at Vam Kenh Moi (near Da Bac), Ca Mau Province (Photo: SIWRR)

The most important parameter for the design of a rubble mound breakwater is the required stone size of the armour layer. This size is influenced by:

- the design wave height
- the characteristics of the armour layer (thickness, arrangement)
- the slope of the armour layer
- a possible overflow

Following the approach of Hudson (CEM, 2002), the required specific weight can be assessed as:

W_{50} = Weight of a single armour stone
γ_s = Specific weight of the stone material
H_s = Design wave height
K_D = Stability coefficient
γ_w = Specific weight of water
θ = Slope

$$W_{50} = \frac{\gamma_S H_S^3}{K_D\left(\frac{\gamma_S}{\gamma_W}-1\right)^3 \cot\theta}$$

After the length of the breakwater, the distance to the shoreline and the number of breakwaters are set, e.g. by means of numerical modelling, and then the construction of the breakwater itself has to be designed. Design parameters include the crest height, crest width, permeability and slope.

For a design wave height of 0.60 m, which is relevant for parts of the tidal flat coasts of Soc Trang Province and Bac Lieu Province, the weight of a single armour stone can be calculated according to the Hudson-Formula:

$$W_{50} = \frac{\gamma_S H_S^3}{K_D\left(\frac{\gamma_S}{\gamma_W}-1\right)^3 \cot\theta} = \frac{25\cdot 0.60^3}{1.2\cdot(\frac{25}{10}-1)^3\cdot 3} = \underline{0.44\ kN}$$

Additionally the mean diameter of the armour stones can be calculated:

$$\frac{H_S}{D_{N50}} = \left(\frac{\gamma_S}{\gamma_W}-1\right)(K_D\cdot\cot\theta)^{1/3}$$

$$D_{N50} = \frac{H_S}{\left(\frac{\gamma_S}{\gamma_W}-1\right)(K_D\cdot\cot\theta)^{1/3}} = \frac{0.60}{\left(\frac{25}{10}-1\right)(1.2\cdot 3)^{1/3}} = \underline{0.26\ m}$$

The Hudson-Formula contains some simplifications. For example, regular waves are assumed, while wave periods and the duration of a storm are not taken into consideration.

The formula of van der Meer can be applied for a comparison. It is a modification of the Hudson-Formula, and also considers the breaker type, porosity, damage to the armour layer and the number of waves occurring during the storm event:

$$\frac{H_S}{\left(\frac{\gamma_S}{\gamma_W}-1\right)\cdot D_{N50}} = P^{-0.13}\cdot\left(\frac{S}{\sqrt{N}}\right)^{0.2}\cdot\sqrt{\cot\alpha}\cdot\xi_m^P$$

D_{N50} = Mean diameter of an armour stone
P = Porosity of the armour layer (0.1 … 0.6)
S = Degree of damage of the armour layer
N = Number of waves during design storm event (<7,500)
ξ = Irribaren number (ξ_m = 2.9, ξ_{crit} = 2.5)

$$D_{N50} = \frac{0.60}{\left(\frac{25}{10}-1\right)\cdot 0.5^{-0.13}\cdot\left(\frac{8}{\sqrt{3600}}\right)^{0,2}\cdot\sqrt{3}\cdot 2.9^{0.5}} = \underline{0.19\ [m]}$$

The results of the two approaches are comparable. Due to the larger number of considered parameters, the formula from van der Meer should be applied, but should also involve a risk assessment.

Within the last decade, geotextiles have been used to construct breakwaters and groins. Geotextiles have a synthetic, very tough texture filled with sand or a sand-fluid-mixture. Different types include bags, mattresses and tubes (Pilarczyk, 2003). Only a few design approaches exist for these systems. Experiences from successful and non-successful projects are integrated into new applications.

Geotubes (Figure 23) have been used as an erosion protection element (breakwater) since the late 1980s (Pilarczyk, 1999). They are supplied as ready-for-use tubes with intakes at regular distances. Filling of the tubes is done by pumping a sand-fluid-mixture into the tube, and a major advantage is short transport of the filling material.

The design is based on the approach of Pilarczyk (1999), and the stability of a geotextile tube is ensured if the following condition is met:

Δ = Ratio of the densities of water and filling
b = Width of the tube [m]
d = Mean height of the tube [m]

$$\frac{H_S}{\Delta\cdot b} < 1$$

$$\frac{H_S}{\Delta\cdot d} < 1$$

Due to internal instabilities of the sand, the maximum wave height for Geotubes used as breakwaters is between 1.50 m and 2.00 m.

For the existing loads at tidal flat coasts at Soc Trang and Bac Lieu (see above), the dimensions of the Geotube can be calculated as follows:

$$\Delta = \frac{\rho_s-\rho_w}{\rho_w} = \frac{1.6-1.025}{1.025} = 0.56$$

$$\rightarrow d > \frac{H_s}{\Delta} = \frac{0.60}{0.56} = \underline{1.07\ m}$$

The sizes of Geotubes can vary, but due to deformations, large tube widths are necessary to achieve the desired heights. Therefore, Geotubes are massive constructions, and a perimeter of 15 m is required for a height of 2.00 m, which results in a width of approximately 4.00 m. The Geotube requires a sufficient foundation, which can be made from a gravel bed after preparation of the sea bed, or from two smaller Geotubes.

The costs for a breakwater constructed from Geotubes vary widely depending on the foundation, the dimensions, the personnel costs and the costs for construction equipment. The price for a Geotube in Viet Nam (including customs and import tax) is around 300 USD per running metre, plus associated costs for construction, sand and personnel[5].

In Viet Nam, Geotubes have been applied with temporary success in Loc An District, Ba Ria in Vung Tau Province (Figure 24). However, after several years in a tropical environment, the Geotube was torn away. The same product was applied at Hoa Duan, Thua Thien in Hue Province and failed due to abrasion of the geotextile in an exposed location.

The construction of conventional breakwaters is always a major project with relatively high costs. Furthermore, the construction of foundations for heavy structures such as rubble mound breakwaters and Geotubes is very complex and expensive, especially in muddy environments.

In the context of a pilot study along the coast of Vinh Tan Commune in Soc Trang Province, different arrangements, placements and designs of breakwaters were investigated using numerical and physical modelling. The effectiveness of conventional constructions as well as different designs using alternative, local materials was tested. Bamboo fences yielded very good results and have additional advantages due to the strength, availability and low cost of bamboo (Albers & Von Lieberman, 2011).

The detailed design of bamboo structures is described in Chapter 5.2.3. Parts of the results of the numerical and physical modelling that lead to the arrangement and dimensions can be found in Chapters 7.4 and 7.5. In May 2012, a 100 m long bamboo breakwater was installed on the coast of Vinh Tan in Soc Trang Province (Figure 25). After completion, a monitoring programme was started to assess the effects of this measure.

[5] Information from Huesker Synthetic GmbH Germany.

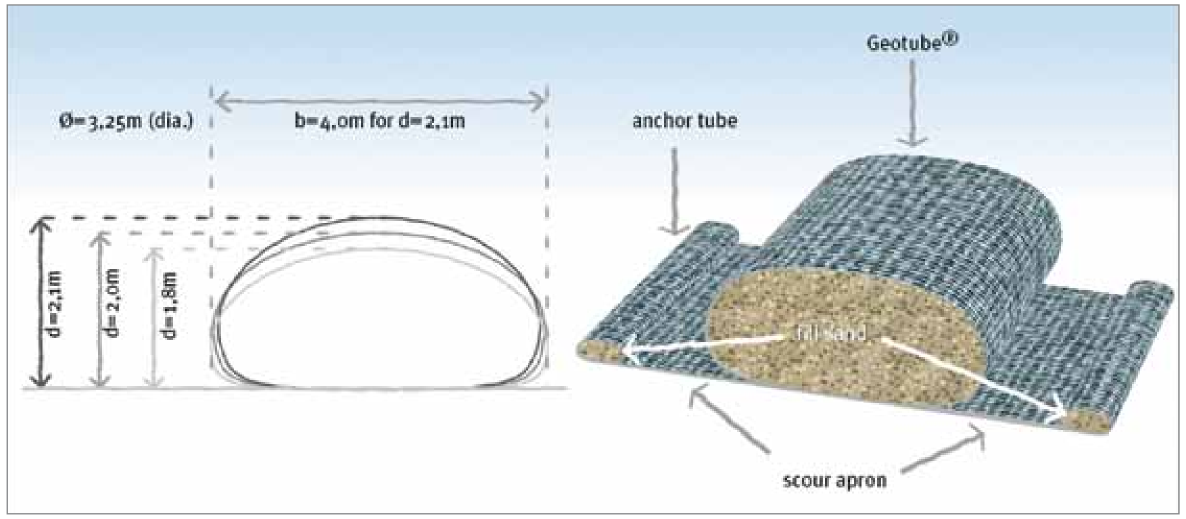


Figure 23: Examples of various Geotextile-Tube sizes (modified from Pilarczyk, 1999)

Figure 24: Beach protection using Geotubes at Loc An, Ba Ria in Vung Tau Province (Photo: SIWRR)

Figure 25: Bamboo breakwater in Vinh Tan Commune in Soc Trang Province (Photo: Albers)

Figure 26: Revetment of natural stones on the coast of Can Gio District, Ho Chi Minh City (Photo: SIWRR)

5.2.1.2 Revetments

A revetment is a facing of stone or concrete units built to protect an embankment, the foot of a dune, a dyke, or a seawall against erosion by wave action, storm surge and currents. This definition is very similar to the definition of a seawall, but a revetment does not protect against flooding. Furthermore, a revetment often supports other types of protection such as seawalls and dykes. Revetments can be exposed structures as well as buried structures. A buried revetment can be constructed as part of a soft protection, e.g. as an emergency measure to protect an endangered dune before further beach and dune nourishment is carried out.

Figure 27: Revetment of concrete blocks on the coast of Go Cong District, Tien Giang Province (Photos: SIWRR)

Revetments are always constructed as sloping structures and very often constructed as permeable structures using natural stones (Figure 26). The application of protruding concrete blocks applied on an impermeable revetment as shown in Figure 27 enhances wave energy absorption and reduces the wave run-up. If the concrete blocks are not installed properly and if their dimensions are not designed well, they may be the origin for erosion of the dyke, due to momentums induced by wave run-up. Figure 28 shows an impermeable revetment of concrete blocks combined with a narrow sea wall in Tra Vinh Province. The curved form of the sea wall reduces wave overtopping. The protruding concrete blocks are highly exposed to waves and may be displaced if they are not installed properly and maintained regularly.

Figure 28: Revetment of concrete blocks combined with a low sea wall at the coast of Tra Vinh Province (Photo: Pham Thuy Duong)

Net mesh stone-filled mattresses, such as gabions, are also frequently used (Figure 29, left). However, they are only recommended for use at fairly protected locations (Mangor, 2004). At locations with higher wave load, the steel wire net cannot take up the forces that result from moving stones in stormy conditions (Figure 29, right).

Figure 29: Gabion revetment at a sluice gate in Soc Trang Province (left), damaged gabion revetment in Vinh Tan Commune, Soc Trang Province (right); (Photos: Albers)

Figure 30: Beach protection project at Doi Duong, Phan Thiet City, Binh Thuan Province by Geotubes (Photos: SIWRR)

Revetments can also consist of sand-filled geotextile fabric bags, mattresses and tubes. Such structures must be protected against UV-light to avoid weathering of the fabric. Sand-bagging is often used as emergency protection. Geotextile fabric revetments are fragile against mechanical impact and vandalism, and their appearance is not natural. Figure 30 shows revetments made of Geotubes at the beach protection project at Doi Duong, Phan Thiet City, Binh Thuan Province. The weathering effects are clearly visible in the picture on the right.

All types of revetments have the inherent function of stopping beach degradation, as they are used at locations where the coast is exposed to erosion. A revetment will fix the location of the coastline, but it will not stop the ongoing erosion of the coastal profile (Mangor, 2004). Without accompanying measures, the beach in front of the revetment will gradually disappear. However, as a revetment is often constructed as a permeable, sloping structure, it will normally not accelerate the erosion, as do seawalls. On the contrary, rubble revetments are often used as reinforcement for seawalls which have been exposed due to the disappearance of the beach. Such reinforcement protects the foot of the seawall and minimises the reflection.

A revetment, like a seawall, will decrease the release of sediments from the section it protects, and for this reason it will have a negative impact on the sediment budget along adjacent shorelines. A revetment is thus a passive coastal protection measure and is used at locations exposed to erosion or as a supplement to seawalls or dykes at locations exposed to both erosion and flooding.

Rubble revetments and similar structures are permeable and have a fairly steep slope. A 1:2 slope is often used, which is not convenient for recreational use or for the landing or hauling of small fishing boats. Therefore, this kind of structure should not be used at locations where the beach is used for recreation or fishing activities. For such locations, other types of protection measures must be considered, but if a revetment is required, a more gently sloping structure with a smooth surface is recommended.

At Ganh Hao in Bac Lieu Province or at Mui Ne, Phan Thiet City, Binh Thuan Province, revetments with steep slopes and rough surfaces were used as beach protection and ruined any touristic intentions (Figure 31).

As for breakwaters, toe protection for revetments and the application of different gradual layers is essential for the stability and durability of the construction. Figure 32 shows a revetment under construction at sluice gate 16 in Soc Trang Province. In this case, flat concrete slabs are used and form a relatively impermeable structure with a smooth slope. On the left photo, the different layers are visible: top layer of the dyke (geotextile), equalising and filter layer (gravel), and cover layer. The toe protection is formed by an in-situ concrete wall and riprap. The right photo shows the sheathing of the concrete wall.

If the flat concrete slabs are too large and form a nearly impermeable surface, there is a considerable danger that the wave load will break the slabs due to imperfections of the subsoil or due to washing out of sediments from the subsoil (Figure 33). Thus, a sound preparation of the subsoil, the application of different gradual layers including filter layers and a sound gearing of the surface are essential.

Figure 31: Steep slopes and rough surfaces of revetments hampers recreation activities at Ganh Hao, Bac Lieu Province (Photo: GIZ Bac Lieu)

Figure 32: Revetment under construction in Soc Trang Province; different layers (left) and construction of the toe protection (right); (Photos: Albers)

Figure 33: Damaged revetment at sluice gate 2 in Soc Trang Province; (Photo: Albers)

5.2.1.3 Seawalls

A seawall is defined as a structure separating land and water areas, and is designed to prevent coastal erosion and other damage due to wave action and storm surge, such as flooding. Seawalls are normally very massive structures because they are designed to resist the full force of waves and storm surge.

A seawall is typically a sloping concrete structure; it can be smooth, stepped-faced or curved-faced. A seawall can also be built as a rubble-mound structure, as a block seawall, and as a steel or wooden structure. The common characteristic is that the structure is designed to withstand severe wave action and storm surge. A rubble mound revetment often protects the foot of such non-flexible seawalls. A rubble mound seawall bears a great similarity to a rubble-mound revetment, but a revetment is often used as a supplement to a seawall or as a stand-alone structure at less exposed locations.

The nearly vertical seawalls, which were mainly used in the past, had negative characteristics in terms of wave reflection, and resulted in accelerated disappearance of the beach. However, all kinds of seawalls involve beach degradation, as they are used at locations where the coast is exposed to erosion. The seawall will fix the location of the coastline, but it will not stop the on-going erosion of the coastal profile. On the contrary, it will, to a certain degree, accelerate the erosion. It is quite normal that the beach disappears in front of a seawall and it will very often be necessary, after some years, to strengthen the foot of the seawall with a rubble revetment.

A seawall will decrease the release of sediments from the section it protects and will have a negative impact on the sediment budget along adjacent shorelines.

A seawall is a passive structure which protects the coast against erosion and flooding. They are often used at locations in front of exposed city fronts, where good protection was needed and space was limited. Promenades have often been constructed on top of these seawalls. Seawalls are primarily used at exposed coasts, but can also be found at moderately exposed coasts (Mangor, 2004).

Figure 34 shows the structure of a seawall at Ganh Hao in Bac Lieu Province. An example of a seawall from Tra Vinh Province is shown in Figure 28.

Figure 34: Structure of a seawall at Ganh Hao, Bac Lieu Province (Photo: GIZ Bac Lieu)

5.2.1.4 *Melaleuca* fences

The GIZ Project 'Conservation and Development of the Kien Giang Biosphere Reserve' has tested coastal protection fences with the aim to reduce wave energy at the shoreline and to increase sediment deposition. A distinction is made between wave breaking fences in exposed areas and sediment trap fences in less exposed areas. The fences are constructed of *Melaleuca*, an inexpensive timber, which is readily available in most parts of the Mekong Delta, and the fences run parallel to the coastline to reduce onshore wave action. They can therefore be considered as a special form of longshore elements.

The wave breaking fence consists of two rows of *Melaleuca* poles with 0.5 m distance between the rows (Figure 35). The *Melaleuca* poles are pushed into the mud to a depth of 2 m. The space between the rows is filled with small branches and twigs. In Kien Giang Province, the wave breaking fence was constructed in areas of high erosion approximately 30 m seaward from the shoreline or located at a water depth of approximately 1 metre at mean high water. In areas of low erosion or deposition, the fences were built at the mean low water line (Russell et al., 2012).

These wave breaking fences were tested in combination with a sediment trap fence (Figure 36) in areas with strong erosion. The sediment trap fence is located landward of the wave break fences about 20 m from the coastline or at a depth of 0.5 m at mean high water. The fence has one row of small diameter *Melaleuca* poles placed close together. A layer of bamboo mats (1.0 m high, 1.5 m long) and protective fishing nets are placed in front of this row. Support frames made from small diameter poles are attached to the front and back of the row of poles (Russell et al., 2012). In general, this kind of construction is complex and time-consuming to build.

The effectiveness of the different *Melaleuca* fence designs concerning wave attenuation, sedimentation rates, and seedling growth and survival rates has been monitored over two years. Through the dry season (November to April) when winds are offshore, minor changes in mud elevation were recorded. In the wet season (June to October), larger changes in the sedimentation rate were observed, and a mild wave and wind climate in the early part of the season resulted in deposition. Stronger winds and larger waves in the middle of the wet season eroded parts of these sediments. The mean sedimentation rate behind the fence is up to 0.20 m per year (Russell et al., 2012). A temporal and spatial extrapolation of this rate has to be considered as not significant.

Figure 35: Wave breaking *Melaleuca* fence in Kien Giang Province (Russell et al., 2012; Photo: GIZ Kien Giang)

The reduction of wave energy behind the wave breaking fence is up to 65% (Russell et al., 2012). This means a reduction in wave height of approximately 40% (due to the quadratic influence of the wave height on the wave energy). Due to the irregular character of sea state and swell, this value is not significant without indication of additional parameters (freeboard of the fence, wave length).

Continuous fences without gaps and parallel rows of fences, including dense sediment trap fences, may have negative effects on the linkage with adjacent systems. Connectivity is an important issue in terms of the ecological and habitat function of mangroves as feeding habitat for mobile or visiting fauna (Frey & Ewel, 2003; Sheaves, 2005; Meynecke et al., 2008; Nagelkerken et al., 2008).

Figure 36: Sediment trap *Melaleuca* fence in Kien Giang Province (Russell et al., 2012; Photo: GIZ Kien Giang)

5.2.2 Cross-shore elements

Groins are normally straight structures perpendicular to the shoreline. They interrupt the natural longshore sediment transport and lead to accretion at the windward side. The sediment transport to the lee side is reduced at the same rate that sediments are deposited on the windward side. If the impact of the groin is too strong, downdrift erosion occurs. Groins can have special shapes and can be emerged, sloping or submerged. They can be arranged either by themselves, or in groups, in so-called groin fields. Groins are normally built as rubble mound structures (Figure 37), but they can also be constructed with other materials, such as concrete units, timber, etc.

Impermeable groins form a complete barrier against longshore transport. After deposition at the windward side is completed, material is transported over and around the groin. Permeable groins are constructed if a certain transport through the groin is desired. This leads to a sufficient sediment supply to avoid downdrift erosion. Groins are well suited to explain various basic morphological responses including lee side erosion effects.

Figure 37: Rubble mound structure of an impermeable groin system at Can Gio District, Ho Chi Minh City (Satellite Image: Google Earth, Photo: SIWRR)

Groins are normally constructed from the coastline to some distance into the sea. Their effectiveness in trapping sand from the littoral drift depends on their extension or, in other words, how much of the littoral drift they block. The sand accumulation on the windward side and the lee side erosion depend on the type of groin.

Groins are normally designed to only cover parts of the surf zone. As the littoral drift varies over the coastal profile, it is important to know the transport characteristics of that coastal section to be able to predict the shoreline response. The landward end of the groin must be constructed on the coastline at the foot of the cliff/dunes so that it is not back-cut during storm surges and high waves. Its height at the landward end must not be lower than the top of the backshore. The height of the groin further seawards can be lower, depending on the requirements for the sediment bypass etc.

Groins used to be a very common coastal protection system, and in many cases the intended effects were achieved. But in other cases, the effectiveness was limited and some examples are known, where groins caused severe damages due to downdrift erosion. For this reason, the construction of groins needs to be planned carefully. The design of a groin field requires great care in order to avoid temporary erosion within the field. It must be remembered that the protection provided by a groin field is always equal in extent to the lee side erosion. These obvious disadvantages of groins mean that they are used less today than in the past. If, for one reason or another, they are still used in new protection schemes, it is normally as part of the project to fill sand artificially into the groin system in order to avoid temporary erosion (CEM, 2012).

As a general rule, groins are constructed in groups with the intention of protecting larger coastal sections. In a group of groins, the distance between two groins has to be defined so that the protecting effect is large enough to avoid erosion caused by currents and waves. The distance between impermeable cross-shore groins of the same length is defined as $s_n = 2 \cdot e \cdot \cot \beta$ (Figure 38).

If groups of groins are constructed along the coastline, the length of the groins has to be adapted to fit the transition area between the groins and the unprotected sections of the beach. The grains have to be reduced from their full length to approximately

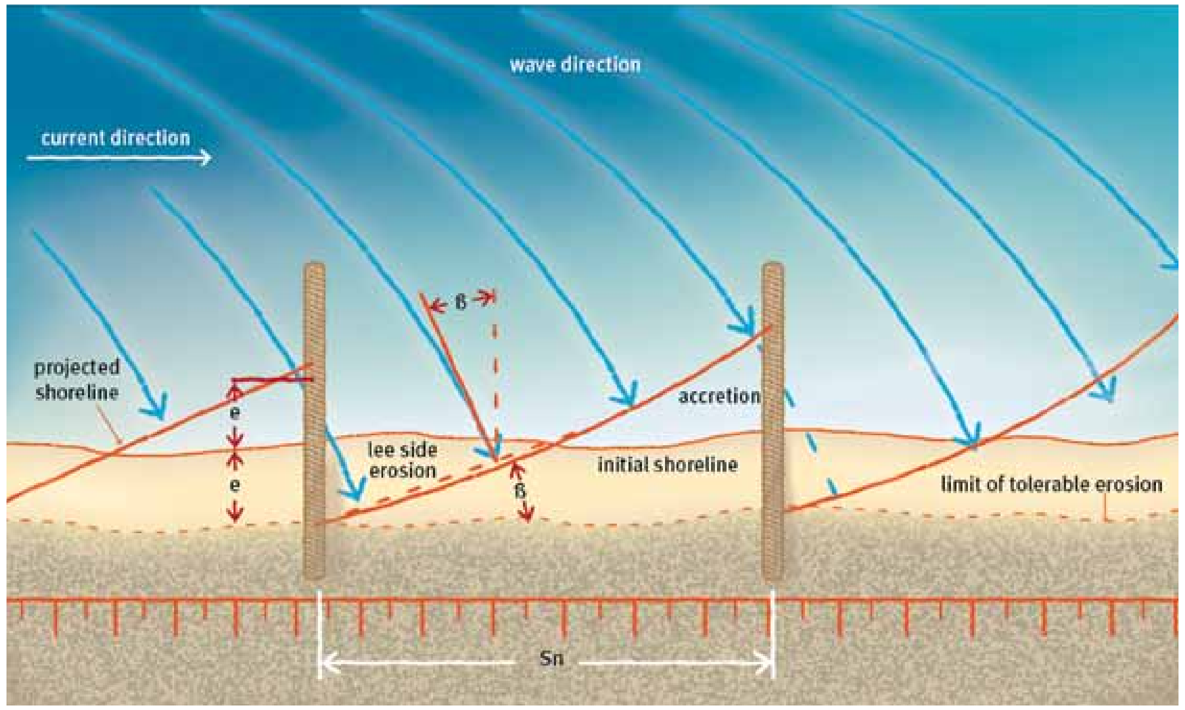


Figure 38: Procedure to calculate the distances between groins

one fourth of the full length before the protection with groins ends. The Handbook of Coastal Engineering (Herbich, 1999) gives recommendations concerning the calculation in this situation.

Figure 39 shows different profiles of groins. The design influences the impacts of the construction, and groins with a wide crest avoid wave overtopping, which might lead to further erosion in the lee side groin field.

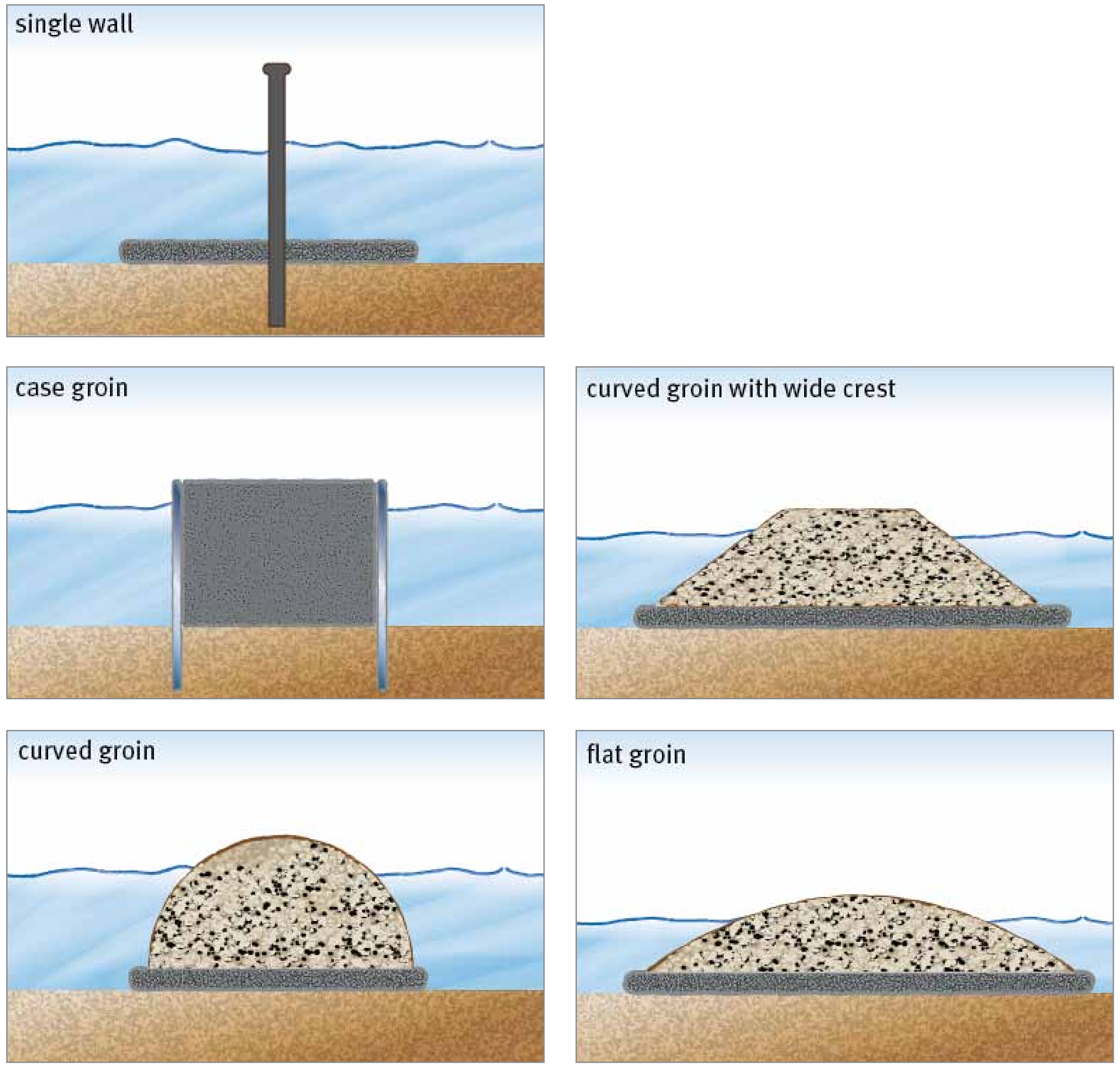


Figure 39: Examples of groin profiles

5.2.3 Area coastal protection

Active measures of area coastal protection can be divided into floodplain management and nourishment. Floodplain management is a sustainable and effective method of coastal erosion and flood protection. Systematic land reclamation to create floodplains has been carried out at the German North Sea coast for more than 150 years. This principle of land reclamation and floodplain management has been transferred to the east coast of the Mekong Delta and has been adapted to local boundary conditions, for example by using local materials such as bamboo.

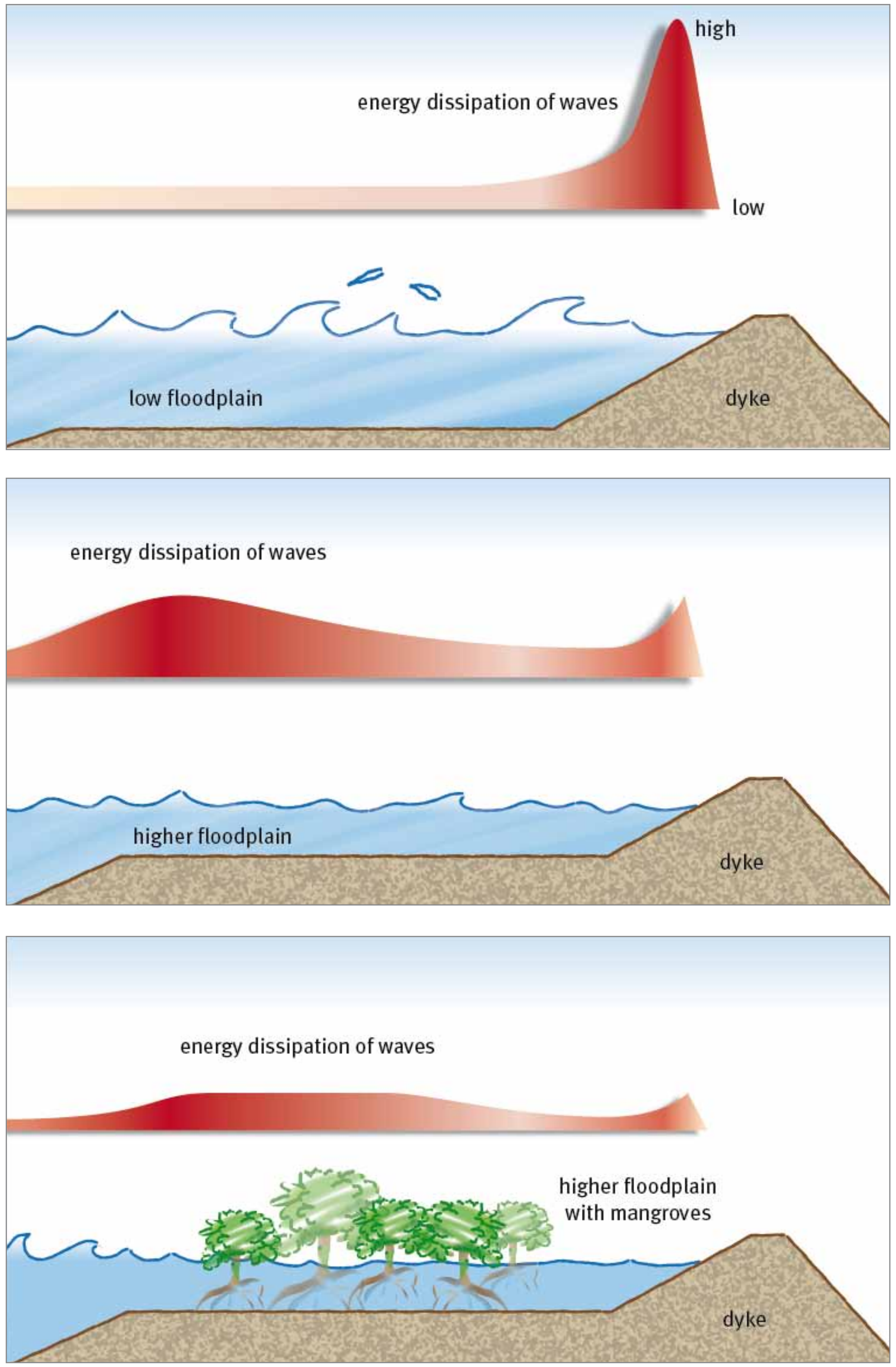
On coasts with low-lying floodplains, consisting either of marsh or a mangrove belt, the floodplain is an important stabilising element of the coastal protection system. It protects against coastal erosion and flooding. The higher the floodplain, the greater the wave dissipation on the floodplain, and as a result, the wave load on the dyke is decreased significantly. In the presence of mangroves, the wave reduction effect is even larger (Figure 40). Mangroves also reduce storm surge water levels by slowing the flow of water and reducing surface waves. Therefore, mangroves play a role in coastal defence, either by themselves or alongside other measures such as engineered coastal defence structures (McIvor et al., 2012A and 2012B).

In many cases, the mangrove belt at the coast has been severely damaged by cutting the mangroves, by pollution or by modification of the hydrology, for example through preventing the natural flow of water, sediments and nutrients by dyke construction or by measures in front of the dyke.

Due to the soil stabilising characteristics of mangroves and their impacts as sediment traps, the loss of mangroves is equivalent to the loss of the floodplain. This heavily increases the wave load on the dyke and therefore the risk of erosion and flooding of the hinterland. Thus, restoration of the mangrove platform is a very important step towards sustainable coastal protection. Even the higher loads due to the rising frequency and intensity of storms can be dealt with by using integrated coastal floodplain management.

Mangroves grow along sheltered tropical and sub-tropical coastlines. They do not grow naturally in sites with strong erosion. At sites where severe erosion has destroyed the mangrove belt, coastal protection and climate change adaptation through mangrove rehabilitation is only possible after the wave energy has been reduced by physical barriers (Balke et al., 2011). This combination of hard (physical barriers) and soft (mangroves) coastal engineering measures can be achieved by technical solutions, which reduce erosion, stimulate sedimentation and, based on their placement and design, avoid downdrift erosion as much as possible.

Figure 40: Impact of the floodplain on wave energy dissipation



5.2.3.1 Floodplain management

In many cases, the construction of dykes reduces the width of the floodplain and increases the erosion of marshy areas. This reduction of the floodplain influences natural morphological processes. Restoration of marshy floodplains is therefore important in order to increase the safety level against flooding and to stop the erosion of the floodplain.

Mangrove floodplains can be restored by imposing restrictions on cutting of mangroves, by re-establishment of the natural hydrology in the mangrove area, for example by the backwards displacement of dykes, or by the planting of new mangrove vegetation (Eisma, 2010; Schwartz, 2005).

These measures require a high level of management and active participation of the local coastal communities. Such programmes should, therefore, be associated with education and awareness campaigns (Kamphuis, 2010) and should involve participatory management with the involvement of local communities. Planting mangroves is of little use if the plantations are not effectively protected afterwards. Newly planted forests must be protected from human impacts such as destructive fishing methods, logging and encroachment. Furthermore, established mangroves must be managed effectively and protected from human impact. This can often best be achieved through mangrove co-management (Schmitt, 2012).

However, before the restoration of the mangrove forest in erosion sites takes place, a stable floodplain has to be established. The growth of floodplains can be enhanced by constructing sediment traps on the shallow tidal flats. This can be achieved using elements which decrease currents and waves, such as breakwaters, groins or combinations of both.

Suspended sediments and bedload are transported by tidal currents and waves. Due to decreasing turbulence, the transport capacity of the current decreases and sediment particles start to settle. This process takes place, for example, in basins and at the lee side of islands. The same principle can be applied to increase the deposition of sediments in an artificial way on the coast by means of systematic floodplain management measures. A mesh of chequered fields of calm water areas can be created through the construction of fence-like permeable structures which form a barrier against the turbulent currents and waves and support the deposition of sediments.

Land reclamation at the German North Sea Coast

On the German North Sea coast, land reclamation using fences started around the year 1365 after several severe storm surges caused large losses of land on the coasts. In 1847, systematic land reclamation was established by the Danish government (Probst, 1996). Until the middle of the 20th century, the aim of land reclamation was to create new fertile areas for agricultural cultivation, but during the last three decades, land reclamation has been used as an active measure aimed at coastal protection (Kramer, 1989). Figure 41 shows an example of successful land reclamation by floodplain management on the German North Sea island Amrum. There, two rows of fields with cross-shore and longshore fences were installed within a time period of fifteen years. The left

Figure 41: Land reclamation using fences on the German North Sea island Amrum (Photos: Albers)

photo shows the younger, the seaward field, where sedimentation occurred over 5-6 years. The right photo shows the longshore fence of the seaward field. The field is already vegetated by the pioneer plant 'Saltwort', which is adapted to saline environments. In areas affected by overtopping waves and drainage openings in the longshore fences, the sedimentation and vegetation has not progressed as much. The fences consist of two rows of timber with brushwood packed between the two rows.

Bamboo fences in the Mekong Delta

This principle of land reclamation and floodplain management has been transferred to the east coast of the Mekong Delta (Albers & Von Lieberman, 2011; Albers, 2011). In the context of a pilot study along the coast of Vinh Tan Commune in Soc Trang Province, which is subject to severe erosion, sustainable area coastal protection measures have been designed based on numerical models simulating hydrodynamics and shoreline development. Field measurements have been used to understand the morphodynamic processes and to verify the models. Different arrangements, placements and designs of erosion protection measures, which are a prerequisite for mangrove rehabilitation at erosion sites, were investigated using numerical and physical modelling. The effectiveness of conventional constructions as well as different designs using local materials was tested. Bamboo fences yielded the best results and have additional advantages due to the strength, availability and low cost of bamboo (Halide et al., 2004, Albers & Von Lieberman, 2011).

Cross-shore and longshore constructions form fields approximately 50 m x 50 m in size, where currents and waves are damped and deposition of sediments is supported (Figure 42). The cross-shore constructions decrease the longshore currents and the longshore constructions damp the incoming wave energy. The fences parallel to the shoreline have openings 20 m in width to secure the drainage of the fields. A system of drainage ditches, which will be created naturally by the water flow, enhances the drainage of the fields, and also helps to accelerate the consolidation process. The development of the drainage ditches can be accelerated by dredging works.

Figure 43 shows the flow and sediment transport patterns in the fields during flood tide (left) and ebb tide (right). During flood tides, and especially while water levels are below the crest of the fences, the flow resistance is reduced within the openings, resulting in larger flow velocities in this area compared to the flow velocity along on the landward side of the fences ($v_{f,1} < v_{f,2}$). A larger volume of water and more sediments are transported through the openings into the fields compared to sediment transport through the fences. On the landward side of the openings, the flow cross-section widens, flow velocities decrease ($v_{f,3} < v_{f,1}$ and $v_{f,4} < v_{f,2}$) and the transported sediments are distributed in a fan-shaped manner into the fields (brown arrows), and start to settle as a consequence of the decreased flow velocities. This improves the sediment input into the fields compared to structures without openings, which especially hinder sedimentation in areas further landward of the fences. In addition, such gaps between fences also do not interrupt the habitat linkage for aquatic species.

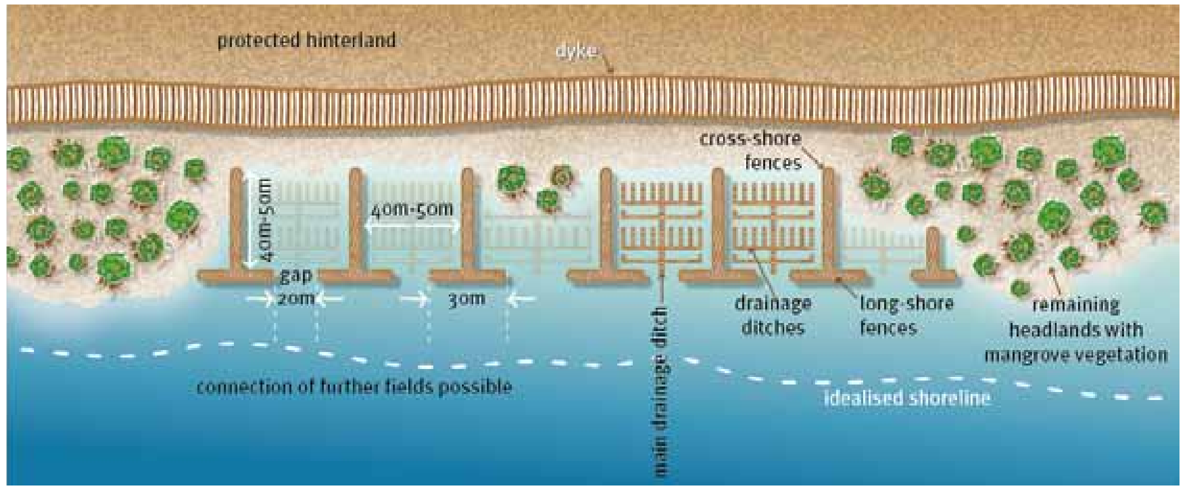


Figure 42: Land reclamation using cross-shore and longshore fences

During ebb tide, the flow resistance is reduced within the openings compared to flow through the fences ($v_{e,2} < v_{e,3}$). The flow pattern in the field is directed towards the openings, and as a consequence, drainage is improved and accelerated through the openings, causing the water content of the soil in the fields during low tide to decrease and therefore accelerating the consolidation process in the fields. Consolidation is important for increasing stability against erosion (see Chapter 2.4.3). The current velocity in the fields during ebb tide ($v_{e,1}$) is smaller than the critical current velocity that induces erosion. The sediments therefore remain within the fields. The critical current velocity is only exceeded in the drainage ditches (either man-made or created by the water flow; in Figure 43 indicated with dashed brown lines), which keep up the drainage of the fields.

Generally, the fences are constructed by two rows of wooden piles with several layers of bundles in between (Figure 44, further details are provided in the Appendix on page 120). The bundles are fixed with stainless wire, and scouring around the wooden piles can be avoided by roughcast at the toe of the fences or by a filter layer. Normally, the top of the construction is equal to the mean high water level (MHW). The elevation of the tidal flats should not be lower than MHW -0.70 m to -0.80 m.

Along the east coast of Soc Trang, Bac Lieu and Ca Mau Province, in many places, remaining headlands with mangrove vegetation are interrupted by gaps where floodplains are eroded and the waves directly reach the dyke (see Figure 11; eroded gap between two headlands in the middle foreground of the photo). The primary goal of floodplain management should be to close these gaps (Figure 42). This will create a smooth shoreline (as indicated with the idealised shoreline) with contour lines more or less parallel to the coast. As a result, cylindrical currents in the gaps between the floodplains that generate further erosion are avoided. The idealised shoreline is a relatively stable morphologic situation, which very often indicates the former shoreline. The construction of a second row of T-fences in front of the idealised shoreline, with the aim of land reclamation, will change the hydrodynamic conditions significantly and will lead to downdrift erosion. This kind of expansion should be avoided due to negative impacts on adjacent coastal sections, high costs and high risk of failure.

When the floodplain reaches an elevation of MHW -0.50 m to MHW -0.30 m, an artificial drainage system may be created to enhance the dewatering of the fields (Figure 42). The drainage system consists of main ditches (cross shore) and lateral drainage ditches. Smaller ditches lead the drained water to the lateral ditches. To secure the discharge capacity of the small ditches, they can be dredged if necessary. The excavated material can be dumped in the middle between the small ditches to accelerate the siltation process.

Within the design process, current and wave-induced loads, breaking waves, impacts such as floating

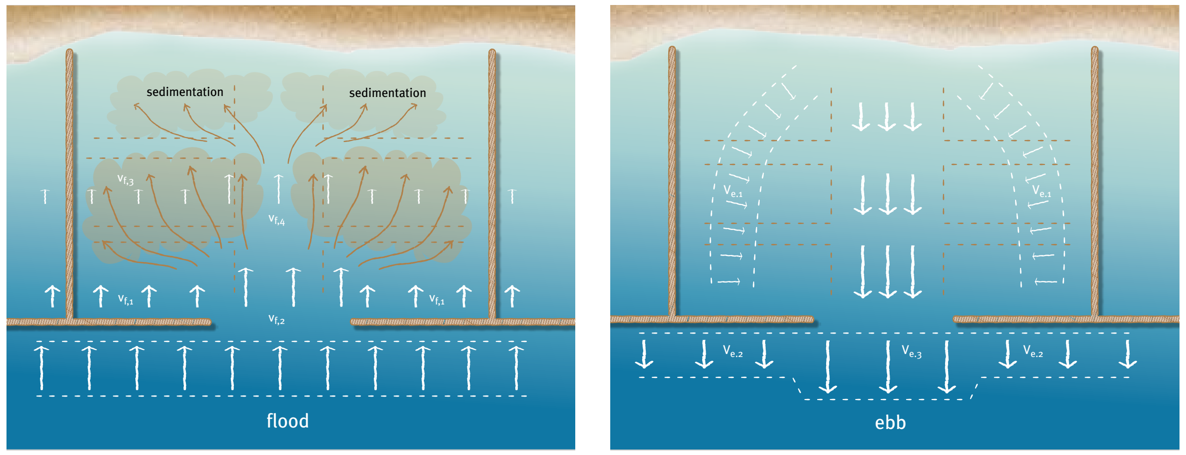


Figure 43: Flow patterns and sediment transport in the fields protected by the fences

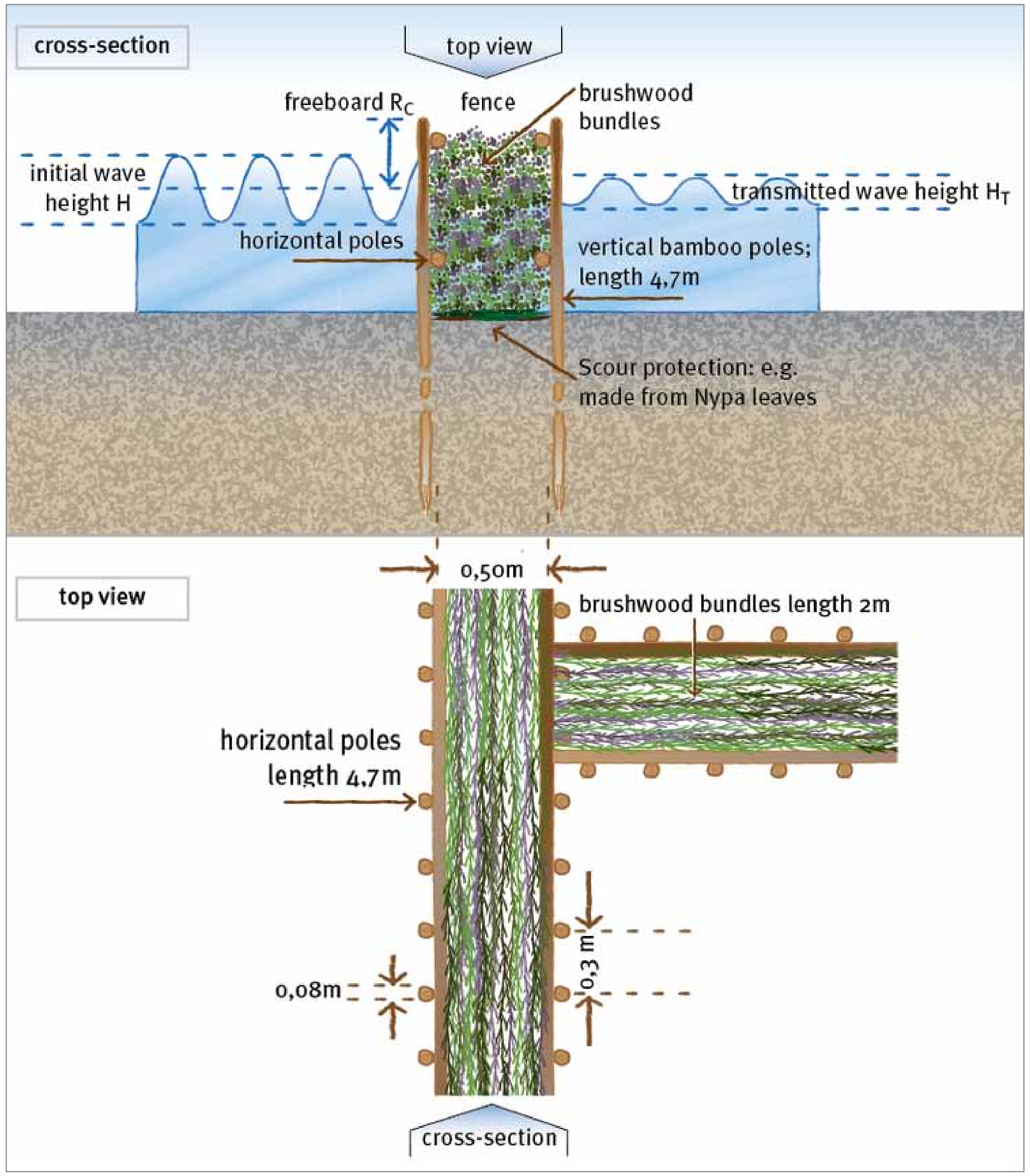


Figure 44: Construction of a fence in a sedimentation field (cross-section and top view)

items or vessels as well as man load were taken into consideration (Albers, 2011).

The longshore bamboo fences are especially exposed to currents and waves. The loads resulting from currents and waves have been calculated based on the superposition method. Breaking waves can induce high compression stresses on poles in the front row above the static water level. These 'slaps' or 'slams' appear for very short times (in the range of milliseconds) and therefore are not important for the overall design. Abnormal forces can result from the impact of floating items such as flotsam or vessels. International standards for the certification of mobile flood protection walls use the impact of a 300 kg item for the approval of the systems (BWK, 2005). This value has also been considered as sufficient for the static design of the bamboo constructions taking into account boundary conditions like water depth and external circumstances. Additionally, a vertical load of 1 kN (comparable to man's weight) is assumed for each bamboo pile based on German Standards (DIN 1055, Part 3).

The fence consists of two rows of vertical bamboo poles with a mean diameter of 8 cm. The distance between the two rows is 0.40 m for cross-shore sections and 0.50 m for the longshore sections. The distance between two poles in a row is approximately 0.30 m. Two rows of horizontal poles are connected to the vertical poles on each side. The brushwood bundles consist of bamboo branches. The material used to lash the joints should be stainless steel wire to assure a durable and stable connection (Figure 45). As scour protection at the bottom, a double layer of *Nypa* palm leaves, was installed. However, due to hydrodynamic laws, scouring always occurs when a cylindrical item is installed in a current. Thus, the depth of embedment of the vertical poles in the mud was chosen to be large enough so that local scouring does not affect the stability of the fences. In Vinh Tan, the length of the vertical bamboo poles is about 4.70 m with an embedment depth of 3.40 m. As a rule of thumb, the depth of embedment must not fall below 1/3 of the total length of the pole. Of course, the actual depth of embedment must be chosen according to the in-situ soil characteristics and based on sophisticated geotechnical approaches (Albers, 2011).

The cross-shore and longshore bamboo fences form fields measuring approximately 50 m x 50 m. The final arrangement always has to be adapted to the local conditions, and the fences were installed in the gap between the remaining floodplains as indicated in Figure 42. When designing the placement of T-fences, it is important to create a smooth shoreline and thus to reduce downdrift erosion. Therefore, the seaward end of the fences cannot extend beyond the connecting line between the heads of the floodplains.

Between May 2012 and September 2012, bamboo fences measuring a total of 700 m were installed on the coast of Soc Trang. With minor adaptations, the design was transferred to the coast of Bac Lieu, where

Figure 45: Joints made with stainless steel wire; (Photos: Albers)

500 m bamboo fences were constructed in May 2012 (Figure 46). In a second phase in October and November, an additional 2,000 m were constructed on the coast of Soc Trang and an additional 2,000 m on the coast of Bac Lieu (Figure 47).

Construction of the bamboo fences in Soc Trang and Bac Lieu served as a pilot project for erosion protection and mangrove rehabilitation in erosion sites, which will also be used to gain knowledge for future application and optimisation through detailed documentation and monitoring.

Monitoring of bamboo fences

Immediately after the construction was completed, a comprehensive monitoring programme started, consisting of wave measurements to quantify the wave damping effect of the bamboo fences during various storm and tidal conditions. The changes to the shoreline are monitored as well as the mud density and the elevation of the mud. Furthermore, tensile tests were carried out to assess the strength of the bamboo construction.

Wave measurements

Waves were measured at two locations on the seaward and the landward sides of the longshore bamboo fence, each at a distance of approximately 5 m from the fence. Pressure transducers were used for the measurements, which were recorded continuously for approximately six months with a frequency of 10 Hz. The wave data were analysed and summarised in significant wave heights of 15-minute periods. These long-term measurements offer representative results for the wave damping effect of the bamboo fences in various wave and tidal conditions.

Figure 48 shows a time series of the significant wave heights on the seaward and landward sides of the bamboo fence derived from the field measurements. In general, the wave height on the landward side of the fence is lower than on the seaward side, but the results shown in Figure 48 are just a snap-shot. The reduction in wave height and thus the effectiveness of the bamboo fence very much depend on the wave parameters of the incoming waves and the tidal conditions. To derive quantitative and significant conclusions from the field measurements, a different kind of analysis and illustration is necessary.

Figure 49 meets these requirements and shows the results of the field measurements in comparison with the results of the physical modelling (the latter is described in Chapter 7.5). Figure 49 shows the wave dampening effect in percent of incoming waves independent from the actual wave height. On the left side of the graph the water level is above the fence, on the right side the water level is below the fence.

The wave transmission coefficient K_T is displayed on the y-axis. A transmission coefficient is calculated as the ratio between the transmitted wave height (H_T) on the landward side and the initial wave height (H) on the seaward side (see cross-section, top view Figure 44). Thus, a transmission coefficient of 0.3 means that the transmitted wave height (H_T) is 30% of the initial wave height (H), and therefore the reduction of the wave height is 70%.

On the x-axis, the influences of the tidal conditions (the water level) and the characteristics of the approaching waves (explicitly the wave height, and implicitly the wave length) are considered and combined into one coefficient. The freeboard (R_C) is the distance from the top of the structure to the water surface and thus indicates the water level in relation to the bamboo fence (see cross-section , top view Figure 44) A negative freeboard indicates a submerged crest, e.g. when the water level is above the T-fence, as does a negative coefficient R_C/H. Furthermore, the initial wave height (H) is considered in this coefficient. The wave length, which is also important for the effectiveness of the structure, is considered implicitly in the water depths.

Figure 49 shows the results of physical modelling carried out in a wave flume in 2010 (black triangles; Albers & Von Lieberman, 2011) and from field measurements in Vinh Tan over a period of six months (orange and blue circles). The transmission coefficient derived from the field measurement is approximately 0.75 when the water level is above the crest of the bamboo fence ($R_C/H < 0$), which means a reduction of

Figure 46: T-shaped bamboo fences on the coast of Bac Lieu Province (Photo: GIZ Bac Lieu)

Figure 47: Second construction phase of T-shaped bamboo fences on the coast of Bac Lieu Province (Photo: Cong Ly and GE Wind)

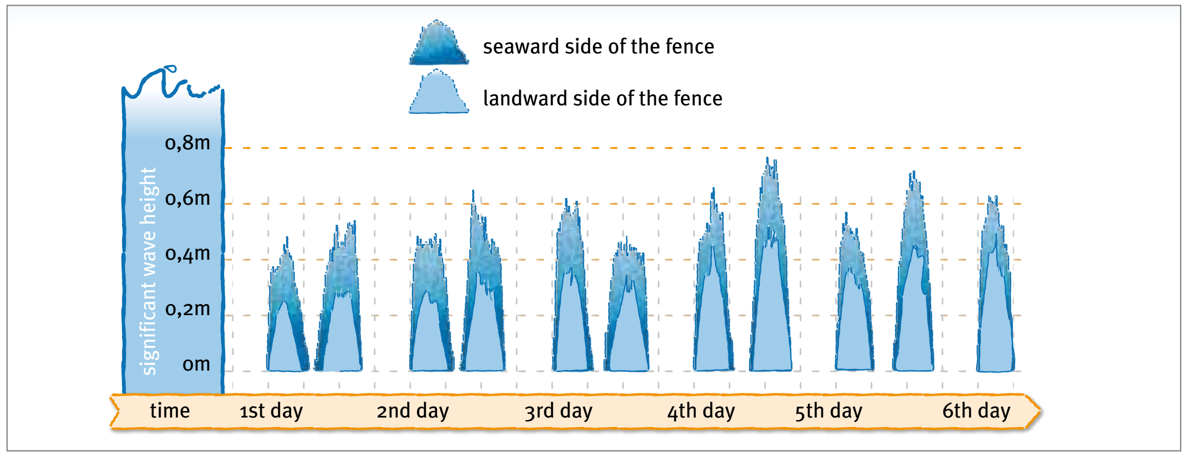


Figure 48: Time series of significant wave heights derived from the field measurements

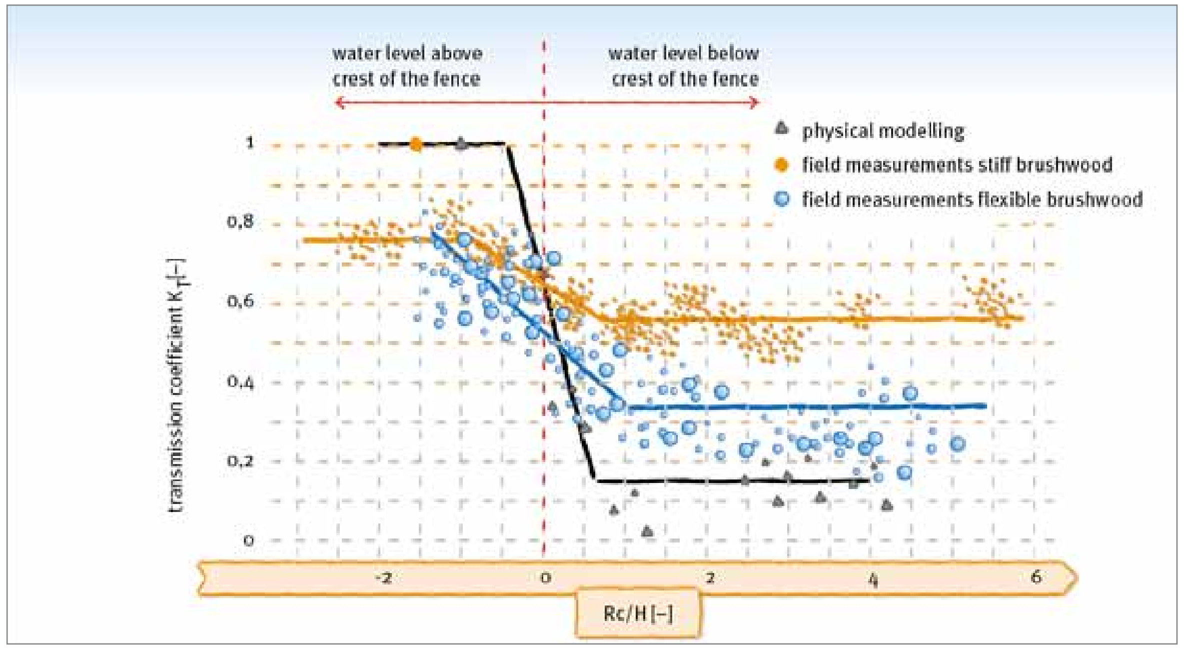


Figure 49: Wave transmission coefficients derived from physical modelling and field measurements

the initial wave height of 25%. When the water level drops below the crest of the bamboo fence ($R_C/H > 0$), the transmission coefficient is between 0.60 and 0.20 depending on the structure of the brushwood bundles. Flexible bundles lead to smaller wave transmission coefficients (blue dots) than stiff bundles (orange dots), and thus have a larger wave damping effect. They can reach up to an 80% reduction of the initial wave height. The blue, orange and black lines represent the best-fit through the measured values.

The wave transmission coefficients derived from the physical modelling are smaller because the poles of the bamboo fences in the physical model (see Chapter 7.5) were placed closer together than in the fences constructed in Vinh Tan, where the bamboo poles where placed to leave a gap of 0.30 m. This wider spacing was implemented during field testing when the design of the model was optimised by taking into consideration static design aspects and economic reasons.

Shoreline survey

As part of the monitoring programme, regular records are kept of the development of the shoreline, the floodplains and the tidal flats between the dyke and the bamboo structures. To assess the effect of the structures compared to other locations, where no measures were applied, one other location is monitored regularly. This will help to identify morphodynamic processes that are related to temporary superior trends, e.g. if increased sediment loads from the Mekong reach the east coast of the Delta. These effects, which are mostly seasonal, are temporary since the sediments are transported along the coast to the southwest, but have to be considered when assessing the effects of the floodplain management. Due to the general character of the shoreline survey (subjective evaluation of the location of the shoreline) and the accuracy of the equipment used (accuracy of a standard GPS ~ 3 m), the shoreline survey must be regularly repeated and carried out for more than two or three years before robust conclusions can be drawn. Thus, no data are presented in these guidelines, but all recorded data are stored in a data base and will be analysed to provide detailed information on the success of the measures. Additionally, the data can be used for the calibration and verification of numerical models.

Mud density and elevation of the mud

Mud density, characterised by the bulk density and the dry density of a mud sample and related parameters such as water content, pore content and voids ratio, describe the morphological conditions of the mud. The sedimentation and consolidation processes can be monitored through regular analysis of the mud density. Freshly deposited material has very limited consolidation, and thus a low bulk density and dry density as well as a high water content, high pore content and a high void ratio (relative number of pores). After a while, the additional weight of the deposited material presses the water out from the layers below and thus decreases the water content and pore content (and the voids ratio), and increases the dry density and bulk density (see Chapter 2.4.3). This process can occur together with a temporary decrease in mud elevation. Especially if the sediment supply is not constant, the process of sedimentation and consolidation in a field protected by fences can oscillate between increase and stagnation or increase and partial decrease (during consolidation) of the elevation of the mud. Thus, monitoring of the mud level is recommended in order to draw conclusions about the effects of the floodplain management.

In 2 locations within a field protected by the bamboo fences on the coast of Vinh Tan in Soc Trang Province, the mud density has been analysed three times since the completion of the construction in November 2012 (Table 4). The bulk density and the dry density increased significantly within the first three months. The water content decreased significantly within the first three months due to water being pressed out from the mud in the process of consolidation. The pore content and the voids ratio decreased as well. Within the following 6 months a stabilisation of the mud parameters occurred. The mud consolidated and the erodibility of the soil decreased. This consolidation process goes along with a slight reduction in the elevation of the mud.

Changes of the elevation of the mud level are recorded with benchmarks that are installed in several fields in Soc Trang and Bac Lieu Province. Figure 50 shows these changes in elevation of the mud level at different sites in Bac Lieu Province. At site 4 approximately 500 m bamboo fences were constructed in May 2012 and monitoring started in July 2012. At this site 12 benchmarks were installed. Benchmarks in naturally developed drainage ditches and seaward of the fences were not considered in the diagram because they are not representative for the sedimentation process in the fields protected by the fences. Therefore, data of 8 benchmarks recorded monthly at site 4 were averaged and are shown in Figure 51. Beginning after the first month of the monitoring, a continuous sedimentation was recorded. In 7 months almost 17 cm of sediments were deposited. Eight months after the installation the sedimentation rate decreased and reached a temporary equilibrium. In site 4 mangrove rehabilitation started soon after construction of the fences. Figure 50 shows photos from the site from May 2012 before the installation and from September and December 2012 after installation of the fences and rehabilitation of mangroves. The mangroves grow well in the area that is protected by the fences from waves and currents. The mangroves also have an influence on the sedimentation rate.

At site 3.1 approximately 400 m bamboo fences were constructed in September 2012 and monitoring started in October 2012. At this site 8 benchmarks were installed. Benchmarks in naturally developed drainage ditches and seaward of the fences were not considered in the diagram because they are not representative for the sedimentation process in the fields. Data of 5 benchmarks at site 3.1 were averaged and are shown in Figure 51. Site 3.1 is more exposed to waves than site 4. After a sedimentation phase in the first month of the monitoring, the mud level decreased. This was due to the consolidation process described above, due to a different season of construction but mainly due to damages to the fences caused by floating barges during construction works at near-shore wind turbines. After the repair of the damaged parts of the fences the mud level stabilised. Continuation of the monitoring will show how the development will continue after this, most likely, temporary equilibrium. In general, site-specific characteristics have to be taken into consideration, even when longer time series of data are analysed.

Table 4:
Analysis of the mud density near sluice gate 4 in Vinh Tan, Soc Trang Province

	21.11.2012 Location		26.02.2013 Location		14.08.2013 Location	
	I	II	I	II	I	II
Bulk density ρ [g/cm³]	1.186	1.290	1.577	1.490	1.677	1.596
Dry density ρ_d [g/cm³]	0.378	0.488	0.872	0.746	0.847	0.733
Water content w	2.138	1.643	0.808	0.997	0.980	1.177
Pore content n	0.859	0.819	0.676	0.723	0.685	0.728
Voids ratio e	6.116	4.512	2.085	2.606	2.176	2.670

Figure 50: Changes at site 4 at the coast of Bac Lieu Province after installation of the T-shaped bamboo fences, photos from May 2012 (left), September 2012 (middle) and December 2012 (right); (Photos: Steurer)

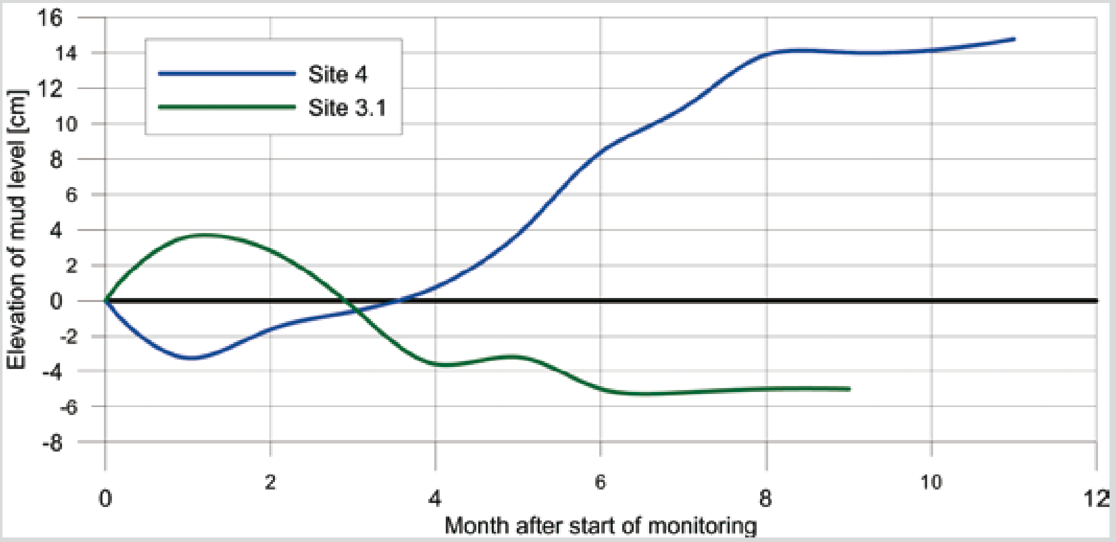


Figure 51: Changes of the elevation of the mud level at site 4 and site 3.1 at the coast of Bac Lieu Province after installation of the T-shaped bamboo fences (Data source: Lisa Steurer, Dang Cong Buu & Phong Trieu; GIZ Bac Lieu, Adaptation to Climate Change through the Promotion of Biodiversity)

Tensile tests

A sample section of the bamboo fences, which was constructed on a beach in Soc Trang Province, was used to carry out tensile tests. Using a dredger, the sample section was stressed until failure. The dredger arm was used to pull in a horizontal direction perpendicular to the direction of the sample section, and the maximum load was 6.6 kN (~660 kg) as indicated in Figure 52. At that load, the upper horizontal pole broke due to the punctiform load through the drag force. This force did not lead to a complete failure of the structure, and the maximum distortion (ε) of the vertical pole that was primarily loaded was approximately 5 cm. The main results of the tensile tests are:

- Even a very high punctiform load does not lead to a complete failure of the tested section of the bamboo fence.
- Distortions are limited to the pole that is primarily loaded, and are limited to 5 cm.
- The bedding modulus of sand is larger than estimated in the design process.

A further advantage of the bamboo breakwater and bamboo fences is, that damaged parts can be replaced easily. Only the damaged part has to be replaced. This has implications on the maintenance costs of the structure.

Ecosystem services provided by mangroves

Mangroves provide a wide range of ecosystem services (benefits people obtain from ecosystems). The Millennium Ecosystem Assessment (2005) groups these services under four categories:

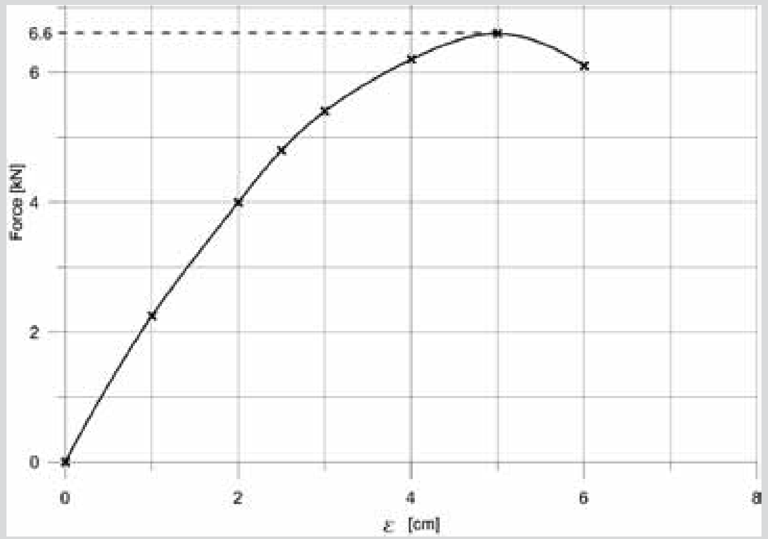


Figure 52: Results of the tensile tests

- Regulating Services: protection of beaches and coastlines from storm surges, waves and floods; reduction of beach and soil erosion; stabilisation of land by trapping sediments; water quality maintenance; sequestration of carbon dioxide; and climate regulation.

- Provisioning Services: subsistence and commercial fisheries (food, habitat and nursery ground for aquatic life); aquaculture; honey; fuel-wood; building materials (timber); and traditional medicines.

- Cultural Services: tourism and recreation; and spiritual appreciation.

- Supporting Services: cycling of nutrients; and habitats for species.

Essential services In the context of climate change adaptation are protection of beaches and coastlines from storm surges, waves and floods; reduction of beach and soil erosion; stabilisation of land by trapping sediments; and sequestration of carbon dioxide (Barbier, 2007; Nagelkerken et al., 2008; Walters et al., 2008).

Mangrove forests can act as bioshields for the protection of people and assets from erosion and storms. Their effectiveness, however, depends on many variables and they do not provide effective protection against all hazards such as extremely large tsunami waves (Wolanski, 2006; Mukherjee et al., 2010). The effect of mangrove coastline protection has been demonstrated by Mazda et al. (1997) who showed that a 1.5 km wide belt of 6 year old mangroves reduced the height (and energy density) of incoming waves from 1.0 m to 5 cm (at the coastline/dyke). In areas without mangroves, the waves were reduced to 75 cm in height, due to bottom friction. This protection function also has clear financial benefits: USD 1.1 Million invested in mangrove rehabilitation in northern Viet Nam saved USD 7.3 Million annually for dyke maintenance (Brown et al., 2006).

The ecosystem services provided by mangroves also have implications for food security and income. Up to 80% of global fish catches are directly or indirectly dependent on mangroves (Hamilton & Snedaker, 1984) and one hectare of healthy mangrove forest produces about 1.08 tonnes of fish per year (Schatz, 1991). For a comprehensive overview of economic values of mangroves, see Conservation International (2008) and Quoc Tuan Voa et al. (2012).

5.2.3.2 Nourishment

Nourishment can be regarded as a natural way of combating coastal erosion as it (artificially) replaces a deficit in the sediment budget over a certain stretch with a corresponding volume of sand. However, as the cause of the erosion is not eliminated, erosion will continue in the nourished area. This means that nourishment as a stand-alone method normally requires a long-term maintenance effort. In general, nourishment is only suited for major sections of a shoreline; otherwise the loss of sand to neighbouring sections will be too large. Regular nourishment requires a permanent well-functioning organisation, which makes nourishment as a stand-alone solution suitable for privately owned coastlines.

The success of a nourishment scheme depends very much on the grain size of the nourished sand, the so-called borrowed material, relative to the grain size of the native sand. The characteristics of the sand determine the overall shape of the coastal profile expressed in the equilibrium profile concept. Furthermore, in nature, the hydrodynamic processes tend to sort the sediments in the profile so that the grain size decreases with increasing water depth. Nature will attempt to re-establish a new equilibrium profile, so changes will always occur in the nourished profile. This means that in practice it is neither possible to perform a short-term nor a long-term stable nourishment on an eroding coast. If the borrow sand is finer than the native sand, it will tend to form a flatter profile than the natural one (Dean, 2002).

5.3 Elements of flood protection

5.3.1 Dykes

A dyke is a sea defence structure protecting low-lying coastal areas and coastal hinterlands from being flooded as a result of storm surges, high tides and wave run-up. The risk of flooding is a major aspect for the safety of people and economic, cultural, and ecological values in coastal zones.

This aspect has been of great importance since people first thought about defending their dwellings against flood hazards. In the distant past, dwelling mounds were built to protect families or small communities from the sea. They are known from several low-lying coastal areas in the world, for example, from the North Sea coast of Germany and the adjacent Dutch coast, where they have been occupied since 2,500 BP. Population increase made it necessary to develop a more active method of flood prevention. People started to construct dykes to keep the water out of whole regions, thus protecting lives and properties against the sea. To achieve this, the dwelling mounds were first connected and formed into a ring dyke. Later, the different dyke sections were connected and formed a closed dyke system along the coast.

Coastal defence has become more and more of an engineering activity. Presently, the design criteria for sea dyke construction are determined based on two important aspects: hydraulics and construction. Hydraulics mainly determines the required height of the dyke. Construction is particularly important for the dyke's life span. For both aspects, the geotechnical conditions of the soil and the subsurface are important for the strength of the dyke.

5.3.1.1 Dyke design

Hydraulic factors influencing the water level variation at small temporal scales include the tidal range, wave heights, wave run-up, and the setup of the water level due to wind conditions. Dykes have to be designed for extreme water levels, especially the occurrence of spring tides, wave characteristics and water level setup during storms. High-water exceedance frequency curves are used for the establishment of extreme water levels. This method is based on finding a systematic relation between the height of a water level and the number of times this specific level occurs in a century. Extrapolation of observed water levels enables a probability calculation for the chance of occurrence of an extreme high-water level, which has not been observed before. Moreover, the effects of long-term changes in sea level and storm frequency as well as subsidence must be taken into consideration (CEM, 2002; Mangor, 2004; EAK, 2002).

In general, dyke design considers:

- the relevant storm surge water level (called design water level)

- the relevant height of the wave run-up

- a safety addition (around 0.5 m)

The design water level can be calculated based on three possible values:

- Statistical method: The design water level is equal to the storm surge water level that occurs once in 100 years.

- Compared value method: The design water level is equal to the highest storm surge water level that has been recorded so far.

- Single value method: The design water level is equal to the summation of the mean tidal high water, the largest increase due to spring tide and the largest observed wind set-up.

The wave run-up can be determined by means of empirical formulae that were developed based on physical and numerical modelling. A safety value is added on the determined relevant wave run-up to cover the general uncertainties of the design (EAK, 2002).

Every 10 to 15 years the safety status of the existing dykes should be checked in relation to the water levels and the wave run-up. According to the current state of knowledge, a dyke with a sound dyke body and a grass cover can resist an overtopping volume of 2 litres per second and metre without damage. This value can be set as a limit for allowed overtopping, but has to be evaluated based on the existing dyke structure and quality.

With regard to rising sea levels, the current practice of dyke design shows disadvantages. It does not consider the probability of flooding and the resulting damage. Climate change and thus sea level rise will have a major influence on dyke design. Allowance for future sea level rise should be considered in current dyke construction projects.

5.3.1.2 Dyke construction

The main function of a dyke is to prevent flooding of low-lying coastal hinterland, which means that the height of the dyke is the most important design parameter. However, the dyke must also be able to resist the large forces of waves during extreme events. Many centuries of experience in dyke design have led to an optimised design (Figure 53). A sea dyke is a system consisting of different parts, starting with the foreshore or floodplain further offshore. The seaward slope ratio was decreased to reduce the wave energy and therefore erosion induced by the run-up and overtopping of waves. Nowadays, the seaward slope of the dyke is 1:6 or flatter. In some cases, a berm is installed to reduce the wave run-up and to simplify the maintenance of the dyke after storm surges. The width of the dyke crest should be 3 m or more. This decreases wave overtopping and allows an effective dyke defence.

Dyke defence is defined as the sum of measures to regularly control the condition and the quality of the dyke (at least twice a year; before and after the storm surge season, but also after heavy storm surges) and during storm surges, to maintain the dyke, to take action in case of smaller or severe damages during extreme events and to repair the dyke after such events.

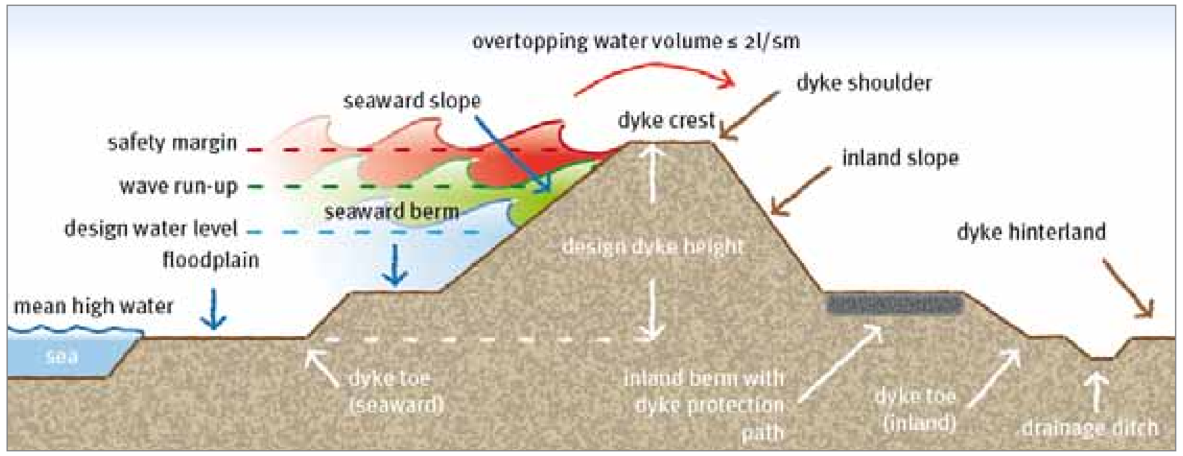
A solid dyke toe on the seaward as well as on the landward side is very important for the stability of the dyke. On the landward side, a sound drainage system must be available to discharge the overtopping waves. A dyke defence lane is recommended for material transport and maintenance in the case of damage during storm surges.

In many coastal flooding disasters (e.g. in the Netherlands in 1953), the effect of overtopping waves on the landward slope of the dyke appeared to be the most frequent reason for dyke failure. Thus, the slope ratio of the landward slope was also decreased. Nowadays, the landward slope of dykes is approximately 1:3 (EAK, 2002).

The composition of the subsoil is relevant with regard to groundwater flow. A dyke is meant to be impermeable for water. However, groundwater can flow through the subsoil underneath the dyke, due to a difference in hydrostatic pressure on both sides of the dyke. This seepage causes saltwater intrusion landward of the dyke. If the currents of the seepage are sufficiently strong to erode the underlying sediment, this process affects the stability of the dyke and may result in a complete failure.

The construction of a dyke requires large amounts of materials. In the past, the preferably clayey material was dug up locally. Nowadays, dykes usually have a sandy core, covered by clay to make it impermeable. Suitable clay is often rare, whereas sand occurs in larger quantities near the coast. A dyke with a sandy core has the advantage that sand, the largest part of the building material, is often found nearby and does not need to be transported over long distances.

Figure 53: Typical dyke cross-section



To avoid erosion of the seaward slope and undermining of the dyke body, revetments can be applied. Usually, revetments are provided with a filter layer to prevent erosion of the underlying material. Permeable as well as impermeable revetments are applied (see Chapter 5.2.1.2).

Dykes are often constructed in areas with tidal flats or floodplains, and in areas where the coast consists of low meadows or mangroves. Under such conditions, revetments are not necessary because the dissipation of the largest part of the wave energy takes place on the floodplains and not at the toe of the dyke (see Figure 40). It is therefore important that the floodplain, tidal flats and its vegetation is well maintained and an integrated part of the defence system. In many cases, cutting of mangroves has resulted in the erosion of the floodplain and thereby the destabilisation of the dyke (Schwartz, 2005).

5.3.1.3 Emergency sea dyke rehabilitation

In the case of severe erosion of the floodplain in front of the dyke, at the dyke toe or even in the case of dyke failure, emergency measures must be carried out. Dyke rehabilitation must be quickly available and applicable and should be economically feasible. Typical dyke rehabilitation measures will not exceed a length of 500 m. Damage during former storm surges has shown that dyke breaches have widths of 100 - 200 m (Von Lieberman, 2005) and dyke rehabilitation will include the damaged section and the neighbouring sections, but not a longer stretch of the dyke.

Emergency dyke rehabilitation measures have been planned for an endangered dyke section in Soc Trang Province (Roos et al., 2009). The described measures are very extensive and thus very cost-intensive. Re-establishment of floodplains and mangroves in front of the dyke is essential to ensure the sustainability of dyke rehabilitation.

Roos et al. (2009) summarised their recommendations as follows. To connect the new sections to the existing dyke, the crest and slopes should be adapted according to the existing dyke cross-section along a transition section, which is approximately 10 m long. The dyke body will be constructed with a slope inclination of 1:5 by cutting and placing material while the existing core body is left as it is. The seaward slope will be secured by placing a revetment consisting of stone blocks on a filtration-resistant base layer consisting of sand and gravel. In addition, a sheet-pile wall can be constructed to provide toe protection at the seaward side. This toe protection will be backed up by an additional waterside toe filled with stones. A filtration-resistant toe filter will be placed at the land-side dyke toe. To avoid surface erosion in the future, the slope on the land side should be completely covered by grass turf. The dyke crest will be 4.50 m wide with a slope of 3% toward the land-side to ensure drainage, and will be covered by a gravel surface without cohesive material. Table 5 summarises typical dimensions of endangered dyke sections and the dyke geometry after dyke rehabilitation:

Table 5:
Dyke geometry before and after rehabilitation

	Current	Planned
Crest height	+ 2.2 m to + 3.5 m*	+3.5 m*
Crest width	~ 6 m	4.5 m
Seaward slope inclination	< 1:2	1:5
Landward slope inclination	< 1:3	1:5

* Based on Vietnamese reference level; equivalent to the mean sea level in Hai Phong.

Local boundary conditions may require special pre-arrangements or measures during the construction phase. For example, existing shrimp ponds close to the dyke should be drained, if possible, to allow for a sound dewatering of the construction site. In most cases, the accessibility of the construction site is limited – especially during the rainy season – and there must be careful planning well in advance.

Vegetation on the dyke and in the construction area has to be removed completely, including the roots. Vegetation on the dyke – except grass cover – must be avoided in future.

The top layer (~ 20 cm) of the dyke has to be removed. This material may be used as a cover fill after placing the revetment.

A sheet-pile wall is an effective but very expensive construction for the toe protection. Its application must be decided in advance of the dyke rehabilitation. It should be installed before commencing any further earthwork. The top edge of the sheet-pile wall is at an elevation of + 1.50 m (based on Vietnamese reference level) for the entire construction period. The pile-driving subgrade should be designed according to the technical requirements and the equipment used. After installation of the revetment, the sheet-pile wall should be cut down to the level of the revetment on the seaward side. In front of the sheet-pile wall, a waterside toe fill should be placed using stones from existing protection layers. To place this toe fill, a 3.0 m wide trench should be excavated to a depth of 1.20 m under the top level of the final sheet-pile wall (after flame cutting). The excavated material is put in intermediate storage. A 0.25 m deep filter layer consisting of sand should be placed in this trench and covered by a geotextile. After this, the trench is backfilled using the stones from an existing protection layer. Any excavated material may be placed in the area of the water-side dyke toe after completing the construction works, partly covering the revetment.

A protective strip with a width of approximately 5 m should be established on the seaward and the landward side, which should not be used for any farming except green covering and regular maintenance.

5.3.2 Storm surge barriers

Storm surge barriers can be constructed to shorten the coastline along bays and the mouths of estuaries. They are temporarily closed during storm surges and prevent the storm surge wave from entering the bay or the estuary (Figure 54). Therefore, the heights of the dyke behind the barrier along the bay or the estuary can be lower than in front of the barrier. Besides the closure function, a storm surge barrier must control the drainage of discharge from the estuary during storm surges. The design level of storm surge barriers must include future developments such as sea level rise, because the life span is 50 years and more.

The location of a storm surge barrier must be chosen very carefully with regard to environmental impacts and risk reduction. Storm surge barriers built in the mouth of an estuary provide flood protection all along the dykes on the landward side of the barrier. In addition, this location offers the possibility of the largest retention in case of longer closure of the barrier and large river discharge. A major disadvantage of constructing the barrier in the mouth is associated with higher costs due to the larger width of the construction and greater wave loads. Moreover, the choice of the location must not affect shipping, and sluices have to be planned in the storm surge barrier.

The tidal regime and the river discharge also play a very important role in the selection of the site. The axis of the barrier should be perpendicular to the main flow direction. The location of the barrier and the alignment of the construction should be optimised so that tidal currents may pass through the structure without being significantly influenced.

A storm surge barrier is always a major intervention into the hydrodynamics and morphodynamics of an estuarine or coastal system. In nearly all cases, the sediment flux into the estuary increased significantly after construction of a storm surge barrier. Therefore, besides their function in terms of coastal protection, most of the storm surge barriers have to be used to control the sediment dynamics of the estuary and minimise the negative impacts of the construction. The gates must be used to increase the rinsing effect during ebb tide by opening them when the water level difference on both sides is largest. This creates higher current velocities around the barrier and

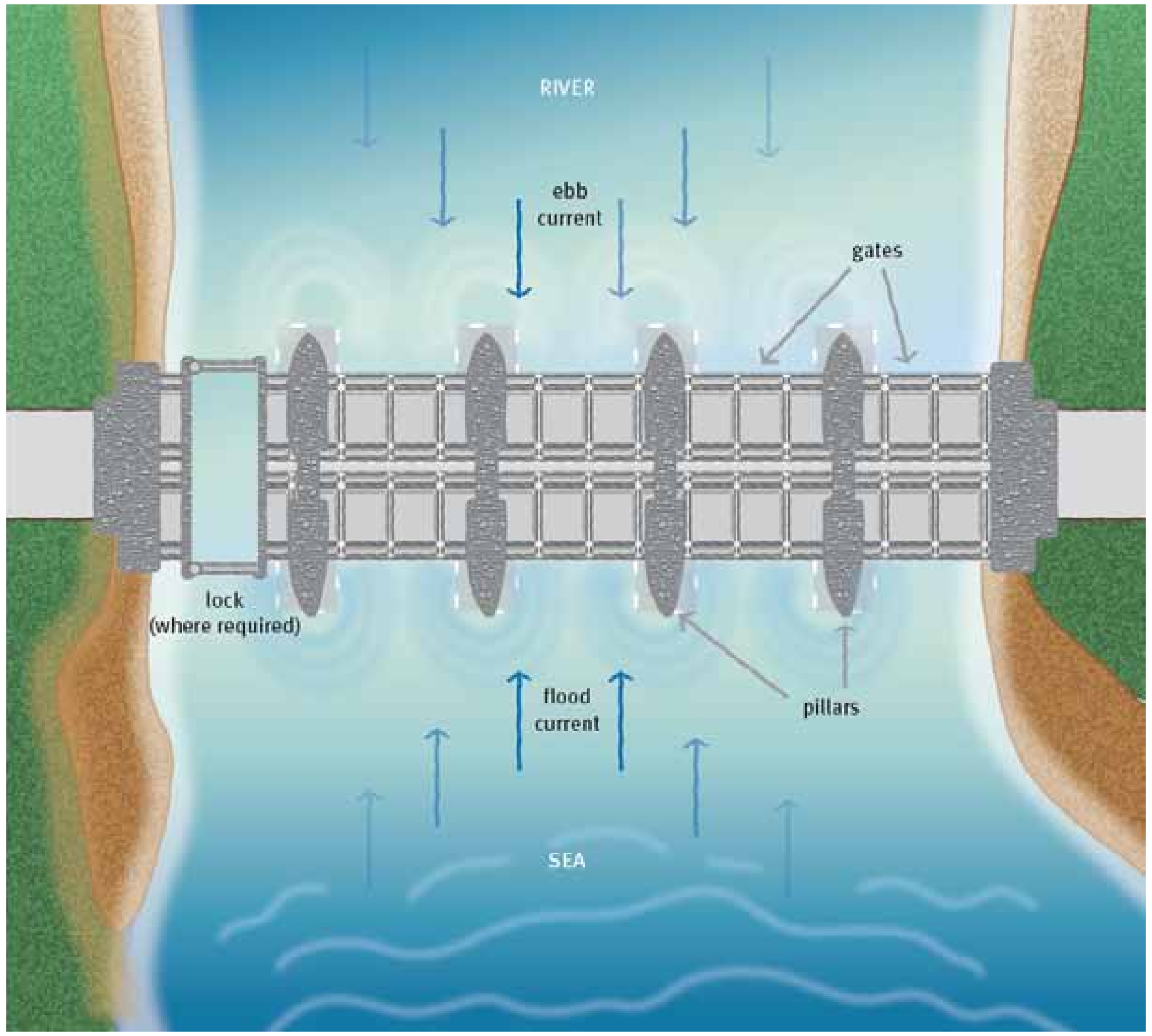


Figure 54:
Storm surge barrier

transports larger amounts of sediments to the sea, but at the same time increases the danger of scouring. The success of these adaptation measures depends on different boundary conditions, but is always limited.

In many cases, negative impacts after the construction of a storm surge barrier caused severe problems in the estuarine system. Many applied solutions were not aligned with natural processes and had negative impacts on the morphodynamics, hydrodynamics and ecology of the surrounding tidal flats. This led to the general insight that the storms surge barrier should be built further upstream and at narrower places in order to reduce interference with the tidal regime.

5.4 Elements of drainage

The protection of coastal areas from storm surges and flooding by means of dykes, storm surge barriers, sea walls etc. causes another major issue in coastal engineering: the drainage of the hinterland.

The secure discharge of surface water from the hinterland to the sea is of great importance for flood protection and agriculture. Along many low-lying coasts, drainage is achieved through a branched system of channels and ditches. Dykes form an artificial barrier and require technical drainage solutions. The water, which is collected behind the dyke, is discharged into the sea or into an estuary through tidal outlets (sluices) or pumping stations.

Natural discharge can only take place while the seawater level is below the water level in the hinterland. Due to morphologic conditions that occur especially on engineered coasts of deltas, the hinterland may be lower than the mean sea level. In this case, and when heavy rainfall requires larger drainage rates, pumping stations are essential.

Sedimentation of the tidal outlets and rising sea levels will make drainage more difficult and pumping stations must be upgraded so they can handle the increasing water volumes. The run-off from many newly sealed areas (infrastructure development), an increase in precipitation and rising sea levels will further contribute to increasing water volumes, and therefore the capacity of pumps needs to be increased in a timely manner (Naulin & Albers, 2010).

5.4.1 Sluices

The construction of sluices began parallel to the construction of a closed dyke line along the coasts. The first sluices were built and designed based on the principle of trial and error. With growing technical knowledge, the cross-sections of the tidal outlets were enlarged and their number was reduced due to increasing sizes of the corresponding catchment areas.

Sluices are installed within the dyke body and consist of flaps or gates that control the discharge (Figure 55). In their simplest form, sluices consist of wooden, iron or concrete tubes with a flap on the seaward side that opens automatically when there are higher inland water levels. With larger sluices made of concrete, wooden or steel gates were used instead.

In Figure 55, the two possible cases are shown. When there are high sea water levels, the gates are closed and the sea water cannot flow into the hinterland (right gate in Figure 55 and sea water shown in darker blue). When there are low sea water levels, precipitation and surface water from the hinterland flow through the sluice chamber, which is the actual passage from the inland side to the sea (left gate in Figure 55 and water shown in lighter blue). The gates are opened and closed in accordance with the water levels, and the mechanism functions either automatically using hydraulic pressure, or is controlled manually.

The location of sluices should be protected from waves to avoid uncontrolled slamming of the gates. A sluice gate is always a weak spot in the dyke and thus the transition zone between the sluice and the dyke must be especially well-protected. Figure 56 shows a

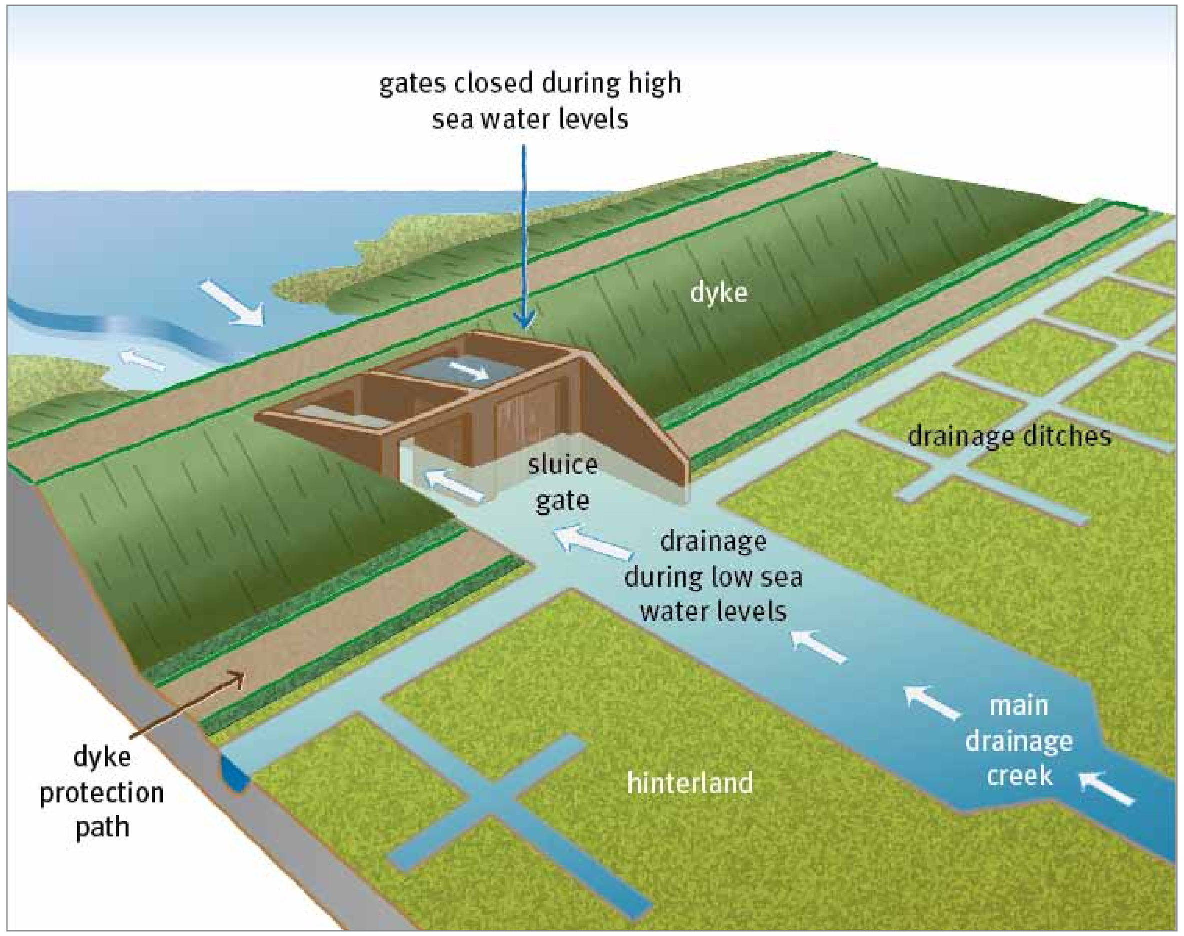


Figure 55: Sluice in the dyke and principle of drainage of the hinterland

Figure 56: Damaged sluice gate (left) and erosion of the surrounding coastal section (right) in U Minh District in Ca Mau Province (Photos: Albers)

Figure 57: Funnel-shaped erosion at sluice gate 3 in Soc Trang Province (IKONOS Satellite Image 2012; Photo: Albers)

damaged sluice gate and erosion of the surrounding coastal section in U Minh District in Ca Mau Province.

Larger sluices are massive constructions and a sound foundation is therefore important. Furthermore, the sluice can have severe impacts on the shoreline. Very high current velocities occur around opened sluice gates due to the water level differences between inland areas and the sea. Severe erosion of the surrounding floodplains and mangrove forests can occur, especially if the sluices are not being used just for drainage, but also for the water management of inland aquaculture. In that case the sluice gates are opened during high water levels in the sea so that large masses of brackish water can enter the hinterland where the brackish water can be used to fill shrimp ponds. The developing currents create funnel-shaped erosion of the surrounding mangrove belt. Figure 57 shows this funnel-shaped erosion at sluice gate 3 in Soc Trang Province. The mangrove belt to the southwest of the outflow has been eroded, while the mangroves east of the outflow are hardly affected. The orientation of the funnel depends on the general tidal conditions and wave climate.

5.4.2 Pumping stations

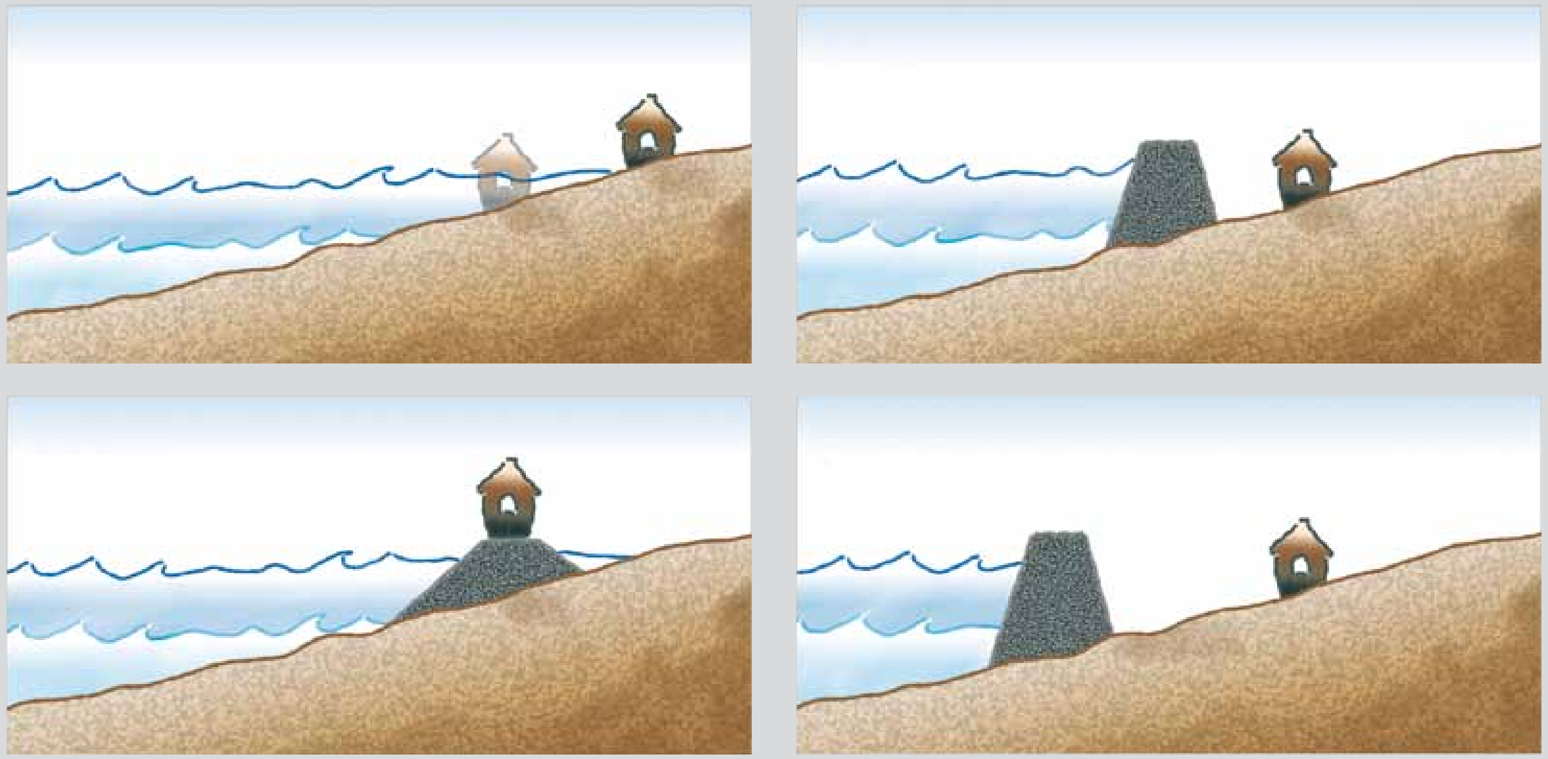
Pumping stations have to be used to pump the precipitation and surface water from the hinterland into the sea in the case of storm surges with high sea water levels when natural drainage through the sluices is not possible for several tidal periods.

The general task of pumping stations is to raise the water from a lower to a higher level, either from the hinterland to the sea or into a retention polder in the hinterland. In many cases, sluices, pumping stations and retention polders are combined. The polders are used for temporary storage of the water in the case of high tides. Thus, the drainage can be optimised and the pumping time can be limited.

The first pumping stations were constructed in the middle of the 19th century. In the past, scoop wheel, chain pumps or Archimedean-screws were used to lift the water, often driven by wind power. Nowadays, electric or motorised water pumps of various types are used, and are driven by regionally available energy sources. The applicability of wind energy to supply the electric pumps depends on the local correlation of wind and required pumping time (Naulin & Albers, 2010).

A pumping station must be operationally ready 24 hours a day and seven days a week in order to regulate the water levels behind the dykes even in the case of intense rain. In the past, the control of tidal gates and pumping stations was the responsibility of experienced technicians, who were available day and night. Today, technologies are available, which make control by humans superfluous.

6 SHORELINE MANAGEMENT



Management of shorelines and the design of coastal engineering measures are very sophisticated procedures not only due to complex physical processes, but also due to the large range of interests in coastal areas. Coastal protection and the shipping, tourism/recreation, fishing and agriculture industries have partly conflicting goals and have to be coordinated, with the safety of the coastal areas being given the highest priority. In an environment that is morphologically highly dynamic and ecologically valuable, all coastal protection measures must be planned carefully. Negative impacts have to be avoided or minimised. The design of coastal protection measures must be based on a sound knowledge of hydrodynamic and morphodynamic processes, a comprehensive data base and different supporting tools such as numerical and physical modelling.

6.1 Conflicts and compatibility

Sustainable shoreline management deals with the interaction of current and potential coastal evolution and the existing conflicts in the coastal area. It should minimise negative impacts as much as possible. Shoreline management has become more important with accelerating development pressure in coastal areas and quite strict sector requirements for preservation and restoration of natural resources in the coastal zones. The main challenge is to combine public interests such as shoreline protection and public utilities, private interests such as development projects and coastal protection, and industrial interests such as industrial development and navigation. Therefore, it is essential to have public participation in planning and construction projects, a balanced weighing of conflicting interests and a fair distribution of costs among all involved parties.

For successful planning, it is important that experts in the fields of coastal morphology, coastal engineering, landscape architecture and planning and environmental management participate in the elaboration of shoreline management activities.

Coastal engineering requires technical skills to be able to make informed decisions. These skills must be based on geological, biological, legal, engineering and other training. Although this management is interdisciplinary, the basis for all decisions is still an engineering one. To support this process, decision-makers need to be properly informed and need to establish necessary and appropriate networks with other disciplines (Kamphuis, 2010).

6.2 Protection strategies

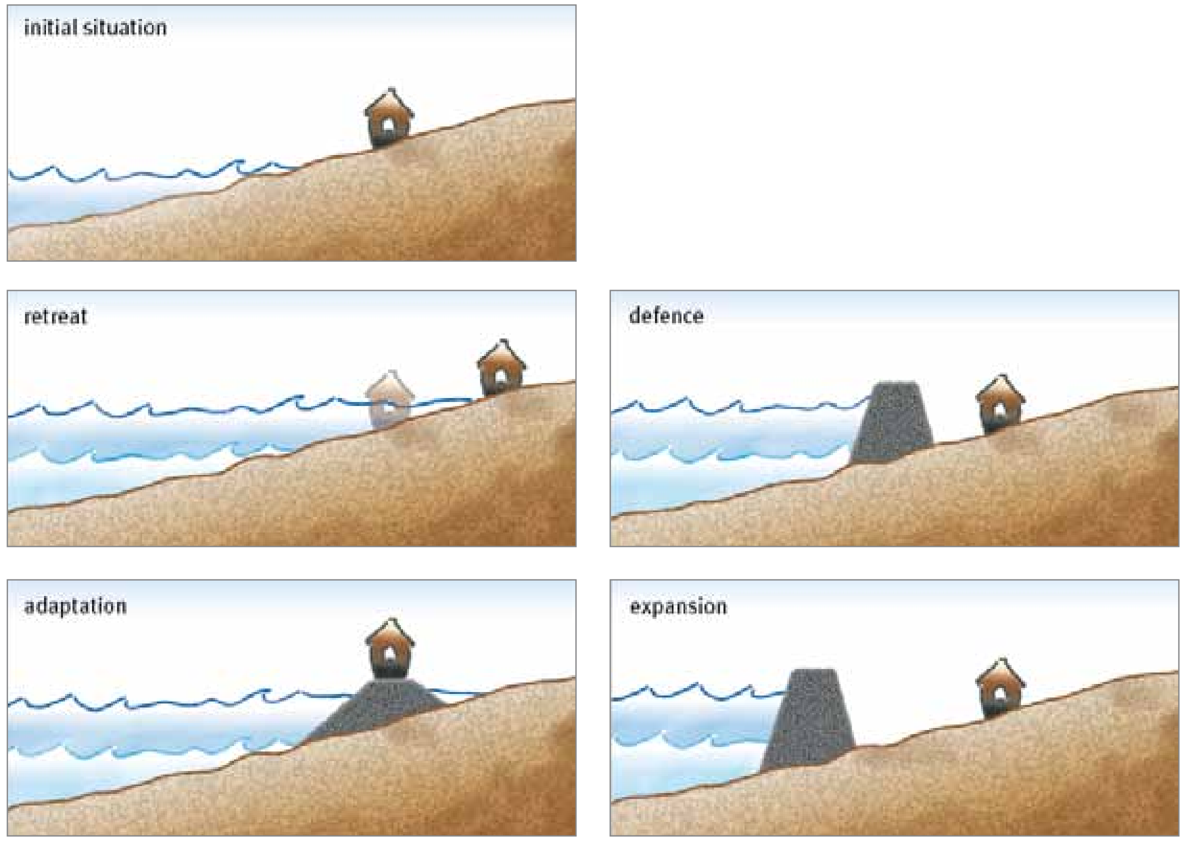


Figure 58: Coastal protection strategies

Traditionally, four general strategies can be distinguished in coastal protection (Figure 58). Around 2,300 BP, people living near the German North Sea coast were threatened more and more by rising sea levels and storm surges. The rapid encroachment of the sea banished them from their settlements, because the natural elevation of the land did not offer sufficient protection anymore. This was the strategy referred to as 'retreat'. In line with an 'adaptation' strategy, dwelling mounds were built. Later, they were connected to small ring dykes protecting the settlements. In the next step, a closed dyke line was established along the coast. This is referred to as the strategy of 'defence'. After very heavy storm surges caused a massive loss of land, lost territories were reclaimed by means of the establishment of floodplains and the successive embankment of the reclaimed areas. This is referred to as the strategy of 'expansion' (CEM, 2002).

Even nowadays, these different strategies can still be applied in order to establish an appropriate coastal protection system. The general decision for a protection strategy affects the design of the protection measure. Linham & Nicholls (2010) state that a successful coastal protection strategy consists of more than just implementing one of the basic interventions. Rather, a coastal protection strategy is a policy and implementation process involving comprehensive decision making and technology.

6.3 Coastal design

Coastal engineering and management are disciplines for which only a few codes of practice or design manuals are available. Some standard procedures exist, but any application of standard procedures is limited because solutions are generally site-specific.

Before implementing a coastal protection measure, a detailed description of the status quo and the formulation of the explicit problem are essential for the design. Moreover, by capturing the situation and the problems on-site, including the different interests, the general protection strategy can be defined and coastal protection measures can be adapted and designed more effectively.

The applied coastal protection measure must be chosen according to the site-specific situation and the design process must be based on data with a sufficient spatial resolution. Different protection elements are combined to form a coastal protection system, and this measure must be part of the general strategy. After identification of a sufficient coastal protection system the single measures have to be prioritised based on tools such as cost-benefit-analyses (Linham & Nicholls, 2010).

In general, the design of a coastal engineering measure should refer to:

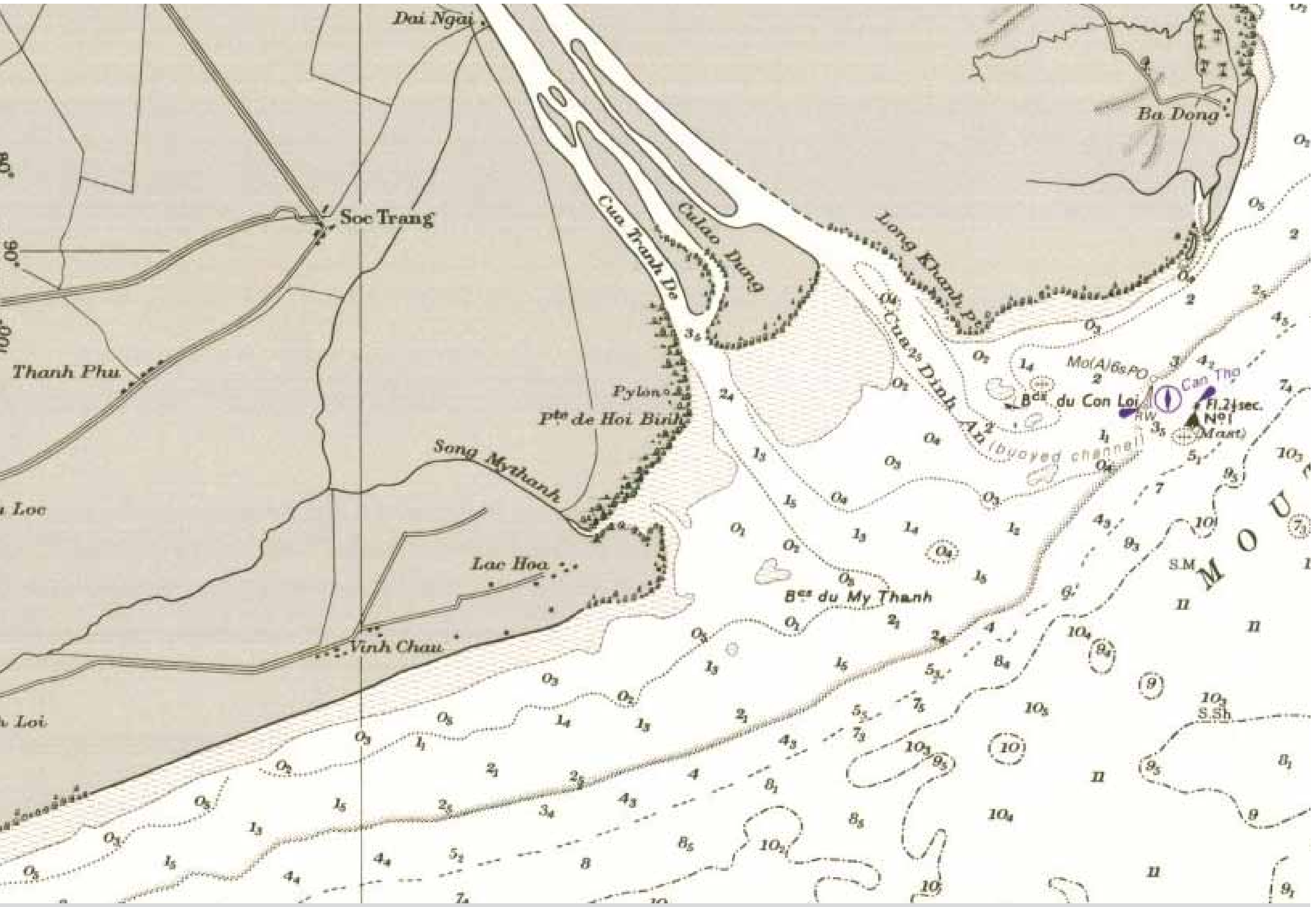
- Related plans and the legal framework
- Historical information about the area of interest on different temporal and spatial scales
- Current information about the area of interest on different temporal and spatial scales derived from existing data, field measurements, numerical modelling and physical modelling
- Identification of the boundary conditions (meteorological, hydrological, geological etc.) and classification of the shoreline
- Assessment of the main morphodynamic processes
- General strategy developed and accepted by stakeholders
- Cost-benefit analysis and risk assessment
- Priority list

Within the design process, the decision-makers should be provided with the necessary information about the impacts of the planned measures. Future developments, covering the life span of the structure, should be taken into consideration.

Modern coastal engineering tools allow for the generation of huge amounts of data. Numerical hindcasting even allows for the use of historical data and information to improve numerical models for the simulation of future trends. Modern measurement equipment records data in an increasing spatial and temporal resolution. This flood of data has to be managed. The analysis and evaluation of the field measurements, as well as the numerical and physical modelling has to be done by experts. The compilation of meta-data and the preparation and summary of the results are as essential as the subsequent dialogue between experts and decision-makers.

Computer-based decision support systems (DSS) structure and link natural-scientific, environmental-scientific and socio-economic data. By means of integrated mathematical models, DSS allow the interdisciplinary analysis and effective application of those data and hence result in improved decision-making. However, the maintenance of the DSS and sufficient training of personnel is essential to assure the sustainable benefit of such a system. Open source products promote the widespread practical application of the DSS due to the free availability of the software. Standardised data interfaces allow the integration of own data. The practical application and the freely available source code promote the further development of the DSS.

7 METHODOLOGY OF COASTAL DESIGN



In the context of shoreline management activities, hydrodynamic and morphodynamic studies have to be applied to provide a comprehensive basis for decision-making.

Such studies can be divided into four different types:

1. **Collection of existing data**
2. **Field measurements and surveys**
3. **Numerical modelling**
4. **Physical modelling**

Depending on the location, the available information and the planned activities, one or more different study types can be applied in the course of the design of a measure.

Chapter 7.1 gives an example of the use of the methodology of coastal design from Soc Trang Province. In Chapters 7.2 to 7.5 the various steps of coastal design are explained in more detail.

7.1 Case study from Soc Trang Province

Sufficient erosion protection measures were planned within the context of a coastal design study along the coast of Vinh Tan Commune in Soc Trang Province (see also Chapter 5.2.3.1). Figure 59 shows the process which has been applied for the design of the bamboo fences in Soc Trang Province (Albers & Von Lieberman, 2011; Schmitt et al., 2012).

7.1.1 General method

In collaboration with the Southern Institute of Water Resources Research (SIWRR) in Ho Chi Minh City, available data relevant to the coast of Soc Trang were researched and analysed. Although data on the bathymetry, water levels, river discharges and sediment loads were available, essential data about the erosion site at Vinh Tan Commune, especially about the wave climate, were missing. Therefore, a concept was developed to close this information gap and build the basis for sophisticated and effective erosion protection measures. Additional field

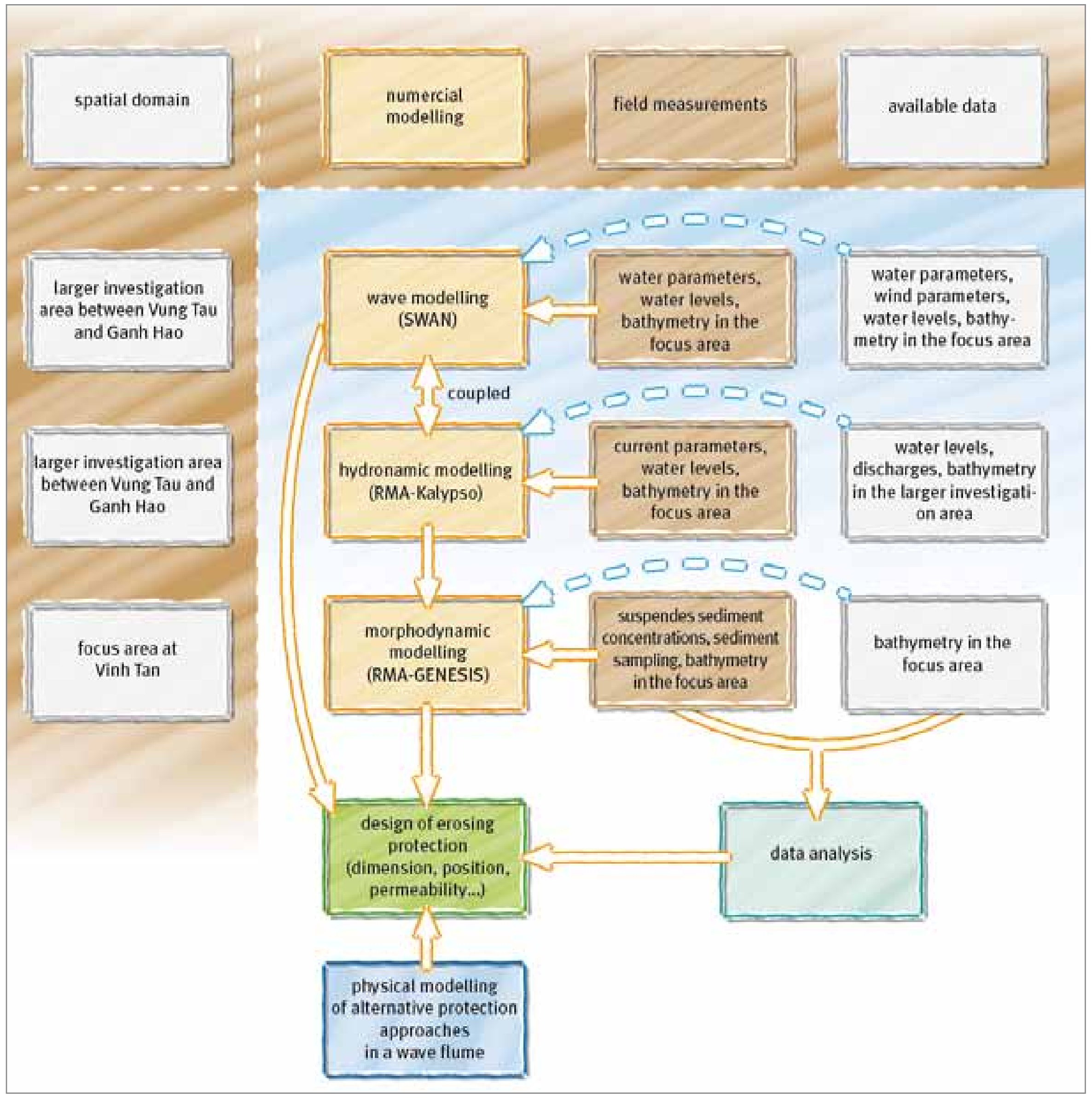


Figure 59: Process for the design of coastal protection measures, an example from Soc Trang Province

measurements were carried out to understand the hydrodynamic and morphodynamic processes in the focus area and to verify the results of the subsequent numerical modelling.

Data were recorded during three measurement campaigns, on currents, waves, sediment concentrations and the bathymetry. The field measurements covered the northeast and southwest monsoon seasons. Mobile and vessel-based measurements (bathymetry, currents, sediment concentrations) were carried out along with stationary measurements. At the stationary measurement positions near the endangered dyke at Vinh Tan, wave parameters, suspended sediment concentrations and currents were recorded. Vessel-based current measurements were carried out at 17 two-kilometer-long cross-shore profiles along a 20 km section of the coast of Vinh Tan during different tidal phases.

Field measurements cannot cover all possible weather conditions. In order to obtain the missing information, the available and generated data were used to set-up, calibrate and verify different numerical models. Shoreline changes were computed taking into consideration various erosion protection measures.

Hydrodynamic and morphodynamic models were developed for the design of wave-breaking barriers. On the basis of the bathymetric data, a two-dimensional depth-averaged numerical hydrodynamic model was set-up. The Open Source Software RMA•KALYPSO was used for this purpose (http://kalypso.bjoernsen.de/), consisting of various sophisticated hydrological, hydraulic and damage modelling tools and modern decision support tools for spatial planning and flood risk management. The source code is a modified software distribution of the numerical model RMA-10S (King, 2006), which is based on RMA2 (Donnell et al., 2006). Further development of the model was carried out by the Institute of River and Coastal Engineering of the Hamburg University of Technology (Schrage et al., 2009). The drying and rewetting of the finite elements of the tidal flat areas was modelled with the marsh porosity method, which is a form of the thin slot algorithms (Nielsen & Apelt, 2003).

To design the breakwaters, information about the wave climate in the focus area was necessary. To obtain the wave parameters for different scenarios, the numerical wave model SWAN (www.swan.tudelft.nl), which was integrated into RMA•KALYPSO and coupled with the hydrodynamic model, was set up, calibrated and verified.

The results of the hydrodynamic modelling were used in the morphodynamic model GENESIS (Hanson & Kraus, 1989), which was used to compute the required structure and position of erosion protection measures in the focus area.

The results of both the field measurements and the numerical modelling were used to define important boundary conditions for the design of countermeasures. In addition to conventional techniques, an alternative approach using local materials was investigated. Physical tests in a wave flume were carried out and analysed for this purpose.

7.1.2 Results of the study

7.1.2.1 Results of the field measurements

Wave measurements showed a clear dependency on the monsoon season. Recorded currents showed a strong long-shore component due to the approach of the tidal wave along the South Vietnamese coast. These currents were increased by the northeast monsoon.

The course of the suspended sediment concentration was affected by tidal currents, while the peaks of suspended sediment concentrations were influenced by current velocities and the wave heights. During flood tide, long-shore currents occurred at the same time as the peaks of the suspended sediment concentration. This indicates long-shore sediment transport, which reaches the highest values at the end of the rainy season due to high sediment loads in the branches of the Mekong River. During the main period of the northeast monsoon, higher waves were recorded in the focus area. The waves approached the coast of Soc Trang and Bac Lieu with a strong long-shore component. In winter, while the sediment plume of the Mekong is less pronounced and less material is available, the northeast monsoon winds cause increased coastal longshore drift and erosion (Albers & Von Lieberman, 2011).

7.1.2.2 Results of the numerical modelling

The numerical modelling was done in three steps. A wave model was set up in a larger investigation area reaching from Vung Tau to Ganh Hao (approximate distance 250 km) and 40 km out from the coast into the sea. The results were used as design parameters for the erosion protection measures at the coast.

One scenario simulated waves during the northeast monsoon season with peak wind velocities of 25 m/s (Figure 63, left). For the coast at Vinh Tan, significant wave heights of 0.63 m were computed. Due to refraction, the wave direction changes from north-east offshore to east near Vinh Tan (Figure 63, right). This causes a larger longshore sediment transport component.

The wave model was coupled with the hydrodynamic model, which simulated tidal currents and wave-induced currents. The model results showed the approach of the tide from northeast to southwest and the resulting current velocities and directions. The flood current is running parallel to the coastline, and lower water depths and an increasing influence of the bottom friction decelerate the current velocities with decreasing distance to the shore. In the nearshore area, the current velocities are between 0.20 and 0.50 m/s (Figure 62). The current measurements in the focus area were used to verify the results of the simulation.

The results were then used as input parameters in the morphodynamic model, which simulated the shoreline changes. This third model covered the coast around the focus area at Vinh Tan. It simulated shoreline changes based on the current and wave regime. Various structural (erosion protection) measures were integrated into the model, and the resulting effects were simulated. The model was used to get a first estimation of the efficiency of the measures, the optimal positions and the best characteristic values. The aim of the structural measures is to reduce erosion and to increase accretion. Negative effects such as downdrift erosion must be avoided as much as possible.

The results of both the field measurements and the numerical modelling were used to define important boundary conditions for the design of countermeasures (Albers & Von Lieberman, 2011).

7.1.2.3 Results of the physical modelling

In addition to the application of conventional breakwaters, adapted approaches using local materials were investigated. Physical tests in a wave flume were carried out and analysed for this purpose. Figure 64 shows a photograph of the tests with the waves approaching from the left side. On the right side of the structure, the area of attenuated waves is clearly visible. Regular waves were generated at the left end of the flume with a wave paddle, and wave parameters were measures in front of and behind the bamboo fence. The results of the physical modelling are shown in Figure 49 and explained in Chapter 7.5 in more detail.

7.2 Collection of existing data

For all projects dealing with coastal morphology, it is essential to acquire and analyse available relevant data to initiate the design of a measure. The data shall serve the following purposes:

- Description of the site conditions and the history of the development at the site in terms of coastal structures (coastal protection works, ports etc.), shoreline development and development of habitation and infrastructure.
- Basic description of the present conditions at the site.
- Definition of the need for further data collection and data generation in the form of field investigations and hindcast studies.
- Calibration basis for numerical modelling.

The data and information described in Chapters 7.2.1 to 7.2.9 are often available. A shoreline management project will therefore often be initiated by collecting and analysing these types of data and information (Mangor, 2004).

7.2.1 Geological data

Geological maps show the surface geology of the coastal area and normally are sufficient for the performance of a coastal engineering measure.

Subsidence of coastal areas is often a result of the geological history of the area; however, it can also be caused by extraction of oil, gas or groundwater. Subsidence of coastal land will in all cases cause coastline retreat. Tidal water levels of the same elevation will advance further inland, when the elevation of the surface decreases due to subsidence. The advancing line of the tidal high water level is equivalent to a loss of land. Therefore, information on subsidence is important for analysing the morphological development of an area.

7.2.2 Topographic maps

Topographic maps are available in most countries in the form of new maps and varying series of historical maps. In many cases, recent maps are available in digital form.

7.2.3 Bathymetric maps and special surveys

Bathymetric maps in the form of international and national sea charts are available for all sea areas of the world, however many of the sea charts are at a relatively large scale. Furthermore, they are often based on relatively old data and are not very detailed at shallow water, as sea charts are mainly made to support navigation (Figure 60). Sea charts are often sufficient for the general layout of coastal engineering measures. Special bathymetric surveys may be available near port entrances and in tidal inlets, as sedimentation and maintenance dredging in these areas requires frequent surveying. Bathymetric data are very scarce for tidal flat coasts.

7.2.4 Aerial photos

Aerial photos are available in sufficient resolution for many locations. Historical aerial photos are also often available. Aerial photos can be very informative for studying shoreline development or mangrove dynamics as shown for Soc Trang Province in Joffre (2010).

7.2.5 Satellite images

Satellite images are available in many different qualities and resolutions. Newer satellite images (e.g. Figure 57) have spatial resolutions of a few decimetres. An advantage of satellite images is the availability and the coverage of large areas. This makes them applicable for investigations in remote and undeveloped areas where other data are rare. A disadvantage is that older satellite images are of a relatively coarse resolution. Newer, high resolution images are expensive. Cloud cover can also be a problem in satellite images. Due to uncertainties in the geo-referencing and changing resolutions, images provided by Google Earth have to be handled with care, but they can support the general layout of coastal engineering measures.

7.2.6 Shoreline development

The historical development of shorelines is often a very valuable tool for studying coastal morphological development in general and for overall calibration of the littoral transport budget modelling. Shoreline development can be extracted from historical maps and surveys, from aerial photos and from satellite images. Well defined shoreline accretion upstream of coastal structures, such as groins or inlet jetties, is especially suited as a basis for calibration of littoral drift and shoreline development modelling.

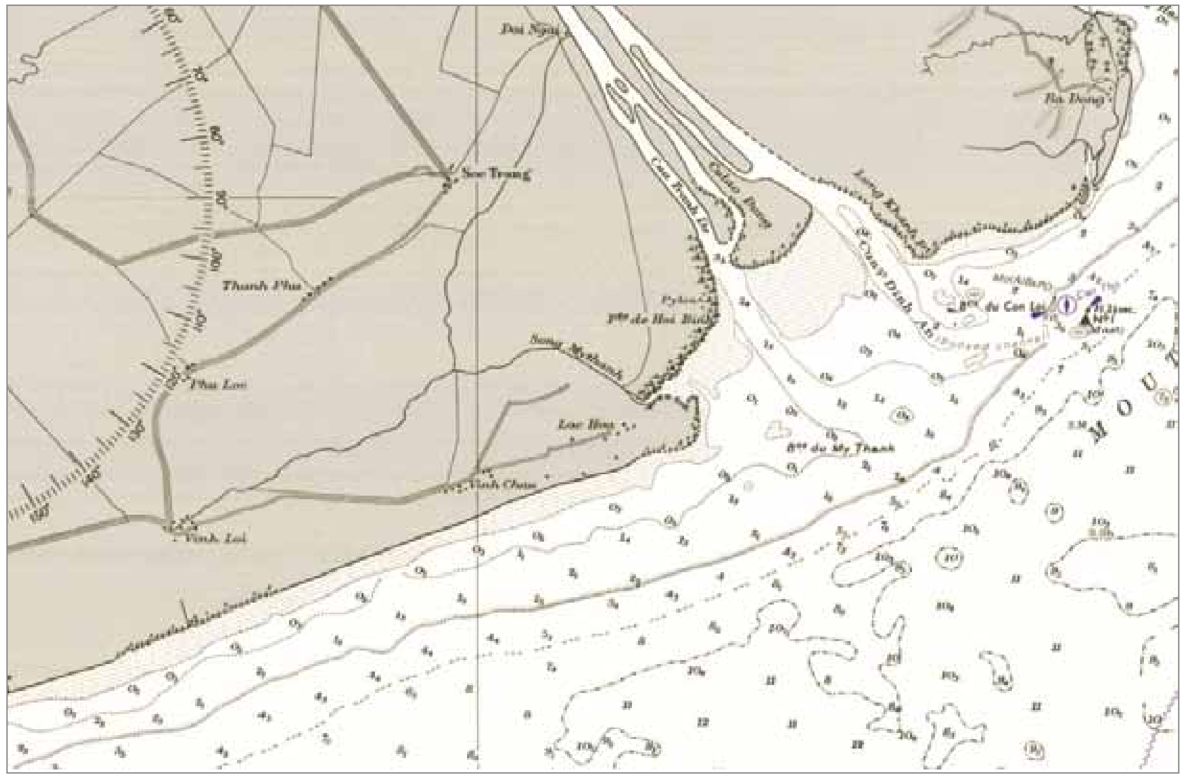


Figure 60: Map section of a sea chart of the Vietnamese East Sea from 1973 (Bassac mouth and coast of Soc Trang); Source: Published at the Admiralty, 26th Aug. 1960 under the Superintendence of Rear Admiral E.G. Irving, O.B.E. Hydrographer, London, Crown Copyright 1974

7.2.7 Sediment sources and sinks

Quantitative information on sediment sources in a coastal area is of great importance for the assessment of the littoral drift budget. The most important active source is the supply of sand from rivers, which is heavily influenced by human interventions in the river basin. As a result, the historical development in the supply from rivers is of importance for the historical shoreline development. Although it is only the result of a deficit in the littoral drift budget, the sediments released in connection with coastal erosion also have to be considered. The amount of nourished material is small in comparison with naturally transported material. Nourishment is 100% controlled by human activity, as it is used as a countermeasure against erosion. However, it is a sand source and should be considered in the sediment budget.

Sediment sinks can be natural (e.g. offshore loss during extreme events) or caused by human interventions (e.g. trapping of sand at structures or in navigation channels or ports). Maintenance dredging at ports, tidal inlets or in navigation channels constitutes another sediment sink. It is equivalent to the loss of sand from the littoral budget, unless it is bypassed back to the shoreline. Thus, information on maintenance dredging and eventually on dumping is important for the assessment of the littoral drift budget.

7.2.8 Land use maps

Erosion protection measures should only be executed if valuable infrastructure, buildings or other installations are endangered. Land use maps provide a good basis for the evaluation of the need of coastal erosion protection and thus are useful for shoreline management activities.

7.2.9 Meteomarine data

Meteomarine conditions in coastal areas, such as wind, waves and tides, are the controlling forces for morphological development. Available data on the following subjects should be collected as a basis for the description of the hydrological conditions in the area of interest and as a basis for further analysis and numerical modelling.

Wind and barometric pressure

A general description of the wind and pressure system should be researched. If the site of interest is located at a spatially limited water body with fetch lengths less than approximately 200-300 km, waves should be modelled on the basis of long-term wind data from nearby meteorological stations. If the site is located out in major water with fetch lengths larger than 300 km, it will be more accurate to base the wave modelling on time series of large-scale barometric pressure or wind fields.

Winds caused by typhoons require special consideration, as typhoons are rare events relative to the impact at a specific site. Data describing the strengths, paths and frequency of tropical typhoons should be collected and analysed.

Tides and storm surges

Tidal conditions for a certain area can be described on the basis of the tidal constituents, which are published in appropriate tide tables. Storm surge data can be analysed from tide records. Thus, it can be necessary to procure time series of tide records from nearby hydrographic stations and gauges. Time series covering several years are required in order to analyse extreme storm surge conditions.

An analysis of extreme storm surges can also be obtained by numerical modelling of typical typhoon tracks based on standard typhoon parameters followed by a statistical analysis of the results.

Sea level rise

Sea level rise is analysed by many national hydrographical institutions. The Intergovernmental Panel on Climate Change summarises many studies. Rates of sea level rise for an area of interest can be obtained from these studies. It is important to include the influence of sea level rise in the design of dykes and other structures sensitive to flooding.

Waves

Waves are of large importance for the morphodynamic processes at the coast and for the design of coastal protection and thus for shoreline management activities. Wave monitoring programmes or operational wave modelling programmes are operated by hydrographic or coastal authorities in many countries, from where data can be obtained. Such data are useful if the recording location is close to the site of interest. If the recording stations are further away, a transformation of the wave data by means of numerical modelling is necessary. Additional wave measurements at the site of interest are recommended to verify the results of the numerical modelling.

Wave data are also available from global wave models and from satellite monitoring. Often the quality and resolution of these data is not sufficient for the design of coastal protection, and the data must be verified in any case.

Currents

Wave generated longshore currents underlie spatial and temporal variations and depend on the wave conditions. Reliable long-term measurements of longshore currents are usually not available. Information on such currents is usually computed using numerical modelling.

Information on tidal currents in straits and tidal inlets sometimes are provided for nautical reasons in sea charts. Usually the available data are not suitable as a basis for shoreline management projects. However, the charts provide useful information on the general current conditions in an area.

In conclusion, relevant current data for a shoreline management project will normally not be available. Current data for shoreline management projects will usually be provided by numerical modelling, which takes into account astronomical tides, wind stress, barometric pressure and radiation stress gradients caused by wave breaking. Additionally, current measurements are recommended to verify the results of the numerical modelling.

7.3 Field measurements

The extent of field surveys depends primarily on the availability of existing data. A summary of typical types of field surveys and their relevance for different types of shoreline management activities are discussed in the following.

7.3.1 Geological survey and seabed characteristics

Sampling of seabed and beach material to provide information about the existing material and its geotechnical properties will typically be performed in lines perpendicular to the coastline covering the beach and the littoral zone. Borings may be required to provide the thickness of the sand layer. Sub bottom surveys in the form of seismic surveys and vibro-core borings may be required for projects, which involve foundations for major structures (bridge piers and port structures).

7.3.2 Topographic surveys

Topographic surveys can be done based on traditional land surveys using DGPS-technique (Differential Global Positioning System). The recorded data provide information on coastal profiles or on coastal structures such as dykes and sluice gates. In addition, remote sensing can be used. The airborne LIDAR (Light Detecting and Ranging) is a system with a very good horizontal and vertical accuracy for topographic surveys of large areas. It is especially suitable for tidal flats, where the water depths are too shallow for bathymetric surveys.

7.3.3 Bathymetric surveys

Bathymetric data shown in standard sea charts are not detailed enough for the design of coastal engineering measures. Additional surveys are usually required:

- Water levels are recorded by echo soundings. Due to varying water levels, a combination with a positioning system, such as Real Time Kinematics GPS (RTK-GPS), is essential to provide the reference level of the recorded data and thus to compute coastal profiles. Echo sounding can only be performed for water depths greater than approximately 1.0 to 2.0 m, depending on the type of equipment and the survey vessel. However, it is usually a requirement that the surveys cover the entire coastal profile from the closure depth (where the water depths are so large that waves have no influence on the sea bottom) to the coastline. Usually it is also required that echo sounding be combined with traditional land based surveying techniques to cover the section from 1.0 to 2.0 m water depth up to the coastline.
- Multi-beam echo sounding combined with a positioning system not only provides profiles, but records the complete sea bottom of an area. Compensation for the ships' movements is essential. Thus, this survey is complex and expensive.

Repeated bathymetric surveys, often combined with topographic surveys and/or aerial photography, can be used to monitor the impact of coastal structures on the shoreline evolution and on the bathymetry adjacent to the structures (IHO, 2008; Jensen, 2008).

7.3.4 Recording of meteomarine data

The analysis of meteomarine data is important in connection with all shoreline management studies, as the study of the littoral transport will always be an important part of such studies. Descriptions of the overall meteomarine conditions in an area are often established on the basis of existing data as described above. Depending on the quality and extent of existing data, additional field measurements are required (Van Rijn, 2007).

Wind

Long term wind data are usually available from nearby stations, which means that wind recordings are normally only required in connection with intensive field surveys. Wind recordings can also be relevant at locations where land and sea breeze effects dominate the daily wind pattern, as this may not be represented in data from stations that are not located on the coast.

Tides and storm surges

Water level recordings are relevant in the following situations:

- As a reference for bathymetric surveys or other field investigations in the area.

- At sites located far from tidal gauges and at sites with a complicated bathymetry, which makes tidal prediction difficult. For the calculation of tidal constituents two months of data are sufficient. The assessment of characteristic correlations between wind conditions and surge requires one year of data as a minimum. The establishment of extreme water levels caused by storm surges requires decades of data. Such analyses are usually performed on the basis of long-term recordings from existing recording stations or from numerical hydrodynamic modelling of extreme events.

- Measurements at two locations for the establishment of boundary conditions for hydrodynamic modelling of an area.

- Measurements at one or more locations inside the modelling area for calibration and verification of hydrodynamic models.

- Recordings as part of construction activities.

Sea level rise and subsidence
On the whole, recordings of sea level rise and subsidence are not part of a specific shoreline management project, as this requires very long time series.

Waves
Waves are the most important parameter for shoreline management activities. Detailed information about waves in the project area is very often established based on numerical modelling, which has reduced the need for wave recordings in connection with shoreline management projects over the last decades. However, actual recordings of waves are essential in the following situations:

- To provide data for calibration and verification of numerical wave modelling. This will normally require recording at one or two stations for 3 to 6 months.

- To provide background data for other field investigations in the area, such as water sampling for analysis of concentrations of suspended sediments or in connection with recordings of local current patterns. This will generally require recordings for some months in two characteristic seasons (Batholomä et al., 2009).

- Wave conditions at ocean coasts are difficult to simulate by local wave models as the wave characteristics depend on the history and variation of the wind over huge areas. Consequently, it can be relevant to perform offshore wave recordings at such locations. Many years of recordings are required for establishment of reliable descriptions of the normal wave conditions and of design data. Such long recordings are generally performed by relevant authorities, from where data can be acquired. A local wave climate can be established using numerical modelling, and the offshore conditions can be transferred to a specific site.

- Shorter nearshore recording periods (6 to 12 months) are sufficient for the confirmation of specific local wave characteristics at sites where the overall wave conditions have been determined by other means. This is especially applicable at sites dominated by regular wave climates, such as monsoon climates.

- Wave recordings can be relevant as reference parameters in connection with monitoring programmes performed after the construction of coastal engineering measures such as fences.

Currents
Longshore currents and current patterns in shallow areas close to coastal structures are especially important for shoreline management projects. Measurements of currents are relevant in the following cases:

- Current measurements at fixed locations for the:
  - provision of basic information for planning or design,
  - calibration of a numerical model,
  - documentation of currents in connection with suspended sediments sampling and computations of sediment transport,
  - monitoring before and after the implementation of a certain project and
  - monitoring of currents in straits and at ports for nautical purposes.

- Current measurements by ADCP (Acoustic Doppler Current Profiler):
  - Installed in a frame on the seabed for the provision of time series of current profiles, typically used for documentation of stratified flow in straits and estuaries.
  - Installed at the bottom of a survey vessel for the provision of current profiles across a strait, a major river or a coastal profile. The measurements can provide flux information through the application of integration software.

- Current measurements by drifters for the documentation of current patterns in areas characterised by complicated current patterns. This is often used as a calibration basis for numerical modelling in combination with measurements of currents at fixed locations.

Temperature and salinity
Temperature and salinity are often recorded together with current data in connection with oceanographic investigations in areas with stratified flow.

7.4 Numerical modelling

7.4.1 Introduction
In coastal engineering, the application of numerical models has increased during the last three decades. This development was driven by the increasing computer power combined with research and increased understanding of the physics (hydrodynamics and sediment transport).

Morphodynamic models predicting the bathymetric development have become a powerful tool in connection with shoreline management projects. The models are set up and run on the basis of bathymetric and meteomarine data. However, reliable morphological modelling is presently only applicable for studying scenarios over a relatively short duration, such as extreme events, whereas morphological modelling of the long-term development still contains large uncertainties (Heyer et al., 1986).

Numerical models can provide information about causes of present problems and consequences of different measures planned. The interpretation of the simulation results requires a comprehensive understanding of the large-scale coastal morphology and the physical processes involved at a smaller scale. Numerical models are only useful when applied in combination with qualified engineering judgement. Predictions from numerical models can be useful if the following conditions are fulfilled:

- The input data must be of good quality and be available for calibration, validation and scenario runs.

- The models should meet a high scientific standard and cover the relevant subjects, such as waves, hydrodynamics and sediment transport.

- All numerical models include mathematical descriptions of selected physical phenomena. This implies that certain assumptions have been made and simplifications have been introduced. Thus, it is essential to realise which assumptions have been made and what the model can represent with reasonable accuracy.

7.4.2 Morphological loops

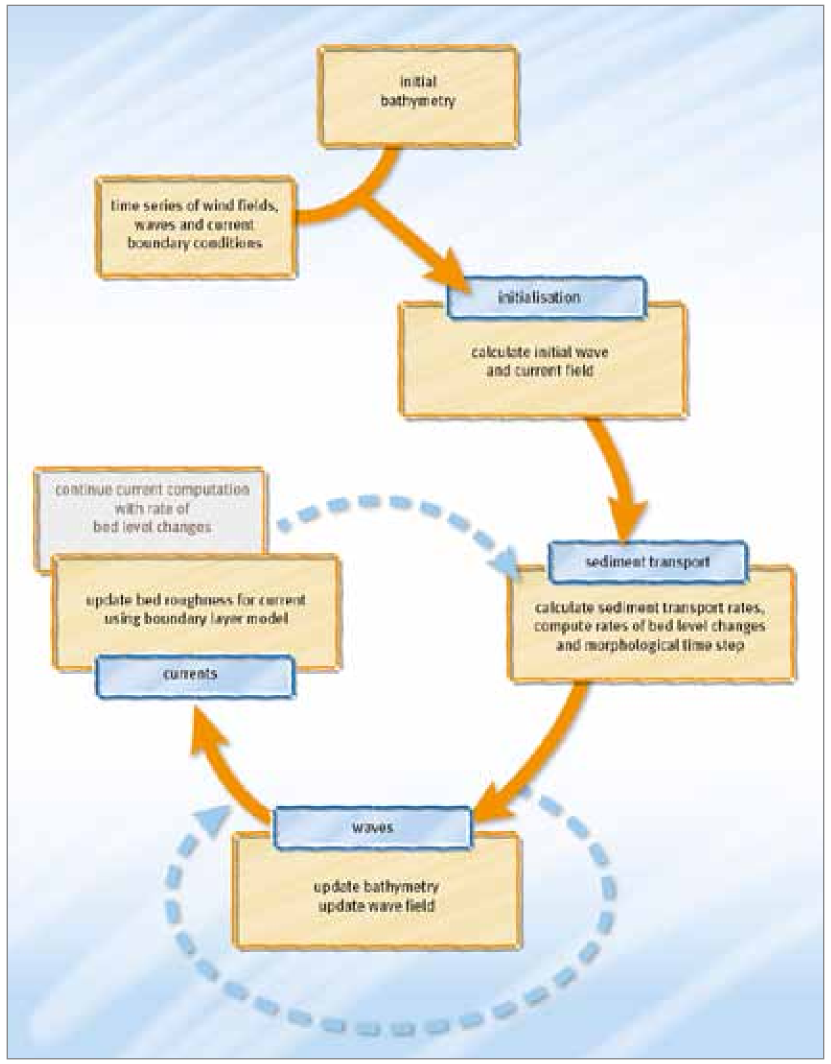
A study related to coastal erosion management will usually involve the description of a wide range of different hydrodynamic and sediment transport processes at very different temporal and spatial scales. No single model is available that encompasses all processes and scales, and thus morphodynamic modelling can be viewed as a cascade of models, where each model uses results from other models and in turn provides data to the following models in the form of boundary data. Typically, the model cascade will include the following elements:

- Wave model, simulating the wave field over the model area as determined by the bathymetry, the water levels, the wind forcing and/or the incident waves.

- Current model, which can be driven by tide/surge, wind and/or by the breaking waves in the surf zone. The current model thus relies on the wave model for a significant part of its forcing.

- Sediment transport in coastal areas is a function of the bathymetry and the bed conditions with current and the wave conditions as forcing elements. The model for sediment transport thus uses the current and wave fields as input.

Figure 61: The morphological loop (modified from Mangor, 2004)



- Erosion/deposition, the divergence in the sediment transport field determines the local rate of bed level change and the field of erosion and deposition.

The interaction of the models involves loops. The most important loop is the morphological loop (Figure 61), where the erosion/deposition field is used to update the bathymetry for the next morphological time step. A dynamic simulation of the development of the bathymetry with time can thus be made by taking the feedback from the morphological development into account in the wave, current and sediment transport models (Mangor, 2004; Plüß & Heyer, 2007).

7.4.3 Hydraulic models

2-D models simulate the conditions in a two-dimensional (horizontal) domain, which may include the coastline, coastal structures and for example a river mouth. A 2-D model is suitable when significant changes to the wave and/or flow and/or sediment transport conditions occur over a short distance along the coast. This may involve the simulation of a complex bathymetry or the deposition and erosion of sediments at coastal structures.

Figure 62 shows current velocities and directions during flood tide along the coast of Soc Trang computed with a 2-D model. For this simulation, the RMA•KALYPSO model was used in the context of the coastal design study along the coast of Vinh Tan Commune in Soc Trang Province (see 7.1.2.2). The geometric basis for the model was the complex bathymetry of the Lower Mekong Delta with its several river mouths. The approach of the tide from the northeast to the southwest and the resulting currents are clearly visible. The flood current is running parallel to the coastline, whereas lower water depths and an increasing influence of the bottom friction decelerate the current velocities with decreasing distance to the shoreline.

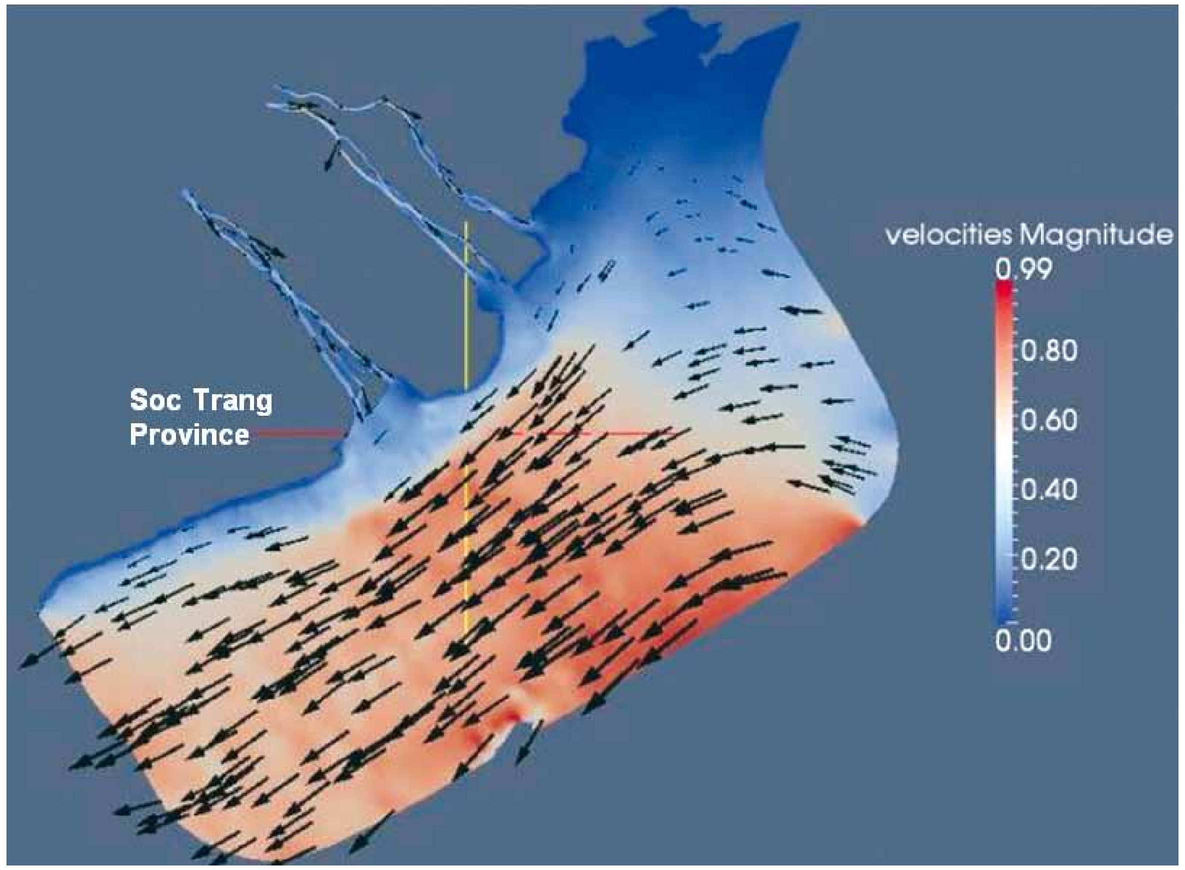


Figure 62: Computed tidal currents in m/s on the coast of Soc Trang Province

Area models may be classified according to the calculation mesh that is used to represent the bathymetry and to calculate the hydrodynamic or sediment transport parameters of interest. Structured models make use of rectangular elements of constant size over the entire simulation domain, whereas unstructured models typically utilise triangular or rectangular elements of varying dimensions. Smaller elements (i.e. higher spatial resolution) are used in this second case in areas of particular interest, such as tidal inlets, around coastal structures or in the surf zone.

Waves are the most important parameter for practically all investigations related to shoreline management. Thus it is important to obtain a reliable description of the nearshore wave climate for a specific project site. In many cases, the wave conditions are known at an offshore location with a water depth of tens of metres and several kilometres from the coast. Offshore wave data may be available from field measurements or from an ocean wave study based on time series of wind and barometric pressure fields. A transformation of the offshore waves is necessary in order to obtain wave conditions in the nearshore project area. Numerical wave models are very powerful and useful tools for such a transformation of wave data. The transformation of wave data from an offshore location will often require a relatively large modelling area, typically an area of 10-20 km by 20-50 km. The nearshore wave model includes wave generation by wind forcing, wave breaking in the surf zone, depth refraction and shoaling.

A typical application of a wave transformation model is presented in Figure 63. Here, the numerical wave model, SWAN, which was integrated into RMA•KALYPSO and was coupled with the hydrodynamic model, was set up, calibrated and verified (see 7.1.2.2).

7.4.4 Sediment transport models

Length scales of sediment transport processes are in the order of the grain size. This is small compared to the length scales of the wave and current models, and the simulation of the sediment motion is usually not coupled directly with the other models in the area modelling system. Instead, sediment transport is calculated by a model using results from wave and current models as input parameters. The transport of sand can be calculated using a numerical model as a function of the current velocity, the water depth, the wave conditions and the sediment characteristics (Davies et al., 2002).

The simulation of the sediment transport is the single most important source of uncertainty in numerical modelling related to shoreline management studies. This is partly because the predicted transport is very sensitive to variations in the input parameters, but even under well-controlled conditions, the model predictions can be far from the actual transport rate. A factor of two between predicted and measured transport rates is often considered as an acceptable deviation, and in many cases the factor is significantly larger (Van De Graaff & Overeem, 1979; Bayram et al., 2001; Camenen & Larroudé, 2003; Albers, 2012).

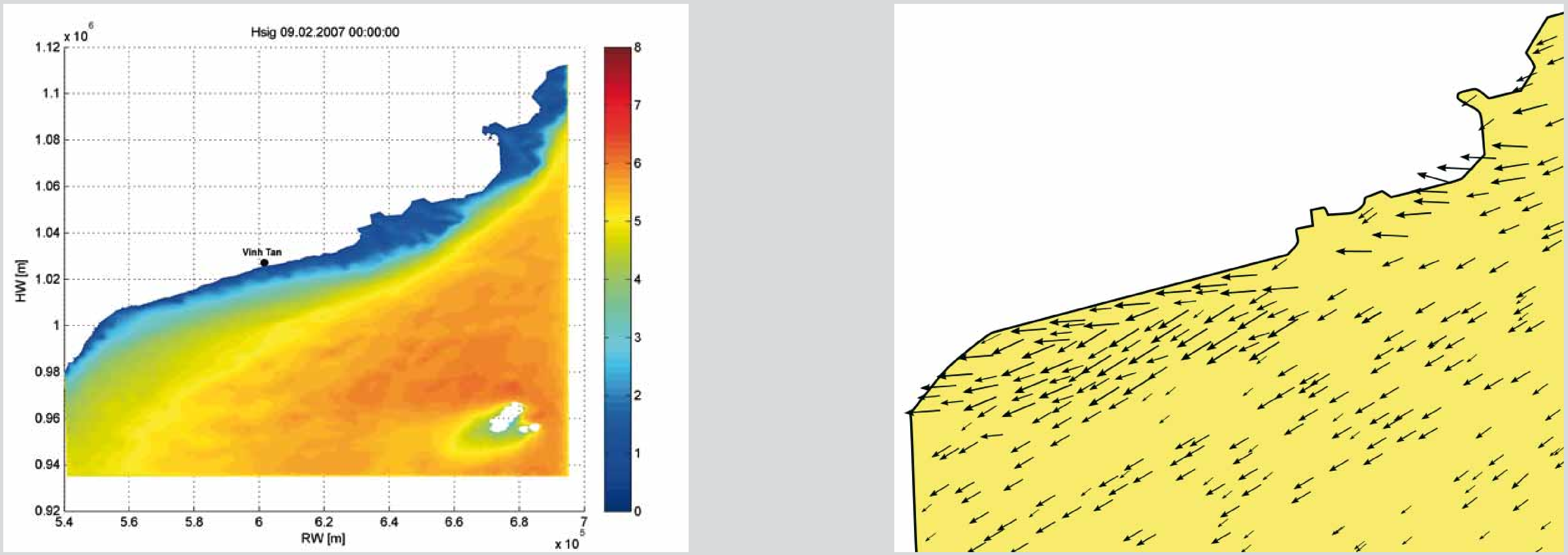


Figure 63: Simulated significant wave heights (left) and mean wave directions (right) in the modelling area during northeast monsoon

7.4.5 Shoreline evolution models

Shoreline evolution models calculate variations in the shoreline position over time by solving the continuity equation for the total longshore transport and by assuming that the coastal profile advances or retreats in response to shoreline accretion/erosion, while keeping its general shape.

Due to relatively small computational efforts associated with the calculation of littoral drift budgets and shoreline evolution, these models are applicable to the investigation of shoreline evolution over time scales of years.

Again, the model must be calibrated and validated prior to use for long-term prediction. The longer the calibration and validation periods, the longer the prediction period that can be chosen.

7.4.6 Profile models

The shape of the beach profile changes considerably in response to the incident wave conditions. The adjustment of the beach profile is mainly related to gradients in cross-shore sediment transport. Most profile evolution models have been developed based on this assumption.

Numerical models for the computation of beach profile evolution typically include the calculation of wave propagation and transformation along the coastal profile. These results are coupled to a description of the hydrodynamics and sediment transport under unbroken and broken waves outside and within the surf zone, respectively. Gradients in the calculated rates of cross-shore sediment transport are then inserted into the continuity equation for sediment transport, which is used to update the beach profile assuming longshore uniform bathymetry and hydrodynamic conditions.

Numerical modelling of cross-shore sediment transport is not an easy task, due to the number and complexity of the processes that are involved. Thus, profile evolution models should be applied with great care and only after extensive calibration and validation has taken place.

7.4.7 Concluding remarks

There is no guarantee that the results from a numerical model will be a true and accurate representation of the natural conditions, just because the model has been set up and run for one site. The quality of the input data is essential, and results of the modelling are never better than the quality of the input data. The quality of the model also depends on the underlying assumptions and simplifications that have to be known and evaluated (Davies et al., 2002; Mayerle & Zielke, 2005).

Sound engineering judgement shall always be applied when interpreting model results and deriving conclusions from model results. Likewise, numerical models should always be seen as advanced support tools for coastal engineering, in general, and for shoreline management, in particular, but never as a substitute for common engineering sense.

7.5 Physical modelling

7.5.1 Introduction

A physical model is a physical system reproduced at reduced size so that major dominant forces governing the system and the important processes are represented in the model in correct proportion to the actual physical system.

The scale (μ) of a model in relation to a parameter (y) is defined as the ratio of the parameter in the model to the value of the same parameter in the prototype.

When talking about model scales in coastal engineering, the reference parameter used is normally the length (l). For example, if a model is scaled so that 1 m in the model corresponds to 30 m in the prototype, the length scale is μ = 1:30.

Increasing the scale means increasing the size of the model, for example, a 1/20 scale is larger than a 1/30 scale.

A main advantage of physical models is that it incorporates all the governing processes without simplifying assumptions that have to be made for numerical models. Physical models are useful if processes are so complicated that a numerical model has not yet been developed or is computationally too difficult to use. The small size of the physical model permits easier data collection than in the field. The conditions in the model can be controlled, repeated and simultaneous measurements can be carried out, which is not the case in the field. Watching a physical model in operation often gives the researcher an immediate qualitative impression of the physical processes and provides inspiration for arriving at the best solutions.

Disadvantages of physical models include scale effects that occur in models, as it may not always be possible to simulate all governing or relevant variables in correct relationship to each other. Sometimes it is difficult to create realistic boundary conditions in a laboratory, e.g. if a unidirectional wave model approximates directional waves that occur in nature. Some boundary conditions, such as wind, cannot be modelled in a laboratory. Physical models are normally more expensive to set up than numerical models. However, once the physical model is established, it will often be much faster and cheaper to do one extra test than in a numerical model.

Physical models are normally only covering fairly small areas as they are limited in size by the dimensions of the model facility, which is typically on the order of 20 - 40 m by 30 - 60 m. It is seen that a typical physical model only covers areas of dimensions of one to five kilometres. This puts a natural limit on the use of physical models. For the same reason, physical modelling is seldom used in connection with shoreline management planning (Mangor, 2004).

However, within the field of coastal engineering, physical modelling is sometimes used in connection with optimisation of the hydraulic design of coastal projects, such as marinas and coastal structures.

In coastal engineering, two general kinds of models are differentiated:

- Fixed bed models, which have solid boundaries (the seabed) that cannot be modified by the hydrodynamic processes going on in the model, and
- Movable bed models, which have a bed composed of material that can react to the applied hydrodynamic forces.

A fixed bed model deals mainly with hydraulic design problems and studies of hydraulic processes, whereas the most important physical aspect in shoreline management, namely sediment transport and the associated coastal processes, cannot be studied quantitatively in fixed bed models.

A very important aspect of shoreline management is to understand, and to quantify, sediment transport and coastal processes, including the response in the coastal morphology of various interventions such as construction of ports and protective coastal structures, etc. However, before numerical models could do this, these processes could only be studied in physical models with a movable bed (IAHR Design Manual, 2011).

7.5.2 Fixed bed models

Fixed bed models are used to study the interaction of waves and currents under controlled circumstances as well as the interaction of hydrodynamic forces with solid bodies, such as armour elements on breakwaters etc. Scale effects associated with such models can normally be kept sufficiently small, in which case such models will be very reliable.

Fixed bed models can be divided into two-dimensional models (wave flume models) and three-dimensional models (wave basin models).

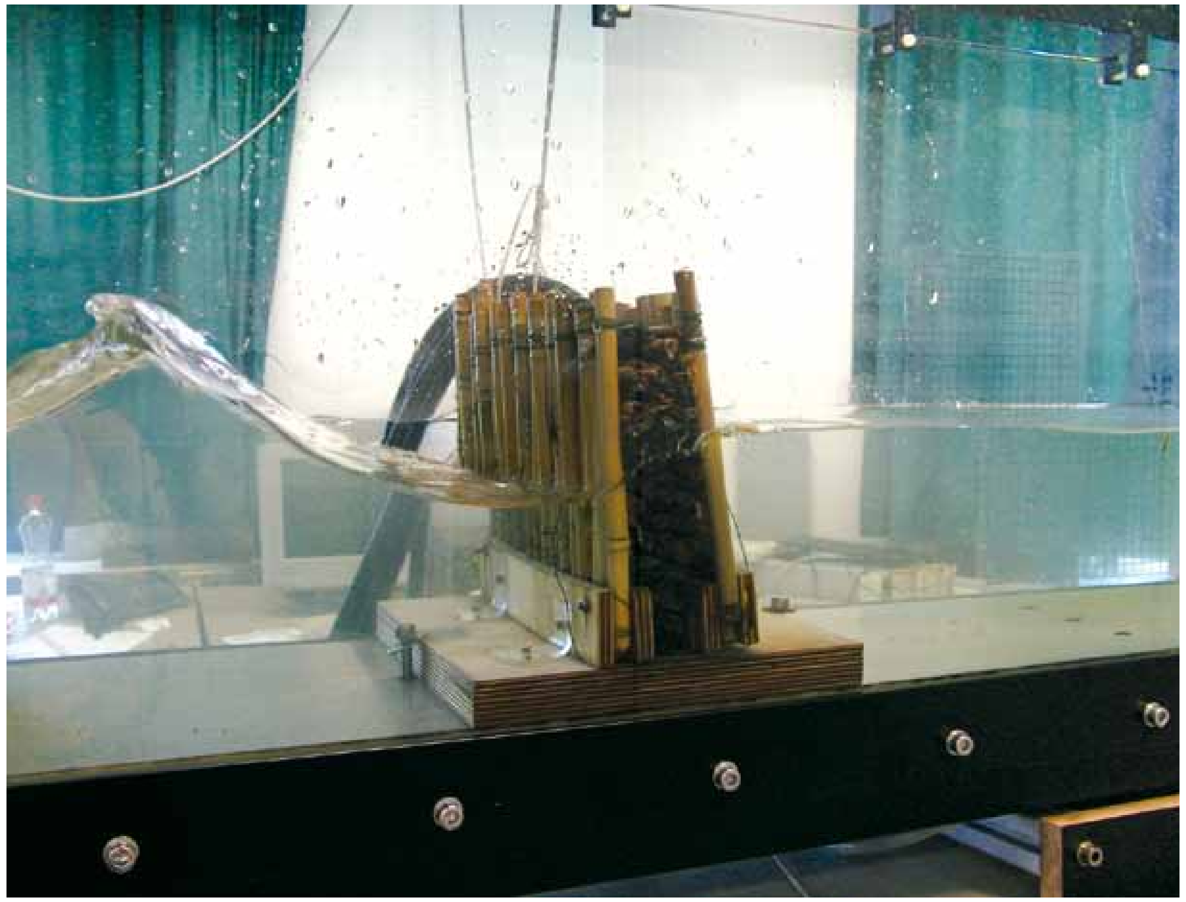
Figure 64 shows a photograph of wave flume tests that were carried out in the context of the coastal design study along the coast of Vinh Tan Commune in Soc Trang Province. The scale of the tests is 1/20 (Albers & Von Lieberman, 2011). The setup of the experiment is described in Chapter 7.1.2.3.

7.5.3 Movable bed models

A movable bed model is mainly used to study sediment processes. However, scaling of the prototype sand grain according to the Froude model law introduces major scale problems. If, for example, a prototype sand with $d_{50,p}$ = 0.2 mm should be scaled for use in a model with a scale of 1:40, this will result in model sediment with $d_{50,m}$ = 0.005 mm. This is in the silt fraction. When the model sediment becomes so fine, it will behave completely differently from sand. This means that sand cannot be scaled correctly if sand material is used as model sediment.

It is time consuming and complicated to perform movable bed modelling. As an example, surveying bed changes requires emptying the model basin and comprehensive surveying procedures. Performing movable bed tests requires a well-equipped laboratory, considerable understanding of scale effects and, not least, experience.

Figure 64: Physical modelling of wave transmission with a bamboo fence (Photo: Albers)



It can be concluded that it is normally not possible to simulate the correct quantitative sediment transport conditions in a model. The quantification of the sediment transport can be established by using a numerical sediment transport model based on the modelling results from the physical model.

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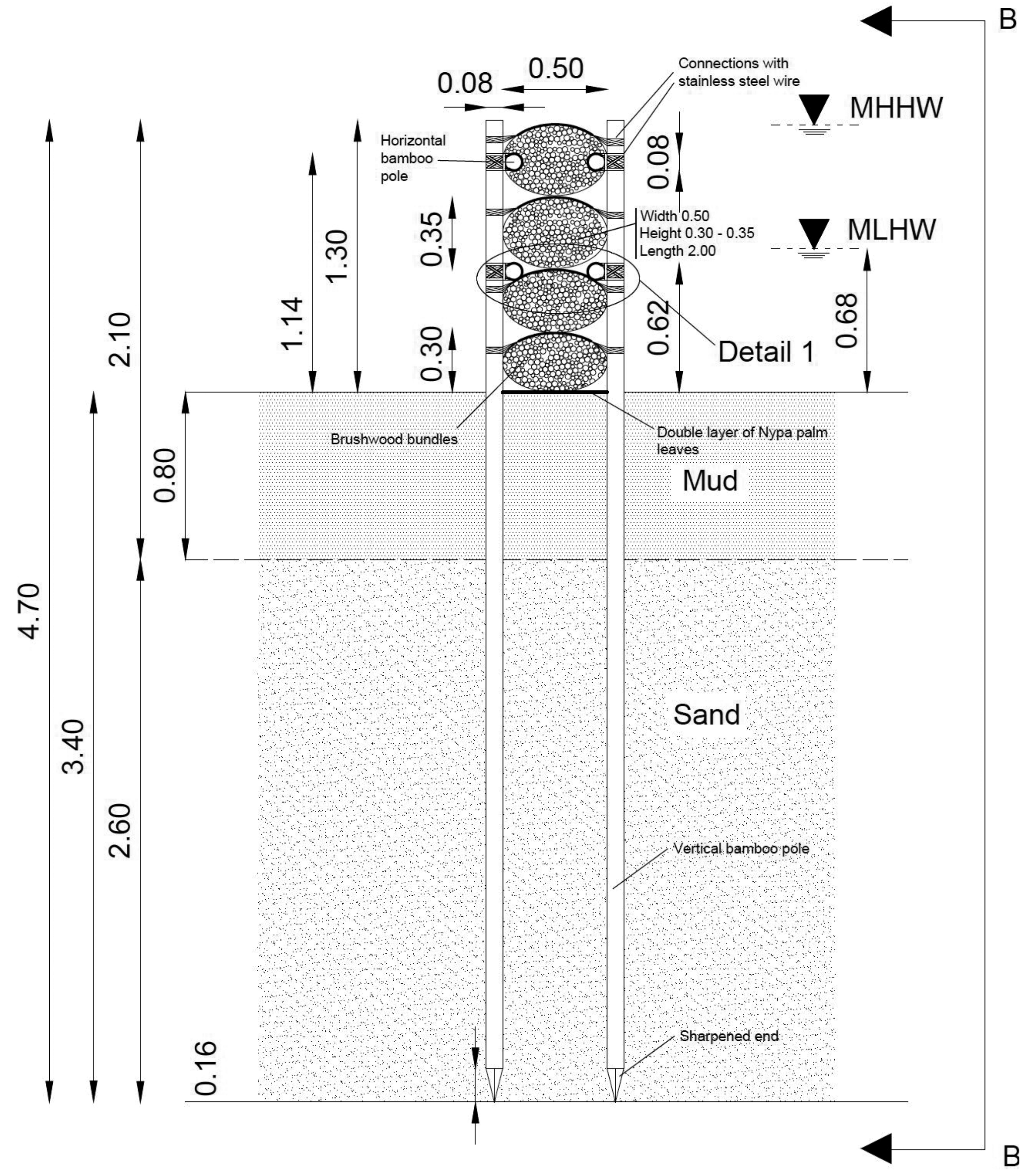
APPENDIX

The following bullet points summarise the technical specifications of the bamboo fences. The values and dimensions have been calculated, and are only valid, for the coast of Soc Trang Province. Embedment depths and the lengths of the bamboo poles are site specific and must be adapted to the site specific situation of the soil. The depth of the mud layer must be considered. Diameters of the bamboo poles must be adapted to site specific water levels, bathymetry, wave and current parameters.

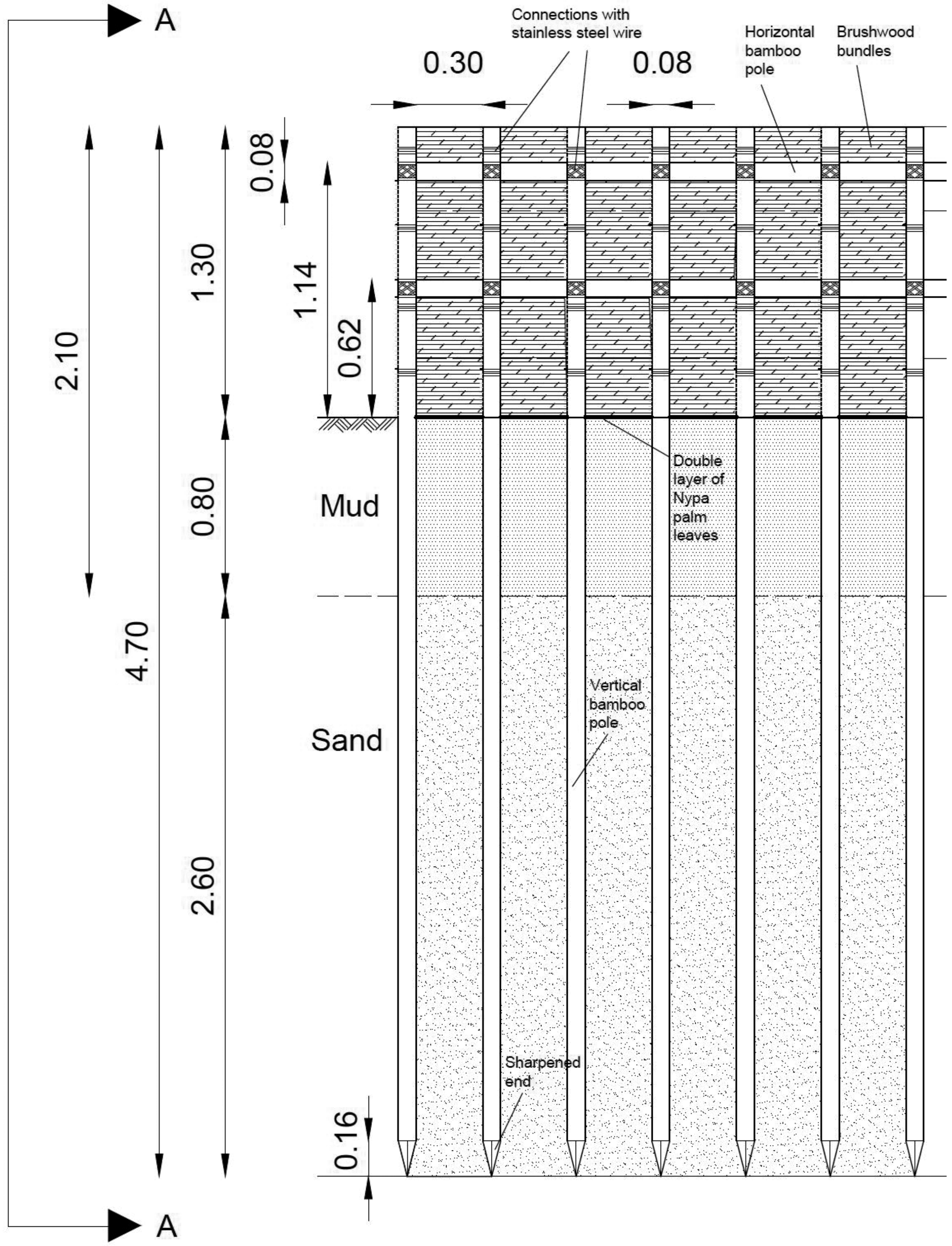
Summary of the technical specifications

- Two rows of vertical bamboo poles
- Distance between the two rows: 0.5 m
- Distance between the single bamboo poles in a row: 0.3 m
- Length of the vertical bamboo poles: 4.7 m
- Depth of embedment of the vertical poles: 3.4 m
- Diameter of the vertical poles:
  8 cm for longshore parts; 6 cm for cross-shore parts
- Two horizontal bars at each row; one attached near the bottom, one near the top according to the technical drawings
- Diameter of the horizontal poles:
  8 cm for longshore parts; 6 cm for cross-shore parts
- Length of the horizontal poles: 3 - 5 m
- All horizontal poles are attached to every vertical pole with stainless steel wire (diameter 3.0 mm ± 1 mm; ductile behaviour)
- Adjacent horizontal poles must overlap by a minimum of 30 cm
- 4 - 6 layers of bundles (depending on the degree of compaction) are placed between the two rows of vertical poles according to the technical drawings so that the top of the bundles is flush with the top of the vertical poles
- The crest of the bamboo breakwater must be 1.3 m above the bottom
- All layers of bundles are attached to the vertical and horizontal poles with stainless steel wire (diameter 3.0 mm ± 1 mm; ductile behaviour)
- The structure of the brushwood used for the bundles must be flexible and open; the branches must not be too thick (diameter < 15 mm)
- The brushwood that forms the bundles must be tied properly with stainless steel wire at a minimum of three locations per bundles (ends, centre)
- The bottom layer of bundles should consist of very fine branches
- A double layer of *Nypa* palm leaves must be installed as bottom layer of the fences
- At the ends of the fences, one vertical bamboo pole with the same specifications as the vertical bamboo poles described above must be installed in the centre between the two rows of vertical poles for additional stability of the bundles

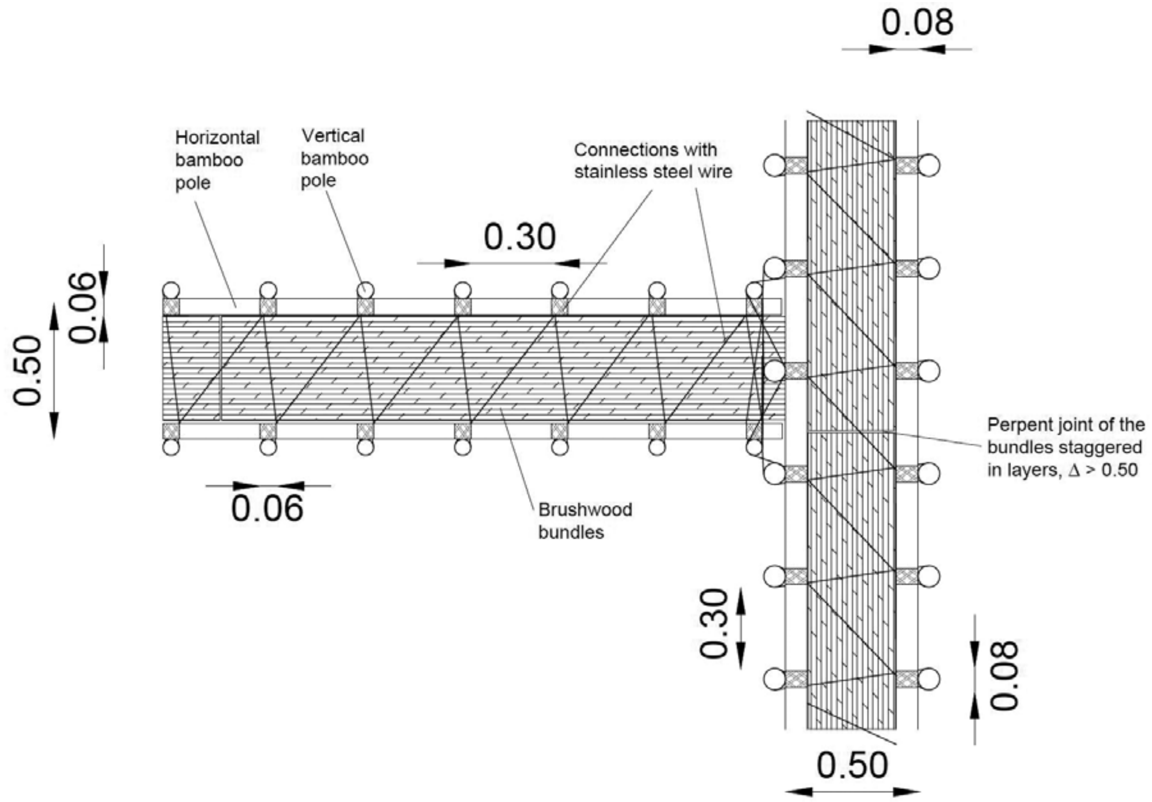


Bamboo fence, cross-section A-A

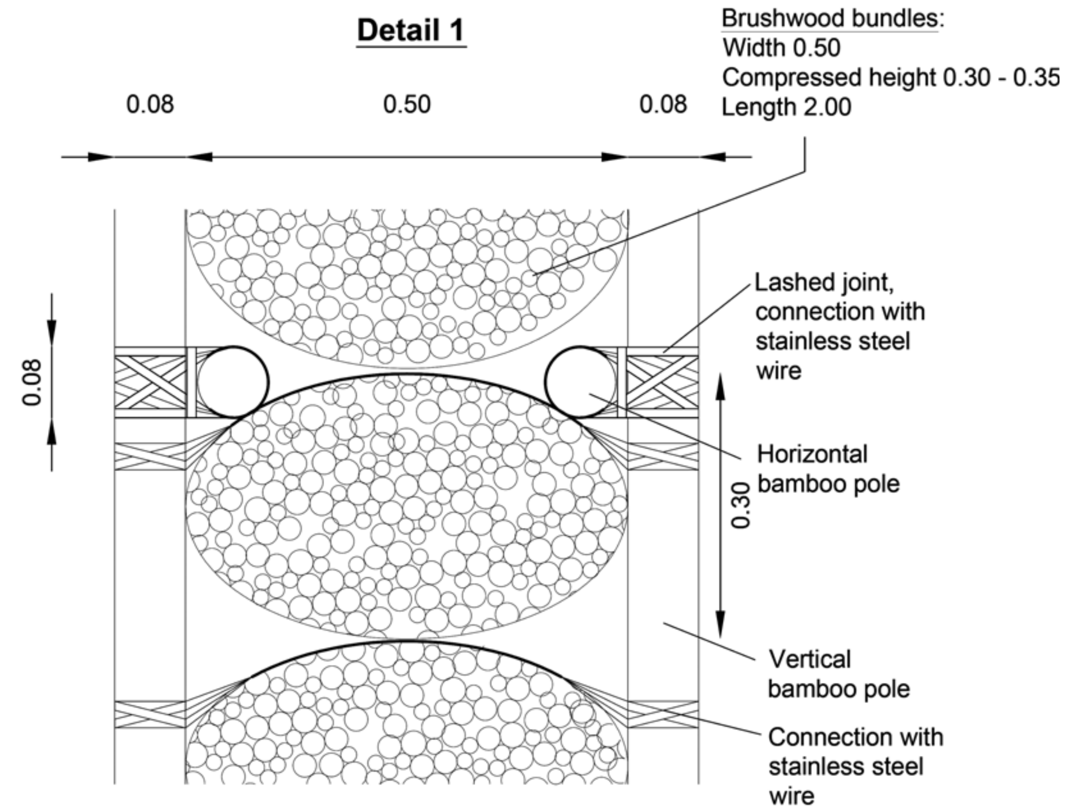
Bamboo fence, cross-section B-B



Top view connection bamboo fences, longshore/cross-shore part



Bamboo longshore fence, detail 1



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