GOVERNMENT OF INDIA
CENTRAL WATER COMMISSION
COASTAL MANAGEMENT DIRECTORATE

Guidelines for "Protection and Control of Coastal Erosion in India"

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Preface

The manual on “Protection and control of coastal erosion in India” was published by CSIR-NIO in 1980. Since then, many shore protection works have been carried out in India. The experiences gained through such works need to be documented. Hence, during the Third meeting of Coastal Protection and Development Advisory Committee (CPDAC) held at Goa in 1998, it was suggested to update the manual. Accordingly,CSIR-NIO was requested to update the manual during the sixth meeting of CPDAC held at Puducherry in April 2004. CSIR-NIO has submitted a proposal for updating the manual as a guideline for “Protection and control of coastal erosion in India” in June 2004. Central Water Commission, New Delhi has accepted the proposal, and the work was started in December 2004.

The objectives of the study were:

- To provide the preliminary design parameters for suitable coastal protection works for different stretches of the coastline.

- To review, update and prepare the guideline.

Main environmental parameters, which need to be considered in the planning and design of the coastal protection works are waves, currents, tides and storm surges along with the data on near-shore bathymetry, the properties of the seabed materials and coastal geomorphology. The environmental parameters differ for different stretches of the coastlines. Significant amount of data on the environmental parameters at select locations are collected by different agencies like CSIR-NIO (National Institute of Oceanography), CWPRS (Central Water and Power Research Station), NIOT (National Institute of Ocean Technology), ICMAM (Integrated Coastal and Marine Area Management) Project Directorate,etc. The available design parameters for coastal protection works for different stretches of the coastline are compiled and included.

Along the Indian coastline, a number of shore protection works have been carried out. The detailed information on the coastal protection works carried out is available with different state government agencies. The following information was sought from different state government.

- Locations and length of coastlines, where protection works were carried out.
- Types of protection measures taken up (seawalls/revetments/Groynes/offshore breakwaters/artificial beach nourishment etc.).
- Design details of the coastal protection structure.
- Maintenance record of coastal protection measure, if any.
- Present status of the structure and the coastline.
- Effect of the structure on the nearby coastline.
- Failures, probable causes and remedial measures taken.

Accordingly, different state Government agencies were contacted to obtain the above information. All the required details could not be obtained from different states.CPDAC sub-committee visited existing coastal protection works of different coastal states to review their performance. The conclusive remarks of such review have been presented in this guideline.We thank different state Government officials who have provided the relevant information.

The Central Water Commission constituted a steering committee with following members to review the work done.

Chief Engineer (P & D), CWC, New Delhi	- Chairman
Director, Coastal Erosion Directorate, CWC, New Delhi	- Member Secretary
Director, Beach Erosion Directorate, CWC, Kochi	- Member
Director, CWPRS, Pune or representative	- Member
Head, Ocean Engineering Division, NIO, Goa	- Member

The guidelines presented here are only for guidance and all the relevant legal and statutory requirements should be followed. Since the coastal environment is highly dynamic and variable and is not fully understood till today, sound engineering judgment and experience are required while carrying out the design of the coastal protection measures. All analysis and design methods are beyond the scope of this guideline. The designer should be aware of the assumptions made and the limitations of the various solutions. The designer should explore alternate method(s) available in the literature.Design details of all the coastal protection measures are available in the Coastal Engineering Manual (CEM), US Army Corps of Engineers and the latest available version can be referred for further details.

There is a continuous development in the field of coastal engineering and there is always a certain time gap between new development (products and designs criteria) and publishing them in manuals or professional books. Therefore, it is recommended to follow the professional literature on this subject for updating the present knowledge and/or exchanging new ideas.

There has been considerable change in the length of coastline and the areas of erosion and accretion as indicated in the recent studies of National Hydrographic OfficeDehradun,Space Applications Centre Ahmedabad, National Centre for Sustainable Coastal Management Chennai and Integrated Coastal and Marine Area Management Project Directorate Chennai. These institutions and their reports should be referred for further update on these details.

The erosion sites mentioned in the guideline are based on available information as obtained from various state governments. The literature review showed that published information on coastal erosion quantities is very minimal and restricted to regions, where major coastal research and academic institutions are located.

The first draft of this guideline was submitted in the “14th meeting of Coastal Protection and Development Advisory Committee (CPDAC) held in Goa during 27-28, February 2014. The support of CWC, CPDAC and numerous agencies who have provided information and support in bringing out this guideline is greatly acknowledged.

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Definitions of symbols used

ρ = mass density of sea water

α_b= breaker angle with respect to coastline

ρ_s = mass density of the sediment

B=width of breakwater

C=a constant

d_c= depth of closure

F' = non-dimensional freeboard

g = acceleration due to gravity (9.81 m/s^2)

G=gap between breakwaters

H_b = breaking wave height

He = near-shore extreme significant wave height

H_i=incident wave height

Ho' = the un-refracted deep water wave height

Hs = Significant wave height

K = dimensionless constant relating sand transport to long-shore energy flux

K_t=transmission coefficient

Ls=length of breakwater

m_0 = zeroth moment of the wave spectrum

m_2 = the second moment of the wave spectrum

p = porosity of sediment

Q = volume of long-shore transport rate

R_c=Crest freeboard

T = wave period

Tp = Peak period

Tz = Mean wave period

1. COASTAL EROSION AND COASTAL PROTECTION MEASURES

Coastal areas are given vital importance in recent years, due to increasing human population and accelerated developmental activities near coasts. The developmental activities have put tremendous pressure on the fragile coastal environment and about 20% of the Indian population resides in the coastal area. Many thickly populated and industrialized cities like Mumbai, Chennai, Kolkata, Kochi and Visakhapatnam are located along/near the coastal regions.

Beaches are located between the lowest low tide level and a landward limit, which is usually defined by a coastal cliff or a dune and permanent vegetation or by some human-made structure**(Figure 1.0.1).** The general composition of beach materials varies with locations. But the processes that create and maintain beaches throughout the world are similar. Many studies were carried out all over the world to evolve suitable solutions for arresting beach erosion and accretion at specific sites as well as to provide general solutions.

The coastal zone consists of wide range of coastal ecosystems like mangroves, coral reefs, sea-grasses, salt marshes, sand dunes, etc. **(Figure 1.0.2).** The features present along the coastline are rocky headlands, sandy beaches, estuaries, lagoons, etc. (**Figures 1.0.3to 1.0.5**).For further reading on coastal zone and coastal ecosystems, one can refer"Coastal Environments:An Introduction to the Physical, Ecological, and Cultural Systems of Coastlines (Carter, 1988)".

1.1 Coastal erosion

Coastlines are dynamic landforms and are constantly subjected to erosion and/or accretion. Coastlines are modified by winds, waves, tides, currents, geomorphology, sediment supply to the coast and anthropogenic activities. Beach erosion is a universal problem and it has been estimated that 70% of the beaches in the world is eroding (Bird, 1985). The erosion of the coastal reaches by the ocean waves, together with the near-shore currents is a problem, faced by all the coastal states of India. Generally, for undeveloped areas, beach erosion is a natural and cyclical process, whereas,in developed areas, it is progressive and hence a disaster for local residents. Due to erosion, there is considerable loss of land and damage to valuable properties and establishments and also coastal structures. **Figure 1.1.1** shows typicalsand dune erosion and cliff erosions. Any attempt to handle the coastal problems either to arrest erosion or prevent deposition requires a thorough understanding of the factors and processes involved in the coastal geomorphological system.

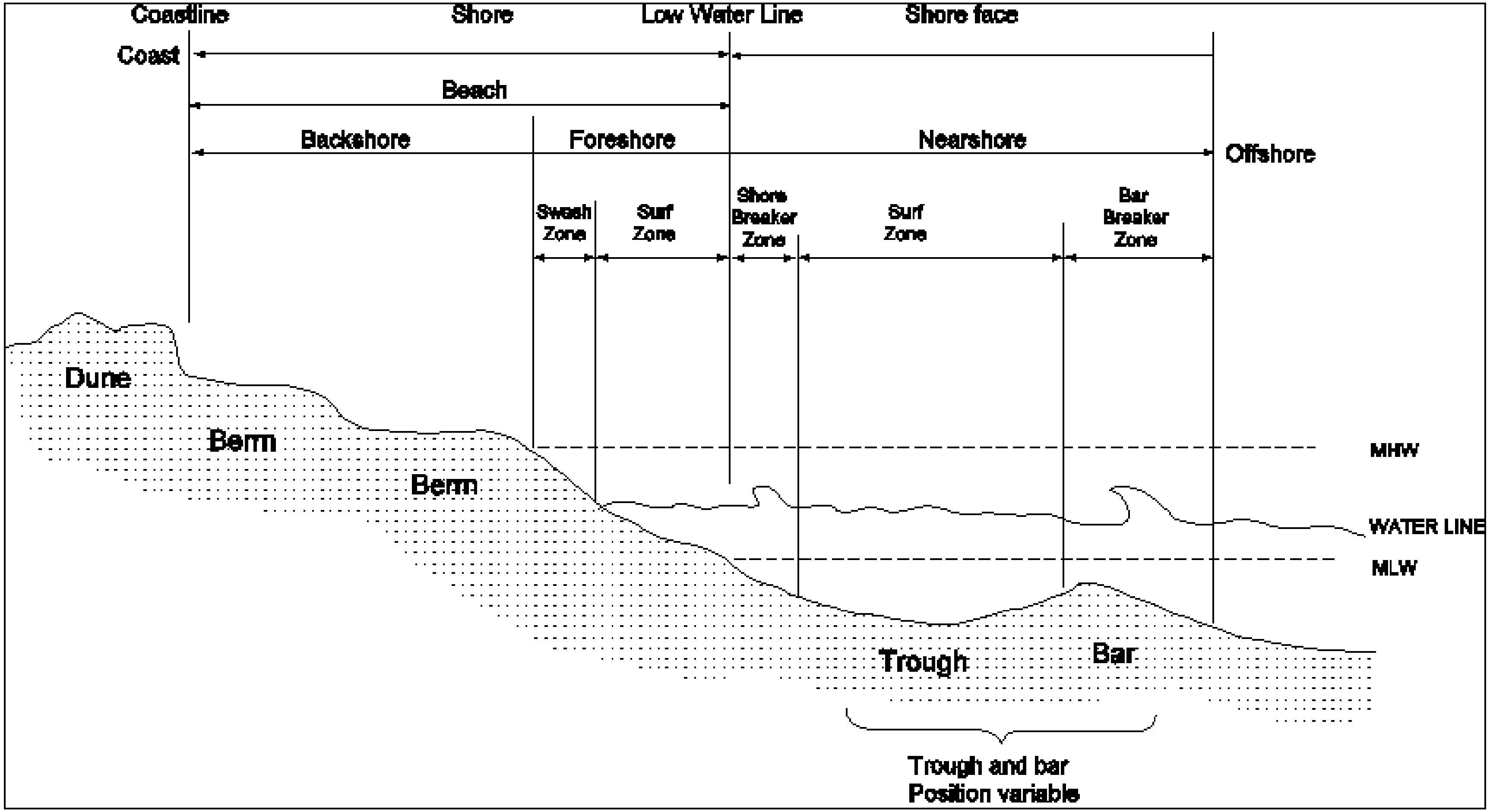


Figure 1.0.1. Definition of beach and related terminology

(a) Mangrove in the Poomarichan Island in Gulf of Mannar

(b) Coralsat Shenbaga muruvai reef patch near Manuli Island of Gulf of Mannar

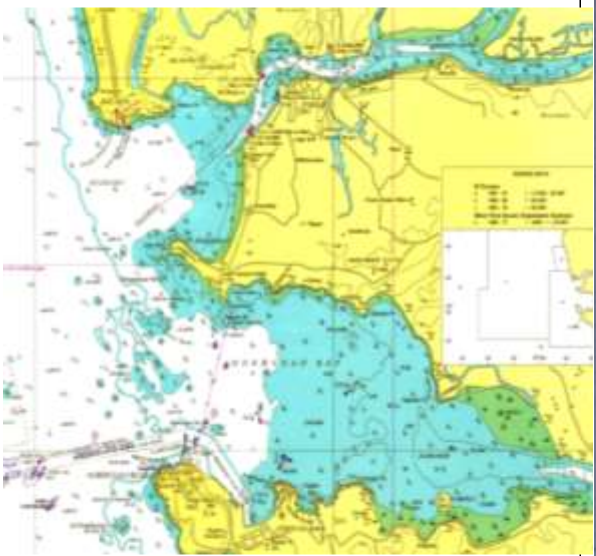
(c) Sea-grass bed is near Mulli Island in Gulf of Mannar

(d) Sand dunes near Meghavaram, Andhra Pradesh

Figure1.0.2. Different coastal eco systems (a) Mangroves, (b) Corals, (c) Seagrasses, (d) Sand dunes

(a) Rocky coast at Jaigarh

(b) Sandy beach at Kundapura



(c) Mandovi-Zuari estuary (NHO chart No.2022

(d) Kavaratti lagoon, Lakshadweep

Figure 1.0.3. Different features along the coastline (a) Rocky coast, (b) Sandy beach, (c) Estuary, (d) Lagoon

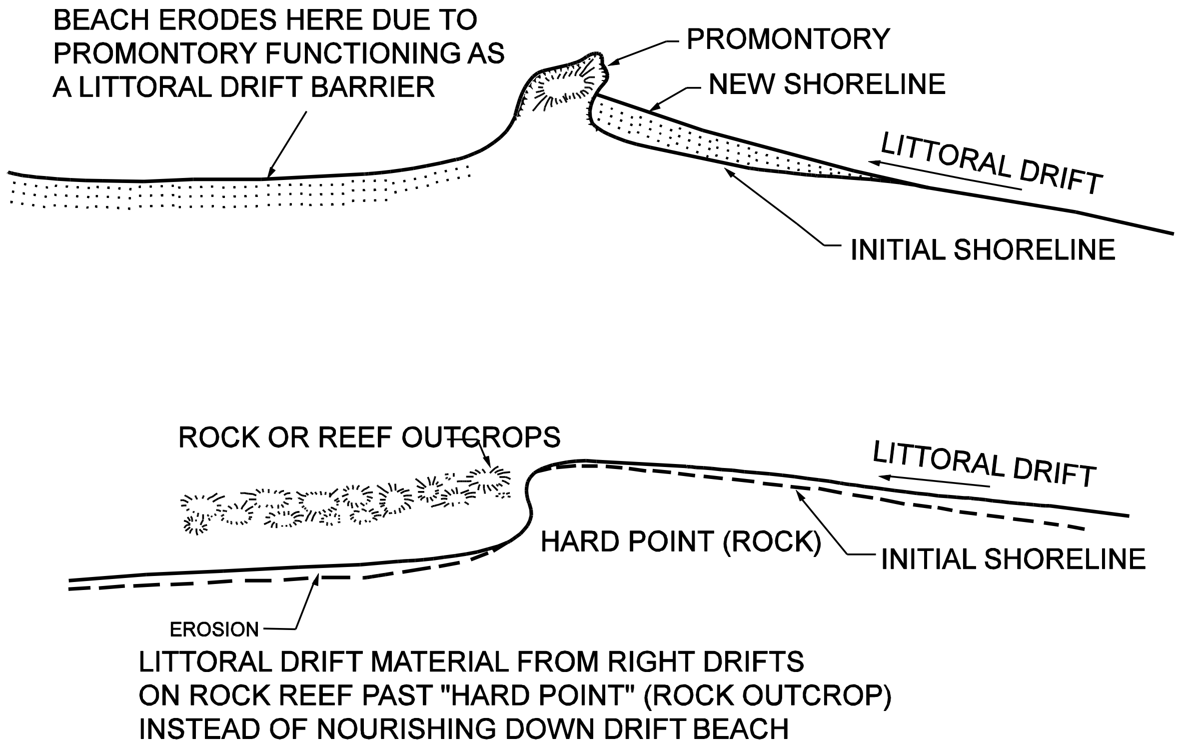
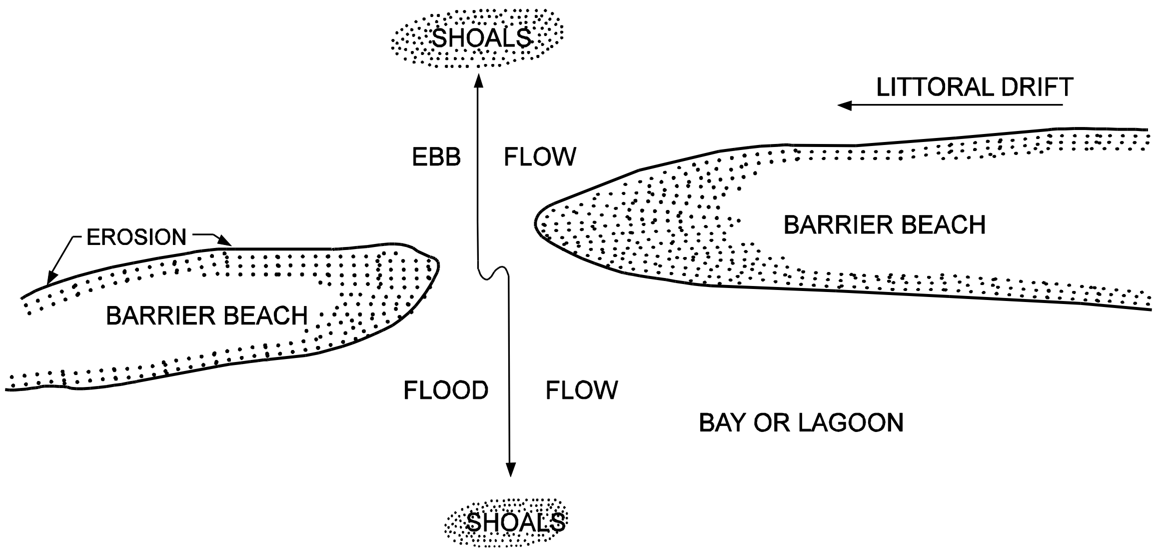
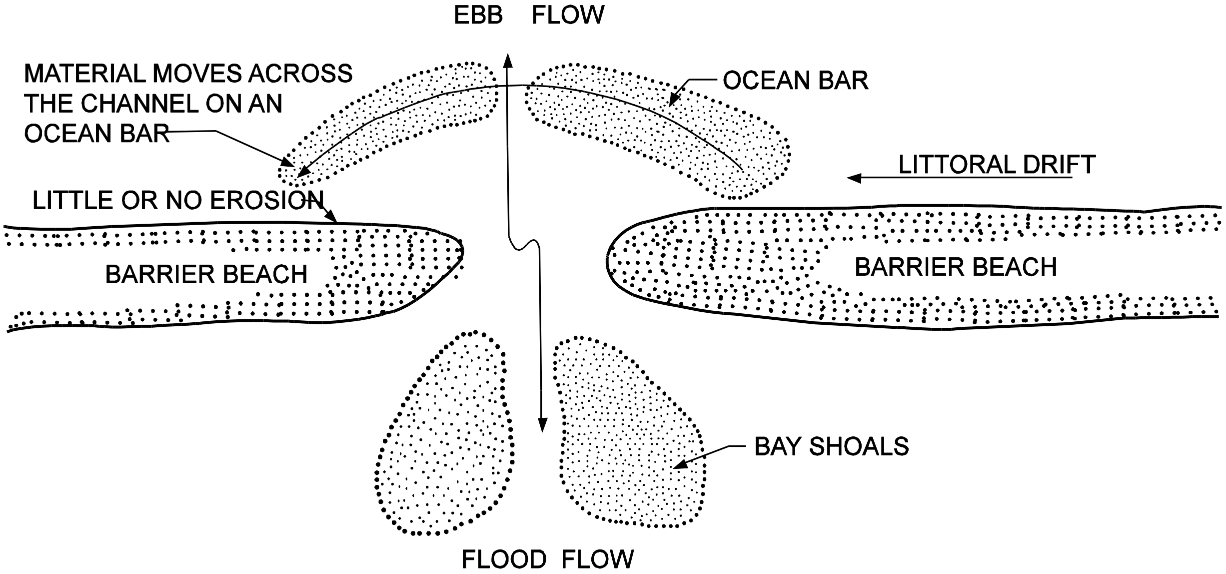


Figure 1.0.4. Different features along the coastline (a) Promontory and(b) rock or reef outcrops



INLET WITH LARGE TIDAL PRISMS CAUSE EROSION BECAUSE LITTORAL DRIFT MATERIAL IS JETTED FAR OUT IN THE OCEAN OR IN THE BAY WHERE IT IS DEPOSITED IN SHOALS



INLETS WITH SMALLER TIDAL PRISMS CAUSE LESS OR NO EROSION DOWN DRIFT AS MATERIAL DRIFT ACROSS THE CHANNEL ON AN OCEAN BAR

Figure 1.0.5. Barrier beach and inlets

(a) Sand dune erosion at Paradip, Orissa.

(b) Cliff erosion at Anjuna, Goa.

Figure 1.1.1(a) Sand dune erosion and (b) cliff erosion

1.1.1 Causes of coastal erosion

The causes of coastal erosion are either natural or human-made or combination of both.

a) Natural causes

i) <u>Environmental change</u>:

The main force acting on a coast is due to waves and the wave activity depends on the wind. The nature of weather pattern is cyclic and so is the erosion and accretion pattern of the coast. This cycle can be as short-term as a single cyclone or seasonal monsoons. Local wind, rainfall and river flow also influence the availability and movement of sand on the beach face. Any changes to wave direction or energy could bring about a long-term erosion/deposition trend.

Cyclones and severe monsoons cause erosion due to increased wave activity. During cyclones, the high and steep waves break on the shores producing highly turbulent waters and large wave run-up which often attack the dunes or coastal platform directly, cause erosion and create vertical scarps. **Figure 1.1.2** shows the beach profile during monsoon and non-monsoon period.

The Tsunami caused either by earthquakes with epicenters located below the ocean floor or mudslides on the ocean floor or volcanic eruption can also causeaccelerated coastal erosion.Tsunami waves can bring sediment from offshore and deposit on the coast. But the backwash of tsunami waves can erode significant amounts of sediments from beach face and deposit offshore. Field information in this aspect is limited.

ii) <u>Sea Level Change</u>:

Sea level rise and their possible link to global warming are being studied around the world. If the current trend of sea level rise continues then the problems associated with coastal erosion will also increase. As the sea level rises, low-lying areas will be inundated and the land surfaces will be exposed to the wave action resulting in erosion. The sea level rise along the Indian coast varies from 1 to 2 mm per year, (Unnikrishnan and Shankar, 2007). The observed global mean sea level rise rate between 1993 and 2012 is estimated as 3.2 mm per year (Unnikrishnan et al., 2014).

iii) <u>Loss of sediment supply</u>:

Sand is continuously moved along the beach by the wind and in the swash and surf zone by waves and currents. If there is a loss of sediment supply to the down-drift side, erosion occurs.

iv) <u>Headland erosion</u>:

The erosion of headlands at either end of a beach embayment may also expose a beach to long-term changes that may include a corresponding coastline landward migration and beach erosion.

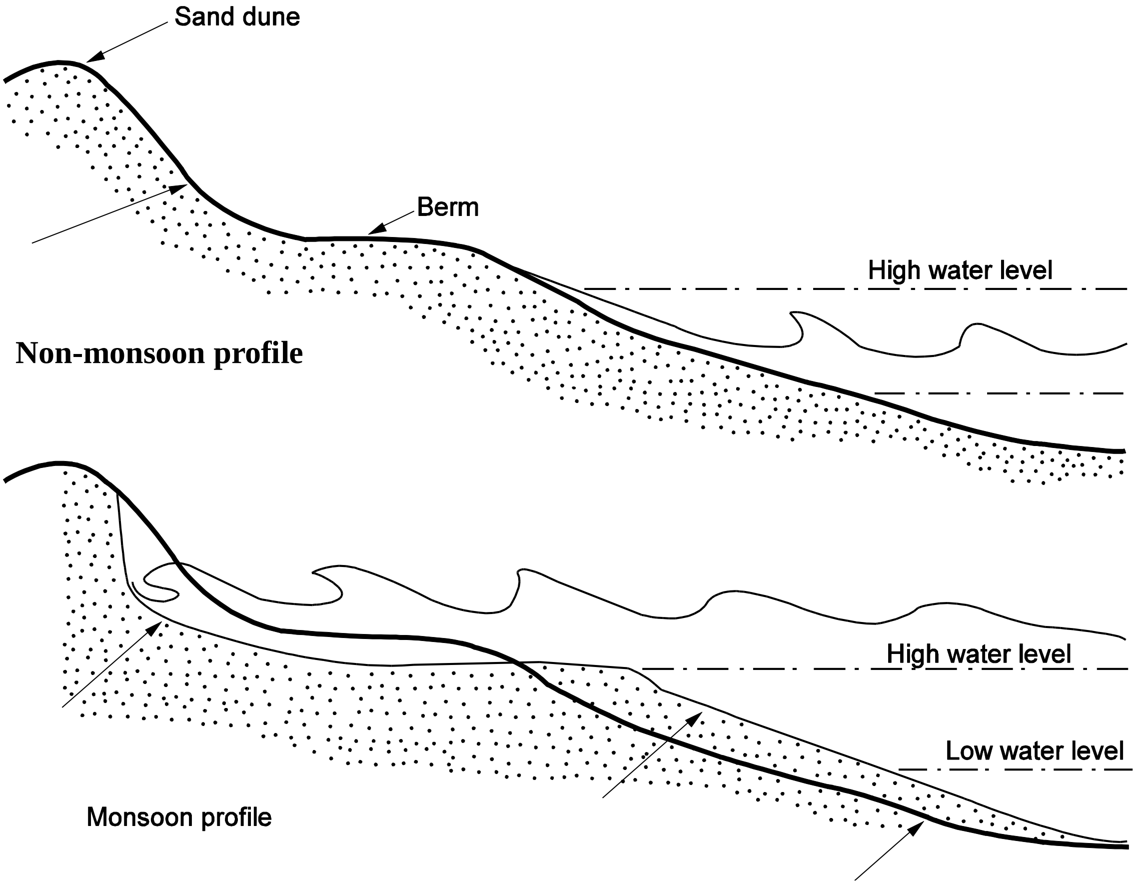


Figure 1.1.2. **Typical beach profile during monsoon and non-monsoon period**

b) Man-made causes

Human interference in the coastal zone and rivers alter the natural balances in sediment supply. Coastal developments restrict the natural supply of beach material and prevent dune or cliff erosion. Erosion control structures such as seawalls and revetments usually have anadverse impact on the adjacent beach, as they will prevent any new material from entering the littoral zone from the shore. Dams on rivers reduce the sediment supply to sea and alter the sediment budget.

i) <u>Construction of new structure:</u>

Interception of natural sediment transport by coastal structures such as breakwaters, Groynes, jetties and seawalls changes the morphology of the nearby area. **Figure 1.1.3** shows the erosion due to the construction of a jetty at the inlet. Few examples are given below.

Chennai Port breakwater: The main cause of erosion of the north Chennai coastline was the construction of Chennai port in 1876. It is estimated that during 1900 to 2001, beach area of about 4 km^2 (400 ha) eroded due to the construction of the Port. To protect the coast, a 5 km long seawall was constructed along the seafront resulting in the migration of erosion site further north. Subsequently, the entire stretch of 13 km long coast north of ChennaiPort lost its natural beach (Ramanamurthy et al., 2004a).

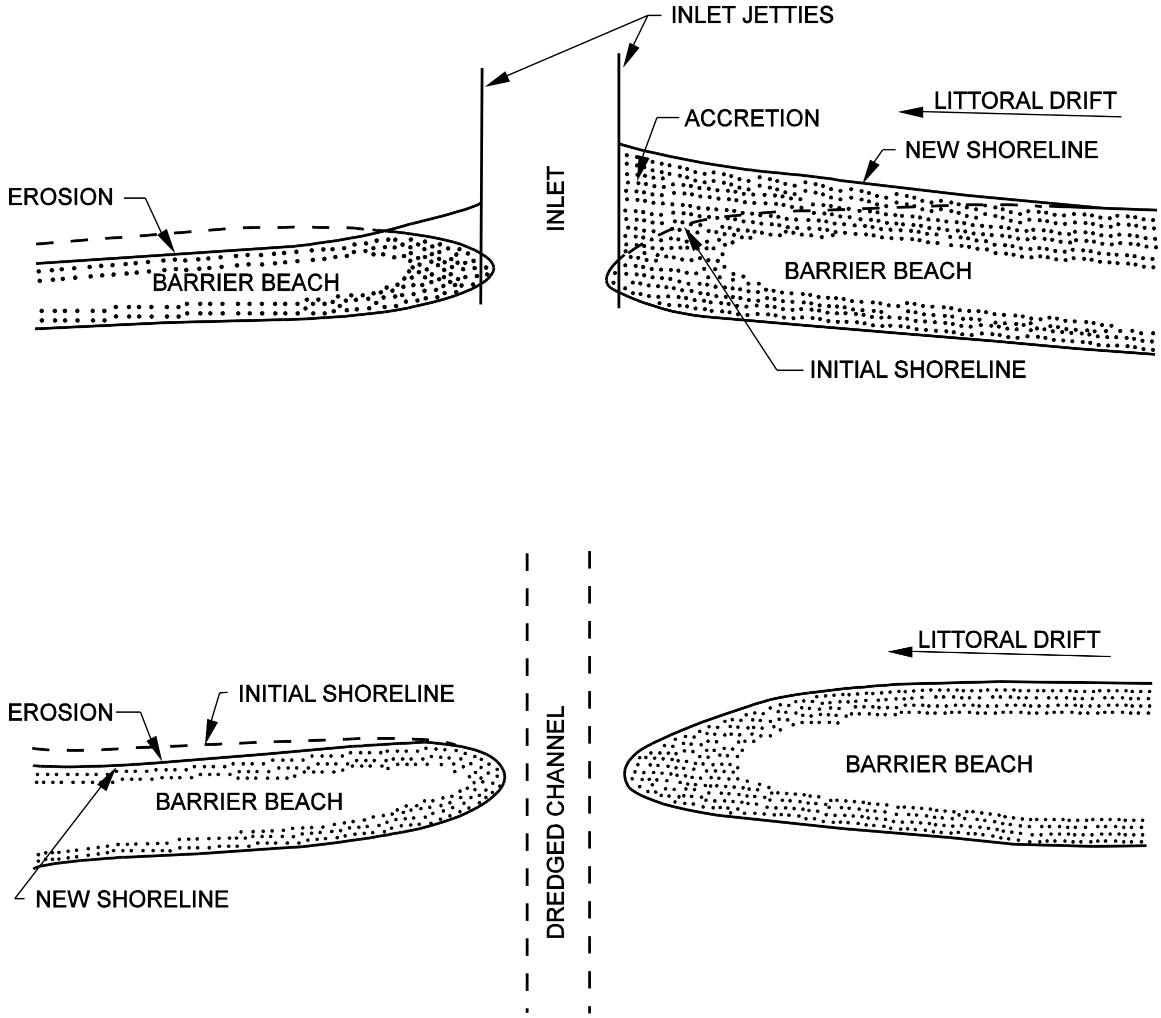


Figure 1.1.3. Shoreline change due to construction of jetties

Ennore Port breakwater: After the construction of Ennore port breakwaters, shoreline north of the Ennore port is experiencing erosion (Sundar, 2004). Anticipating erosion in the northern coastline, port authorities have carried out beach nourishment by placing 3.5 million m^3 of sand, dredged from the harbour basin and approach channel. Beach fill has a dimension of 600m length by 300m width, with a transition length of 400m to maintain integrity with coastline(Ramanamurthy et al., 2004a). The beach south of port is accreting at a rate of 50m per year, extended 300m offshore, and 2.6 km alongshore **(Figure 1.1.4)**

Paradip Port breakwater: The breakwater was installed at Paradip port during 1963-64 and erosion observed along the north of the harbour entrance channel and advancement of shoreline at south of southern breakwater. To prevent erosion, seawalls were constructed on the north side along with the proposal to bypass sand from the sand trap at the end of the south breakwater (Malleswara Rao and Harikrishnan, 1989).

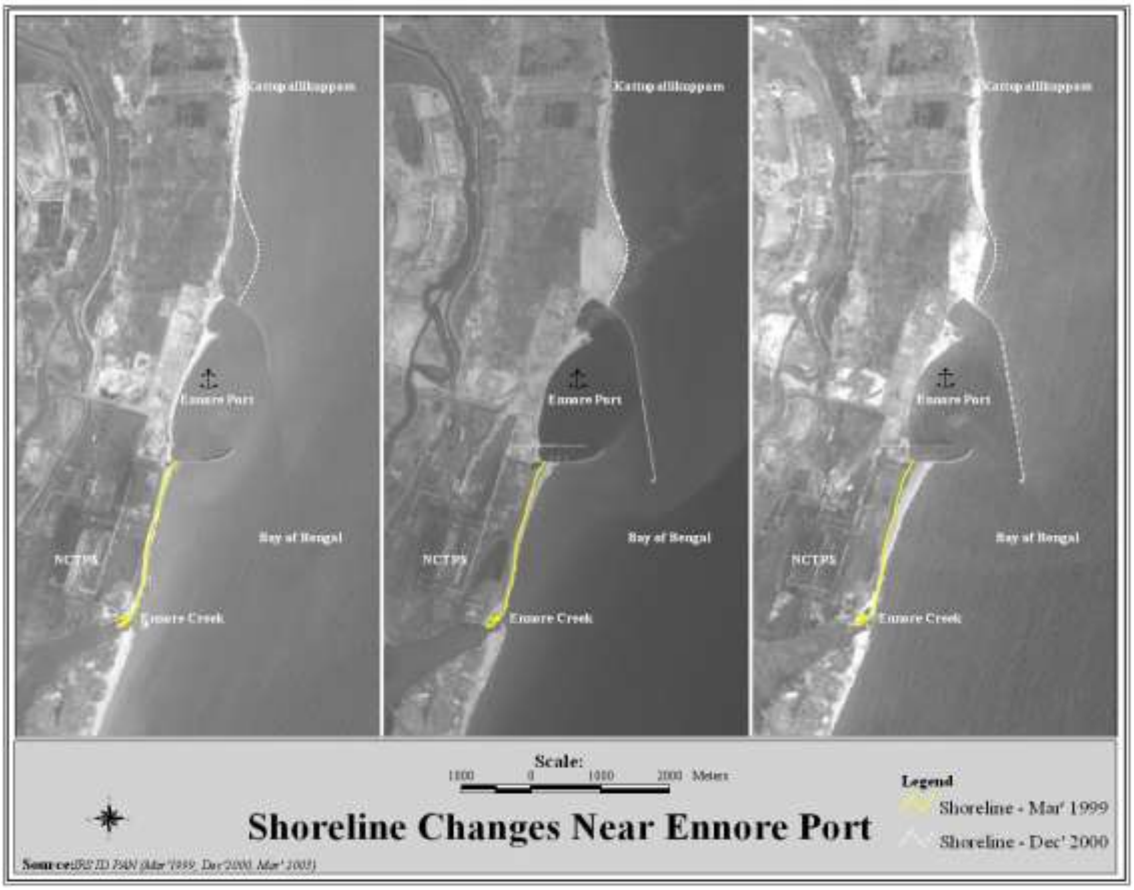


Figure 1.1.4. Shoreline changes near Ennore Port (Ramanamurthy et al., 2004a)

<u>ii) Sand mining and dune removal:</u>

Sand removal for construction purpose through trucks is a practice at some locations. Even though the quantity of sand removed is in small scale, it will have an impact on the coastline. Mining of sands from coastal areas for minerals also will have an impact on the coastline.The sand dunes and coastal cliffs are the natural barriers against tsunami and storm surge. Removal of dune will allow the waves to reach inshore and initiate shoreline erosion.

<u>iii) Removal of coastal vegetation:</u>

The removal of coastal vegetation (salt marsh, grass, mangrove) will trigger or allow mud shore instability. The root system provides fiber reinforcement to the soil. Above the bed, the body of the vegetation protects the mud from shear due to currents and waves and creates a calm layer close to the bed to encourage deposition and settlement.

1.1.2. Impacts of shore protection measures

Careful assessment of shore protection measures for its performance and likely cross impacts on the adjacent coast is essential before implementation of the project. Down-drift shoreline response to coastal structures is a major concern in the design of erosion control projects. In most of the cases, construction of shore protection structures alters the long-shore currents and coastal geomorphology. In some cases, it causes loss and fragmentation of coastal habitats by preventing the access to the beach and estuaries, which the marine organisms need for breeding. Hence impact assessment studies need to be done before and after implementing any shore protection measures.

1.1.3. Shoreline management

Coastlines are national heritage and to sustain it for the future generation, proper management of coastal erosion is required. The pre-plan activities should start with the gathering of information, identifying gaps in knowledge and consultation with a wide range of interested parties and these are considered as fundamental elements to plan preparation. Next step is to determine the appropriate position of the shoreline, define which part to be defended against erosion. Then the strategies or policy options for consideration needs to be adopted through regulatory measures (Ramanamurty et al., 2004b). The various steps to be considered while preparing the shoreline management plan are given in a flowchart in **Figure 1.1.5.**

Coastal zone is a dynamic environment, which may respond to interventions in an unexpected way. So while planning any interventions at a particular location, the adjacent coastal area also needs to be considered. The environmental parameters, which influence the coastal processes along with the history of shoreline needs to be studied well before planning any interventions. Shore protection is to be part of coastal zone management in which the uses and functions of the shore, as well as benefits and cost of maintaining, are evaluated.

The various options available for shoreline management are given below.

a) <u>Do nothing</u>: The no action or do nothing approaches is commonly used by engineers to evaluate different courses of action.However, this option is not recommended where lives and property are at stake.

b) <u>Retreat</u>: The best option against coastal erosion is to retreat as envisaged in the Coastal Zone Regulating Act of 1991 wherein, the Government of India has declared the coastal stretch upto 500 m on the landward side from the High Tide Line as the Coastal Regulation Zone and has put severe restriction on the activities in this zone.

c) <u>Relocate</u>: In some cases, it may be less expensive to relocate the endangered structures than to invest in large-scale shore protection.

d) Protect: Since most of the coastal areas are thickly populated with houses, important establishments and roads, in most of the cases it becomes necessary to protect the eroding area.This option must be considered when the adjoining coastal erosion has higher societal and/or financial impact. However, sufficient precautionary measures on the repercussions of shore protection on adjoining shoreline must be considered.

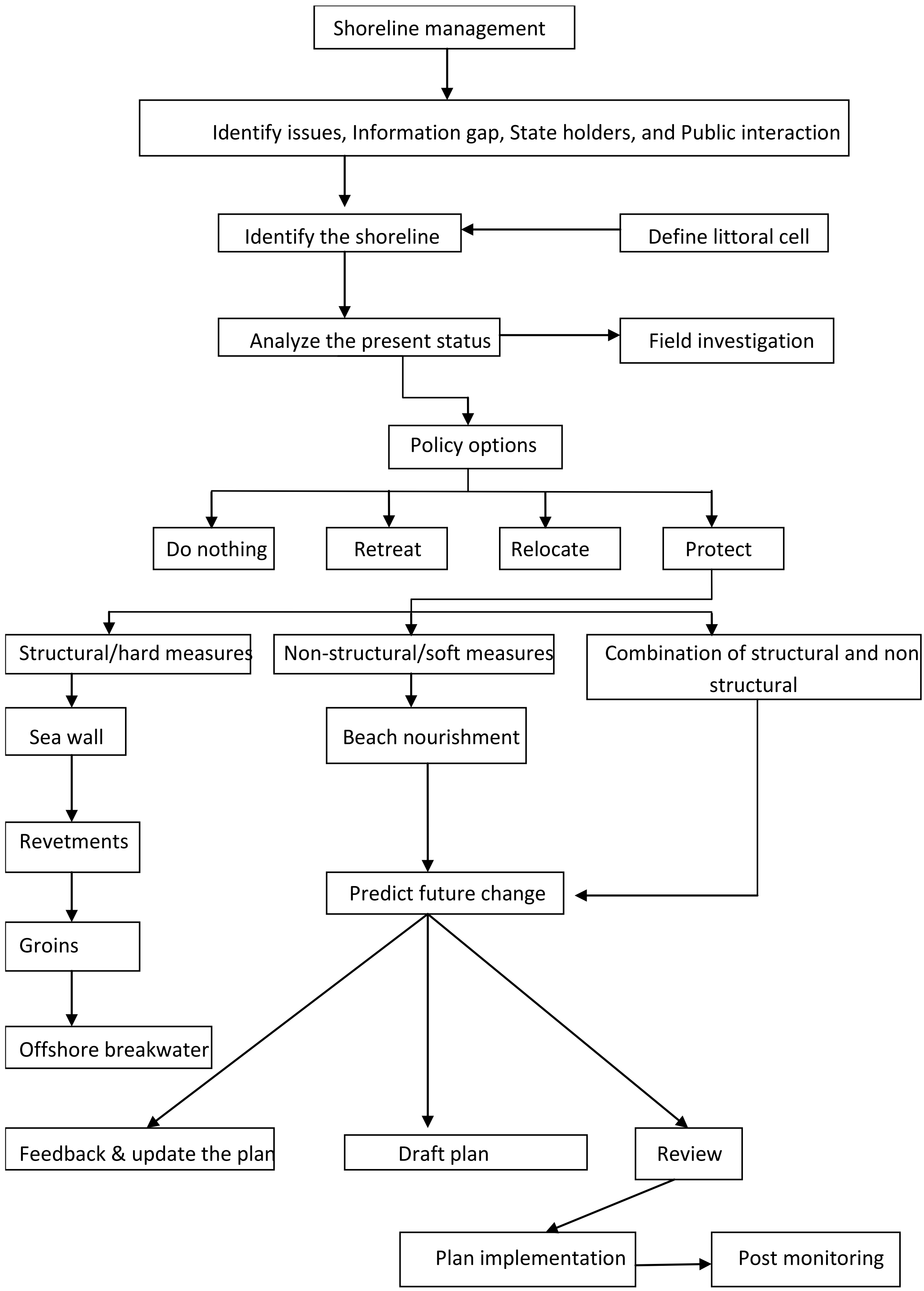


Figure 1.1.5. Various steps to be considered while preparing the shoreline management plan

1.2 Commonly used coastal erosion protection measures

Mainly there are three types of approaches towards coastal protection i.e. hard measures, soft measures and a combination of hard and soft measures.

a) Structural or hard measures*:* Structures are designed to resist the energy of the waves and currents and protect the coast. Structures include; breakwaters and seawalls designed to resist wave energy, Groynes designed to increase sediment storage on the shore, and flood embankments and barrages designed as water tight barriers.

b) Non-structural or soft measures*:* Measures are provided to work with nature by manipulating natural systems, which can adjust to the energy of the waves, tides and current. This approach has economic benefits while minimizing the environmental impact of traditional engineering structures. The methods, which can be used, include artificial nourishment and plantations of coastal vegetation, sand dune vegetation and mangroves.

c) Combination of structural and non-structural measures: Combination of beach nourishment (non-structural) with Groyne construction (structural) permits sand to immediately begin to bypass the Groyne field system. Such systems will help to overcome the negative perceptions of Groynes and Groyne fields and promote the appropriate use of these structures for shore stabilization.

1.2.1. Seawalls and revetments

a) Seawalls

Seawalls are the structures primarily designed to resist wave action along high value coastal property. They are either gravity or pile supported structures made of either concrete or stone. Seawalls have a variety of face shapes.

Curved face: designed to accommodate the impact and run-up of large waves while directing the flow away from the area being protected. Large wave force is resisted and redirected. This requires a massive structure with adequate foundation and toe protection.

Stepped face: designed to limit wave run-up and overlapping. They are generally less massive than curved-face seawalls, but the general design requirements for structural stability are the same as that of curved face.

Combination: incorporates the advantages of both curved and stepped face seawalls.

Rubble: it is a rubble breakwater placed along the beach. The rough surface tends to absorb and dissipate wave energy with a minimum of wave reflection and scour.

Different types of seawalls are shown in **Figure 1.2.1.** In India, the most widely used shore protection structure is the Rubble Mound Sloping Seawalls (RMS). Most of the seawalls in Kerala and Tamil Nadu are the gentle slope type RMS. As the RMS seawalls are flexible structures, they need regular maintenance.

The shape of the seawall is generally protected by rock armor. If the wave conditions are high and the rock size is not economically available in the nearby area, concrete armor units are used in place of rock armor. Rubble mound seawalls are designed like a rubble mound breakwater**. Figure 1.2.2**shows the seawalls at some locations along the Indian coastline.

b) <u>Revetments</u>

Revetments are sloping hard structure designed to dissipate wave energy. They are built to protect embankment or other shoreline feature against erosion. Major components are armor layer, filter and toe. Armor layer provides the basic protection against wave action. Filter layer supports the armor, allows water to pass through the structure and prevents the underlying soil from washed through the armor. Toe protection prevents displacement of the seaward edge of the revetment.**Figure 1.2.3** shows the revetments at some locations along the Indian coastline.

c) <u>Bulkheads</u>

Bulkheads are the retaining walls, which hold or prevent back fill from sliding and provide protection against light-to moderate wave action. They are used to protect eroding bluffs by retaining soil at the toe and increasing stability, or by protecting the toe from erosion and undermining. Bulkheads are used for reclamation projects, where a fill is needed seaward of the existing shore. Used in marinas and other structures where deep water is needed directly at the shore.

1.2.2. Detached seawall/bunds

The seawalls constructed in the inter tidal zone is called the detached seawall. A detached seawall consisting of seven segments with each segment of 67 m long is constructed at Udwada, Gujarat.

1.2.3. Groynes

Groynes are structures placed perpendicular to the coastline to capture and hold sand that may be available in the littoral zone. Groynes are easy to implement and less costly than offshore structures. Groynes are built at few locations along the Kerala coast and North Chennai coast. **Figure 1.2.4** shows the Groyne field and the shoreline change. **Figure 1.2.5** shows the Groynes installed at some locations along the Indian coastline. If the understanding of the function of the Groyne and the location where it should be used is not clear, then the Groynes will become a disaster to the coastline.

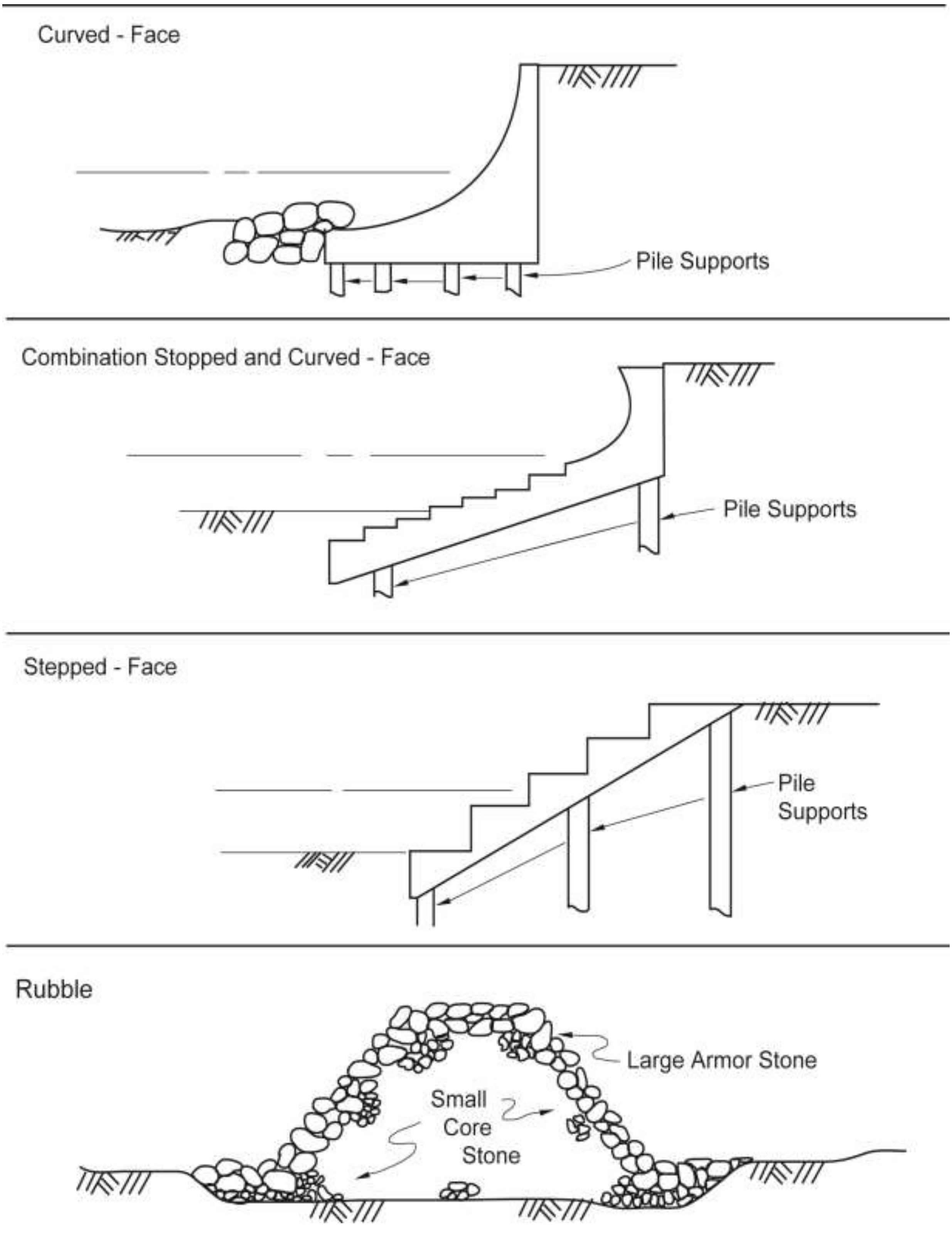


Figure 1.2.1. Different types of seawalls

(a) Seawall at Vatanapally, Kerala

(b) Seawall at Maravanthe, Karnataka

(c) Seawall north of Paradip port, Odisha

(d) Seawall at Marine drive, Mumbai

Figure 1.2.2 Seawalls at some locations along the Indian coastline (a) at Vatanapally, Kerala, (b) at Maravanthe, Karnataka, (c) north of Paradip port, Odisha and (d) at Marine drive, Mumbai

Figure 1.2.3. Revetment along Dona Paula, Goa Coast

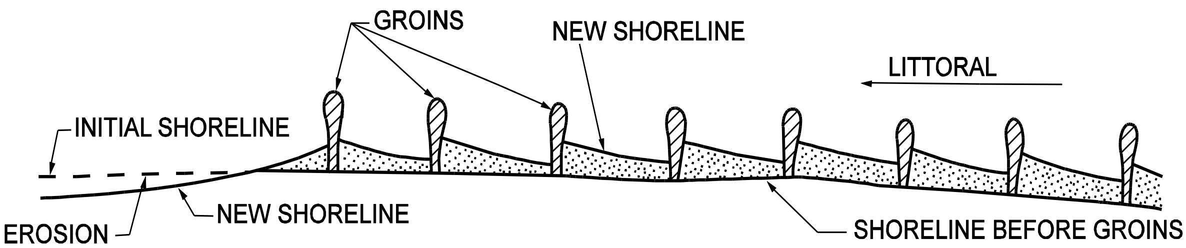


Figure 1.2.4. Groyne field and shoreline change

(a) Groyne field north of Chennai Fishing harbour

(b) Groyne at north of Chennai fishing harbour during construction period

Figure 1.2.5. Groyne field at north of Chennai fishing harbour

Groynes are classified according to geometry of the Groyne and length of Groyne. Generally,Groynes are straight and perpendicular to the shoreline.However, they can also be curved, hooked or may have a T-shape towards the front end of the Groyne. Based on length, Groynes are classified as long and short Groynes. Groynes that traverse the entire surf zone are considered long, whereas that extend only part across the surf zone are considered short.

1.2.4 Offshore breakwater

Offshore breakwaters are constructed parallel to the shore to reduce incoming wave energy and long-shore transport of sand along the beach. Offshore breakwaters are mostly used in shore protection in an eroding coastline, where the loss of sediment occurs and a new recreational beach is required.

Major types of offshore breakwaters used for coastal protection measures are single detached breakwater, multiple detached breakwaters, artificial headlands and submerged sill structure.

A salient will develop when sand is trapped behind the breakwater. This bulge in the shoreline can develop till it reaches the breakwater and this plan form is called tombolo(**Figure 1.2.6**). When a salient is formed, long-shore transport can still go on (although on lower level) but a tombolo will act as a total barrier (like a Groyne) for long-shore transport. Total barrier will cause down-drift erosion. Therefore, a salient seems a better shoreline response than a tombolo.

There are two reasons to use offshore breakwaters for beaches.

- Reducing the volume of sand needed for the beach fill: this can be achieved by trapping sediment. When the offshore is close enough to the shore and enough sand is available (by long-shore transport), tombolos will form behind the offshore breakwaters providing a wide recreational beach/bay. At these places (where a tombolo will develop), the volume of sand needed for the beach is less.

- Preventing transport of the beach sand (to elsewhere): without protection, the beach fill may be transported along the coast (of offshore) and the new beach will disappear. To avoid this transport of sand, offshore breakwaters can be used.

It is important to predict the beach response well. If the offshore breakwater is too short, then the beach can erode, but if the breakwater is too long, a tombolo can develop resulting in negative effects.Offshore breakwaters are not usedoften in India for shore protection.

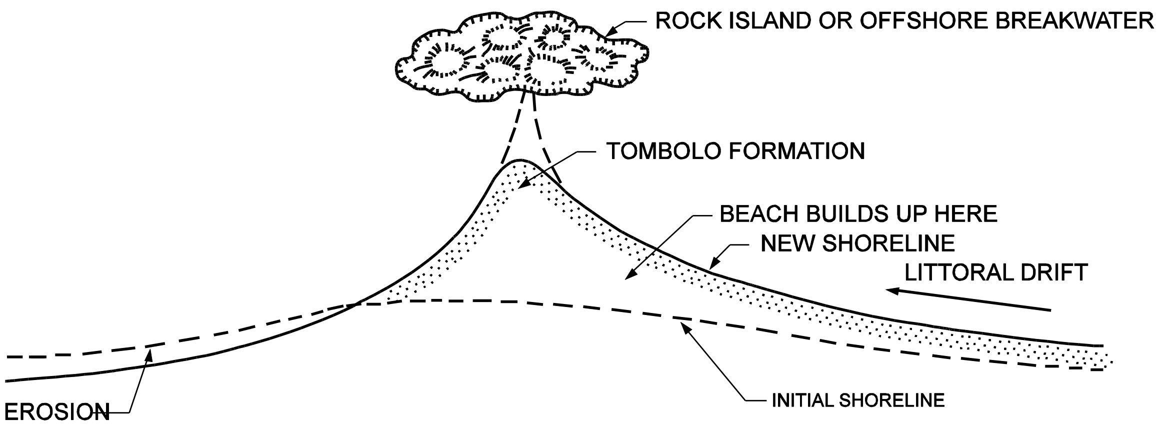


Figure 1.2.6 Development of tombolo behind offshore breakwater

1.2.5. Beach nourishment

Beach nourishment is the process of mechanically or hydraulically placing sand directly on an eroding shore to restore or form, and subsequently maintain, an adequate protective or desired recreational beach (USACE, 1984). It is the introduction of material along a shoreline. Nourishment of beach is the good method as it keeps the natural balance intact. Here the beach profiles are maintained by nourishing the eroded beach with a suitable material such as sand. This is a continuous process involving recurring expenditure. Beach nourishment is also known by the terms beach replenishment and beach fill.

Some of the advantages associated with beach nourishment include: 1) a wider recreational beach; 2) protection to shoreline structures; 3) possible beneficial use for dredged material from nearby sources; and 4) the ability to switch to other beach management methods in the future. Beach nourishment can also protect threatened or endangered plants in the dune area, and restore habitat for sea turtles, shore birds, and other transient or permanent beach organisms. Beach nourishment was done at the north of Ennore port.

Sand bypassing is the mechanical movement of sand, from an area of accretion to a down-drift area of erosion, across a barrier to natural sand transport (e.g.: port breakwater). At Visakhapatnam sand bypassing is done from south of the south breakwater to the north of the north breakwater.

1.2.6. Vegetation

Developing vegetation on the beaches especially raising casuarina plantations has helped in combating erosion at few places. Vegetation is an effective and inexpensive way to stabilize dunes and protect marshes. In undisturbed environments, vegetation is often one of the most important elements in the natural protection of the land. Roots and stems tend to trap fine sand and soil particles, forming an erosion resistant layer once the plants are well established. In marshes, vegetation also absorbs some part of the wave energy. When vegetation is used as an erosion control measure, careful selection is needed to match particular varieties of plants to local conditions of soil, wind and water.

1.2.7 Other measures

Beach face dewatering is lowering of the groundwater table along the coastline, which is accomplished by draining water from buried, almost horizontal, filter pipes running parallel to the coastline. The pipes are connected to a collector sump and pumping station further inland. Gravity drains the groundwater beneath the beach and through the pipes to the sump and then the water is pumped from the sump. The sand-filtered seawater can be returned to the sea or used for other purposes.

2. DESCRIPTION ON COASTLINE OF INDIA

2.1 Different types of coastline

The Indian coastline is about 7517 km with the coastline along the mainland of about 5423 km and the Andaman, Nicobar and LakshadweepIslands of about 2094 km (Kumar et al., 2006). The length of the coastline in different maritime states is shown in **Table 2.1.1.**The coastline length is under revision by National Hydrographic Office (NHO) and should be consulted for further recent details.

Table 2.1.1. Types of coastline in different maritime states

States	Sandy beach (%)	Rocky coast (%)	Muddy flats (%)	Marshy coast (%)	Total length (km)	Length of coast affected by erosion* (km)	Length of coast protected (km) as on March 2006	Coast yet to be protected
Gujarat	28	21	29	22	1214.7	36.4	4.0	32.4
Maharashtra	17	37	46	-	652.6	263.0	127.0	136.0
Goa	44	21	35	-	151.0	10.5	3.85	6.65
Karnataka	75	11	14	-	280.0	249.6	55.77	193.79
Kerala	80	5	15	-	569.7	480.0	378.5	101.5
Tamil Nadu	57	5	38	-	906.9	36.15	9.68	26.47
Andhra Pradesh	38	3	52	7	973.7	9.2	0.49	8.7
Odisha	57	-	33	10	476.4	107.55	10.00	97.55
West Bengal	-	-	51	49	157.5	49.0	14.16	34.84
Daman & Diu					9.5	--	-	-
Puducherry					30.6	6.4	6.4	0.0
Total	43	11	36	10	5422.6	1247.9		
Lakshadweep					132.0	132.0	44.4	87.6
Andaman & Nicobar					1962.0	--		
Total					7516.6	1379.5		

* As per different state Governments in 2006

The coastline comprises of headlands, promontories, rocky shores, sandy spits, barrier beaches, open beaches, embayment, estuaries, inlets, bays, marshy land and offshore islands. As per the NHO charts, Indian mainland consists nearly 43% sandy beaches, 11% rocky coasts with cliffs and 46% mud flats and marshy coast. The oscillation of the shoreline along Indian coast is seasonal. Some of the beaches regain their original profiles by March/April.

Fifty percent of the beaches, which do not regain their original shape over an annual cycle, undergo net erosion. 23% of the shoreline along the Indian mainland is affected by erosion in the year 2006.

The continental shelf is narrow along the east coast and wider in the west. On the west coast, the shelf width of about 340 km in the north tapers to less than 60 km in the south. On the east coast, the shelf width is broad off the Ganges delta and is 30-35 km for other major river deltas. Large quantities of sediments are brought to the coast by a number of rivers.

2.2 Geomorphology

2.2.1 Gujarat

Gujarat coast (**Figure 2.2.1**) can be classified into five regions viz., the Rann of Kachchh, the Gulf of Kachchh, the SaurashtraCoast, the Gulf of Khambhat and the SouthGujaratCoast. The coastal area of Gujarat including the Rann of Kachchh is the largest in the country and covers an area of about 28,500 km^2. Rann of Kachchh comprises of the Great Rann and the Little Rann, which remain saline desert for the greater part of the year. Area of the lower Indus deltaic plain situated on the west of the Great Rann of Kachchh is characterized by the tidal creeks and mangroves. In the Gulf of Kachchh,the shoreline has extensive mudflats and is highly intended with a number of rocky islands with cliffs. It is fringed by coral reefs at many places and mangroves, algae, salt marsh, dunes and salt pans are common. Saurashtra coast is less indented but has numerous cliffs, islands, tidal flats, estuaries and embayments. Sandy beaches are present around Veraval and Porbandar. Gulf of Khambat coast is enclosed by a number of estuaries, mud flats, salt marshes, islands, cliffs and mangrove forests. Tides in the Gulf of Khambat are semi-diurnal with very high tidal ranges (up to 10 m). Series of estuaries, creeks, mudflats and marsh vegetation are present in south Gujarat coast.

2.2.2 Maharashtra

The coastal region lies within the six districts of Thane, Mumbai City, Mumbai Suburban, Raigad, Ratnagiri and Sindhudurg. The coastline of Maharashtra (**Figure 2.2.2**) is very irregular, associated with features like cliffs, notches, promontories, sea caves, wave cut platforms, embayments, submerged shoals and offshore islands. Isolated cliffs and sandy beaches are also seen. Ratnagiri has rich mangrove forests. The coastline between Mulgund and Shiroda is about 200 km long and is hilly, narrow, highly dissected with transverse ridges of the Western Ghats, and at many places extending as promontories into Arabian Sea (Ahmad, 1972). Many west flowing rivers viz. Kodavali, Tulsanda and Vaghotan Rivers, and Danda and Pungerwadi creeks join the sea in this region and form estuaries, bays, mudflats, creeks and tidal marshes. Many headlands protrude into the sea between Vijayadurg and Ambalgarh. Sea cliffs are present in the vicinity of Vijayadurg harbor. In addition to pocket beaches, long sandy beaches are also present along the south Maharashtra coast. Continental shelf of the south

Maharashtra coast is relatively wide with 50 m depth contour occurring approximately 25 km away from the coast. Till 100 m water depth, the seabed mostly consists of silty clay, and between 100 and 200 m, it is covered with sand (Wagle, 1987). About 4 km long beach is present at Kalbadevi, north of Ratnagiri. Mirya headland is situated at Ratnagiri enclosing a bay. Small pocket beaches are present in Ratnagiri. No beach is present between Ratnagiri bay and Ambalgarh. Ratnagiri bay, Pavas bay and Purangad bay are situated over this region. KajviRiver joins at Ratnagiri bay and MachkandiRiver joins Purangad bay. Remaining stretch mostly consists of rocky outcrops and vertical cliffs. A 4.5 km long beach is present north of Ambalgarh headland. Ambalgarh bay and Rajapur bay are situated further south. The coastal region close to Jaitapur comprises of a long beach north of Ambalgarh, pocket beach between Ambalgarh Headland and Musakazi Point and a few small pocket beaches along the mouths of Rajapur and Vaghaton rivers. Vijayadurg harbour is located at the confluence of Vaghotan River. Between Vijayadurg and Devgarh, the coast mostly consists of headlands and vertical cliffs. Devgarh harbor is situated at the Devgarh river estuary. There are three small pocket beaches between Devgarh and Munga. A 6 km long beach is situated at Munga. Beach of 10 km long is present between Achra River and Gad River. Chain of rocky patches is observed, within 20m water depths, between Malvan and Vengurla. A small fishing port is situated at Malvan bay. A 12 km long beach is present till KarliRiver. Further south, till Vengurla, there are rocky outcrops and headlands. South of Vengurla, there is a beach of about 5 km long near Ubadanda. TalavadaRiver joins near Shiroda. There is about 5 km long beach at Shiroda. An offshore anchorage port is present at Redi.

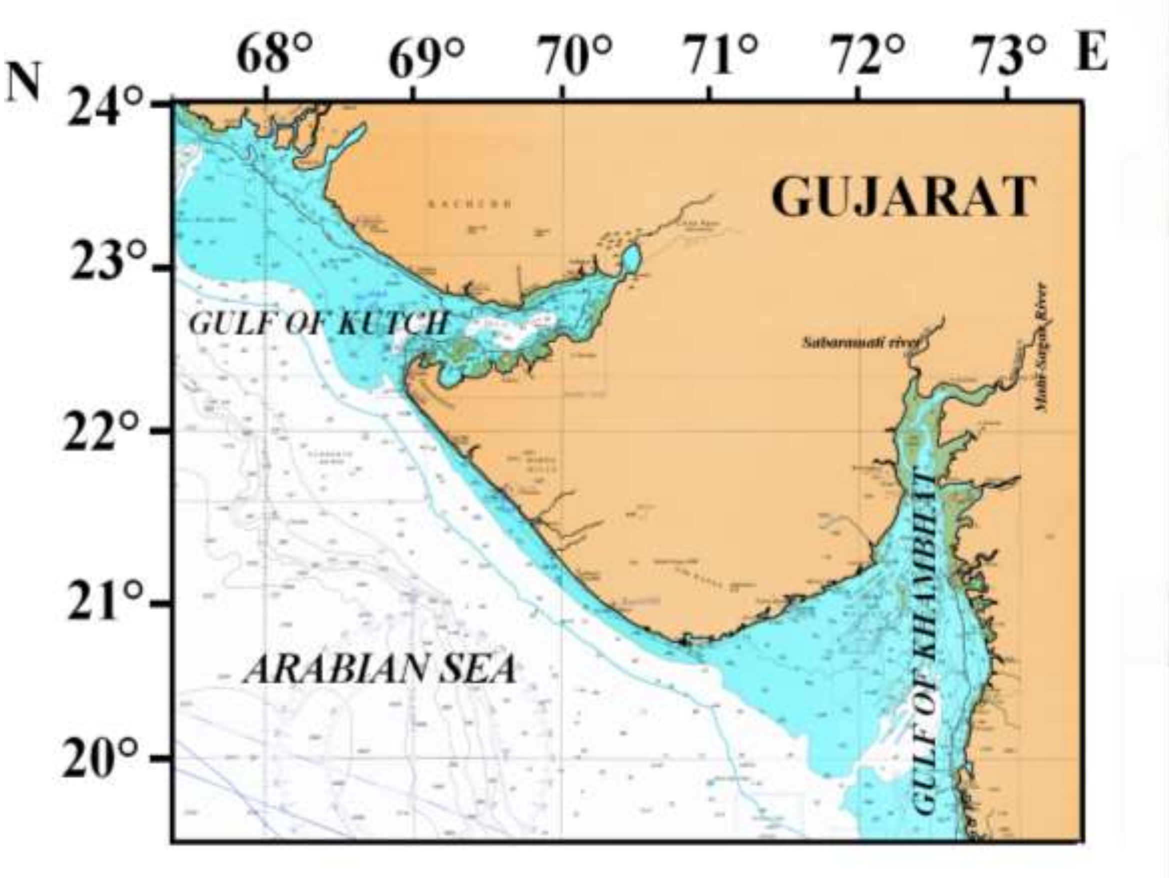


Figure 2.2.1 Coastline of Gujarat

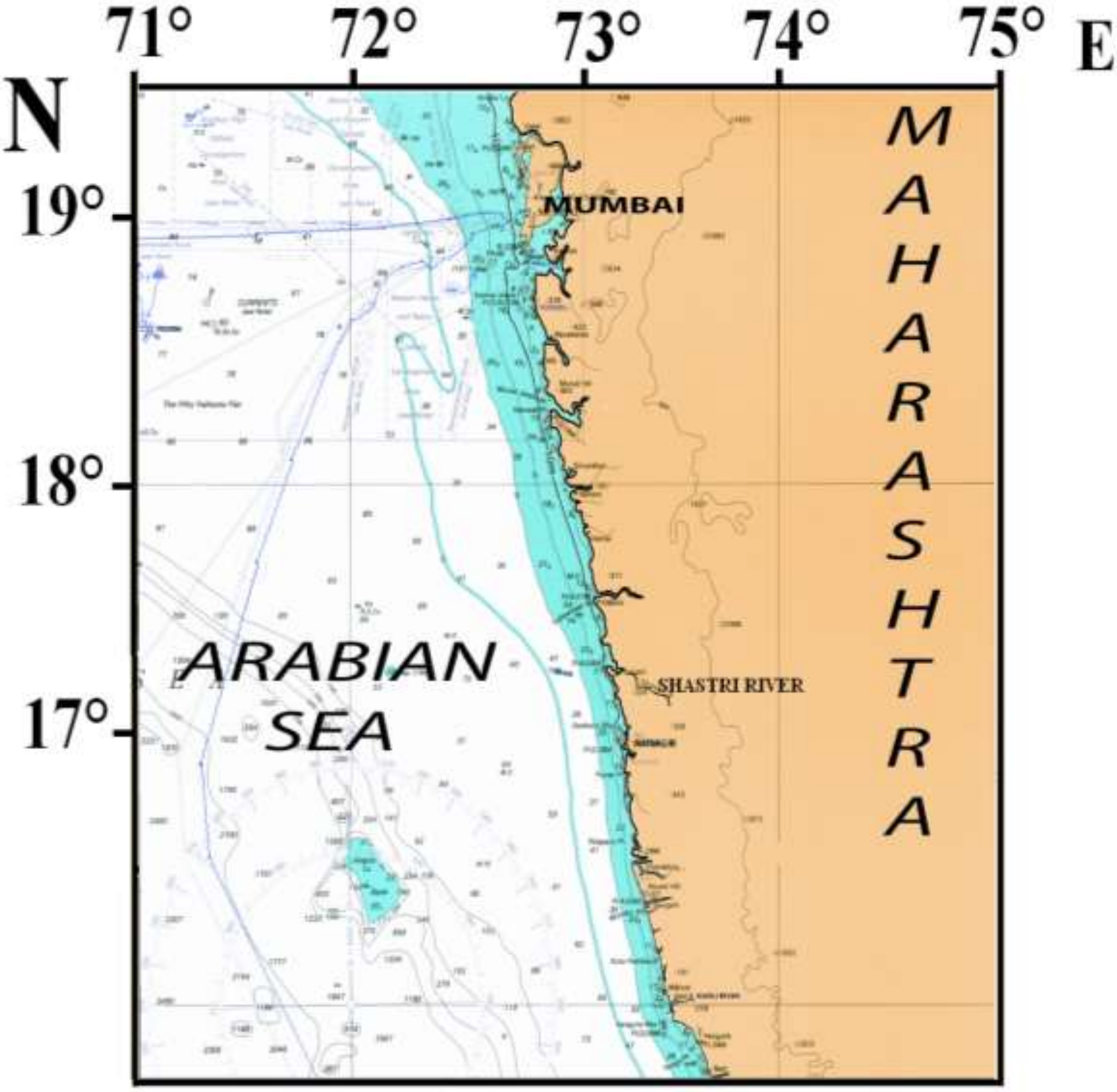


Figure 2.2.2 Coastline of Maharashtra

2.2.3 Goa

Goa coast (**Figure 2.2.3**) can broadly be classified into the coastal tract consisting of beaches, sea cliffs, promontories, pocket beaches, alluvial plain, estuaries, spits, dunes, beach ridge and broad hard rock wave-cut platforms. The continental shelf off Goa is relatively wide, with 50 m contour depth occurring 35 km, 100 m at 80 km, and 200 m at 100 km away from the coast. Seabed mostly consists of silty clay till 50 m water depth, sandy silt from 50 m to 100 m water depth (Nair and Hashmi, 1989). Beach sediments mainly consist of quartz along with feldspars and other heavy minerals. They are represented by medium to fine sand, well to moderately sorted, and negative to very negatively skewed. TiracolRiver joins the sea at the northern border of Goa. South of Tiracol, there is about 5 km long beach at Harmal. Rocky outcrops are present till ChaporaRiver. Rocks and vertical cliffs are seen between ChaporaRiver and Baga point. Anjuna and

Vagator are pocket beaches present over this stretch. Calangute beach is about 8 km long, formed between Baga point and Aguada Point. Miramar beach is about 4 km long situated along the southern bank of the Mandovi river estuary. ZuariRiver joins the sea forming a large bay, and it encloses the major port at Mormugao. South of Mormugao Head, offshore islands are present within 15 m water depth.

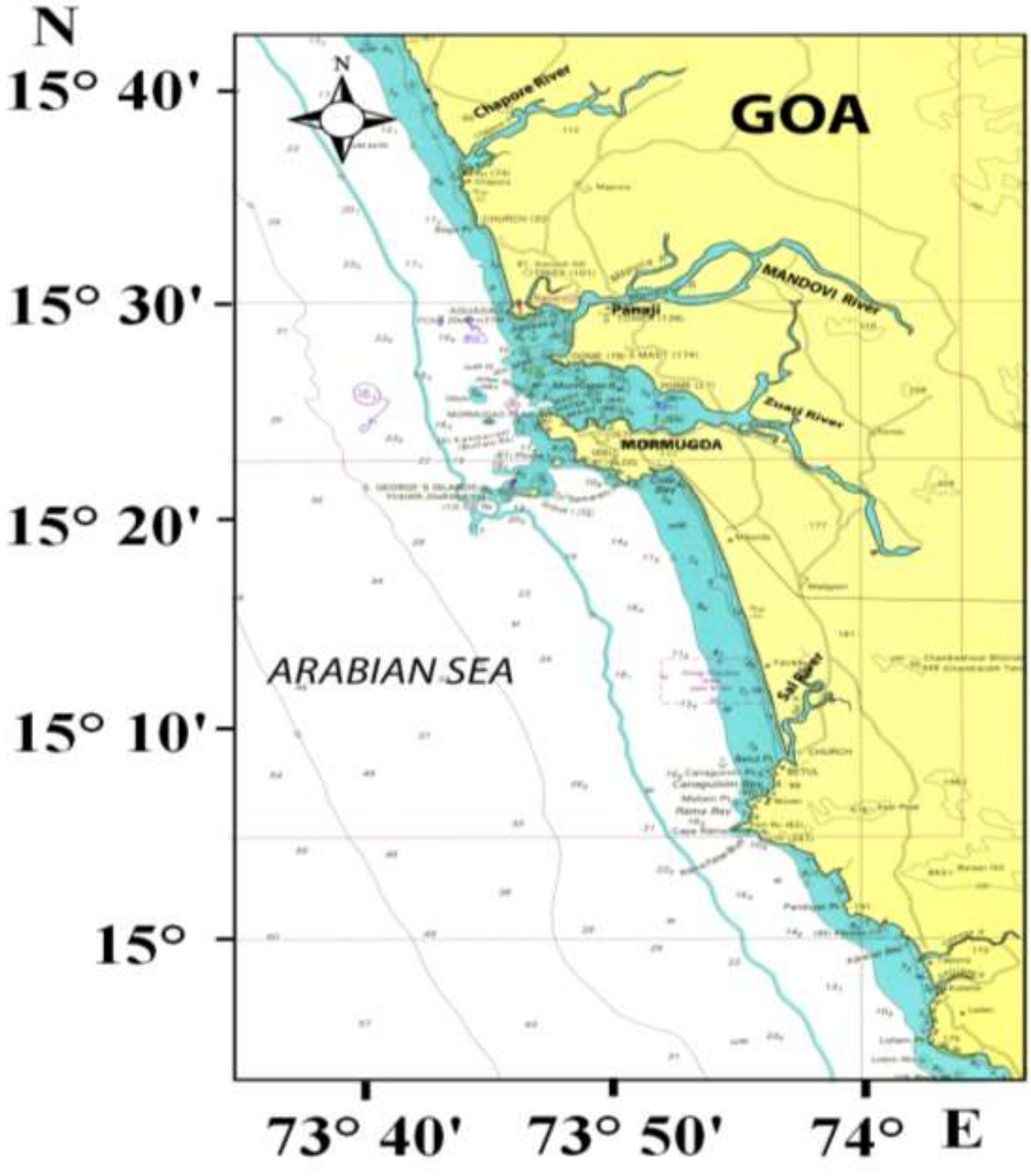


Figure 2.2.3 Coastline of Goa

The shore consists of rocky outcrops and vertical cliffs from Mormugao Head to Santarem Point. Further south, the 27 km long, Colva beach is present till Betul point. SalRiver joins at Betul. Betul Point to CapeRama, the shore is mostly of laterite cliff. Small pocket beaches are present near Pandigat Point, Kankon bay and Loliem. The prominent landform consists of laterite-capped mesas extending 25 to 30 km inland. The beaches situated along the open coast mainly consist of quartz along with feldspars and other heavy minerals. They are represented by medium to fine sand, well to moderately sorted (Wagle, 1987). Beaches in Goa are extensively used for recreation.

2.2.4 Karnataka

Karnataka coast (**Figure 2.2.4**) is broadly divided into Uttara Kannada and Dakshina Kannada coast, which exhibit different geomorphic setup. Uttara Kannada coast is highly irregular shoreline with many embayment promontories, cliffs with pocket beaches and islands, whereas the Dakshina Kannada coast is characterized by sea bond terrain having more or less straight coastline. The shelf off Karnataka has an average width of 80 kilometers and the depth of shelf break is between 90 and 120 m. There are a few islands off the coast, the major group being St. Mary's Island, 4 km off the coast near Malpe.

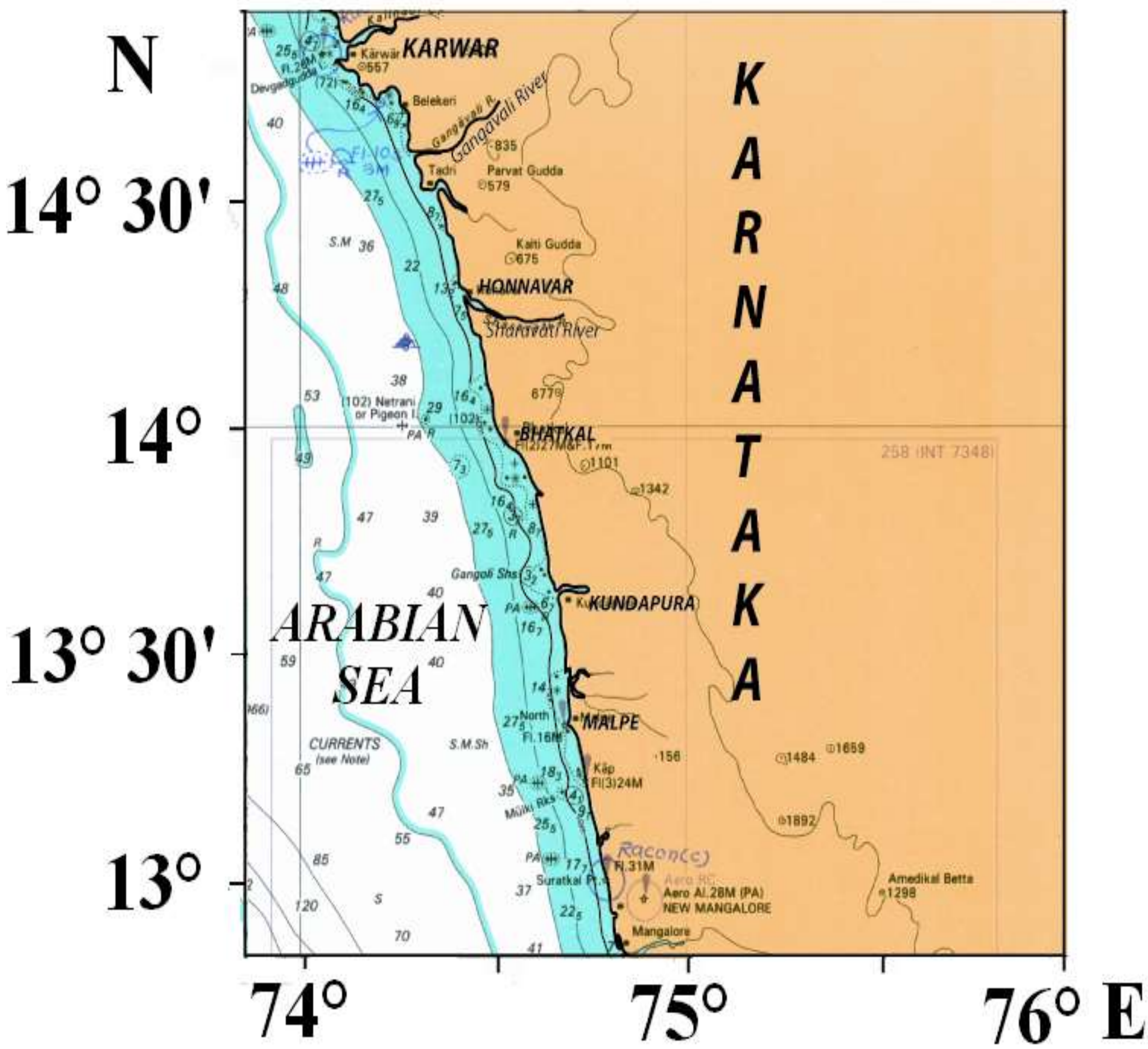


Figure 2.2.4 Coastline of Karnataka

The coastal region of Karwar consists of pocket beaches, bays, mudflats, creeks and tidal marshes. Fourteen rivers join the Arabian sea along the Karnataka coast. Important estuaries include the Netravati-Gurpur, Gangolli, Hangarkatta, Sharavathi, Aganashini, Gangavali and Kalinadi. Sand bars are seen in most of the estuaries. There are a number of barrier spits at Tannirbavi, Sasithitlu, Udyavara, Hoode, Hangarkatta and Kirimanjeswara formed due to migration of coastal rivers. There are about 90 beaches along the coast and among these, the beaches at Someshwar-Ullal, Malpe, St. Mary's Island, Belekeri and Karwar have the potential for tourism. Variations in beach levels indicate seasonal pattern viz., fair weather, southwest monsoon and northeast monsoon. A reversal of the process was observed during November to January, during which the eroded beach profiles in the southwest monsoon season were subjected to accretion. The reversal of the angle of wave approach occurring during the southwest monsoon and northeast monsoon seasons seem to be responsible for the reversal in the beach erosion/accretion cycle (Kumar et al., 2001).

2.2.5 Kerala

Kerala is a narrow strip of land in the southwestern part of the Peninsular India extending for a length of about 570 Km (**Figure 2.2.5**). The western margin is a narrow alluvial plain stretching almost from north to south, attaining maximum width around Alappuzha. These alluvial plains are extensively invaded by the backwaters, of which the Vembanad and Ashthamudi lakes are the most important. Physiographically the Kerala region is subdivided into three longitudinal zones, viz. the highlands, the midlands and, the coastal plain. The Western Ghat forms almost a continuous mountain chain on the eastern border of the State, broken by Palghat pass and few other small passes. The highlands are the hilly tracts that lie on the western side of the mountainous Western Ghats covered with dense forests, with peak ranging in height from 915 m to 2690 m. The midland region falling between 8 to 80 m above MSL is a gently sloping land consisting mainly of lateritic flat lands. The lowlands lying close to the sea is an extensively vast plain with negligible undulations, comprising the barrier beaches, strand plain with beach ridges. There are 41 rivers which join the backwaters and enter the coast which brings sediment to the coast. Most of the west-flowing rivers that flow through the coastal zone show regular meandering of channels particularly within the coastal zone.

Mud-banks occurs just after the onset of the southwest monsoon along the Kerala coast. So far, mud banks have been recorded in the sea near Kozhikode, Beypore, Veliyankode, Kochi, Ambalappuzha and Thrikkunnappuzha. Studies have shown that certain mud-banks are permanent or at least they have been in existence for a long time while others are temporary. When active, mud banks are noted for their wave damping effects that a 1.8 m high wave outside the mud bank are reduced to 0.5 m within the mud bank, within a distance of 1.1 km. This reduction can be 100% in a fully developed mud bank. Apart from the beneficial effect on the development of fishing industry, the mud banks have a decisive role on the shore stability of the coast of Kerala. They trap the sediment and it causes erosion in the down-drift coast. The mud bank also provides protection to the coastal zone, by way of allowing accretion.

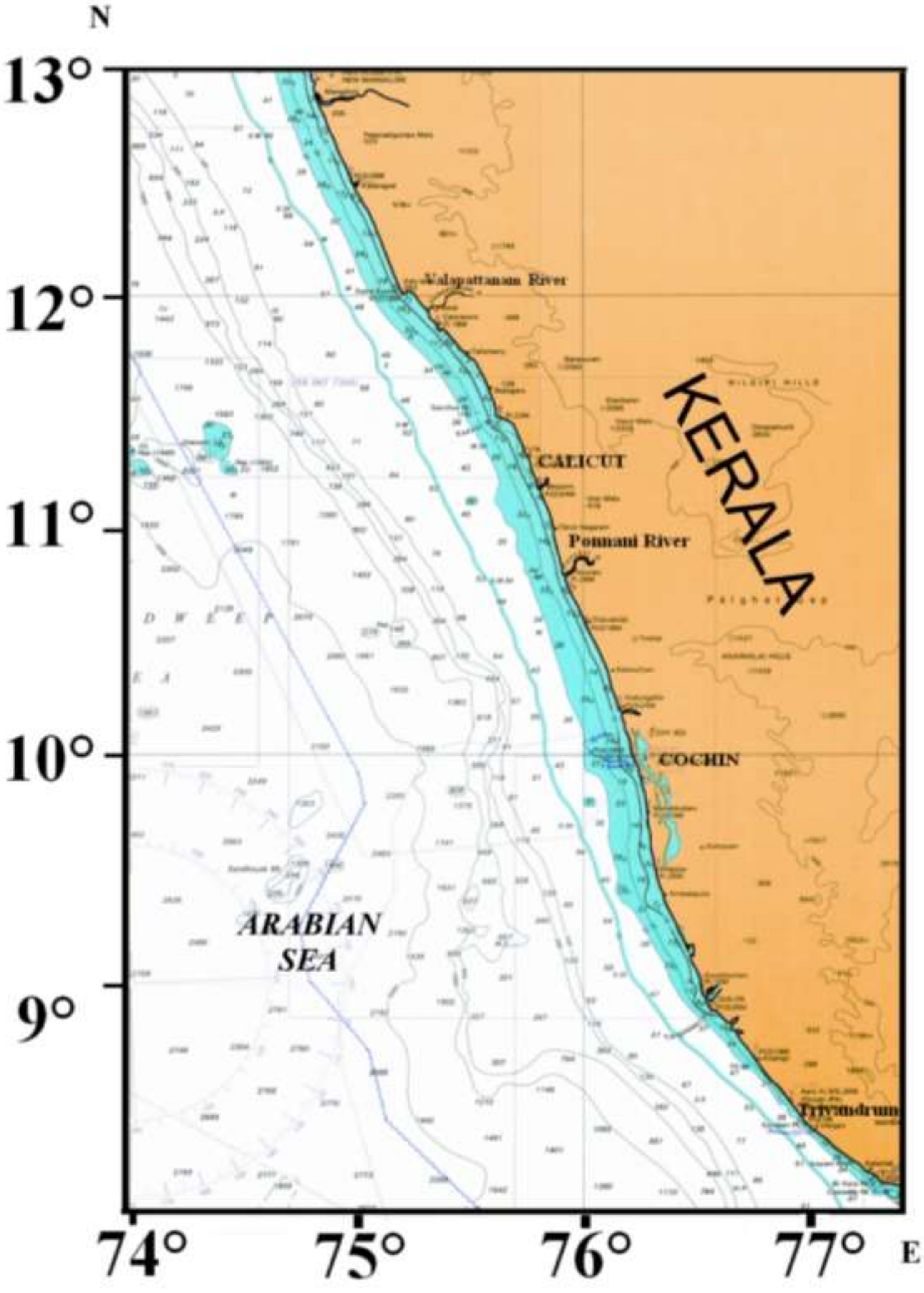


Figure 2.2.5 Coastline of Kerala

2.2.6 Tamil Nadu

Tamil Nadu coast (**Figure 2.2.6**) is straight and narrow without much indentation except at Vedaranyam. Pulicat Lake, the second largest lagoon in India is gradually silting up by the sediments brought by the streams and tides (Ahmad, 1972). The coastline between Vedaraniyam and Rameswaram in Palk Bay, and between Rameswaram and Tuticorin in Gulf of Mannar are partially protected from monsoon waves due to the proximity of Srilankan Island. PalkBay is a shallow bay and is largely occupied by sandbanks and shoals (Agrawal, 1988). Abundant growth of corals, oysters, sponges, and other benthic communities flourish in the relatively calm waters of Gulf of Mannar. Pichavaram, Vedaranyam and Point Calimere have well-developed mangrove systems. In Tamil Nadu, about 46 rivers drain into Bay of Bengal forming small estuaries adjoining coastal lagoons. The CauveryRiver and its tributaries form a large delta supporting extensive agriculture. The other landforms of the Tamil Nadu coast are rock outcrops of Kanyakumari, mudflats, beaches, spits, coastal dunes, salt pans and strand features. Rich deposits of heavy minerals are available in Muttam-Manavalakurichi coast. The southern tip is also known for the Teri sands.

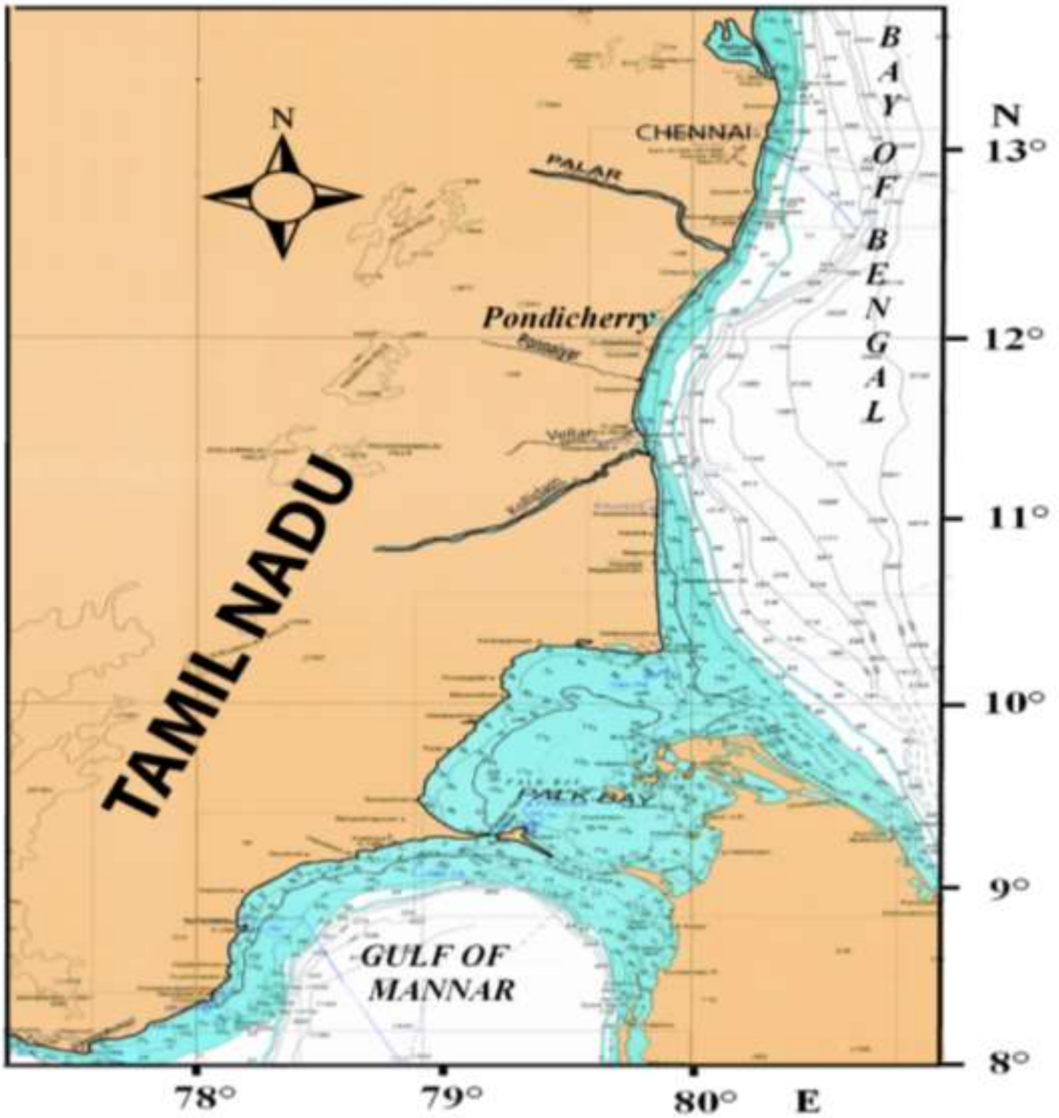


Figure 2.2.6 Coastline of Tamil Nadu

2.2.7 Andhra Pradesh

Andhra Pradesh coast (**Figure 2.2.7**) is marked by long sandy beaches backed by rows of high sand dunes. It has frequently been attacked by cyclones and inundated by storm surges. The coastline is long with indentations only in the extreme south (in the saltwater lagoon of Pulicat Lake) and between the Godavari and Krishna deltas (which are growing outwards). North of Godavari delta is rocky, south of Krishna delta is a sandy and in between the inter-delta is vegetated with mangroves. The unique feature of this coast is the formation of 15 km long sand spit off Kakinada owing to heavy sediment load brought by Godavari River (Ahmad, 1972, and Chandramohan et. al., 1988). The residual hills and ridges of the north are common here. The deltaic coast comprises of bays, creeks, extensive tidal mudflats, spits, bars, mangrove swamps, marshes, ridge and swale areas and coastal alluvial plains. Kolleru lake is situated in the inter-delta. This was formed due to the coalescence of the deltaic deposits of the rivers and later it was cut off from the sea. The Pulicat Lake has extensive tidal flat and 12 km long spit. The deltaic and southern coast is rich in agriculture and aquaculture production.

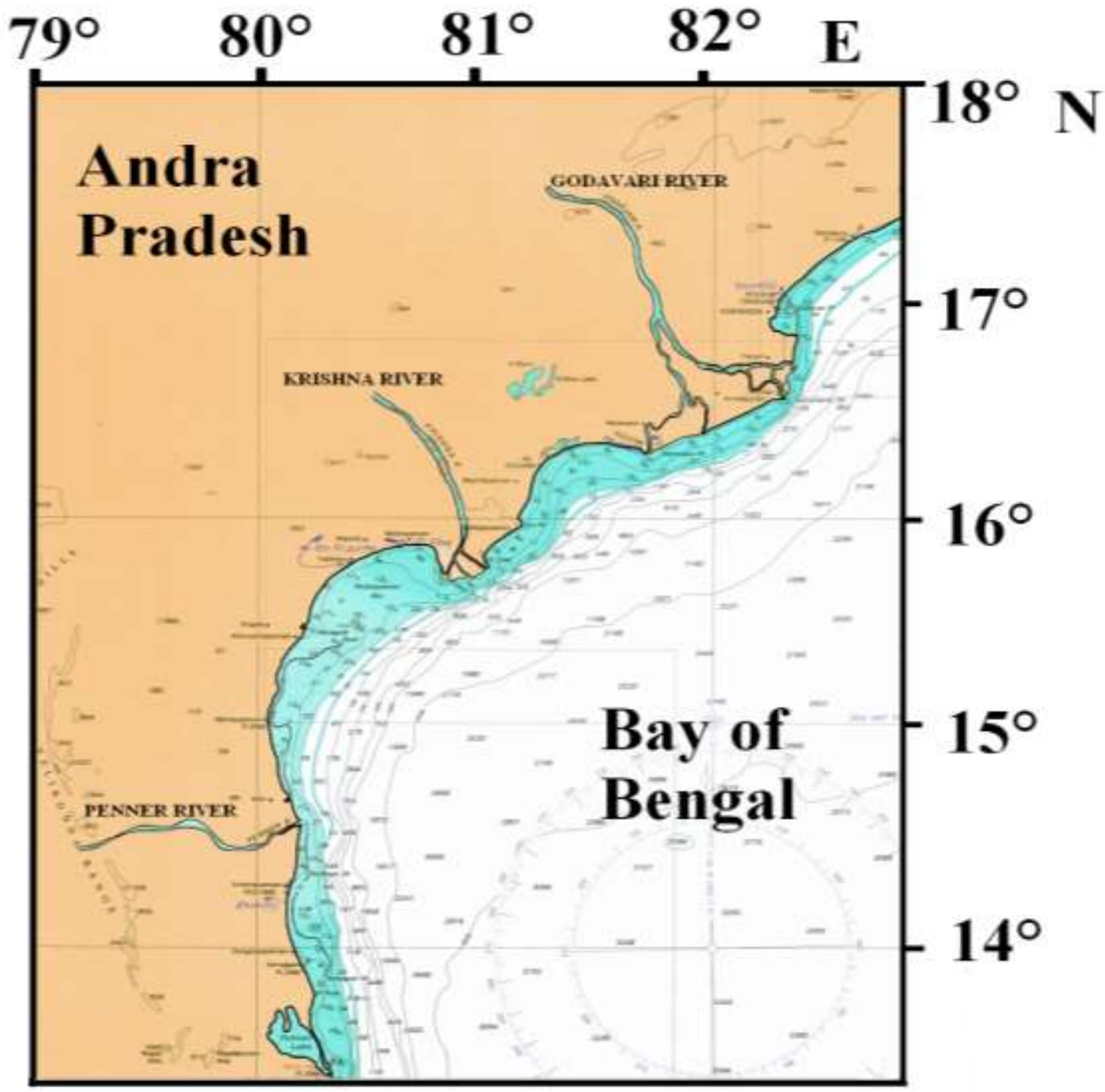


Figure 2.2.7 Coastline of Andhra Pradesh

2.2.8 Odisha (Orissa)

Odisha (**Figure 2.2.8**) is marked by long sandy beaches with high and wide backshore. Odisha coast is mainly depositional in nature formed by the Mahanadi and the Brahmani-Baitarani deltas. It is exposed to severe cyclones. The Chilka lagoon, the largest natural water body of the Indian coast is along the Odisha coast. The Bhitarkanika and Hatmundia reserve mangroves are extensive. Wide sand beaches with elevated rows of sand dunes are seen between Gopalpur and Mahanadi mouth. Gopalpur is rich in heavy minerals. Mudflats, spits, bars, beach ridges, creeks, estuaries, lagoons, floodplains, paleomudflats, coastal dunes, salt pans and paleo-channels are observed along the Odisha coast. The growth of long sand spits at Chilka Lake indicates the large movement of littoral sediment and subsequent deposition.

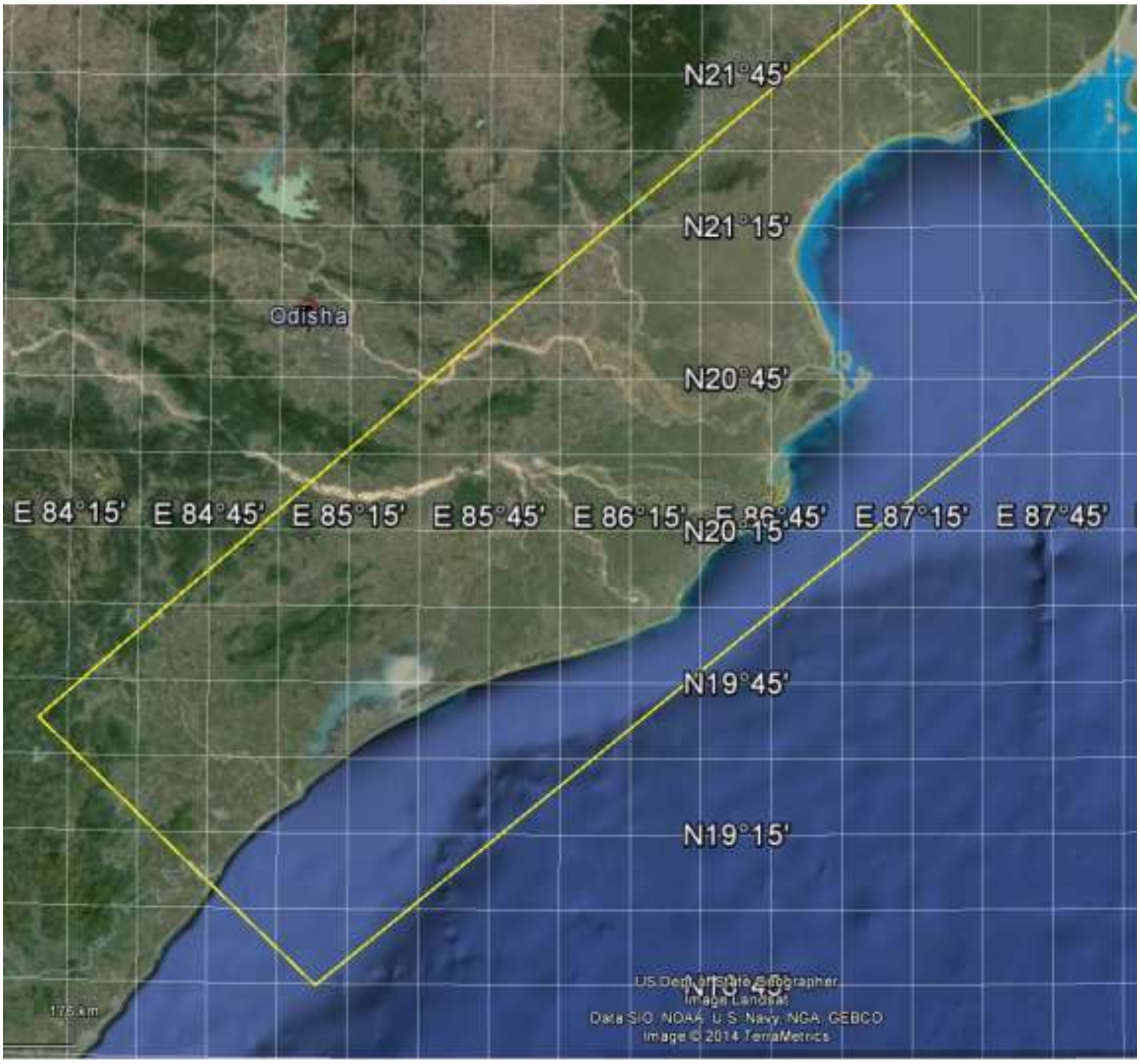


Figure 2.2.8 Coastline of Odisha

2.2.9 West Bengal

Major length of West Bengal coast (**Figure 2.2.9**) is the Sundarban region of the Ganges mouth with many shoals, sand spits, mud flats and tidal swamps (Ahmad, 1972). The major geomorphic features are mudflats, bars, shoals, ridges, estuaries, extensive network of creeks, paleo-mudflats, coastal dunes, significant number of islands and salt pans Mud flats are exposed during low tide near Digha, part of Sundarban and opposite to the Hooghly mouth. Sagar islands, Bhangadun Island, Dalhousie Island, Lothean Island and Mahisand Island are present opposite to the mouth of the river Hooghly. The Sundarbans with coverage of about 1,430 sq. km, is one of the largest single blocks of the halophytic mangrove systems of the world.

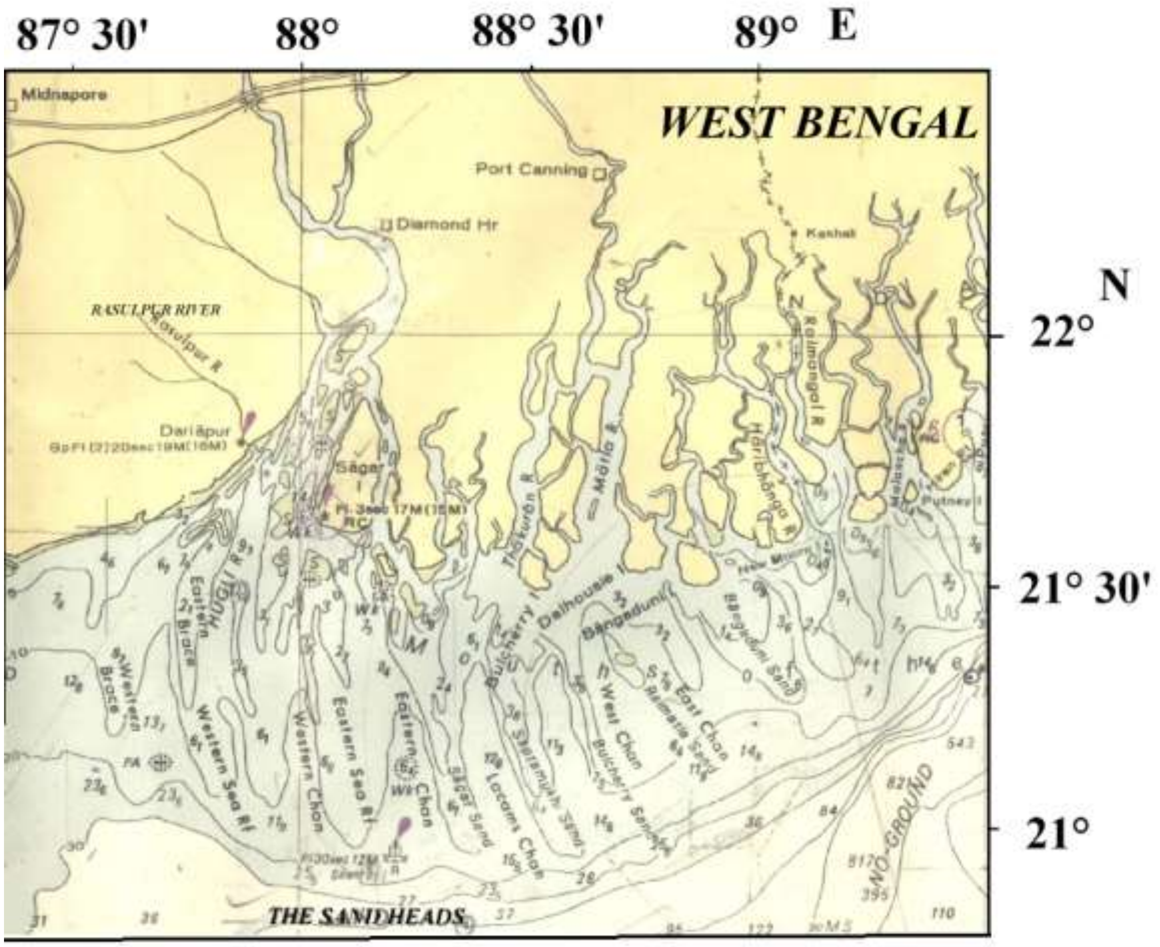


Figure 2.2.9 Coastline of West Bengal

2.2.10 Lakshadweep

Lakshadweep group is an archipelago of coral islands in the Arabian Sea. It consists of 36 islands, 12 atolls, 3 reefs and 5 submerged coral banks. 11 islands are inhabited. These islands are 3 to 9 m above the mean sea level. Lagoons are an integral part of most of the islands.

2.2.11 Andaman and Nicobar

Andaman and Nicobar group of Islands consist of around 300 islands and most of them are composed of rocks like fossiliferous marine petroliferous beds, conglomerates, sandstone and limestone (Ahmad, 1972). These islands are volcanic in origin and emerged part of a mountain chain. The coastline has coral reefs, sandy beaches, lagoons, mangroves, creeks, bays, cliffs, saline areas and forestland. An active volcanic island is observed in Nicobar group of islands.

2.3. Coastal erosion sites

This section on coastal erosion sites comprises of the erosion reported/observed by the state authorities as per their communication as well as the information from earlier literature which is more than two decades old in certain cases. It is likely that these areas could have been protected in due course of time and therefore this section should not be considered as final. The coastal atlas prepared by Space Application Centre includes coastal erosion regions based on satellite data which could be consulted for further details.

2.3.1 Gujarat

Shoreline erosion is observed in Gujarat at Ghoga, Bhagwa, Dumas, Kaniar, Kolak and Umbergaon and sediment deposition is observed as sand spits at the estuarine mouths of the Tapti, Narmada, Dhadar, Mahi, Sabarmati, Kim, Purna and Ambica.

2.3.2 Maharashtra

In Mumbai and Mumbai suburban districts, the coastal areas are densely populated. Significant coastline of the city has already been protected (Nariman Point to Chowpati, Haji Ali Tomb area, Worli sea face etc.). The coastal sites of lagebunder and Pachbunder, located along Vasai creek in Thane district, about 70 km north of Mumbai is experiencing erosion. In Raigad district, the coast of Thironda is experiencing erosion. The coast of Jaki Mirya and Bhati Mirya in Ratnagiri district is experiencing erosion during Monsoon. Certain stretches of Harne is experiencing erosion. In Sindhudurg district, coastline of Navabag Ubhadanda in Vengurla Taluk and Kelus are eroding.

2.3.3 Goa

Along the Goa coast, seasonalerosion is noticed at Anjuna, Teri, Talpona, Betalbatim beach and Mandrem (Morji).Certain stretches of Keri beach and Anjuna are provided with hard protection measures.

2.3.4 *Karnataka*

Erosion along the beaches near the river mouths has been commonly noticed along the Karnataka coast (Chandramohan, et. al., 1991). At many river mouths, the sand spit erodes causing shift in river course or inlet migration. In Uttara Kannada, places affected by coastal erosion are Devbag, Karwar, Harwada, Belambar, Pavinakurve, Medikeri/Bhadrakeri, Bailur and Honnagadde.

The most affected locations are Gangavali river mouth and areas near Honnavar, Shirali, Kundapur kodi, Hangarkatta and Bengre. Erosion/bank collapse in the tidal reaches of rivers is also severe and extends at least to about 12 km. This has been noticed in Manjuguni and Karikodi villages, Pavinakurve and Mavinakurve islands, Bhatkal port area, Kollur and Haladi Rivers, Seethanadi near Mabukal and Ullal side of Netravathi river bank (Coastal Zone Management, Karnataka).

2.3.5 *Kerala*

Even short-term shoreline oscillations with no net erosion can be detrimental to Kerala, as its coastal zone is very thickly populated. Also, there are areas of continuous accretion along the coast. The study carried out by CESS has shown that 150 km of the coastline are undergoing severe erosion (including those protected by seawalls) and about 110 km are consistently accreting (Samsuddin and Suchindan, 1987, Purandara and Dora, 1989 and Samsuddin, et. al., 1991). Based on the Coastal zone management plan for Kerala (CESS, Thiruvanathapuram, 1998), the erosion sites at Kerala are given in **Table 2.3.1.**

Table 2.3.1 Erosion sites at Kerala

Sr No	District	Place
1	Thiruvananthapuram	Kulathur, Thiruvallam, Poonthura, Valiathura, Anchuthenga, Vettoor, Edava
2	Kollam	Paravoor, Iravipuram, Sakthikulangara, Neendakara, Panwana, Chavara, Alappad
3	Alappuzha	Kallikkadtura, Vattachal, Arattupuzha, Thrikkannapuzha, Purakkad, Ambalapuzha, Mararikulam, Omanapuzha, Kochanakukyara, Pattanakad
4	Ernakulam	Chellanam, Kuzhapilli, Pallipuram, Ilamkunnapuzha, Vypeen, Idavanakkod, Nayarambalam, Narakkal
5	Thrissur	Eriyad, Edavilangu, Mathilakam, Kaipamangalam, Valappad, Nattika, Vadanapalli, Engandiyur, Punnayurkulam
6	Malappuram	Ponnani, Vettam, Tanur
	Kozhikkod	Elathur, Chamancheri, Chengottukavu, Koyilandy, Thikkodi, Payyoli, Vadakara, Onchiyam, Cherode, Azhiyur

7	Kannur	Gopalpetta, Dharmadam, Muzhappilangad, Kizhunna, Thottada, Pallikunnu, Meenkunne, Mattul, Madayi
8	Kasargod	Kizhur, Manjeswarem

2.3.6 Tamil Nadu

Along the Tamil Nadu coast, erosion was reported at Poompuhar, Tarangampadi, Nagapattinam, Mandapam, Manapadu, Ovari, Kanyakumari, Pallam, Manavalakurichi and Kolachel at the rate of 0.15, 0.65, 1.8, 0.11, 0.25, 1.1, 0.86, 1.74, 0.60, 1.2 m/year respectively (Kaliasundaram, et. al., 1991). The maximum rate of erosion is about 6.6 m per year at Royapuram, between Chennai and Ennore port (IHH Poondi, 2002). Accretion is taking place at Cuddalore, Point Calimere, Ammapattinam, Kilakarai, Rameswaram, Tiruchendur, Manakudi and Muttam at a rate of 2.98, 3.4, 0.72, 0.29, 0.06, 0.33, 0.57 and 0.17 m/year respectively. Usha and Subramanian (1993) reported that the coast near Ovari is exposed to severe erosion in June whereas alternate erosion and accretion trend have been noticed at Kanyakumari. They also stated that the accretion pattern for sites located in the PalkBay, viz. Ammapattinam, Mandapam and Rameswaram was observed.

Severely eroding coast as identified by the state government are Peria Kuppam and Chinna Kuppam, Eranavoor Kuppam, Annai Sivakami Nagar Kuppam and Indiragandhi Nagar Kuppam in Chennai North. Kovalam Kuppam, Oyyali Kuppam, Chinna Kuppam, Periya Kuppam and Alikuppam in Kancheepuram District. Devanampattinam in Cuddalore District. Poompuhar, Tharangambadi, Ariyanattutheru, Seruthur, Velanganni in Nagapattinam District. Periyathalai and Alanthalai in Tuticorin District. Koothankuzhi, Kootapuli, Uvari, Idinthakarai, Kootapanai, Thomayapuram, Perumanal and Kooduthalai inTirunelveli District. Ratchagar Street, Kodimunai, Keezhmidalam, Chinnaturai, Marthandamthurai in Kanyakumari District.

2.3.7 Andhra Pradesh

Insufficient information on erosion is available except that erosion is noticed at Uppada, Visakhapatnam and Bheemunipatnam. Erosion at Visakhapatnam beach was caused due to the construction of outer harbor breakwaters. The 30 km long marine drive from Visakhapatnam to Bheemunipatnam, is facing the threat of erosion. About four decades ago, the seawater lashed the beach road and boulders were dumped along the coast as an emergency measure to stop the surging seawater and to protect the beach. The maximum erosion was seen at the beach near the SubmarineMuseum and at the spot opposite INS Kalinga, near Bheemunipatnam. It is recently reported that similar severe erosion is taking place at same location at Visakhapatnam.

2.3.8 Odisha

Erosion is noticed at Gopalpur, Paradip and Satabhaya. The breakwater was installed at Paradip port in 1963-64 and erosion observed along the north of the harbor entrance channel and advancement of shoreline at south of southern breakwater. Due to the erosion, seawalls were proposed on the north side along with dumping of sand and a sand trap at the end of the southern breakwater.

2.3.9 West Bengal

Major length of West Bengal coast is the Sundarban region of the Ganges mouth with many shoals, sand spits, mud flats and tidal swamps (Ahmad, 1972). Beach erosion is noticed at Digha, Bankiput and Gangasagar regions of the West Bengal coast. Erosion is found near Mandarmani creek also.

2.3.10 Puducherry

After construction of the breakwaters for Puducherry fishing harbor in the Southern part of the Puducherry city, the coastal erosion on the Northern side has increased significantly and the entire beach area of Puducherry is lost. Rubble mound slope protection is provided and of late beach replenishment is being attempted for regaining the lost beaches

2.3.11 Andaman and Nicobar

Land subsidence of 0.8 to 1.3 m has occurred at Andaman and Nicobar due to the 26 December 2004 Tsunami and has resulted in shoreline erosion in some of the islands.

2.3.12 Lakshadweep

Some parts of all the inhabited islands of Lakshadweep experience erosion. Small sized tetrapods have been placed at many locations to counter the erosion of the island shores. The ecosystem in Lakshadweep islands is so fragile with sensitive seabed with coral life that the adoption of hard measures towards coastal erosion is highly discouraged.

2.4 Protected coastal sites

2.4.1 Gujarat

The coast of Nani Danti – Moti Danti is protected against erosion for a length of 500 m by seawall. Since the required size of boulders (≈100 kg) in the design and the required machinery for handling these boulders were not available, flexible gabions were used with relatively small size of boulders (20 to 50 kg).

Flexible gabions are provided at Tithal beach in Kosamba village (Valsad district) to protect the SwaminarayanTemple complex for a length of 330 m from erosion. At Udwada, detached seawall is constructed to provide protection to 500 m coastline.

2.4.2 Maharashtra

The coastal protection measures provided comprises primarily of seawalls/bunds. Due to abundantly available laterite in Ratnagiri and Sindhudurg districts, the protection works were commonly constructed using laterite stone/blocks. Wherever easily available, trap stones have also been used.The coast of Pachbunder towards the mouth of the creek is protected using rubble stone bund. Certain stretches of Jaki Mirya coast is protected by walls/bunds.

Beach nourishment was planned at Malad beach. Nariman point to Chowpati, Haji Ali Tomb Area and Worli sea-face were protected by seawalls. The length of coastal protection works carried out in different district is presented in **Table 2.4.1**.

Table 2.4.1. Coastal protection works carried out at different district in Maharashtra

District	Length (kms)
Mumbai	6.003
Thane	18.400
Raigad	41.110
Ratnagiri	31.230
Sindhudurg	30.923

2.4.3 Goa

At Cabo hill to avoid cliff erosion, protection works were provided. Retaining wall is constructed to protect the shoreline at Campal for a stretch of 2 km. At Guddem Siolim for a length of 800 m, at Reis Magos Penha De Franca for 200 m retaining walls are provided.

Laterite walls are provided at Siolim for 250 m and retaining wall at Dona Paula for 400 m. Seawall of granite stone armour is provided for 200 m at Talpona.Gabion seawall is provided along the southern bank of Terekhol River and along the Keri beach for a length of about 1.5 km. The seawall is already damaged due to the monsoon wave attack at certain stretches of the Keri beach. Tetrapod armoured seawall is provided recently for a length of 115 m in the middle portion of the beach and is further being extended.

2.4.4 Karnataka

At Pavinkurve, close to the confluence of the Badagani River and the Sharavati River with the Arabian Sea, stone block/seawalls were built on the erosion-prone beaches by dumping granite stones. The stone block/seawall along the coast was damaged at many places. In Honnagadde areas of Bhatkal taluk to prevent erosion seawall has been built intermittently and was found ineffective.

Historical evidence showed the trend of northward migration of the Nethravathi-Gurupur river mouth from 1905 to 1968. During this period there was severe erosion of the northern (Bengre) spit and accretion on the southern (Ullal) spit. To reduce the erosion, breakwaters were constructed in 1993-94 and after the construction, the southern spit started eroding and northern spit accreted (Rao, et al., 2004). Seawalls were constructed to protect the National Highway at Maravanthe.Coastal protection works carried out in different Taluka of Karnataka are presented in **Table 2.4.2**.

Table 2.4.2. Coastal protection works carried out at different Taluka in Karnataka

Name of Taluka	Total length protected (km)	Total length under progress (km)
Mangalore	6.779	2.954
Udupi	10.390	6.015
Kundapur	3.355	0.520
Bhatkal	4.585	1.000
Honnavar	6.035	0.750
Kumta	2.250	0.550
Ankola	1.550	1.210
Karwar	2.440	1.910
Total	37.384	14.909

2.4.5 Kerala

Seawalls are the major protection measures adopted along the Kerala coast. Groyne and Groyne-seawall combinations were tried along certain parts of the coast during the early years of coastal protection. However, seawalls are the only coastal protective structures adopted since 1964. The total length of seawall constructed so far is about 378 km. Seawalls constructed along the monsoon berm providing a frontal beach have been found to be more successful. Failures of seawalls have also been reported from certain coast. Based on the Coastal zone management plan for Kerala (CESS, Thiruvanathapuram, 1998), the protected sites in Kerala are given in **Table 2.4.3**.

Table 2.4.3. Length of coastal protection works in different divisions in Kerala

Sr.No	Name of division	Total length of seacoast (km)	Length of vulnerable coast (km)	Total length of seawall constructed so far (km)	Proposed for 12^{th} plan
1	Thiruvananthapuram	69.402	39.562	28	6.91
2	Kollam	69.098	67.445	61	1.21
3	Alappuzha	54.25	49.27	39.85	6.63
4	Ernakulam	45.315	45.315	45	21 groynes
5	Thrissur	58.66	46.90	30.45	0.70
6	Malappuram	50.275	42.975	31	11.0

7	Kozhikode	78	62.0	42.6	6.63
8	Thalassery	53	48.368	36.5	2.49
9	Kasargod	82	76.30	17.4	16.30
	Total	560	478.135	378	51.86+21 Groynes

2.4.6 Tamil Nadu

Rubble mound seawalls were constructed along the Ennore expressway from the fishing harbour at Royapuram, North Chennai for a length of 9.68 km. Towards the north of the fishing harbour 10 numbers of Groynes are provided in two separate stretches (2 km and 1.69 km) consisting of 6 and 4 Groynes (**Figure 2.4.1**). The distance between two stretches is 1.335 km. The distance between Groynes are not uniform and vary from 300 to 600 m.

Rubble mound seawall is constructed between villages Thazhanguda and Devanampattinam. Two Groynes are constructed at Thresapuram, Thoothukudi district. Seven rubble mound Groynes of varying length were constructed along Ratchakar street near Kanyakumari. A single Groyneof 265 m long was constructed at Kovalam, Kanyakumari. At Manakkudi, 10 km away from Kanyakumari, two Groynes were constructed.Two rubble mound Groynes were constructed at Arokiapuram, 5 km east of Kanyakumari. Two rubble mound Groynes were constructed at Periyakadu. Six Groynes were constructed near Colachel.

2.4.7 Andhra Pradesh

490m long coastal protection work has beencarried out along Andhra coast

2.4.8 Odisha

To prevent erosion, seawalls were constructed on the north side of Paradip port.

2.4.9 West Bengal

Rubble mound seawall for a total length of 3.5 km from Jatra Nullah on the west and Sea Hawk hotel on the east, was constructed in stages between 1973 and 1982 at Digha. Due to further erosion the seawall was extended towards east by another 500 m during 2002 to 2004.

2.4.10 Puducherry

For the protection of shoreline, the Puducherry government has built rubble mound seawalls using 0.5 to 1.5 tons boulders for a total length of about 5.4 km. In many places along this seawall, the seabed below the seawall is eroded due to severe wave actions and settlement of seawall is observed.Name of the villages protected in the shoreline stretch of the above 5.4 km are:

Solaithandavankuppam, Muthiyalpetai, Vaithikuppam, Kurichikuppam, Puducherry and Vambakeerappalayam.

1 km coast in Mahe is protected with rock revetment. No coastal protection works were carried out at Karaikal and Yanam region at present.

2.4.11 Lakshadweep

Shore protection work has been taken up in all inhabited islands and a total of 40 km shore length has been protected so far.

3. SURVEYS AND RELATED INVESTIGATIONS

3.1 Beach profile and near-shore bathymetry

The region from beach to offshore is divided into different zones as shown in **Figure 1.0.1**. The beach and the near-shore profile undergo seasonal changes. Limit of seasonal changes is expected up to the depth of closure (dc). Beyond this depth, only negligible sand movement is expected. Hallermeier (1978) has developed a procedure for estimating the depth of closure based on the approximate extreme wave condition for near-shore, and is calculated as:

$$dc = 2.28\, He - 68.5\, (He^2/(gTe^2)) \qquad 3.1.1$$

where:

He = near-shore extreme significant wave height (m)
Te = near-shore extreme significant wave period (s)
g = acceleration due to gravity (9.81 m/s^2)

The depth of closure is also calculated using the Birkemeier equation (Birkemeier, 1985). This approach typically provides a more reasonable estimate, compared to Hallermeier's approach, which usually over-predicts the depth of closure. The Birkemeier equation is as follows:

$$dc = 1.75\, He - 57.9\, (He^2/(gTe^2)) \qquad 3.1.2$$

Beach levels are usually taken at suitable intervals, with reference to a local benchmark on the backshore dune, along the transect seaward till low waterline. Automatic level and a graduated staff are generally used for beach survey. Beach profiles can be easily collected using Kinematic Global Positioning System using real-time kinematic survey techniques. Beach profiles are often taken at a monthly interval for quantifying the beach volume changes.

A wave sled similar to the one shown in **Figure 3.1.1** can be used for measuring the profiles in the near-shore. This sled is deployed beyond the surf zone by a boat and then pulled across the surf zone by one or two persons from the beach using a rope. The level readings are taken from the vertical graduated staff and the distance is measured using the rope which is marked for measuring distances.

If the area to be studied is large, Echo sounder is used for depth measurement and Differential Global Position fixing System (DGPS) for position fixing. Corrections for waves and tides are to be applied to the echo sounding record so that the depth readings with respect to chart datum (CD) or mean sea level (MSL) are obtained.

Figure 3.1.1 Near-shore profiling using wave sled

3.2 Waves

3.2.1 Wave data

The wave data is obtained through (a) wave recording instruments, (b) remote sensing, (c) wave hind-castsusing numerical models and (d) visual observations.

(a) Wave recording instruments

Various instruments are available to measure waves. An underwater pressure gauge can measure the height of the water column above it, and hence, the height and period of waves at the surface. Another method is to place instruments such as accelerometers and pitch-and-roll recorders on moored buoys, known as wave-rider buoys to detect and record the rate of rise and fall, and the direction of slope of the sea surface in response to waves.

Data for deep waters and few shallow water locations collected by the National Data Buoy Programme of National Institute of Ocean Technology is available at http://www.incois.gov.in/portal/datainfo/mb.jsp. Data for few shallow locations are available through the Indian National Centre for Ocean Information Services (INCOIS), Hyderabad (http://www.incois.gov.in/Incois/indofos_coastal.jsp).

(b) Remote sensing

Through remote sensing, the wave data over a large area are obtained by employing radars onboard satellites. This method involves the use of visible light optical techniques, as well as radio backscatter techniques based on microwaves. Over the past two decades, microwave remote sensing has evolved into an important tool for monitoring the ocean wave field. The most important reason for using microwaves is their ability to penetrate clouds. Synthetic Aperture Radar (SAR) is the major sensor used to obtain the wave spectrum. SAR emits an oblique pulse of microwave radiations and measures the intensity of the backscattered energy. The complex phase of the returned signal as well as its amplitude is measured and processed in a special way to reproduce an image of the back scattered cross section of the surface. Data so obtained, however, needs good judgment to interpret. Application of stereophotography to the observation of ocean waves is similar to their conventional use in geodetic survey. Satellite altimeters measure the wave height from the shape of radar return pulse. Each altimeter mission, including GEOSAT, ERS-1, ERS-2, TOPEX, JASON-1, ENVISAT and GFO has collected global measurements of wave heights at various spatial and temporal resolutions. The altimeter products are produced and distributed by AVISO (http://www.aviso.oceanobs.com/).

(c) Wave hind-casting

By hind-casting, the wave heights are computed using numerical model/analytical method for an area using the past meteorological data of the region. Theadvantage of this method is that the wave data can be generated for large area. But the wave hind-cast results need to be compared with measured data. Instrumental data pertaining to waves at present are available for limited area but are more reliable.It is therefore essential for any shore protection or monitoring of coastline to have reliable measurements of wave climate. National Institute of Ocean Technology, Chennai has published a wave atlas based on the wave hind-casting data for 15-year (1998 to 2012) for the Indian seas (Sivakholundu et al., 2014).

(d) Visual observations

Most of the long-term data on waves presently available are based on visual observations made from the ships. A wave atlas for the Indian coast based on the ship reported waves around the Indian coast is published (Chandramohan et al. 1990).Since this wave atlas covers large offshore regions and not focused coastal areas, this wave atlas data should be used cautiously for design purposes

3.2.2 Wave parameters

Wind waves can be broadly classified as seas and swells. Seas, also known as wind waves, are those under the influence of wind in a generating area. In general, wind waves are highly irregular in appearance and tend to be short-crested. Swells, on the other hand, are also wind-generated waves that have travelled out of the region of their generating area. A sea state may consist of just wind waves or just swells or a combination of both.

Wave parameters are determined either by wave statistical method or by the spectral method. The most appropriate parameters to describe the sea state from a measured wave record are significant wave height (its value roughly approximates to visually observed wave height) and the mean wave period. Significant wave height (Hs) is the average height of the highest one-third of all waves occurring in a chosen time period. Mean wave period is the average of all the wave periods in the wave record. The mean wave period obtained by averaging the periods of all the waves with troughs below and crests above the mean water level is also called the zero-crossing period.A typical wave record is shown in **Figure 3.2.1a**.

In the wave spectral method, the time series of the wave record is converted into a form of energy density function and the distribution of wave energy with respect to the frequency and direction is estimated. The wave frequency spectrum is obtained from the time series of the sea surface elevation using the Fourier analysis. The wave frequency spectrum estimated for the wave record shown in Figure 3.2.1a is presented in **Figure 3.2.1b**.

Wave parameters are determined from the wave frequency spectrum using the following equations.

Significant wave height, $Hs = 4\sqrt{m_0}$ 3.2.1

Mean wave period , $T_z \approx \sqrt{\frac{m_0}{m_2}}$ 3.2.2

where m_0 is zeroth moment or total area of the wave spectrum and m_2 is the second moment of the wave spectrum.

Peak period (Tp) is the period associated with the spectral peak. Most often, the frequency spectra along the Indian coastline are multi-peaked (Baba and Harish, 1986, Kumar et al, 2003). One peak may correspond to swells at lower frequencies and one or sometimes more peaks are associated with local wind waves at comparatively higher frequencies. The direction of swells may also differ from those of wind waves.

Environmental conditions that are expected to occur regularly during the life of the structure are known as normal environmental conditions. These are estimated based on the past data available using statistical distribution. The return period of these values are 1 to 2 years. The environmental conditions that occur rarely during the life of the structure are known as extreme conditions and are estimated based on the past data covering 20 to 30 years andthe return period of these values are 50 to 100 years. Design of coastal structures requires the information on design wave height having certain return period.

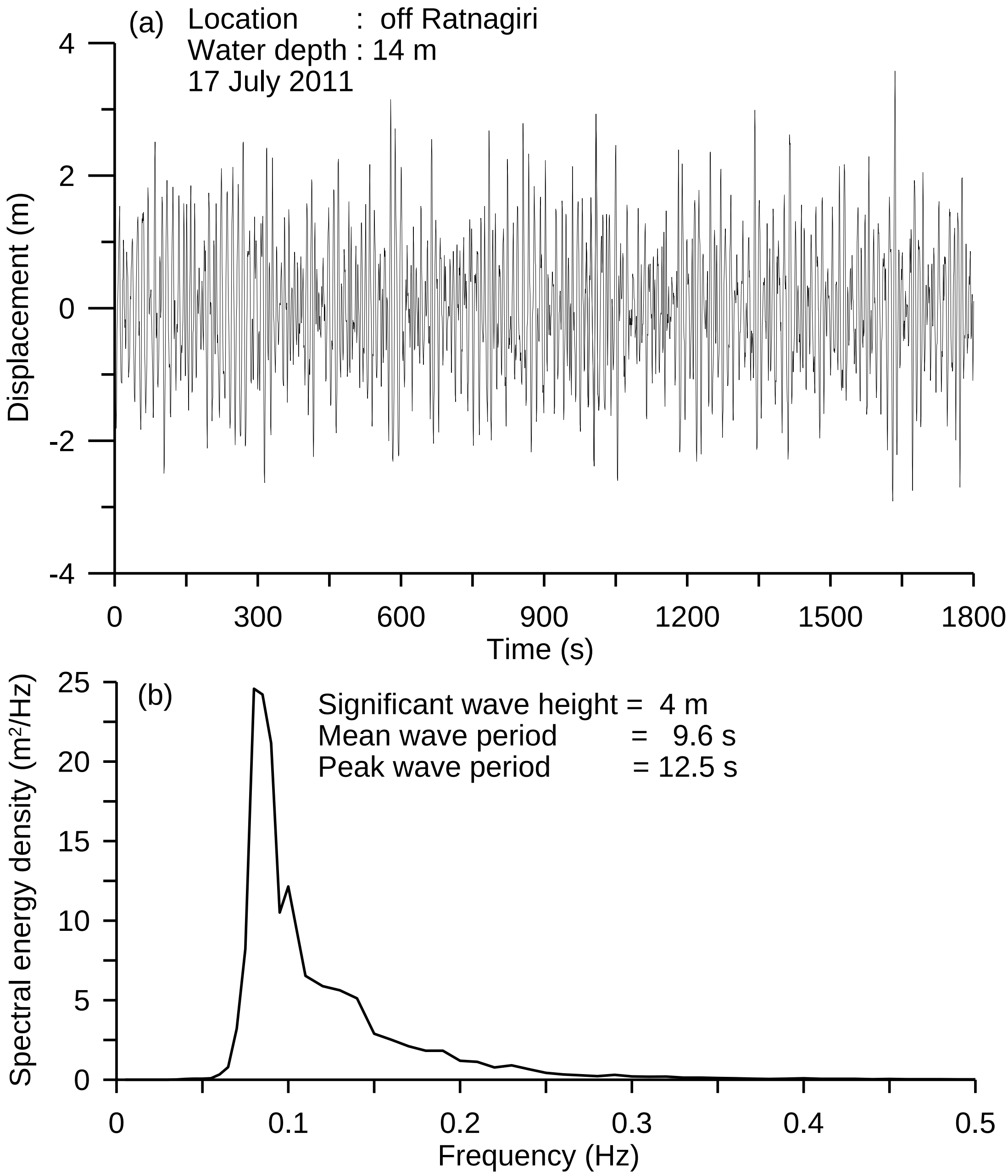


Figure 3.2.1 (a) Typical wave record and (b) estimated wave spectrum

Steps involved in estimation of the design wave height are given below.

- The scatter diagrams of significant wave height (Hs) values are prepared from either the measured data or from the hind-cast data covering large period. From these, the observed cumulative distributions for H_s values are obtained.

- The cumulative distribution of observed Hs is fitted to a suitable probability distribution.Usually for estimation of design wave height, generalized extreme value distribution (Gumbel, Weibull or Fisher-Tippet distributions) or generalized Pareto distribution are used.

- A plotting formula is used to reduce the data to a set of points describing the probability distribution of wave heights.

- These points are plotted on an extreme value probability paper corresponding to a chosen probability distribution function.

- A straight line is fitted, either through the method of moments or by the method of least squares.

- The line is then extrapolated to locate a design value corresponding to a chosen return period.

Wave transformation:

As waves move towards the shore from deep to shallow waters, they undergo a number of changes, which include a decrease in speed and wavelength, an increase in height, energy and steepness, a change in shape and finally the wave breaks. Waves undergo shoaling, refraction and breaking of waves when propagating from deep water to shallow water. Shoaling is the result of decrease in propagation speed due to the reduced depth. When the waves approach the shore at an angle, a part of the wave in deep water travels faster than the part in the shallow water. This makes the wave crest to bend and causes the angle between the wave crest and the depth contours to reduce. Wave refraction not only influences the propagation direction, but also the wave height. Because of energy conservation the wave height increases when the waves are converged and wave height decreases when waves diverged.Breaking occurs either due to high steepness or due to shallow water and the energy will be dissipated and wave height will be reduced considerably. The area, where the dissipation of energy takes place, is called the surf zone.

The wave period is generally regarded as being equal to the deepwater wave period, but in reality the wave period may also vary during wave propagation, as in the sheltered area behind a breakwater.

There are nomograms as well as numerical models for estimating shallow water waves. The details are available in the Coastal Engineering Manual (www.chl.erdc.usace.army.mil) of the US Army Corps of Engineers (CEM, 2002). Some of the numerical models for estimating the shallow water waves are

CEDAS, SWAN, MIKE21, Ref-Dif, Delft-3D. An approximate value of the shallow water wave can be easily calculated using the University of Delaware wave calculator (http://www.coastal.udel.edu/faculty/rad/).

3.3 Currents

The currents in the surf zone derive energy from breaking waves and transport the sediments. The currents beyond the surf zone are mainly governed by the wind, tides and density gradient.Tidal currents vary from place to place depending upon the tidal range, water depth and configuration of the coast. The tidal components of the current in the sea or bay are periodic in behavior and repeat themselves as regularly as the tides to which they are related.

Current measurements are made using Eulerian or Lagrangian approaches. In the Eulerian method, measurement is made as water passes a fixed point and in the Lagrangian method, by following the path of water particles. Both principles have their limitations but measurements at fixed points with current meters are far more common than the path following method using neutrally buoyant floats or drogues.

Longshore current measurements in the surf zone are carried out by using dyes, floats or using surfzone current meters (Acoustic Doppler Velocimeter or electromagnetic current meter).

3.4 Tide

Variation of water levels due to tides can be recorded either by erecting tide poles or by water level recorders. In the case of tide poles, readings are to be taken manually. Measurements using a water level recorder will give continuous data indicating the variation of the tide elevation over required period.

For areas nearer to major harbours, the Indian Tide Tables published by the Survey of India, Dehra Dun provides daily high and low tides for the year (Tide Table, 2017).

3.5 Littoral environmental parameters

Breaking wave height, wave period and direction can be visually observed by an experienced coastal engineer/researcher. Heights of 10 consecutive breakers are visually measured and their average is taken as the corresponding breaking wave height. The time required for consecutive breakers can be noted using a stopwatch and the average can be considered as breaking wave period. The breaking wave angle with respect to the coastline can be measured using a magnetic compass. Wave breaker parameters can be measured by installing submerged wave measuring instruments in the near-shore (e.g., Pressure transducers).

Before planning any coastal protection measures, it is necessary to know the predominant direction of the littoraldrift and its magnitude in either direction alongthe shore. Usually, it is easy to determine the predominant direction of the drift, particularly if the shore has some headlands or reefs or man-made structures, which by the sand accumulation pattern will show the predominant direction of drift. If no natural or human-made obstruction is available, as in the case of many shore segments along the east coast of India, a study of the migration of natural inlets along the coast will give the desired information as the inlets migrate in the direction of the predominant littoral drift. It will, however, be difficult to determine the relative magnitude of the drift in either direction. Long-shore current generated by obliquely incident breaking waves plays a major role in transporting sediment in the surf zone. The long-shore current velocity varies across the surf zone, reaching a maximum value close to the wave breaking point (Galvin, 1967; Basco, 1982). For practical purposes, the average long-shore current measured in the surf zone should be sufficient for estimating the long-shore sediment transport rate (LSTR). LSTR is in general, calculated using semi-empirical equations, which are mostly based on laboratory data (USACE, 1984). One of the simplest and most commonly used methods for calculating LSTR is the Coastal Engineering Research Center (CERC) formula. As per the CERC, the longshore transport rate is given by,

$$Q = KA\frac{\rho g}{64\pi} T H_b^2 \sin 2\alpha_b \qquad 3.5.1$$

where Q = volume of long-shore transport rate in m^3/year, K = dimensionless constant relating sand transport to long-shore energy flux, $A = \frac{1}{(\rho_s - \rho) g (1-p)}$, ρ_s = mass density of the sediment (≈2650 kg/m^3), ρ = mass density of sea water (≈1025 kg/m^3), g = acceleration due to gravity (9.81 m/s^2), p = porosity of sediment (≈0.4), T = wave period in s, H_b = breaking wave height in m, and α_b = breaker angle with respect to coastline.

Using the observed breaker height, measured surf zone width and average longshore current velocity in the surf zone, the LSTR can be calculated using Walton and Bruno equation (Walton and Bruno, 1989):

$$Q = \frac{K A \rho g H_b W V C_f}{0.78 \left(\frac{5\pi}{2}\right)\left(\frac{v}{v_0}\right)_{LH}} \qquad 3.5.2$$

where, C_f = the friction coefficient (0.005), W = surf zone width in m, V = measured long-shore current velocity in m/s and $(v/v_0)_{LH}$ = theoretical dimensionless long-shore current velocity with the mixing parameter as 0.4 (Longuet-Higgins, 1970).

3.6. Beach sediments

Sufficient number of beach sediment samples should be obtained for the grain size distribution to represent the entire beach. Samples should cover (a) along the beach and (b) across the beach. The samples should also cover the pre-monsoon, monsoon and post-monsoon period. Indian Standard classification system of grain size analysis are generally used in coastal engineering practice. The range of particle sizes encountered in soils is very large: from boulders with dimension of over 300 mm down to clay particles that are less than 0.002 mm (**Table 3.6.1**). In theIndian Standard Soil Classification System (ISSCS),soils are classified according to size, and the groups are further divided into coarse, medium and fine sub-groups. The grain-size range is used as the basis for grouping soil particles into boulder, cobble, gravel, sand, silt or clay.

Table 3.6.1. Sediment grain size classification

Very coarse soils	Boulder size		> 300 mm
	Cobble size		80 - 300 mm
Coarse soils	Gravel size (G)	*Coarse*	20 - 80 mm
		Fine	4.75 - 20 mm
	Sand size (S)	*Coarse*	2 - 4.75 mm
		Medium	0.425 - 2 mm
		Fine	0.075 - 0.425 mm
Fine soils	Silt size (M)		0.002 - 0.075 mm
	Clay size (C)		< 0.002 mm

Grain size is also expressed in ϕ scale and the conversion from mm to ϕ scale is as per equation 3.6.1.

$$\phi = -\log_2 D \qquad 3.6.1$$

where D is the size of the particle in mm.

3.7. Wave run-up

Waves undergo several physical processes such as reflection, transmission, wave breaking with the associated energy losses, wave run-up and sometimes overtopping when they interact with coastal structures such as seawalls, revetments, breakwaters and Groynes. Among these physical processes, wave run-up and overtopping are two major complex phenomena that influence the design of structure.

Wave run-up is the maximum vertical extent of wave uprush on a beach or structure above the still water level (Sorensen, 1997). The height of the protection structure will be estimated based on the wave run-up. Wave run-up is influenced by geometrical parameters (slope of the armor layer, water depth, free board and crest width), structural parameters (porosity, permeability, stone shape, size and layer thickness) and hydraulic parameters (mean sea level, wind speed, wave height distribution, spectral shape, wave direction, wave grouping, wave period, wave breaking and currents). Breaker types can be identified by the surf-similarity parameter (ξ). The parameter ξ is also referred to as the breaker parameter or

Irribarren number (CEM, 2002).For armoured rubble slopes with core permeability factor P = 0.1 and porous mounds of relatively high permeability (P= 0.5 to 0.6), the wave run-up can be estimated as per Van der Meer (1988) formula.

$$\frac{R_{ui}}{H_s} = a\xi_m \quad \text{for} \quad \xi_m < 1.5 \qquad 3.7.1$$

$$\frac{R_{ui}}{H_s} = b\xi_m \quad \text{for} \quad \xi_m > 1.5 \qquad 3.7.2$$

The run-up for permeable structures (*P* > 0.4) is limited to a maximum:

$$\frac{R_{ui}}{H_s} = d \qquad 3.7.3$$

Where R_{ui} is the run-up at i% exceedence level (m).
H_s is the significant wave height (m)
ξm = surf similarity parameter = tan α / $\sqrt{s_m}$
α = average slope angle (degree)
sm = offshore wave steepness based on mean wave period = $2\pi H_s$ /g T_m^2
Tm = mean wave period (s)

Values of coefficients a, b and d for exceedence levels of I equal to 1%, 2%, 5%, 10% and significant run-up levels are given in **Table 3.7.1**.

Table 3.7.1. Coefficients for exceedence levels

Exceedance levels i	a	b	d
1%	1.01	1.24	2.15
2%	0.96	1.17	1.97
5%	0.86	1.05	1.68
10%	0.77	0.94	1.45
significant	0.72	0.88	1.35

Run-up estimates for revetments covered with materials other than riprap may be obtained with the rough slope correction factors in **Table 3.7.2**. Table 3.7.2 was developed for earlier estimates of run-up based on monochromatic wave data and smooth slopes. To use the correction with the irregular wave rough slope run-up estimates of the above equation, multiply R_{max} obtained from the equation for riprap by the correction factor listed in the table and divide by the correction factor for quarry-stone. For example, to estimate R_{max} for stepped 1:1.5 slope with vertical rises, determine R_{max} and multiply $R_{max}$by (0.75/0.60)=1.25 for the stepped slope is seen to be 25 % greater than for a riprap slope.

Maximum run-up may be estimated by using the rough slope equation and converting the estimate to smooth slope by dividing the result by the quarry stone rough slope correction factor.

Run-up determinations for vertical and curved face walls should be made using the guidance given in Coastal Engineering Manual (CEM, 2002).

Table 3.7.2. Rough run-up correction factor (Carstea et al., 1975)

Armor type	Slope (cotθ)	Relative size	Correction Factor
Quarry stone	1.5	H/K_r =3 to 4	0.60
Quarry stone	2.5	H/K_r =3 to 4	0.63
Quarry stone	3.5	H/K_r =3 to 4	0.60
Quarry stone	5	H/K_r =3	0.60
Quarry stone	5	H/K_r = 4	0.68
Quarry stone	5	H/K_r = 5	0.72
Concrete Blocks	Any	H/K_r = 6*	0.93
Stepped slope with vertical risers	1.5	$1\leq H_0'/K_r$	0.75
Stepped slope with vertical risers	2.0	$1\leq H_0'/K_r$	075
Stepped slope with vertical risers	3.0	$1\leq H_0'/K_r$	0.70
Stepped slope with rounded risers	3.0	$1\leq H_0'/K_r$	0.86
Concrete Armor Units			
Tetrapods random two layers	1.3 to 3.0	-	0.45
Tetrapods uniform two layers	1.3 to 3.0	-	0.51
Tribars random two layers	1.3 to 3.0	-	0.45
Tribarsuniform two layers	1.3 to 3.0	-	0.50

K_r is the characteristic height of the armor unit perpendicular to the slope. For quarry stone, it is the nominal diameter; for armor units, the height above the slope. K_r is the riser height for stepped slope with vertical risers.

Use Ho' for $d_s/h_o > 3$ and the local wave height, H_s for $d_s/H_o \leq 3$ (Ho is the un-refracted deep water wave height).

Wave overtopping:

Wave overtopping of riprap revetments may be estimated from the dimensionless equation 3.7.4 (Ward et al., 1992).Eurotop Manual on wave overtopping of sea defences and related structures is another reference useful on this topic available at www.overtopping-manual.com.

$$Q' = \frac{Q}{\sqrt{gH_{mo}^2}} = C_o \exp\left(C_1 F + C_2 m\right) \quad 3.7.4$$

Where non –dimensional freeboard, $F' = F/\left(H_{mo}^2 L_o\right)^{1/3}$

m cotangent of the revetment slope, Cotθ

C_o, C_1, C_2=Regression coefficients equal to 0.4578, -29.45, 0.8464 respectively

The coefficient listed above were determined for dimensionless freeboards in the range 0.25<F<0.43, and revetment slopes 1.2 and 1:3.5.

Overtopping rates for seawalls are complicated by the numerous shapes found on the seawall face plus the variety of fronting berms, revetments, and steps. Information on overtopping rates for a range of configurations is available in Ward and Ahrens (1992). For bulkheads and simple vertical seawalls with no fronting revetments and a small parapet at the crest, the overtopping rate may be calculated from equation 3.7.5.

$$\frac{Q}{\sqrt{gH_{mo}^2}} = C_o \exp\left(C_1 F + C_2 \frac{F}{d_s}\right) \qquad 3.7.5$$

Where d_s=depth at structure toe and F is non-dimensional freeboard.

C_o, C_1, C_2= 0.338,-7.85,-2.178 respectively. For other configurations of seawalls, Ward and Ahrens (1992) should be referred and physical model tests should be performed.

Since onshore winds increase the overtopping rate at a barrier. The overtopping rate may be adjusted by multiplying a wind correction factor given by.

$$k' = 1.0 + Wf\left(\frac{h - d_s}{R} + 0.1\right)\sin\theta \qquad 3.7.6$$

Where W_f is a coefficient depending on wind speed, and θ is the structure slope. For a wind speed of 96 km/hr or greater, W_r = 2.0 should be used.

3.8. Shoreline changes

Before planning any coastal protection measures, the present shoreline positions is to be compared with the past one, to find out whether the shoreline is eroding or accreting.

Various survey methods are used to monitor shoreline changes. Methods using GIS and remote sensing techniques are being used to map large areas in short periods. Satellite derived information is economical and less labour intensive. Also historical position of the shoreline can be obtained through satellite images. The synoptic view provided by satellite remote sensing along with its repeated coverage, enables to detect the shoreline changes. Indian Remote Sensing Satellite, IRS–1C provides a spatial resolution of 5.6 m and temporal coverage of 24 days.

4. BASIC DESIGN PARAMETERS FOR DIFFERENT LOCATIONS

Oceanography of the Indian coastal region is dominated by three seasons viz., southwest monsoon (June to September), northeast monsoon (October to January) and fair weather period (February to May).

4.1 Winds

The average wind speed during the southwest monsoon period is about 35 km/hr frequently increasing up to 45 - 55 km/hr. The average speed of the wind during the northeast monsoon prevails around 20 km/hr. Tropical storms known as cyclones frequently occur in the Bay of Bengal during October to January.During cyclonic period, wind speed often exceeds 100 km/hr. IS-875: Part 3 (1987) gives the basic wind speed for all the coastal locations. **Table 4.1.1** presents the basic wind speed for some of the coastal stretches. The maximum wind speed estimated by India Meteorological department for the super cyclone in 1999 was 71.9 m/s (259 km/hr).

Table 4.1.1. Basic wind speed at 10 m height for some coastal locations

Location	Basic wind speed (m/s)	Basic wind speed (km/hr)
Bhuj	50	180.0
Bahruch	47	169.2
Vadodara	44	158.4
Mumbai	44	158.4
Panjim	39	140.4
Mangalore	39	140.4
Kozhikode	39	140.4
Lakshadweep	39	140.4
Thiruvanthapuram	39	140.4
Puducherry	50	180.0
Chennai	50	180.0
Port Blair	44	158.4
Vijaywada	50	180.0
Visakhapatnam	50	180.0
Bhubaneshwar	50	180.0
Kolkata	50	180.0

(Ref: IS 875:Part 3 – 1987)

4.2 Waves

A detailed account of the climate over the southern part of the Bay of Bengal is given in the Bay of Bengal Pilot (1953). While southwest and northeast monsoon have equal impact along the southern part of the east coast, only the southwest monsoon has the significant effect on the west coast. The west coast of India experiences high wave activity during the southwest monsoon with relatively calm sea conditions prevailing during the rest of the year. On the east coast, the wave activity is significant both during southwest and northeast monsoons. Extreme wave conditions are, however, found to occur under severe tropical cyclones, which are frequent in the Bay of Bengal.

Along the west coast, the waves approach from west and west-southwest during southwest monsoon, from west and west-northwest during northeast monsoon and from southwest during fair weather period. Along the east coast, waves approach from southeast during southwest monsoon and fair weather period and from northeast during northeast monsoon respectively.

The design of coastal structures calls for information on design significant wave height (Hs) having a certain return period of 100 years. Such a design wave height is obtained by collecting 3-hourly, over a long period; say a few years at the given location. Based on the wave measurements carried out by CSIR-National Institute of Oceanography (NIO) Goa at different places along the Indian coast and from the published literature, the wave characteristics at different locations are presented in **Table 4.2.1**. These are site specific data and cannot be considered for other locations. Under Asian Development Bank funding FCC ANZDEC, New Zealand has carried out climate resilient coastal protection measures studies (Black et al., 2017). These studies include the design wave parameters under climate change scenarios.

Estimation of extreme wave height during a cyclone/storm has considerable importance in planning and operation of near-shore activities and design of structures. The average wave period for these extreme waves ranges from 9 to 13s. Storm data of the past 40 to 100 years are used and the estimated wave height for 20 to 30 m water depth are presented in **Table 4.2.2** (Kudale et al., 2004).

During the Thane cyclone, Hs of 6.1 m was measured off Puducherry at 14 m water depth. During the Phailin cyclone, Hs of 7.3 m was measured off Gopalpur at 50 m water depth (Amrutha et al., 2014). During the Hudhud cyclone, Hs of 7.6 m was measured off Gangavaram.

Table 4.2.1. Wave characteristics at different locations based on measured data

Location	Water depth (m)	Duration of data (month)	Range of Hs (m)	Hs for 100 year return period (m)	Predominant average wave period (s)
Mundra*	18	6	0.1 - 2.2	4.4	2 - 6
Kandla*	15	12	0.1 - 2.8	4.4	3 -11
Veraval+	15	4	N.A.	5.3	N.A.
Dahej*	20	7	0.1 - 2.0	3.0	2 -10
Hazira*	15	7	0.1 - 2.9	4.2	2 -14
Daman*	27	7	0.1 - 6.0	8.0++	3 -15
Umbergaon*	37	6	0.2 - 4.8	6.6++	3 -16
Vadhavan Point*	24	8	0.3 – 2.8	3.4	3 -15
Bombay High*	75	19	0.4 – 5.1	7.8	3 -16
Mumbai+	30	3	N.A	5.1	N.A
Uran*	10	5	0.2 - 2.5	3.2	4 -16
Dabhol*	14	5	0.4 - 4.6	7.1	3 - 8
Ratnagiri+	10	12	N.A	3.9	N.A
Jaitapur*	16	12	0.1 - 3.3	5.6	3 - 15
Mormugao*	23	12	0.3 - 5.9	9.7++	3 - 9
Mormugao+	14	4	N.A	5.1	N.A
Karwar*	16	48	N.A	6.1	N.A
Mangalore+	13	5	N.A	4.1	N.A
Kavaratti*	10	4	N.A	2.1	N.A
Kalpeni*	11	12	0.2 - 2.3	3.1	3 -12
Androth*	11	12	0.3 - 2.5	3.6	3 - 9
Agatti*	15	12	0.3 – 1.8	2.2	3 - 11
Minicoy*	10	12	0.3 - 1.7	2.3	3 - 11
Kannirajapuram*	12	12	0.3 – 1.9	2.3	3 - 9
Nagore*	10	12	0.2 – 2.0	3.2	2 - 9
Pillaiperumalnallur*	15	12	0.2 – 2.1	2.7	2 - 9
Porto Novo*	80	6	0.3 - 2.1	2.8	3 -12
Machalipattanam*	20	8	0.5 – 2.3	3.0	3 -15
Narasapur*	10	11	0.2 - 4.2	4.6	4 - 12
Yanam*	90	12	0.3 – 2.8	3.5	3 -15
Tikkavanipalem*	12	12	0.3 – 3.9	4.2	3 - 10
Visakhapatnam+	17	36	N.A	4.9	N.A
Gopalpur*	10	12	0.2 – 2.5	3.1	3 - 9
Gopalpur*	15	12	0.2 – 3.3	4.8	4 - 8
Paradip*	16	9	0.1 – 3.7	6.3	3 -10
Sunderban*	20	3	N.A	2.1	N.A

* Based on data by CSIR-National Institute of Oceanography, Goa (Kumar et al., 2006)

+ Based on data by Central Water & Power Research Station, Pune (Kudale et al., 2004)

++ Cyclone crossed the measurement locations

N.A. : details not available

Table 4.2.2. Predicted wave heights using hind-cast storm data

Location	Hs for 100 year return period (m)
Porbandar	6.8
Dahej	5.0
Tarapur	5.1
Mumbai	5.4
Mormugao	6.2
Kochi	4.5
Nagapattinam	9.4
Visakhapatnam	7.6
Gopalpur	7.4
Paradip	8.3

*based on data by CWPRS, Pune (Kudale, et al. 2004)

Since the measured wave data cover only short period (mostly one year or less), the ship reported visual observation documented in Indian daily weather reports published by the India Meteorological department, Pune were also compiled for a period of 18 years from 1968 to 1986 for different regions (5° x 5° grid) along the Indian coastline (Chandramohan et al., 1990) and the design significant wave height for 100 year return period at deep water was estimated and presented in **Table 4.2.3**.

Table 4.2.3. Estimated deep water wave height based on ship reported data

Grid	Latitude	Longitude	Hs for 100 year return period (m)
1	20-25°	85-95°	7.82
2	15-20°	85-90°	8.00
3	15 -20°	80-85°	7.85
4	10-15°	80-85°	7.60
6	5-10°	75-80°	8.40
7	5-10°	70-75°	8.91
8	10-15°	70-75°	8.24
9	15-20°	70-75°	8.88
10	20-25°	65-75°	8.34

When the waves travel from deep water to shallow water, waves undergo different processes such as refraction, shoaling, bottom friction and percolation and will influence wave height and wave direction. Based on the water depth at which the design parameters are required, a near-shore wave transformation needs to be done and the value of the wave parameters obtained need to be used in the design. If the estimated wave height exceeds 0.6 times the water depth, then the wave heights need to be limited to 0.6 times the water depth. If there is no information on waves available for the study region, wave characteristics need to be estimated from the wind data using numerical models (Delft-3D, MIKE21, SWAN, etc.).

4.3. Tides

Tides in Indian coastal region is semi-diurnal with tidal ranges varying from 8.9 m at Bhavnagar, Gulf of Khambhat to 0.6 m along the peninsular tip of India. Different tide levels at some locations along the Indian coast published in the Indian Tide Tables of Surveyof India (Tide Tables, 2017) are shown in **Tables 4.3.1 and 4.3.2**.

Table 4.3.1. Design tide levels at some locations along the Indian coast

1. Location name
2. Mean lower low water springs (m)
3. Mean low water springs (m)
4. Mean low water neaps (m)
5. Mean sea level (m)
6. Mean High water neaps (m)
7. Mean High water springs (m)

1	2	3	4	5	6	7
Navlakhi	0.37	0.78	2.14	4.15	6.16	7.21
Kandla	0.34	0.78	1.81	3.88	5.71	6.66
Bhavnagar	1.21	1.43	3.52	6.07	8.31	10.18
Mumbai (Apollo Bandar)	0.32	0.76	1.86	2.51	3.30	4.42
Tuticorin	0.25	0.29	0.55	0.64	0.71	0.99
PambanPass	0.06	0.10	0.32	0.41	0.48	0.70
Nagapattinam	0.00	0.03	0.20	0.34	0.47	0.65
Chennai	0.09	0.14	0.43	0.65	0.84	1.15
Kakinada	0.15	0.20	0.60	0.87	1.13	1.54
Visakhapatnam	0.02	0.09	0.54	0.84	1.08	1.52
Paradip	0.64	0.71	1.32	1.66	2.02	2.58
DiamondHarbour	0.90	0.94	2.14	3.30	4.42	5.94
Gangra (Hugli R)	0.77	0.83	2.09	3.16	4.12	5.60
Garden Reach (Kolkata)	1.37	1.41	2.00	3.19	4.10	5.62
Haldia	0.73	0.80	2.10	3.23	4.26	5.70
Mayapur (Hugli R.)	0.86	0.91	1.78	3.00	3.98	5.54
Shortt's Island	0.53	0.58	1.43	1.92	2.42	3.34
Sagar (Hugli R.)	0.84	0.92	2.23	3.00	3.86	5.22
Port Blair	0.23	0.28	0.90	1.21	1.53	2.18

Table 4.3.2 Design tide levels at some locations along the Indian coast

1. Location name
2. Lower low water springs near solstices (m)
3. Mean lower low water (m)
4. Mean higher low water (m)
5. Mean sea level (m)
6. Mean lower high water (m)
7. Mean higher high water (m)
8. Higher high water springs near solstices (m)

1	2	3	4	5	6	7	8
Okha	0.05	0.41	1.20	2.04	2.96	3.47	3.89
Porbandar	0.35	0.77	1.46	1.82	2.38	2.66	2.91
Veraval	0.24	0.48	1.09	1.33	1.82	2.09	2.41
Pipavav Bandar	0.01	0.50	1.16	1.76	2.37	3.19	3.92
Mormugao	0.00	0.37	1.05	1.30	1.78	2.06	2.30
Karwar	0.04	0.32	0.92	1.33	1.64	1.90	2.13
Mangalore	0.03	0.26	0.70	0.95	1.26	1.48	1.68
Beypore	0.18	0.37	0.77	0.88	1.11	1.31	1.51
Kochi	0.20	0.29	0.56	0.64	0.79	0.92	1.05
Minicoy,Lakshadweep	0.27	0.48	0.87	1.08	1.18	1.37	1.54

If there are no measured tide data for the study region, tides can be interpolated from the predicted tides between the established stations.

4.4. Currents

Currents near the river mouths are greatly influenced by tides. The regions along the open coast within few kilometer from coastline are mostly dominated by wind and seasonal circulation pattern. Normally the currents in Gulf of Kachchh and Gulf of Khambat are highly influenced by tides with speeds exceeding 2 m/s throughout the year. The typical currents in shallow water based on the measured data available at NIO is shown in **Table 4.4.1**.

Table 4.4.1. Currents at shallow water along the Indian coast (Kumar et al., 2006)

Station	Water depth (m)	Distance above bed (m)	Period	Speed (m/s)	Predominant direction (deg)
Kharo creek	18	10	December 1994	0.3 – 1.0	240 & 300
Positra	20	10	December 1993	0.4 – 0.5	180 & 360
Kandla	10	4	March 1996	0.05 – 1.6	180 & 360
	10	4.5	October 1996	0.05 – 1.5	180 & 360
Vadinar	25	20	March 1994	0.2 – 0.8	60 & 270
Muldwaraka	17	11	January 2000	0.1 – 0.5	290 & 120
Dahej	24	23	July to October 2003	0.01 – 3.2	180 & 360

Dhabol	9	5.6	October 1994	0.1 – 0.5	330 & 150
Mormugao	23	10	April 1998	0.02 – 1.2	180 & 360
	23	7	January 1998	0.03 – 0.3	180 & 360
	5	2.5	April 1996	0.03 – 0.6	120 - 300
	8	2.5	November 1995	0.05 – 0.5	90 - 270
	3	1.5	April 1996	0.02 – 0.6	110 - 270
	3	1.5	September1996	0.1 – 0.6	110 – 300
Karwar	10	5	May-June 1988	0.02 – 0.5	90 & 270
	14	7	May-June 1988	0.02 – 0.6	180 - 270
Mangalore	9	6	May 1999	0.05 – 0.4	180 & 360
Kochi	8	6	April 1998	0.05 – 0.4	170 - 220
	6.5	4.5	April 1998	0.05 – 0.9	170 -350
	4	3	October 1998	0.05 – 1.4	180 -270
Kannirajapuram	4	2	February 1997	0.01 – 0.3	215
	4	2	August 1997	0.01 – 0.2	30 - 60
	4	2	December 1997	0.01 – 0.2	210
	7	3.5	March 1997	0.01 – 0.3	215
	7	3.5	July 1997	0.01 – 0.3	45 - 360
	12	6	March 1997	0.1 – 0.9	270
	12	6	August 1997	0.1 – 0.9	60
Tuticorin	2.5	2	June 1999	0.05 – 0.2	90 - 270
Nagapattinam	16	8	February 1995	0.12 – 0.6	30 & 330
	16	8	August 1995	0.04 – 0.4	180 & 360
	14	7	March 1995	0.1 – 0.4	180 & 360
	14	7	September 1995	0.11 – 0.5	180 & 360
Chinnakuppam	14	7	August 1996	0.03 – 0.3	180 -225
Mahabalipuram	9	7	March 1996	0.1 – 0.3	30 - 360
Tikkavanipalem	12	9	January 1998	0.02 – 0.1	270 - 90
	12	3	January 1998	0.1 – 0.3	60 & 240
Gopalpur	15	3	January 1994	0.1 – 0.4	225
	15	7	February 1994	0.05 – 0.4	45 & 225
Paradip	15	9	May 1996	0.1 – 0.8	65
	30	29	November 1996	0.1 – 1.2	30 - 60

4.5. Storm surge

Storm surge is the rise in water level associated with storms. The meteorological forces, which generate storm surges, are thus the wind stress and horizontal gradients of surface atmospheric pressure associated with traveling weather systems. Tropical cyclones capable of generating surges usually occur during the monsoon transitions (April to May or September to December). A storm surge level of 5.45 m above chart datum was reported by the ParadipPort authorities during the passage of the storm. Maximum possible storm surge amplitude and total water level at selected locations on the west coast of India for wind of 40 m/s is presented in **Table 4.5.1**.

Table 4.5.1. Maximum possible storm surge amplitude and total water level at selected locations on the west coast of India for maximum wind of 40 m/s

Location	Favorable wind direction	Peak surge amplitude (m)	Maximum value of total water level (m)
Rann of kutch	WSW	3.9	6.7
Balachin	W	5.1	6.5
Dwaraka	SW	1.6	8.5
Porbandar	SSW	1.6	2.7
Veeraval	SW	1.5	2.5
Diu	SSE	2.2	3.7
Jafarabad	SSE	3.1	5.2
Mahuva road	SE	2.0	3.4
Mal bank	S	4.3	7.2
Mindola	WSW	5.2	8.7
Suvali Point	WSW	3.3	5.5
Bulsar Kheri	W	4.5	7.5
Dahapu	W	4.0	6.7
AgashiBay	W	4.2	7.0
Mumbai	W	1.5	4.5
Mouth of Patal Ganga river	W	4.3	7.2
Mouth of Rajpuri river(Murud)	W	3.1	5.2
Harnaf	WSW	1.7	2.8
Ratnagiri	W	1.8	3.0
Devgad	WSW	1.5	2.5
Panaji	WSW	1.7	2.8
Bhatkal	WSW	2.7	4.5
Mangalore	WSW	1.8	3.0
Kozhikode	WSW	2.1	3.5
Kochi	W	1.6	2.7
Nagercoil	SW	1.4	2.3
Dhanushkodi	NNE	4.8	8.2
Rameswaram	SE	6.8	11.3
Pamban	NNW	4.4	7.3
Devipatnam	E	4.5	7.5
Adirampatnam	SSE	5.1	8.5
Point Calimere	SSE	4.2	7.0
Nagapattinam	E	1.5	2.5
Karikal	E	0.3	1.3
Chennai	ENE	1.5	2.5
Nizampatnam	SW	4.5	7.4
Mouth of Krishna river	SE	1.6	2.7
Narasapur	S	1.7	2.9
Sacramento shoals(outer sand banks)	SSE	1.4	2.3
Kakinada(outer sand banks)	E	0.6	1.0
Visakhapatnam	SE	0.7	1.2

Kalingapatnam	E	1.1	1.8
Gopalpur	SE	0.9	1.5
Mouth of Devi river	SE	0.8	1.3
False point	SE	1.9	3.2
Balasore	SE	3.0	5.0
Mouth of Hoogly river	S	6.5	10.8

4.6. Provision for extreme events

Tsunami caused either by earthquakes with epicenters located below the ocean floor or mud slides on the ocean floor or volcanic eruption or meteoritic impacts can cause severe damage to the coastal protection measures. Apart from the waves, it generates high-velocity flows and wave run-up. Wave run-up reported during the tsunami along the east coast of India (Ilangovan et al., 2005, Jayakumar et al., 2005) are presented in **Table 4.6.1**.

Table 4.6.1. Wave run-up during the Tsunami along the east coast of India.

Sr. No.	Location	Run-up (with respect to chart datum) (m)
1	Arukattuthurai	3.8
2	Velangani (South)	4.7
3	Velangani (Middle)	3.9
4	Velangani (North)	4.4
5	Samanthan Pettai (South)	1.9
6	Samanthan Pettai (Middle)	3.3
7	Samanthan Pettai (North)	2.5
8	Nagore (South)	2.2
9	Nagore (Middle)	3.2
10	Nagore (North)	1.8
11	Karaikal	2.6
12	Tarangambadi (South)	4.4
13	Tarangambadi (Middle)	4.3
14	Tarangambadi (North)	4.6
15	Poompuhar (South)	0.7
16	Poompuhar (North)	2.2
17	Thirumullaivasal	2.2
18	Thoduvai	3.9
19	Kodiyam Palayam	2.0
20	Velangirayan	3.7
21	Reddiar Pettai - 1	4.2
22	Reddiar Pettai - 2	3.2
23	Kurinjipadi	3.7
24	Thevanampattinam	3.9
25	Pudu Kuppam	3.1
26	Periyakalapet (South)	5.9

27	Periyakalapet (Middle)	5.4
28	Periyakalapet (North)	6.5
29	Nochi Kuppam	3.7
30	Ekkiar Kuppam	4.5
31	Kottai Kadu Kuppam	2.5
32	Alambarai Kuppam	4.6
33	Sadurangapattinam–1	5.8
34	Sadurangapattinam–2	5.1
35	Mahabalipuram	5.4
36	Kovalam	5.4
37	Urur Alcott Kuppam	5.0
38	Pulicat	3.2
39	Krishnapatanam	2.2

4.7. Longshore sediment transport

Rivers are identified as major sources of sediments for the Indian coast. Ganges and Brahmaputra rivers contribute major share of suspended sediments to the Bay of Bengal, whereas Indus supplies more to the Arabian Sea. The river sediment discharge into the sea is 1.2 x 10^{12} kg/year by the Indian rivers. Deposits in the Gulfs, tidal marshes, bays, beach deposits and aeolian inland transports are found to be the primary sinks for the sediments moving along the Indian coast. Problems associated with excessive sediment deposition and siltation have been noticed at all harbour channels and various river mouths. There is significant deposition of littoral materials in Gulf of Kachchh and Gulf of Khambhat along the west coast, and Gulf of Mannar, Palk Bay and Sandhead along the east coast.

Sedimenttransport studies along the east coast of India were initiated by Lafond and Prasada Rao (1954). Hashimi et. al., (1978) and Wagle (1987) carried out the studies on the geomorphology and sediments in Gulf of Kachchh. Murthy and Veerayya (1985), Samsuddin and Suchindan (1987), Purandara and Dora (1989) and Samsuddin et. al., (1991) studied the long-shore current and associated sediment transport in the near-shore areas of Kerala coast. The annual net sediment transport at Visakhapatnam was northerly of about 0.54 x 10^6 m^3/year (Sarma and Reddy, 1988), which is similar to that observed at Tikkavanipalem, 30 km south of Visakhapatnam. The annual net sediment transport of 0.04 - 0.41 x 10^6 m^3/year and gross transport rate of 0.12 - 0.54 x 10^6 m^3/year was reported for Mangalore coast (Jayappa, 1996).

Chandramohan and Nayak (1991) estimated the LSTR at some places along the Indian coast based on the ship reported data and the study showed that along the east coast, the long-shore transport is southerly from November to February, northerly from April to September and variable in March and October. Along the west coast, the long-shore sediment transport is generally towards the south from January to May and in October. It is variable during other months showing northerly drift along the Maharashtra and south Gujarat and southerly along the

Karnataka and Kerala coasts from June to September. The trend gets reversed in November and December.

The long-shore sediment transport at different locations along the Indian coast based on measured data is given in **Table 4.7.1** (Anand et al., 1991, Chandramohan et al, 1993a, Chandramohan et al, 1993b, Sajeev, 1993,Jena, 1997, Kumar et al, 2000, Kumar et al, 2002). There are local reversals in the transport direction along the west coast of India. Coasts near Malvan, Dabhol, Murud and Tarapur in Maharashtra and coasts near Tarangampadi, Karaikal, Nagore, Tuticorin, Virapandianpattinam and Manakkodam in Tamil Nadu are behaving as the nodal drift points, with an equal volume of transport in either direction annually. It is found that the annual gross sediment transport rate is high (1.5 x 10^6 m^3 to 2.0 x 10^6 m^3) along the coast of south Odisha, north Tamil Nadu, south Kerala, north Karnataka and south Gujarat, whereas it is comparatively less (0.5 x 10^6 m^3) along the south Tamil Nadu and Maharashtra coasts.

Table 4.7.1. Sediment Transport rate at different locations

Location	Net transport (m^3/year)		Gross transport (m^3/year)
West coast of India			
Kalbadevi	118580	South	147621
Ambolgarh	189594	South	299997
Vengurla	53040	South	120141
Calangute	90000	South	120000
Colva	160000	North	160000
Karwar	40000	North	140000
Arge	69350	North	200773
Gangavali	142018	South	177239
Pavinkurve	290000	North	400000
Kasarkod	40186	North	77502
Maravanthe	25372	North	29836
Kundapur	178000	North	349000
Malpe	14169	South	106641
Padukare	320000	North	357000
Padubidri	89358	South	385469
Ullal	36165	South	38273
Kasargod	736772	South	958478
Kannur	19434	South	561576
Kozhikode	114665	South	256697
Nattika	192818	North	660276
Andhakaranazhi	202096	South	599484
Alleppey	16929	North	62519
Kollam	383784	South	805296
Thiruvananthapuram	99159	North	1231153
Kolachel	302400	West	946500
East coast of India			
Ovari	1500		251300
Tiruchendur	64100	North	87500

Kannirajapuram	117447	North	145979
Naripayur	36600	South	122500
Pudhuvalasai	5300	South	42900
Vedaranivam	51100	North	94100
Nagapattinam	6200	North	589900
Nagore	96000	South	433000
Tarangampadi	200600	North	369400
Poompuhar	146000	North	478800
Puducherry	134400	North	237000
Periyakalapet	486900	North	657600
Tikkavanipalem	177000	North	405000
Gopalpur	830046	North	949520
Prayagi	887528	North	997594
Puri	735436	North	926637

4.8. Properties of construction material

The choice of construction materials used in the coastal zone is dependent on the following criteria.

- type of structure
- material availability and cost
- construction and installation techniques and availability of equipments
- aesthetic and environmental suitability

Materials commonly used for coastal protection measures are:

- rock
- wood
- concrete
- geotextile
- polymer rope gabion

Details of the commonly used materials are discussed below.

4.8.1 Rock

Rock is used extensively in construction of seawalls, revetments and breakwaters. Basalt, granite and laterite are the most common rock materials used. In addition to the size, shape, quantity and homogeneous quality of rocks from a quarry, the most important qualities of a rock material are:

- density
- water absorption (wet density)
- resistance to weathering
- resistance to impact
- resistance to abrasion

- block integrity (free of cracks, veins, laminations etc.)
- impurities (free of impurities which may affect the soundness of the rock)

The properties and availability of stones in different states of India for construction purpose are available in the Indian Standard Code 7779 (IS 7779). **Table 4.8.1** indicates the general criteria on quality of rock (Smarason et al., 2000).

Table 4.8.1. Properties of rock

Test	Excellent (A)	Good (B)	Marginal (C)	Poor (D)	Comments
Rock type	Gabbro , Dolerite, Porhyritic basalt.	Granite, Anorthosite, Olivinetholeiite, Alkali basalt	Tholeiite basalt.	Rhyolite, Dacite, Hyaloclatite	Guidelines for rock types without correlation to rock density
Density (ton/m^3)	> 2.9	2.65 – 2.90	2.5 – 2.65	< 2.5	Density of rock is a good indicator of hydraulic stability
Water absorption (%)	< 0.5	0.5 – 1.0	1.0- 2.0	> 2.0	Important indicator of alteration and resistance to degradation, especially in cold climate
Freeze/thaw test Flaking (kg/m^2)	< 0.05	0.06 – 0.10	0.11–0.20	0.21 – 0.50	Swedish standard SS137244 in a 3% Nacl solution for concrete
Point load Index Is(50) (Mpa)	> 8.0	5.0 – 8.0	3.0-5.0	< 3.0	Correlates with rock density and indicates resistance to breakage of blocks
Alteration of minerals	No alteration	Little alteration	Considerable alteration	Heavy alteration	Alteration inspected in thin sections
Inner binding of minerals	Excellent	Good	Fairly good	Cleavage Visible	Inspection in thin section

4.8.2 Wood

Seasoned timber is used commonly for piles. Its relatively low cost and ease of workability are attractive for use in small scale works. Limitations in its use include:

- lack of large sizes
- structural strength upper limit
- if immersed, a relatively short lifespan when not protected against attack from marine borers and fungi

4.8.3 Concrete

Concrete is used in many coastal protection measures as armour unit, piles, seawalls, revetments and Groynes. When properly designed, mixed, placed and cured, concrete is a very good material in the marine environment. Specifications for marine concrete should be as per Indian Standard code IS 456 (IS 456, 2000).

4.8.4 Geotextiles

Geotextiles are commonly used in coastal applications as a filter medium between finer sand/silt sediments and coarser gravel/armour rock used in seawalls/Groynes. While selecting the geotextile, the following points to be considered.

- Abrasion and puncture resistance properties need to be stronger and carefully selected for the specific application - field trials can be useful.
- Permeability/hydraulic conductivity will reduce significantly due to clogging of the geotextile by silts and marine fouling, repetitive tidal and wave driven fluctuations in water pressure accelerates the process. Designs dependent upon high geotextile permeability should be avoided.
- Tensile strength requirements are to be selected based on construction methods.
- Many geotextile products deteriorate when exposed to Ultra Violet light and in such situations, UV resistant products should be used.

Geotextile containers of varying shapes and sizes filled with sand are used in temporary and permanent shore protection structures.

4.8.5 Polymer rope gabion

When there is no access for heavy machinery to the beach or when there is no availability of the required size of stone economically, polymer rope gabions are considered for coastal protection works. Due to higher breaking strength and elongation of the rope flexible polymer rope gabions are able to withstand repeated and impact loads better.

The polymer should have excellent chemical and biological resistance and should be able to use in acidic and alkaline environment without the risk of corrosion. Polymer rope need to be UV stabilized. The gabion is to be fabricated in such a way that it is a single, continuous integral structure such that after filling the gabion, the lid portion can be closed at site.

Testing of linear density and length of lay rope is to be done as per British Standard BS EN 919: 1995 "Fiber Ropes for General Service - Determination of certain Physical & Mechanical properties". Breaking strength of rope and rope net, abrasion resistance and thermal stability is to be done as per IS 7071 - Part IV 1986. Punching shear test in the net also is to be done.

5. PERFORMANCE OVERVIEW OF EXISTING COASTAL PROTECTION MEASURES IN INDIA

This section is based on the visual observations made along certain stretches of coastal protection works on the coasts of Kerala, Karnataka, West Bengal, Goa, Lakshadweep, Tamil Nadu and South Gujarat,

5.1 Seawalls

The coastal protection structures are flexible structures and permitted to be damaged under extreme events. Hence periodic maintenance is required. The main cause of damage to the seawall is due to toe scouring, undermining and subsequent sinking of the seawall. The inundation of the land area behind the seawall due to the overtopping and underflow has further aggravated the leaching action below the seawall. Proper filter on the leeside of the seawall was absent at some of the locations and resulted in damage of the seawall.

5.1.1 Seawalls along Ernakulam and Trissur district of Kerala coast

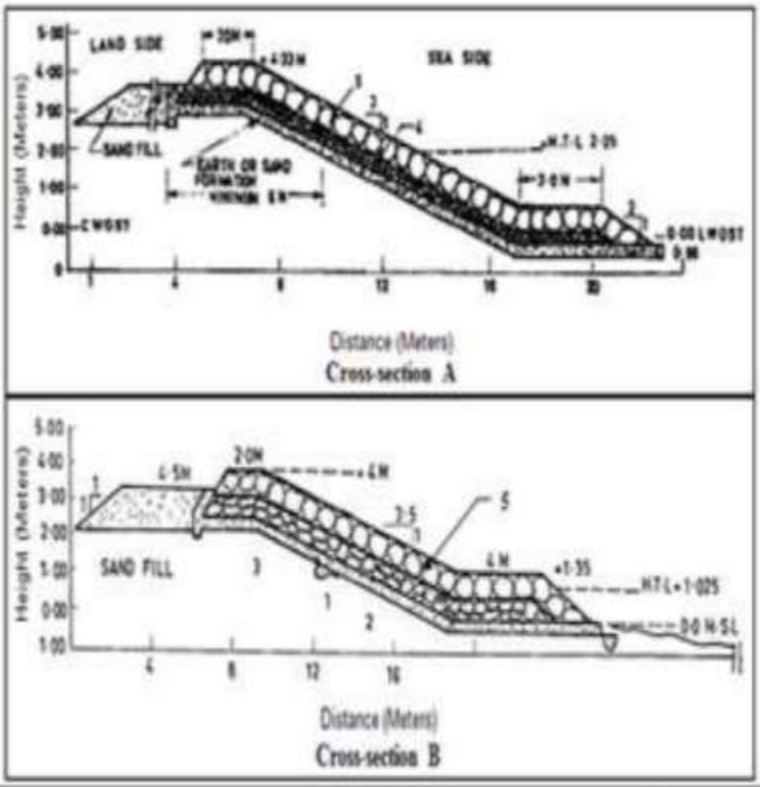
The coastal protection measures adopted in Kerala in the past are mainly seawalls, Groynes or a combination of the two. At Ernakulam district coast, they were constructed30-35 years back and are partially or fully damaged. The main causes of damage to the seawall were due to toe scouring, undermining and subsequent sinking of the seawall. The inundation of the land area behind the seawall, at places due to overtopping and underflow has further aggravated the leaching action below the seawall. Crest level of the seawall constructed was 3.35 m. It was found that overtopping can be limited to a great extent by raising the crest level to 3.9 m. The lowering of bed level in front of the toe of the seawall due to overall changes in bathymetry of the area over the years has increased the wave action on the seawall, rendering them more vulnerable. No regular or worthwhile maintenance was carried out after the construction at any of the locations and the seawalls have suffered moderate to severe damage over the years and the core layers were exposed at few locations.

At many locations, there is seepage of seawater through the seawall on the lee side causing inundation/water logging in the area behind the seawall. This may be attributed to the dislodgement of the armour stones and exposure of the secondary/core layers leading to the passage of water through voids during the up-rush of the wave action. Proper filter on the leeside of the seawall needs to be provided to minimize the flow. Also, drains needs to be provided on the leeside (where area on the leeside is restricted) so that the seepage water is collected and diverted back to the sea.At some locations (Puthu Vypin) due to accretion, the seawall is presently located about 500 m inside the present coastline.The cross section of the seawall adopted earlier is shown in Figure 5.1.1. The modified seawall being constructed is shown in Figure 5.1.2.

(Ref: Minutes of 1st meeting of Coastal Protection and Development Advisory Committee on *Performance Evaluation of Coastal Protection Works,* 12th July 2004)

5.1.2 Seawalls along Karnataka coast

As the erosions along the Karnataka coast is primarily due to direct wave attack, the most suitable options economically are the 'hard' options. Among these Groynes are not suitable due to lack of littoral drift and the machinery not available economically to build offshore breakwater. The minor irrigation department of the Government of Karnataka has been adopting a standard seawall design as evolved by the Karnataka engineering research station (KRS). A total of about 37 km length of the vulnerable reaches of the Karnataka coast has been protected with the seawalls.



Particulars	Cross-section A	Cross-section B
1. FILTER	0.3M THICK FASCINE MATTER	HIGH DENSITY POLYTHENE 40 MESH OR TO SUIT BEACH SAND
2. SAND CUSHION BELOW H.T.L	0.3M MAX. SIZE 15.0 M	0.3M THICK SAND CUSHION
3. QUARRY RUN FILTER ABOVE H.T.L	0.3M THICK (52 Kg STONE WT.)	0.3M THICK (15mm TO 15 cm)
4. SECONDARY LAYER	0.66M THICK W 520 Kg. 75% W > 520 Kg. REST BETWEEN 650 & 390 Kg.	0.6M THICK (65 Kg STONE WT)
5. SINGLE LAYER ARMOUR		0.75M THICK (W = 650 Kg.) 75% W > 650 Kg. REST BETWEEN 850 & 490 Kg

UNIT WEIGHT OF ARMOUR STONES = 2.65 T/CUM

W = WEIGHT OF ARMOUR STONES

Figure 5.1.1. Cross section of the seawall adopted earlier

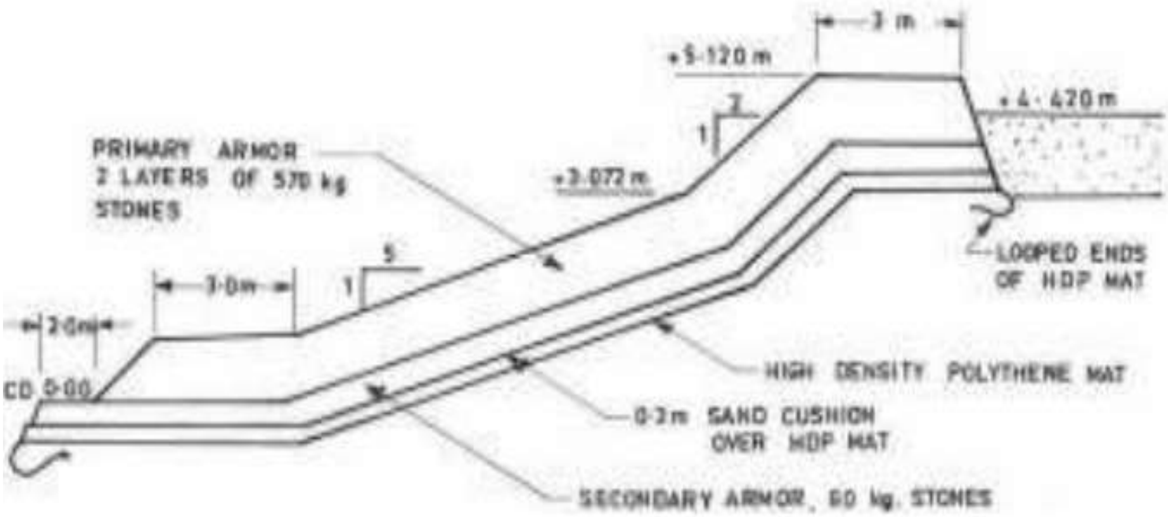


Figure 5.1.2. Cross section of the modified seawall

Dattatri (1994) had carried the evaluation on the performance of the seawalls and the salient findings are given below.

A significant length of the seawalls build has performed satisfactorily while in a few isolated areas, the seawalls have suffered extensive damage. A detailed study of these failures has shown that these seawalls have been built in a forward position on the beach primarily because of the severe encroachment into the active zone of the beach, just beyond the active zone of the beach. The seawalls built seaward will have constant problems related to frontal and end scour. The failures clearly indicate frontal scour loss of support and collapse of toe and part of the seawall.

The construction of the seawalls is generally done in the post monsoon season when the eroded beach would have recovered fully. Construction in this period would require a significant amount of beach to be excavated to expose the back of the beach for the ideal location of the seawall. Only a strict supervision can ensure this.

To meet the increasing public demand for immediate protection against erosion during severe monsoons periods, emergency works are carried out. These constructions are invariably from the top down in these adverse situations. These constructions are not only in the active zones of the beach but to upgrade them later to the standard cross-section is also very difficult. These sections will be the ones to be damaged first in the subsequent monsoons. The ends of seawalls and the gaps in the seawalls for fishing activities are the other zones where failures are more common. Seawalls properly located and constructed have withstood the test of time satisfactorily.

(Ref: Minutes of 2nd meeting of Coastal Protection and Development Advisory Committee on *Performance Evaluation of Coastal Protection Works,* May 2005)

5.1.3 Seawalls along Digha coast

The performance of the existing seawall was carried out by Bhandari (2002). Although the seawall could prevent the sea from encroaching into Digha Township, the beach lowering continued even after construction of seawall. The waves reflected from the seawall might have accelerated beach lowering. It was also noticed that the beach was steepened considerably after construction of seawall. The width of the inter-tidal zone also becomes shorter. Also, the surface profile of the seawall has deteriorated considerably due to moving up and rolling down of laterite boulders due to incident and backwash wave action. The erosion of seawall also occurred due to wave action. In summer and during monsoon the erosion at the toe may be up to a depth of 1 to 1.5 m, but in winter this is covered up due to seasonal sand accumulation. It was reported that there was no overlapping of the seasonal up to 1990. But since 1991, there have been cases of overlapping at few places, during August and September every year, when storm coincides with spring tide. It has been reported that waves reached a height of 1.5 m to 2 m above the seawall crest at those occasions.

5.1.4. Coastal protection works along Goa coast

Most of the beaches in Goa are stable and ideal destination for the tourists. Due to considerable rise in tourism the beach environment is under stress.

While addressing the few erosion reaches, sufficient care has to be taken not toshift the problem to other areas. Seawalls are known to shift the erosion problem to thedown-drift side if constructed without proper design support. A thorough study istherefore necessary to arrive at the most appropriate site specific anti-sea-erosionmeasure that should be adopted.

Planning and execution of anti-sea-erosion works requires considerable baselinedata and Water Resources Department, Goa need to start collecting the coastal data in asystematic manner.

Reference pillars, baselines and benchmarks are to be established at all coastalsites and cross sections to be taken, one prior to monsoon and another after monsoon.The data so collected need to be documented systematically and should be madeavailable to the designers.

The design, construction and maintenance of each coastal structure need to bewell documented.Specific coastal erosion problems need to be referred to institutions such asCWPRS for professional guidance before formulating the protection measures. Benefit-cost analysis need to be carried out while formulating the coastal protection measures, and also, the level of protection that need to be provided at eachlocation based on the importance of the area protected need to be determined anddiscussed in the project reports.

(Ref: Minutes of 3rd meeting of Coastal Protection and Development Advisory Committee on *Performance Evaluation of Coastal Protection Works,* October 2005)

5.1.5 Coastal protection works in Lakshadweep islands

The coastal protection works carried out are as per the designs evolved byCWPRS, Pune. No regular or worthwhile maintenance have been carried out after theconstruction works at any of the locations.

No administrative set up is in place for regular collection of coastal data,except monthly collection of shoreline changes. The design, construction and maintenance of coastal structures are not welldocumented. The present set up of the PWD is not sufficient for the purpose.

Efforts are to be made to explore alternative and better technology which willprovide protection of sea shores and at the same time, the beauty of the beachesare not spoiled.

(Ref: Minutes of 4th meeting of Coastal Protection and Development Advisory Committee on *Performance Evaluation of Coastal Protection Works,* January 2011)

5.1.6 Coastal protection works along Tamilnaducoast

Govt. of Tamil Nadu has been adopting hard strategies like rubble mound sea walls,rubble mount groynes at almost all the protection sites. Although soft measures likenatural bio shield are available along some of the coastal stretches, no active efforts havebeen initiated by Govt. of Tamil Nadu mainly due to the non-availability of technical inputto resort to such alternatives. However, they are inclined towards considering geo tubes,offshore reef, sand nourishment, bio shield as alternative techniques.

With respect to North Chennai Groynesand RMS walls, It has been observed that most of the groynes, the nose has beendisturbed which needs repair. Significant sand accretion and formation of beach has beenenhanced by the group of groynes.In general, it isobserved that the purpose has beenserved by the group of groynes in defendingthe coastal erosion of this reach.

Nose of the RMS wall near Devanampattinam village has been damaged to aconsiderable extent. The rubble has been severely disturbed by the wave conditions. The nearby shorelines have been found to be affected at some places probably due to the construction of this wall.The land behind this RMS wall is safely protected. So far, the objective of constructingthe structure has been achieved. Regular monitoring and periodical maintenance mayenhance the life of the structure.

With respect to groyne at Theresapuram village in Tuticorin district, thesize of rubbles used appears to be not of sufficientsizes. The top layer of the groyne is very undulating and difficult for movement of men orvehicles. Generally, the structure has been found satisfactory. As per observation andenquiry, the performance of the structure so far has been good.

In general, the performance of groynes at various coastal stretches in Kanyakumari district are found satisfactory though some damages to nose of groynes are found due to inappropriate sizes of stones, orientation of groynes and the geometry of the nose design.

Gabion protection at Dhanuskodi withstood extreme conditions and still performing satisfactorily.

(Ref: Minutes of 5thmeeting of Coastal Protection and Development Advisory Committee on *Performance Evaluation of Coastal Protection Works,*November 2011)

5.1.7 Coastal protection works along South Gujarat coast

The anti-sea erosion measures executed by the State Irrigation Department in the three Districts of South Gujarat are largely based on the design solutions evolved by CW&PRS, Pune. The measures adopted have by and largecontributed in minimizing the loss to life and property, besides otheradvantages.

The anti-sea erosion measures undertaken at the six locations visited by theSub-Committee are Rubble Mound Sea (RMS) wall, Retaining wall with stone-filledPoly Propylene Rope Gabions as toe, Stone-filled P.P Rope Gabions(later strengthened with heavier stones).

The RMS wall at sites Dumas, Tithal and Kolak-Udwada is found to haveserved its purpose well. Similarly, the retaining wall with stone-filled P.P RopeGabions as toe is also serving its purpose. However due to lack of periodicalmaintenance, toe scouring and sinking is reported in RMS wall. Thecutting/burning of the ropes by local people has led to gradual deterioration ofthe Rope Gabions.

The anti-sea erosion measure using stone-filled P.P Rope Gabions alone,executed at Onjal Machhivad and Nani-Danti-Moti Danti is found to have gotdamaged due to various reasons. Pilferage and cutting of ropes by local peoplehas led to dislodging of the stones and consequent collapse. Further, theovertopping of the gabions during high wave conditions has inflicted majordamages. It is suggested that, for future projects experiencing similar coastalenvironment, the design solution of using stone-filled P.P. rope Gabions as anti-seaerosion measure has to be critically reviewed in view of the experience inSouth Gujarat. Regular inspection and maintenance is paramount to thelongevity of these measures.

Planning and execution of anti-sea erosion measures requires considerablebaseline data. Systematic and scientific data collection on coastal processes isimportant for evolving appropriate design solutions (hard or soft) which as ofnow is not being carried out in the State. Govt. of Gujarat may considersubmitting locations of vulnerable coastal reaches to CWC for inclusion of thesame in the proposed Coastal Management Information System (CMIS) forestablishing sites for collection of coastal data needed for design of coastalprotection measures.

Holistic planning for anti-sea erosion measures is important to avoid shifting ofthe problem from one reach to the other.Periodic survey and maintenance of the completed coastal protection structuresneeds to be paid due attention. Possibility of the participation of localbeneficiary community in the maintenance of the executed measures needs tobe explored.

(Ref: Minutes of 6thmeeting of Coastal Protection and Development Advisory Committee on *Performance Evaluation of Coastal Protection Works,* June 2015)

5.2 Groynes

The combination of seawall and Groynes (about 30 m long) at about 150 m interval has been working more satisfactorily compared with provision of only seawalls, especially in the northern portion of the coast of INS Dronacharya near Kochi, Kerala.

North of the Chennai fishing harbour, ten numbers of Groynes were provided in two separate stretches of 6 and 4 Groynes, which are found to be satisfactorily functioning. Distance between the Groynes varies from 300 to 600m.

5.3 Beach nourishment

EnnorePort was constructed in the year 2000, north of existing Chennai port to meet increase in demand of cargo. To prevent down-drift erosion, option of artificial beach nourishment was taken up by placing dredged material on northern side of the port. The material dredged from the Ennore port during capital dredging (3.5 x 10^6 m^3) was transported through pipeline to the project site located immediately north of port. Out of total dredged quantity, 0.7 x 10^6 $m^3$was placed over the existing beach to rise the berm height from 2.5 to 6 m above mean sea level and the rest of the material is spread in near-shore to widen the beach by 500 m.

The performance of beach fill and consequent shoreline oscillations on the adjacent coast was carried out by Ramanamurthy et al. (2008). The study shows that from March 1999 to December 2004 an accretion of 300 m at south breakwater and an erosion of 200 m at north breakwater was observed. Beach fill of 1000 m long, and 500 m wide (average) with transition length of 500 m at northern end undergone erosion and 1.43 x 10^6 $m^3$of fill material was lost between 2000 and 2004, against total beach fill quantity 3.5 x 10^6 m^3. Fill started supplying material to the down-drift coast from the inception of project and 250 m wide beach is lost between 2000 and 2004, forming a steep cut at beach fill location.

5.4 Geotextile tubes (Geo-tubes)

Two parallel rows of geotextile tubes, one of larger size and one smaller size adjacent to it, were laid at the site to contain the erosion at Candolim beach, Goa (Parab et al., 2011). These geo-tubes were filled with the sand using pumps. However, over the period of time it was observed that due to wave action the geo-tubes busted and sand filled inside these tubes came out leading to failure of geo-tubes. Since geo-tubes are exposed to ultraviolet light and wave action, they are susceptible to damage result in their failure.

Study by Parab et al. (2011) shows that geo-tubes provide the excellent solution for beach erosion control. However, it needs to be protected from damage due to wave action and ultraviolet light by providing riprap. Also, tidal variation and wave height need to be considered in design of geo-tubes.

5.5 Environmental impact of proposed solutions

Environmental impacts of hard engineering are usually more than that of soft engineering measures. Hard engineering usually result in long term changes in coastal morphology, particularly erosion alongside protected areas. It also often reduces the width of the shoreline as low laying backshore areas will be reclaimed. This leads to decrease in shore habitats. The change in the adjacent shoreline due to the proposed shore protection measures needs to be identified before executing the work. Soft engineering if designed properly is an environmentally friendly approach which works towards providing a dynamic equilibrium at the coast whereby erosion is kept to minimum.

In beach nourishment projects, the potential physical impacts can arise from removal of material. Material for replenishment needs to be sourced from outside the active littoral system unless it is part of a bypassing system. Impacts of removal of material also include changes to bathymetry affecting wave conditions at the beach. While carrying out the beach nourishments work, seasons when marine organisms are most vulnerable to turbidity or bird nesting is most likely to be disturbed are to be avoided. Also the heritage areas such as shipwrecks and marine parks are to be avoided.

6. DESIGN GUIDELINES FOR DIFFERENT COASTAL PROTECTION MEASURES

6.1 General

6.1.1 Design objectives

While designing the coastal protection measures, the parameters to be considered are:

- function of the structure
- physical environment
- construction method
- future maintenance

An important aspect during the design stage is that of making alternatives both during conceptual design and final design. The cost of construction and maintenance is a controlling factor in determining the type of protection measure.

6.1.2 Selection of type of protection

Coastal protection measures are classified in accordance with their ability to provide protection to large and small shore areas and their influence on the adjoining shores are presented in **Table 6.1.1** (Bruun and Nayak, 1980).

Table 6.1.1. Classification of coastal protection measures

Protection measure	Large scale	Small scale	Effect	Influence on neighbouring shores
Groynes	√	√	May stop or decrease shoreline recession but not if offshore erosion continues.	Adverse, often very severe.
Seawalls	√	√	Stop erosion where they are built but do not stop offshore erosion.	May to some extend become adverse.
Shore parallel breakwaters	√	√	Will probably stop erosion and build up beach where they are	Adverse, often very severe.

			erected.	
Artificial nourishment	√		Widens beaches, provides full protection if well maintained.	Beneficial

Details of the performance of seawalls, Groynes, offshore breakwaters and beach nourishment are presented in **Tables 6.1.2 to 6.1.5** (Bruun and Nayak, 1980).

Table 6.1.2. Performance of seawalls

What is wanted	Storm tide and/or extreme protection of shore and beach. Protection of specific valuable areas, industry, building, highways etc.	Energy-adsorbing wall or revetment or dyke or dune. Any type of substantial wall with as little adverse effects as possible.
Layout and geometry	As streamlined as possible. It is best to leave and maintain a beach in front of the wall Influence on adjoining shores	Erosion may be stopped at the wall but artificial nourishment may be needed to maintain beach in front of the wall. Leeside erosion may result if erosion continues leaving wall as protruding headland or if wall is built too far seaward and is not streamlined in horizontal geometry. Transfer of sand or nourishment of down-drift shore may be needed.
Combination with other coastal protective measures	Groynes Artificial nourishment	To break longshore current and possibly build up beach in front of wall To maintain beach in front of wall and/or check down-drift erosion
Design	Energy-absorbing (sloping and/or mound type) Non-energy-absorbing (vertical sheet pile or slab).	Considerate to beach stability due to friction and low reflection. May create local erosion due to less friction against currents and more reflection.

Table 6.1.3. Performance of Groynes

Degree of efficiency wanted	Just beach stabilization also widening of beach	Short Groynes mainly covering the beach. Longer Groynes, possibly extending beyond bar or breaker zone
Layout and geometry	Streamlined in horizontal geometry. No sharp turns or corners.	Reaction of shore protected. Stable or widening and then stable. Influence on adjoining shores: Usually beneficial or neutral up-drift but adverse down-drift.
Combinations with other coastal protective measures	Seawalls. Artificial nourishment.	To cope with extreme conditions including storm surges. To fill Groynes and widen beach initially and maintain width. To eliminate adverse effects on down-drift beaches.
Design Length in agreement with point 1. Height to match beach profile wanted to the practical extent possible. Length/spacing ratio from 1:1 to 1:4 depending upon quantity of drift and beach material. Most common ratio is 1:2.	Impermeable: Energy absorbing. Non energy absorbing. Adjustable elevation. Fixed elevation Permeable: May be adjustable or fixed.	Less reflection, less loss of sand. More reflection, more loss of sand. May be operated to match fluctuations of beach Cannot be operated to match fluctuations of beach. May provide beneficial results where currents are the main agents in transport of materials that means in rivers and estuaries.

Table 6.1.4. Performance of offshore breakwaters

What is wanted	Protection of beach	If breakwater is built on littoral drift shore both are usually obtained.
Layout and geometry	Parallel to shore or largely following depth contours.	Tombolo formation with result on shore to be protected. Severe down-drift erosion, may result due to littoral barrier effect.
Combination with other coastal protective measures	Groynes. Seawalls. Artificial nourishment.	This combination is unlikely unless Groynes are used to check down-drift erosion, thereby transferring problem further down-drift. May be built to protect against extreme storms and tides to check down-drift erosion. May be used to create beach more rapidly if natural supply of material is limited or to check down-drift erosion.
Design	Energy absorbing structures preferable. See Table 6.2. Combination with natural reefs oftenadvantageous	

Table 6.1.5. Performance of artificial nourishment

What is wanted: Layout and geometry:	Protection of beach Follow natural shoreline closely on straight or streamlined shores. Fill in pockets on headland shores and artificial pockets
Combinations with other coastal protective measures	Groynes: to create or maintain beach and to eliminate leeside erosion Seawalls: to protect wall and/or create or maintain beach in front of wall and to eliminate leeside erosion. Offshore breakwaters: to create and maintain protective beach
Design:	Nourishment from land or offshore sources. Offshore equipment under development. Various methods tested in actual operation. Sand shall be suitable for nourishment. Main requirement is that sand should be as coarse or coarser then the natural beach material and of no less specific gravity. Bypassing arrangements by fixed or movable plants including weirs and floating plants. Movable arrangements preferable

6.1.3. Data requirements

a) Seasonal variations of beach profiles:

Seasonal variations of beach profile are to be considered while planning the location and design of the protection measure. Extent of monsoon beach profile lowering will be a factor in determining the type and extend of toe protection.

b) Design water levels:

To arrive at the maximum breaking wave height at the structure and the required crest elevation of the structure, the data on maximum water level is required. Minimum expected water levels are required to estimate the toe scour that may occur and the depth to which the armor layer should be extend. Factors to be considered in water level estimation are:

- Astronomical tides
- Wind setup and pressure effects
- Storm surge

Elevations with reference to chart datum are determined as the sum of the following:

- mean high water springs
- design storm surge
- wave set up
- design wave height
- freeboard

Elevation of the structure is the most important controlling design factor and is also critical to the performance of the structure. Many seawall failures can be directly and indirectly attributed to inadequate elevations. When selecting the height of protection, one must consider the maximum water level, any anticipated structure settlement, freeboard, and wave run-up and overtopping.

c) Design wave parameters and stability considerations:

The design wave parameters, such as significant wave height and period at the location where the structures are proposed are required. Wave heights derived from a hind cast needs to be checked against the maximum breaking wave that can occur at the site. Design wave height will be the smaller of the maximum breaker height or the hind cast wave height.

For the design of rubble structures, if the depth is less than one half the deep-water significant wave height, then design is to be based on the significant wave height at a depth equal to one half the significant deep-water wave height (Goda et al., 1976).

6.2. Groynes

The effectiveness of Groynes in maintaining the required beach area is related to their length, spacing, orientation and crest elevation. Groynes constructed on a shore where the littoral drift is high will result in sand accumulation and lee side erosion. Beach nourishment with Groyne construction is preferred in most of the recent projects (Basco and Pope, 2004).

The design of Groynes is mainly based on empirical formulae which are derived based on previous experience with Groynes performance and laboratory experiments and till now no standard design methodology is found.

Design of Groyne is governed by: 1) littoral processes (wind, wave and tide data, beach slope and grain size); 2) functional design criteria (length, spacing and height) and 3) structural design criteria (type of material and construction procedures).

6.2.1. Functional planning/design

The Groyne length may be taken as the seaward limit of the breaker zone at mean high water level (surf zone width). When the wave directions are variable, with equal long-shore transport in either direction, the Groynes perpendicular to the shoreline is more suitable.

Kraus et al. (1994) listed 13 functional properties attributed to Groynes and presented a critical evaluation (**Table 6.2.1**). The first five are well-accepted properties that have led to general thumb rule to make the Groyne spacing to length ratio about 2 to 4. The length controls water depth at the end and hence the amount of sediment bypassing around the tip. The cross-sectional elevation in the swash zone controls over-passing, the length and the elevation on the beach berm control shore passing and the structure materials control through passing as occurs within rubble-mound and permeable Groynes. In general, the Groyne crest line should be designed to vary in the cross-shore beach profile. The permeability of Groyne will allow hydrodynamics exchange across the Groyne which is important in reducing rip currents and offshore losses.

Table 6.2.1. Functional properties attributed to Groynes and their critical evaluation (Kraus et al., 1994)

Sr No.	Property	Comment
1.	Wave angle and height are leading parameters (long-shore transport).	Accepted. For fixed Groyne length, these parameters determine bypassing and the net and gross long-shore transport rates.
2.	Groyne length is leading parameter for single Groynes (Length control depth at tip of Groyne).	Accepted, with Groyne length defined relative to surface zone
3.	Groyne length to spacing ratio is a leading parameter for Groyne fields.	Accepted. See previous item.
4.	Groynes should be permeable.	Accepted. Permeable Groynes allow water and sand to move along shore, and reduce rip current formation and cell circulation.
5.	Groynes function best on beaches with predominant long-shore transport direction.	Accepted. Groynes act as rectifiers of transport. As the ratio of gross to net transport increases, the retention functioning decreases.
6.	The up-drift shoreline at a Groyne seldom reaches the seaward end of the Groyne.	Accepted. Because of sand bypassing, Groyne permeability, and reversals in transport, the up-drift shoreline cannot reach the end of the Groyne by long-shore transport is required for the shoreline to reach a Groyne tip, for a Groyne to be

		buried, or for a Groyne compartment to fill naturally.
7.	Groyne fields should be filled (and/or feeder beaches emplaced on the down-drift side).	Accepted. Filling promotes bypassing and mitigates down-drift erosion.
8.	Groyne fields should be tapered if located adjacent to an unprotected beach.	Accepted. Tapering decreases the impoundment and acts as a transition from regions of erosion to region of stability.
9.	Groyne fields should be built from the down-drift to up-drift direction.	Accepted. But with caution that the construction schedule should be coordinated with expected changes in seasonal drift direction
10.	Groynes cause impoundment to the farthest point of the up-drift beach and erosion to the farthest point of the down-drift beach.	Accepted. Filling a Groyne field does not guarantee 100% sand bypassing. Sand will be impounded along the entire up-drift reach causing erosion down-drift of the Groyne(s).
11.	Groynes erode offshore profile.	Questionable and doubtful. No clear physical mechanism has been proposed.
12.	Groynes erode the beach by rip-current jetting of sand far offshore.	Questionable. Short Groynes cannot jet material far offshore, and permeable Groynes reduce the rip-current effect. However, long impermeable jetties might produce large rips and jet material beyond the average surf zone width
13.	For beaches with a large predominant wave direction, Groynes should be oriented perpendicular to the breaking wave crests.	Tentatively accepted. Oblique orientation may reduce rip current generation and provide more sheltering.

Kraus et al. (1994) concluded that the up drift shoreline would rarely reach the seawall of the Groyne. Properties No. 7, 8 and 9 have long been accepted standard conditions for Groyne field design and construction. But as noted in No. 10, filling a Groyne field does not guarantee that the system may function as a headland, impounding sand on the up drift side and creating a down drift impact. Properties No. 11 and 12 are often cited by opponents of Groynes but are labeled “questioned” because they cannot be supported by physical mechanisms nor sand conservation.

Ten basic rules for Groyne design are summarized in **Table 6.2.2**. Rule “zero” is included to emphasize the fact that Groynes are only useful where long-shore sediment transport processes are dominant. They are also successful if (1) agreement on the minimum, dry beach width, Y_{min} is reached, (2) modern, numerical beach simulation models such as GENESIS and SBEACH are employed to study their design, and (3) a field monitoring effort is established to measure performance and adjacent beach impacts.

Table 6.2.2. Basic rules for functional design of Groynes (Basco and Pope, 2004).

Rule	**Description**
0	If cross-shore sediment transport processes dominant, consider near-shore breakwater systems first.
1	Conservation of mass for transport of sediment alongshore and cross-shore means Groynes neither create nor destroy sediment
2	To avoid erosion of adjacent beaches width, Y_{min} for upland protection during storm events as a measure to judge success.
3	Agree on the minimum, dry beach width, Y_{min} for upland protection during storm events as a measure to judge success
4	Begin with S/L=2 to 3, where S is the long-shore spacing and L is the effective length of the Groyne from its seaward tip to design shoreline beach fill at time of construction
5	Use a modern, numerical simulation model (eg. GENESIS) to estimate shoreline change around single Groyne or Groyne fields.
6	Use of cross shore, sediments transport model (eg. SBEACH) to estimate the minimum, dry beach width, Y_{min} during storm events.
7	Bypassing, structure permeability and the balance between net and gross long-shore transport rates are the three key factors in the functional design. Use the model simulation to iterate a final design to meet the Y_{min} criterion.
8	Consider tapered ends, alternate platforms, and cross-sections to minimize impacts on adjacent beaches.
9	Establish a field monitoring effort to determine if the project is successful and to identify adjacent beach impacts.
10	Establish a "trigger" mechanism for decisions to provide modifications (or removal) if adjacent beach impacts found not acceptable.

6.2.2. Groyne length, height and Groyne spacing

<u>Step 1</u>: Initially, provide the length of Groyne (L) equal to surf zone width.

<u>Step 2</u>: Assume S/L ratio in the range 2 to 3 and calculate spacing between Groynes (S) in Groyne field.

<u>Step 3</u>: Length of the first Groyne (L_1) in the transition field as shown in the figure is calculated by using the equation.

$$L_1 = \frac{1-\left(\frac{R}{2}\right)\tan 6^0}{1+\left(\frac{R}{2}\right)\tan 6^0} L \qquad (6.2.1)$$

Where,L is the length of the previous Groynes in Groyne field
R is the ratio of spacing to length of the Groyne
Step 4: Spacing between last Groyne in Groyne field and first Groyne in transition zone is given by

$$S_1 = \frac{R}{1+\left(\frac{R}{2}\right)\tan 6^0} L \qquad (6.2.2)$$

Step 5:The length of remaining Groynes in transition zone is calculated using equation 6.2.1 and spacing of Groynes in transition zone is calculated using equation 6.2.2.

Step 6: Height of the Groyne is to be equal to the derived level considering the factors described in 6.1.3.

Step 7: With the planned configuration, check whether the shoreline evolution using a numerical model (eg.: GENESIS, LITPACK). If the desired shoreline configuration is not achieved, then modify the length of the Groyne and repeat steps 2 to 7.

6.2.3. Structural design

In the design of the rock armour structure, the following steps are considered.

1. Obtain the properties of the locally available stones with the range of size (gradation curve of a quarry).
2. Large fraction of the available stone can be used as material for the armour and the smaller fractions for core of the structure.
3. Determine the shape and dimensions of the armour protection, which typically involves increasing the thickness of the armour layer, so that during design wave condition, a stable structure is obtained. This is to be verified using physical model studies. As the dimensions of the armour protection are determined, the relative sizes of core material and armour material will vary to accommodate changes in the relative percentages of armour stone and core material required.
4. While designing the geometry of the cross-section of the armour, the availability of construction equipment at the location and the site characteristics are to be checked.

In most of the cases, rock is used as armor unit and the Groyne is designed for breaking wave condition. The details of design are available in Engineering Manual EM 1110-2-1100 (Part VI)of the US Army Corps of Engineers. Important steps are given below.

Step 1: Find out the Equivalent cube length of median rock using the equation

$$\frac{H}{\Delta D_{n50}} = A\xi^2 + B\xi + Cc \qquad (6.2.3)$$

Where, $\xi = \frac{\tan\alpha}{\left(\frac{H}{L}\right)^2}$ (6.2.4)

H = characteristic wave height (m)

D_{n50} = equivalent cube length of median rock

ρ_s = mass density of stone

ρ_w = mass density of water

$$\Delta = \left(\frac{\rho_s}{\rho_w}\right) - 1 \quad (6.2.5)$$

L = Local wavelength at the toe of the structure

α = Structural armor slope

A, B, C_c are empirical coefficients and the values are provided in **Table 6.2.3**.

Table 6.2.3. Value of empirical coefficients used in Groyne design (EM 1110-2-1100 Part VI)

Armor Type	A	B	Cc	Slope	Range of ξ	Wave condition
Stone	0.272	-1.749	4.179	1V to 1.5H	2.1-4.1	Breaking
Stone	0.198	-1.234	3.289	1V to 2.0H	1.8-3.4	Non-breaking

Step 2: Calculation of weight of single armor unit.

Volume of unit armor unit = D_{n50} x D_{n50} x D_{n50}

Weight of Armor unit = Volume X Specific wt. of armor unit (W)

Step 3: Calculation of Crest Width,

$$B = nK_{\Delta}\left(\frac{W}{w_a}\right)^{1/3} \quad (6.2.6)$$

Where,

n = the number of stones

K_{Δ} = the layer coefficient (as per **Table 6.2.4**)

W = Primary armor unit weight

w_a = Specific weight of armor unit material

Step 4: Similarly, thickness of cover layer and under layer is calculated using the formula,

$$r = nK_{\Delta}\left(\frac{W}{w_a}\right)^{1/3} \tag{6.2.7}$$

r = Thickness of cover layer,

Layer coefficient value for different armour units are presented in Table 6.2.4.

Table 6.2.4. Layer coefficient value for different armour units (EM 1110-2-1100 Part VI, Table No. VI-5-51)

ARMOR UNIT	n	Placement	Layer Coefficient, K_{Δ}	Porosity, P (%)
Quarrystone (smooth)	2	Random	1.02	38
Quarrystone (Rough)	>= 2	Random	1	37
Quarrystone (Rough)	3	Random	1	40
Quarrystone (parallelepiped)	2	Special	----	27
Quarrystone	Graded	Random	----	37
Cube (modified)	2	Random	1.1	47
Tetrapod	2	Random	1.04	50
Tribar	2	Random	1.02	54
Tribar	1	Uniform	1.13	47
Dolos	2	Random	0.94	56
Core-Loc Vol. < 5 m^3 5 < Vol. < 12 m^3 12< Vol. <22 m^3	1	Random	1.51	60 63 64
Accropod Vol. < 5m^3 5 < Vol. < 12 m^3 12< Vol. <22 m^3	1	Random	1.51	57 59 62

Number of Armor units per unit area is calculated as,

$$\frac{N_a}{A} = nK_{\Delta}\left(1-\frac{P}{100}\right)\left(\frac{w_a}{W}\right)^{2/3} \tag{6.2.8}$$

n = the number of quarry stone or concrete armor units in the thickness, n=3

W = the weight of individual armor units

K_{Δ} = the layer coefficient

P = the average porosity

Thickness ‘r’ of a layer of riprap is the greater of either 0.3 m or one of the following; whichever of three is greatest,

$$r = 2.0\left(\frac{W_{50}}{w_a}\right)^{1/3} \quad (6.2.9)$$

W_{50} = Weight of 50% size in the riprap gradation or,

$$r = 1.25\left(\frac{W_{\max}}{w_a}\right)^{1/3} \quad (6.2.10)$$

W_{max} = Heaviest stone in gradation,

Riprap placing density,

$$\frac{W_T}{A} = rw_a\left(1 - \frac{P}{100}\right) \quad (6.2.11)$$

Where,P= Porosity

6.3 Seawalls (rubble mound and concrete) and revetments

6.3.1 Functional planning

The weight of the armor units of the rubble mound seawalls is determined using the Hudson formula and the Van der Meer formulae. Hudson formula is widely used because of its simplicity and long period of application except for a low crest structure. But it does not account of factors such as wave period, angle of incident wave, wave spectrum, interlocking of armor units, size and porosity of the under-layer material.

Functional design consists of estimation of wave run-up, wave overtopping, wave transmission and reflection.

The wave reflection coefficient can be reduced by a) using a sloping wall rather than a vertical wall, b) increasing roughness by using rip-rap and c) use of rock armour, rather than wall.

Hudson formula was derived from a series of regular waves test using breakwater models.

$$W = \frac{\rho g H^3}{K_D \Delta^3 \cot\alpha} \quad (6.3.1)$$

Where, W = weight of an armor unit (N)

H	= design wave height at the structure (m)
K_D	= dimensionless stability coefficient
α	= slope angle of structure
ρ	= mass density of armor (kg/m^3) = 2600 kg/m^3 for rock
g	= acceleration due to gravity (m/s^2)
Δ	= relative mass density of armor = $(\rho/\rho_w) - 1$
ρ_w	= mass density of seawater (kg/m^3) = 1025 to 1030 kg/m^3

The design wave height is $H_{1/10}$ at the site of the structure for non-breaking wave conditions. Where $H_{1/10}$ will break before reaching the structure, the breaking wave height or the significant wave height whichever has the more severe effect are used.

K_D values for rock armour at the trunk and head of structures under non-breaking and breaking wave conditions is given in Table 6.3.3.

Van der Meer formulae for plunging and surging waves are given below.

For plunging waves,

$$\frac{H}{\Delta D_{50}} * \sqrt{\xi} = 6.2\, P^{0.18} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \qquad (6.3.2)$$

For surging waves,

$$\frac{H}{\Delta D_{50}} = 1.0\, P^{0.13} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \left(\sqrt{\cot \alpha} \right) \xi^{P} \qquad (6.3.3)$$

where	H	=	design wave height, taken as significant wave height (m)
	D_{50}	=	Nominal armour diameter equivalent to that of a cube (m)
	Δ	=	relative mass density of armour = $(\rho/\rho_w) - 1$
	ρ_w	=	mass density of seawater (kg/m^3) = 1025 to 1030 kg/m^3
	ρ	=	mass density of armour (kg/m^3) = 2600 kg/m^3 for rock
	P	=	permeability factor (0.1 for relatively impermeable core to 0.6 for virtually homogeneous rock structure)
	α	=	slope angle of structure
	N	=	number of waves
	S	=	damage level = number of cubic stones with a side of D_{50} being eroded around the water level with a width of one $D_{50} = A/D_{50}^2$
	A	=	erosion area in a cross section (m^2)
	ξ	=	surf similarity parameter = $\tan \alpha / \sqrt{s_m}$
	α	=	average slope angle (degree)
	sm	=	offshore wave steepness based on mean wave period
		=	$2\pi H_s / g\, T_m^2$
	Tm	=	mean wave period (s)

The limits of S depends on the slope of the structure. For a two diameter thick armour layer, the lower and upper damage levels have been assumed to be the values given in Table 6.3.1 (CIRIA (1991).

Table 6.3.1. Damage levels for two diameter thick rock slopes

Slope of structure	Damage level S at start of damage	Damage level S at failure
1:1.5	2	8
1:2.0	2	8
1:3.0	2	12
1:4.0	3	17
1:6.0	3	17

The start of damage of S = 2 to 3 is around 5% damage. Failure is defined as exposure of the filter layer.

The slope of the armor structure, Cot α is to be between 1.5 and 6. Wave steepness sm is to be within 0.005 to 0.06.

When value of surf similarity parameter is greater than $\xi c = (6.2\ p^{0.31}\sqrt{\tan\alpha}\ )^{1/(p+0.5)}$ the formula for surging waves should be used.

For cot $\alpha \geq 4$, the transition from plunging to surging does not exist and for these slopes, only formula for plunging waves are to be used.

In general, the residual settlement after completion of construction is to be limited to not more than 150 to 300 mm depending on the type and importance of the structure and the site condition.

6.3.2. Location, height and length of structure

The crest elevation should be determined from wave run-up and overtopping considerations. An allowance for the settlement that will occur in the design life of the structure may also be included while determining the crest elevation.

The crest width should be sufficient to accommodate any construction and maintenance activities on the structure. For rubble mound breakwaters, the minimum crest determined from the following formula:

$$B = 3k_{\Delta}\left(\frac{W_a}{\gamma_a}\right)^{\frac{1}{3}} \qquad (6.3.4)$$

Where W_a=weight of an individual Armor unit(N).
k_{Δ}=Layer thickness coefficient.
γ_a=Unit weight of Armor unit

6.3.3. Design

Design Procedure is as below:

1. Determine the water level range for the site.
2. Determine the wave height.
3. Select suitable armor alternatives to resist the design wave.
4. Select armor unit size.
5. Determine potential run-up to set the crest elevation.
6. Determine amount of overtopping expected for low structures.
7. Design under-drainage features if they are required.
8. Provide for local surface runoff and overtopping runoff, and make any required provisions for other drainage facilities such as culverts and ditches.
9. Consider end conditions to avoid failure due to flanking.
10. Design toe protection.
11. Design filter and under layers.
12. Provide for firm compaction of all fill and backfill materials. This requirement should be included on the plans and in the specifications. Also, due allowance for compaction must be made in the cost estimate.
13. Develop cost estimate for each alternative.

Various formulae used for the design of vertical walls is presented in Table 6.3.2 (**EM 1110-2-1100 Part VI).**

Table 6.3.2. Various formulas used for design of vertical walls

Formula	Wave Condition	Type of Structure	Reference
Sainflou formula (1928)	Standing	Impermeable Vertical Wall	EM 1110-2-1100 (Part VI) Table VI-5-52
Goda formula (1976)	2-D oblique	Impermeable Vertical Wall	EM 1110-2-1100 (Part VI) Table VI-5-53
Goda formula modified by Takahashi, Tanimoto, and Shimosako (1994a)	Provoked breaking	Impermeable Vertical Wall	EM 1110-2-1100 (Part VI) Table VI-5-54
Goda formula Forces & Moments	Provoked breaking	Impermeable Vertical Wall	EM 1110-2-1100 (Part VI) Table VI-5-55

Stone Revetment and Riprap:

a) The design practice for stone revetments is basically the same as for rubble mound breakwaters.
b) Since the primary function is to protect bank and preventing loss of upland material, more care should be exercised in filter design.
c) Application of geotextile filter is common.
d) Close attention should be paid to the hydraulic properties of the structure to prevent toe scouring, piping, bank instability and other hydraulically related failure modes.
e) Pressure build up in the soil behind the structure can result in leaching and loss of soil. Therefore, grading of the stone must be more tightly controlled than for breakwater design.

Table 6.3.3. Stability Coefficient (breaking occurs before the waves reach the structure)

			Structure Trunk K_D		Structure head K_D		
Armor units	No of layer (N)	Placement	Breaking Wave	Non breaking Wave	Breaking Wave	Non breaking wave	Slope Cot α
Smooth rounded Quarry stone	2	Random	1.2	2.4	1.2	1.9	1.5 to 3.0
Smooth rounded Quarry stone	>3	Random	1.6	3.2	1.4	2.3	(c)
Rough angular Quarry stone	1	Random	(d)	2.9	(d)	2.3	(c)
Rough angular Quarry stone	2	Random	2.0	4.0	1.9 1.6 1.3	3.2 2.8 2.3	1.5 2.0 3.0
Rough angular Quarry stone	>3	Special	2.2	4.5	2.1	4.2	(c)
Rough angular Quarry stone	2	Special	5.8	7.0	2.1	4.2	(c)
Parallelepiped	2	Random	7.0-20.0	8.5-24.0	-	-	(c)
Tetrapod and Quadripod	2	Random	7.0	8.0	5.0 4.5 3.5	6.0 5.5 4.0	1.5 2.0 3.0
Tribar	2	Random	9.0	10.0	8.3 7.8 6.0	9.0 8.5 6.5	1.5 2.0 3.0
Dolos	2	Random	15.0	31.0	8.0 7.0	16.0 14.0	2.0 3.0
Modified Cube	2	Random	6.5	7.5	-	5.0	(c)
Hexapod	2	Random	8.0	9.5	5.0	7.0	(c)
Toskanes	2	Random	11.0	22.0	-	-	(c)
Tribar	1	Uniform	12.0	15.0	7.5	9.5	(c)
Quarry stone (KRR) Graded angular	-	Random	2.2	2.5	-	-	-

Thickness of the Armour layer (t) is estimated using

$$t = nk\left(\frac{W}{\gamma}\right)^{\frac{1}{3}} \quad (6.3.5)$$

Where, W = weight of the individual Armour unit
n = number of Armour layers
k = layer thickness coefficient
γ = Unit weight of Armour unit

Under layers and core

Weight of the under layer rock should not be less than one-tenth of the weight of the Armour. The size of individual under layer rock should be within $\pm$ 30% of the nominal weight selected. For concrete Armour units, the weight of under layer rock is to be as per British Standard, BS 6349 : Part 7 : 1991 (BSI,1991).

This thickness of the under layer t_u should contain at least two layers of rock and may be determined from the following formula.

$$t_u = nk_{\Delta}\left(\frac{W}{\gamma_r}\right)^{\frac{1}{3}} \quad (6.3.6)$$

Where, W= Weight of a rock in the under layer (N)
N=Number of rock layer
k_{Δ}=Layer thickness coefficient, equal to 1.15 for rock.
γ_r = Unit weight of rock (N/m)

While designing the filters, the following filter criteria (BSI, 1991) may be used to determine the size of the under layers in relation to the core.

$D_{15U}/D_{85C} \leq 4$ to 5

$4 \leq D_{15U}/D_{15C} \leq 20$ to 25

Where D is the nominal size of an equivalent cube
Suffix 'c' refers to cores
Suffix 'u' refers to under layer
Suffix '15' and '85' refer to the percentage of material passing through that size

When applying the above criteria, some disturbances of finer material and possible migration through the overlying material due to varying wave induced water movements is still possible. A conservative approach should be adopted in the design of the filter.

When the rubble mound structure is protecting reclamation, adequate filter should be provided to prevent loss of fine material through the core. The following filter criteria are given in BS 6349: Part 7:1991.

$D_{15(larger)}/D_{85(smaller)} \leq 4$ to 5

$4 \leq D_{15(larger)}/D_{15(smaller)} \leq 20$ to 25

$D_{50(larger)}/D_{50(smaller)} \leq 25$

Where, D is the nominal size of an equivalent cube.

Suffixes'15','50'and '85' refer to the percentage of material passing through that size.

The following points should be noted when designing the filter layer between the rubble mound structure and the reclamation fill.

- No filter layer should contain more than 5% of material by weight passing 63μm sieve and that fraction should be cohesion less.
- Filter material should be well graded within the specified limits and its grading curve should have approximately the same shape as the grading curve of the protected material.
- Where the retained fill material contains a large proportion of gravel or coarser material, the filter should be designed on the basis of grading of that proportion of the protected material finer than a 20 m sieve.
- Where the retained fill is gap graded, the coarse particles should be ignored and the grading limits for the filter should be selected on the grading curve of the finer soil.
- Where a filter protects a variable soil, the filter should be designed to protect the finest soil.
- The thickness of filter layers should be ample to ensure integrity of the filter when placed underwater. In practice, the thickness of filter layer at 1 m below and 0.5 m above water level should be the minimum thickness of 40 D_{85}.
- The filter should cover the full depth of the structure.

Slope of structure

The slope angle of the structure depends on hydraulics and geotechnical stability, and should generally be not steeper than 1.

Crest structures

Usually the crest structure is constructed to provide access or act as a wave wall to prevent or reduce over topping. The underside of the crest structure may be keyed into the underlying material to increase sliding resistance.

Toe protections and transitions

Damage to a seawall initiates from the toe or the transition area. Wave action in front of the structure can cause turbulence at the seabed, leading to erosion of seabed material and sourcing of toe. The structural toe is designed to prevent layer sliding and toe scouring. Geo-textiles are more often used in revetment toe structures.

Transitions are common in seawalls, mostly for cost savings but also for accommodating different coastal slopes. Discontinuities of pressure and permeability are likely to occur at the joints, which make them the weak links. Material discontinuity also could lead to the development of seams and eventual separation and loss of material. The above concerns should be incorporated into the design. Overlapping layers are often used to soften the impact.

When currents are combined with wave action, it is suggested that the weight of the rock for protection against wave scour should be increased by 50% (BSI, 1991). Alternatively, the shear stresses due to the combined effect of wave and currents may be calculated to determine the required toe protection. Fine material at the seabed is liable to be scoured. The design may include placement of rubble to act as falling apron for toe protection.

Gabions are made of polymer hawser laid ropes. A special process to fabricate the gabions in various sizes appropriately weaves these ropes. Gabions are generally available in a prefabricated collapsible form with the bottom & four sides held together by appropriate binding and with a flip flop open top lid. The border & body ropes may be of different sizes ranging from 6mm to 12 mm. The sizes are selected depending upon the severity of the problem & the method of installation to be adopted.

Gabion installation

1) Slope shall be prepared to extend shown on the plans or as directed by the engineer. Prepare toe trench and anchor trench as specified. All loose or unwanted materials shall be removed. All depression shall be carefully backfilled up to desire grade and compacted to density at least equal to that of the adjacent foundation. Any buried debris protruding from the foundation that will impede the proper installation and final appearance of the gabion or gabion mattress shall also be removed and the void carefully backfilled and compacted as specified in the drawing.
2) Geotextile material with specified properties shall be placed along the prepared slope before placing a gabion boxes or gabion mattresses.
3) Assembly of gabion boxes
4) Installation of gabion boxes:-
    - Place the fabricated gabions along the slope.
    - Place corner bamboos or any support to avoid free-falling of empty gabions.

Stone filling operations shall be carefully proceeded with placement by a hand or machine to avoid damage to the polymer rope, to avoid between the filling material. Filler stone shall be hard, durable, clean and shall naturally and 75 to gabion mattresses.

Undue deformation and bulging of the gabion mesh shall be corrected prior to further stone filling. To avoid localized deformation, the gabion unit in any row are to be filled in stages consisting of maximum 300 mm courses. At no time shall any cell be filled to a depth exceeding 300 mm more than the adjoining cell. Max height from which the stone may be dropped in to the gabion shall not be more than 1m. Along all exposed faces, the outer layer of stone shall be carefully placed and arranged by hand if required to ensure a net and compact appearance. Last top layer of stone shall be uniformly overfilled 25 to 50 mm for gabions and 25 mm for gabions mattresses to compensate for the future settlement in rock but still allow for the proper closing of the lid and to provide an even surface, which is uniform in appearance.

Lids shall be stretched tight over the stone fill until the lid meets the perimeter edges of the front and end panels. The lid shall be tied with all edges of gabion.

Repeat the procedure up to the required height and length as shown in the design drawings.

Precautions to be taken for construction of seawall with flexible gabions.

1. During the execution of the work, the respective bench marks at both the sites should be utilized for correlating the levels of the designed sections.

2. The trench for the toe should be excavated according to the designs.

3. Geo-fabric filter should be properly designed considering the gradation of the beach material. During the placing of the filter care should be taken for adequate overlapping of the geo-fabric filter cloth.

4. Gunny bags filled with coarse sand and gravel should be kept ready before placing the geo-fabric filter. It should be then placed over the already laid geo-fabric filter.

5. Stones of recommended gradation should be placed in the trench over the gunny bags up to the designed level.

6. The empty flexible gabions of 1 m* 1 m *1 m size should be placed over these stones and filled with 20 to 40 kg stones.

7. The open ends of the gabions should be secured according to the recommendations of the manufactures of the gabions. If, required, it is advisable to fuse the open faces of the gabions.

8. It is possible to tie these gabions laterally also and the same should be tied accordingly.

9. Place the core stones according to the recommended design.

10. Cover this layer with the flexible gabions according to the procedure indicated above.

11. Complete the lee side of the seawall sections as recommended.

It is essential to create awareness amongst the local residents that this coastal protection work is being under taken for their own benefit and they should extend their full co-operation during and after the execution of the work. It should be ensured that the residents do not cause damage to the structure by cutting of the ropes of the gabions or by removing the stones.

6.4. Near-shore breakwater (also offshore breakwater)

Low crested and submerged structures such as detached breakwaters and artificial reefs are becoming common coastal protection measures. In some cases submerged structures are used in combination with the artificial sand nourishment.

Usually near-shore breakwaters or low crested submerged structures provide environmentally friendly coastal solutions. But the high construction cost and the difficulty of predicting the response of the beach are the two main disadvantages on use of near-shore breakwaters. Near-shore breakwaters are relatively expensive to construct.

Main function of the near-shore breakwater is to reduce the amount of wave energy reaching the shoreline. Near-shore breakwaters also reduce the offshore sand transport.

Design of the near-shore breakwater depends on the length of shoreline to be protected and the level of wave protection required. If the length of shoreline to be protected is large a number of near-shore breakwaters are protected with gap between the breakwaters. The submerged shore parallel breakwater is known as shore parallel near-shore sill. If the near-shore breakwater is constructed too close to the shore, a tombolo can develop and may block the long-shore sand transport.

Numerical models have the advantage of simulating shoreline response to time varying wave condition.

Main parameters for multiple breakwater systems are length of the individual breakwaters, distance offshore, distance between the breakwaters and crest elevation.

Commonly the near-shore breakwaters built as rubble mound structures. Sand filled bags, timber sheet piles and sand filled pre-cast concrete boxes are used for sill construction.

The ratio of gap width to the sum of the break water length and gap width, known as the exposure ration, ranges from about 0.25 to 0.66.

With the planned configuration, the shoreline evolution is to be checked using numerical computer simulations.

6.4.1 Conceptual design

Main parameters which control the shoreline response due to near-shore break water are:

- Distance offshore
- Length of the structure
- Transmission characteristics of the structure
- Beach slope
- Mean wave height
- Depth of the structure
- Mean wave period
- Orientation angle of the structure
- Predominant wave direction
- Gap between the structures in case of multiple breakwaters

For submerged structures the transmission coefficient (Kt) is estimated as given below (d'Angremond et al., 1996).

$$k_t = -0.4\frac{R_c}{H_i} + \left(\frac{B}{H_i}\right)^{-0.31}\left[1 - \exp(-0.5\xi\right]C$$

$\xi = \tan\alpha /(Hi/L_0)^{0.5}$
α = seaward slope angle
Rc=Crest free board
Hi=incident wave height
B= breakwater crest width
C = 0.64 for permeable structures
= 0.80 for impermeable structures

Empirical geometrical criteria for layout and shoreline response of exposed offshore breakwater are given below (Harris & Herbich, 1986; Dally & Pope, 1986).

For Tombolo formation: Ls/X > 1 to 1.5

For Salient formation: Ls/X = 0.5 to 1

For Salient, in case of multiple breakwaters: $G\ X/Ls^2 > 0.5$

Where, Ls is length of breakwater
X is the distance to the shore and
G is the gap width between breakwaters

Empirical geometrical criteria for layout and shoreline response of submerged near-shore breakwater are given below (Pilarczyk, 2003).

For Tombolo formation: $Ls/X >$ (1 to 1.5)/(1-kt)

For Salient formation: $Ls/X <$ 1/(1-kt)

For Salient, in case of multiple breakwaters: $G\, X/Ls^2 > 0.5/(1-kt)$

In case of multiple breakwaters, the gap width is usually $L \leq G \leq 0.8\, Ls$

Where L is the wave length at the structure = $T\,(g\,d)^{0.5}$

d is the water depth

After the carrying out the design through the above procedure, the morphological shore response needs to be simulated and tested using the numerical models (GENESIS, Mike21, Delft3D).

6.4.2 Design

For rubble mound structure, the procedure on estimation of the weight of the rock is similar to that followed for the Groyne structure.

Programs like CRESS, which is accessible in the public domain (www.cress.nl) can be used for the design of rubble mound breakwaters.

6.5. Floating Breakwaters

A floating breakwater attenuates incident wave energy by one or more of the following mechanisms:

- Reflection by leading edge of the breakwater
- Dissipation through turbulence of wave breaking
- Interference with internal orbital wave motions
- Superposition of waves generated by breakwater motion with transmitted waves

The performance of floating breakwater can be evaluated by the wave transmission coefficient, k_t C_t. The transmission coefficient is the ratio between the wave heights at the leeward side of the floating breakwater relative to the wave height of the incident wave, given by:

$$C_t = \frac{H_t}{H_i} k_t = H_t / H_i$$

in which H_t=H_t = transmitted wave height and H_i= H_i =incident wave height (Figure 26). Similarly used is the wave suppression coefficient, η:

$\eta = 1 - C_t$ η = 1-k_t

All analysis must be consistent in the use of one or the other parameter. It should be noted that most contemporary work on floating breakwaters has been confined to the laboratory. Field measurements of prototype performance are scarce.

Major aspects of structural design of a floating breakwater are

- Shape
- Width of the floating section of the structure
- Draft of the structure
- Mass of the structure
- Permeability of the structure
- Station keeping

Structural width

The influence of the structural width on the hydrodynamic behavior depends on the draft and the weight of the structure. The larger the draft, the larger the influence of the horizontal wave force. Since the draft and the structural mass are connected to one another, the influence of the structural width can be verified by first calculating with a constant draft, a varying width and thus a varying mass and second by setting the mass as a constant and varying the width and draft. A wide structure is less vulnerable for roll motion compared to a narrow structure. This is due to the increase of the hydrodynamic parameters.

Draft / Mass

When the structural width is increased, the draft decreases. The sway reaction depends on the width-draft-mass relation. Increase in the mass and width while keeping the draft constant leads to the decrease of the sway motion amplitude. An increase of the draft results in an increase of the sway motion amplitude whenever there is a surplus in the wave exciting force relative to the hydro-mechanical forces. When the structural width is increased, while the draft is kept constant, the mass increases, resulting into a decrease of the heave motion amplitude. This decrease is due to the increasing mass as well as the increase of the hydrodynamic coefficients.

A wide structure with little draft will move along with the water particles when relative long waves are considered. The structural draft increases when the mooring lines stiffness is increased. The heave motion decreases when the mooring stiffness gets larger. The underflow decreases when the structural draft increases. The larger the draft, the smaller the part of the wave energy that transmits underneath the floating breakwater.

Rigid screen underneath the floating breakwater

A screen increases the structural draft of the structure and is assumed to be weightless. Due to the presence of a screen, the hydrodynamic coefficients of roll and sway will increase. Since the structural mass will have no influence in this case, the effect of an increasing screen draft on the sway motion mainly depends on the wave period. Small wave periods will have no influence on the sway motion when the screen length is large enough. However, longer waves will cause larger sway motion amplitude due to the surplus of wave force. A screen results in an increase of the hydrodynamic coefficients and thus a decrease of the roll motion amplitude.

Mooring stiffness

An increase of the vertical mooring line stiffness results in a decrease of the heave motion and thus a decrease of the transmitted wave height, generated by this motion. All the wave generating factors change when the vertical mooring stiffness is changed. This is due to the fact that an increase of the vertical mooring stiffness results into an increase of the draft.

Optimal floating breakwater design

The analysis of the influence of the several structural variables on the attenuating performance of the floating breakwater revealed the following:
- The width/draft ratio of floating breakwaters should be large enough when small wave periods are considered in order to maintain the phase shift of $-\frac{1}{2}\pi$ for the heave motion generated wave.
- A decrease of the width/draft ratio is necessary when longer wave periods are considered. When the magnitude of this ratio is kept around 1, limited influence of the roll motion transmitted wave is observed.
- Increasing the draft of the structure with a rigid screen is only valuable when small wave periods are considered. For longer waves, the presence of a screen underneath the floating breakwater might even have a negative influence on the performance.

Advantages of floating breakwaters:

- Usable where fixed breakwaters are not feasible because of poor foundation conditions, deep water or sediment transport problems
- Low initial cost in deep water
- Material and construction costs are lower for some types
- In general, require little heavy equipment and erection type (as FTB)
- Generally do not interfere with water circulation, sediment transport, fish migration
- Free from scour
- Continued effectiveness during seasonal water level fluctuations
- May be moved as protection needs change (multiple use potential)
- Suitable for temporary protection
- May be repaired in the water
- Low profile may be aesthetic advantage
- May enhance biological resources by acting as an artificial reef

- Collects debris and attracts sea gulls away from recreational boats

Disadvantages of floating breakwaters:

- Provide less wave protection than bottom resting breakwaters
- Do not effectively damp waves of long period or low steepness
- Can fail to meet design objectives abruptly, with no progressive structural damage as warning (as for long period waves)
- Ongoing maintenance costs may exceed those for fixed breakwaters
- Shorter structure life
- Lack of open-water prototype data
- Uncertainties in magnitudes of applied loads dictate conservative design principles and increased costs
- Some materials used may not be aesthetic (as tyres of FTBs)

6.6. Beach nourishment

Beach Nourishment is the placement of new sediments on the eroded beach with sediments obtained from off-site or on-site sources. It has been widely used as a method of erosion control to maintain a wide beach for both coastal protection and recreation.

For beach nourishment volume calculation, the following steps are followed.

Step 1:- Perform coastal measurements (for at least 10 years).

Step 2:- Calculate the loss of sand in cubic meters per year per coastal section.

Step 3:- Add 40 % for losses.

Step 4:- Multiply this quantity by a convenient life time.

Step 5:- Put this quantity on the beach between the low water minus one meter line and the dune foot.

6.6.1 Source of Replenishment Material

The material for beach replenishment should have a similar grading or slightly coarser of the native beach. If finer material is used, material loss will be large. If the replenishment material is much coarser than the native material, a steep and more reflective beach may form and this can result in less sand on the lower part of the beach.

Proportion of fines (commonly < 0.1 mm) should be low to minimize turbidity at the placement site. If dredging is used to get the material, fines content is also important in considering the turbidity produced at the source site. Turbidity control methods such as bunding or silt curtains may need to be considered at source and deposit sites if fines content is high and better quality sand is not available.

6.6.2 Method of Replenishment

Generally the method of replenishment is using a trailer suction dredger with sand pumped on to beach. Another method is transporting from onshore beach accumulation areas for placement within and above the tidal beach. Collecting from near-shore or harbour entrance deposits by jet pump or adapted systems and pumping to deposit site is another method.

Operational issues for selection or assessment of suitable methods include:

- Wave and wind climate and potential dredge downtime.
- Depths of deposit for dredging and for discharge if using barges.
- The distance between source and discharge sites.
- Tides may limit beach width for along-beach trucking/pumping methods, and soft sand can present difficulties for trucks.

6.6.3 Design

The calculation of the minimum volume of material required is based on techniques with high degree of uncertainty. Repeated replenishment may be required and that the initial fill volume will be a compromise between delaying the need for a repeat replenishment and the high initial cost and possible loss rates from a large initial project.

The design may include hard engineering structures such as Groynes, seawalls, offshore breakwaters, or artificial reefs to improve the efficiency of the replenishment.

Placement of material on specific portions of the beach (dune, beach berm, intertidal or near-shore), depends upon the requirement for replenishment and the methods/equipment available.

Frequency of repeat replenishments can be estimated, although is best assessed from monitoring of previous replenishment projects at the site. The effect of extreme storms or a net loss of sand by transport out of the system on actual timing of repeat replenishments is one of the uncertainties of beach replenishment and is an important aspect which needs to be recognized in the project management.

During beach replenishment, the following parameters need to be monitored.

- Near-shore and beach profiles to determine volume changes.

- Water quality at source and deposit sites.

- Monitoring of benthic/terrestrial environment and extent of disturbance.

Ongoing monitoring and assessment of requirements for repeat replenishment are:

- monitoring sand volume changes across the active beach (dune, beach berm, intertidal and near-shore),
- buffer dune volume monitoring,
- development and application of trigger criteria for repeat replenishment.

The beach replenishment management issues may include:

- the use of economic techniques to compare various coast protection methods. Need to identify and attempt to assess social/tourism/economic/environmental benefits of a beach as well as coast protection benefits and construction and maintenance costs,
- the availability of information on possible environmental impacts and on ecological vulnerability. Information on measures to minimize environmental impact,
- consultation with the public, local and or State governments, beach user groups, residents groups, commercial groups,
- support from key groups,
- development approval requirements,
- seasonal recreational beach use including school and public holidays, and major events,
- possible disturbance to recreational or commercial fishing operations,
- the intensity and duration of a replenishment campaign,
- management of potential sand drift with fencing and/or planting,
- the need to maintain storm water outlets during replenishment to ensure outlets are not buried, water does not pond nor create backwater flow conditions,
- the possible need to close beaches during replenishment,
- possible early adjustment of the profile. Movement of sand from a replenished beach to the near-shore zone can give the perception of project failure.

- possible softness or unevenness of newly deposited uncompacted sand,

- different sand texture and rock/shell content of replenished beach compared with the “native” beach

6.7. Other measures

6.7.1 Use of Geo-fabrics

Geo-fabrics are used in many varieties in coastal protection. An important function of geo-fabrics is that they have filter properties, and may replace granular filters to prevent the washing out of the fine particles. An important function of geo-fabrics is that they can be used to construct containers for cheap aggregates, like sand, and in this way form large units to withstand the erosive forces of currents and waves. In this way, packed sand can become a substitute for rock and concrete elements. Three types of applications are:

a) Large geotextile bags

Geotextile materials can be formed into bags and long, sausage-shaped cylinders (called Longard Tubes) and filled with sand. They can be deployed as revetments for dune protection, as near-shore breakwaters, and as Groynes. The design life of a geotextile filled bag depends on many factors. It is generally less than properly designed rock structures serving the same function. However, if found to cause negative impacts to adjacent shorelines, the bags can be cut open and removed with the filled sand remaining on the beach. The long-term survivability of this system has yet to be determined.

Koerner (2000) reported that geotextile tubes can provide better protection for beach erosion. Geotextile tubes of diameters of up to 3m, made up of woven or knitted high strength fabric have been effectively used to control both river bank erosion and coastal erosion.

The use of simple sandbags is already quite old. For centuries the sandbag is used to combat flooding. However, as long as the sandbags have to be handled by hand, the size has to be limited. Sandbags should not weigh more than 50 kg; otherwise accurate placing by hand is impossible (additionally European Labour Regulations limit the maximum weight of a bag to be handled by a single person to 25 kg. A 50 kg bag may only be handled by two persons). But by using machines larger bags can be used.

At this moment bags with a size of 1 m^3 are quite standard for transport and storage of bulk material in industry. These bags can also be used easily for emergency dikes; during the river floods in recent years these bags have been applied often. For water boards, it is an attractive option, because the bags are very cheap (they usually are bought second hand), ample available on the market, and easy to fill and handle with forklifts or cranes.

For permanent structures these types of bags are not often used. However, custom-made bags using strong non-woven material are used also for more permanent structures. At this moment such bags are also marketed as Soft Rock (trademark of Naue Fasertechik, Germany). For permanent structures, it is very important to guarantee a sufficient degree of filling, otherwise the base are not stable under wave conditions.

Usually the bags are applied as a "hidden protection". In fact they form a layer of coastal protection, which only becomes effective during storms, in order to prevent excessive cross-shore erosion. In case of erosion due to a gradient in long-shore transport long-shore protections are not effective. However, bags can be applied also to construct a Groyne (groyne), although in most cases preference is given then to Geo-tubes.

The long-shore constructions are often executed as "hidden protection" to prevent that UV-radiation damage to the geotextiles as well as to make them less vulnerable to vandalism. Although damage by vandalism can be repaired, this is costly and requires more technical expertise.

Because the bags usually are not fully stable, they will deform. A slight deformation is not a problem from a strength point of view, but gives a negative visual impact. Usually this is not acceptable for beaches with a tourist function.

One should realize that a long-shore hidden protection can be executed easily, but it is not possible to construct Groynes (groynes) with sandbags as a hidden construction. They only way to hide sandbags in a Groyne is cover them with rock. However, in most cases this is economically not attractive.

b) Geo-containers (Geotextile containers)

Containers made of geotextiles (Geo-containers) are relatively new engineering systems. Nicolon has developed the system and also copyrighted the name Geo-container (Rijkswaterstaat-Nicolon, 1988). Geo-containers are in fact large bags, filled in the hopper of a split barge and dumped by that barge on a selected position. Geo-containers has been applied at several places in recent years, mainly as fill units, shore protection and as breakwaters. The application depth is up to 30 meters. An overview of Geo-container technology is given by Pilarczyk [2003].

The standard basic material of Geo-containers is the high grade Geolon PP with tensile strengths in both length and cross directions of 80 – 100 and 200 kN/m. Geo-containers are always custom built to fit the hold of the split-bottom barge to be used; hold capacities vary from 200 m^3 to 300 m^3.

The procedure is that the empty Geo-container is placed in the hold of the split barge, the container is filled with an appropriate material, and the container is closed by sewing.

Then the barge sails to the right position and the container is dumped to the right position.

The advantages of the system are :

- Containers can be filled with locally available soil; this can be from a land source or from near dredging activities;
- Containers can be placed relatively accurately regardless the weather conditions, current velocities, tide and water depths;
- Contained material is not subject to erosion during or after placement;
- Containers can provide a relatively quick system build-up.

This implies that Geo-containers will mainly be applied in situations where sand is abundantly available and rock is costly; where gentle construction slopes have to be avoided and where erosion by currents and waves may be a problem.
The main design considerations include sufficient strength of the geotextile and appropriate filling. Because Geo-containers are applied under water, the effect of UV and vandalism are usually negligible.

A Geo-container will always contain a certain amount of air in the pores of the sand; the behaviour of this air determines largely the behaviour of the Geo-container during sinking. The most relevant problems are:

- The positioning of the Geo-container during sinking;
- The geotechnical stability of the Geoc-ontainers;
- The overload on the Geo-container during dumping

The tests resulted in the conclusions that in water depths of approximately 20 meters is was no problem to build up a 1:2 slope in still water and a 1:3 slope under conditions with waves and currents. The basis for this test was a 300 m^3 container. Placing the first container is the most difficult operation; the following containers can be placed more easily. In shallow water (less than 10m) the placing accuracy is much better; slopes of 1:1.5 may be achieved.

Regarding the strength it was found that a nominal tensile strength of 120 kN/m for waterdepth upto 15m did not cause any problems provided the sand had a low content of fines (less than 20% particles smaller than 63 µm. It is not expected that this conclusion will be changed for larger waterdepths. Only for extremely shallow water the falling energy reduces considerably, which implies that that a tensile strength of 120 kN/m should be applied for all Geo-containers. Also it was found that using dry sand decreases the falling velocity and consequently the impact energy.

The geotechnical stability gave steeper critical slopes than the slopes which could be achieved by dumping; so geotechnical stability is not a concern.

Geo-containers under wave attack are stable for values of $H_s/\Delta d$ up to 1. In this equation d is the height of the container after dumping. Practically it means that Geo-containers are stable up to waves of 3m. The critical velocity for a pile of Geo-containers is given by $u/\sqrt{\Delta d} < 0.5$ to 1. Liquefaction is no problems when the Geo-container is filled with sand without fines (less than 20% silt fraction).

c) Geo-tubes (Geotextile tubes)

Geo-tubes are long woven polypropylene tubes; the name Geo-tube is a registered trademark from Nicolon B.V, the Netherlands (Pilarczyk, K.,2000). The main difference with the Geo-container is that the Geo-container is filled before placement, while the Geo-tube is filled in place. This allows a longer structure. Geo-tubes are mainly used as core elements for dams and dikes, as groynes and as long-shore protection. Recently in the Netherlands Geo-tubes are applied as core elements for guide dams near a lock and an aqueduct (Spelt, 2001]. Experience in Dubai (Weerakoon et al. 2003) with unprotected Geo-tubes showed that with a qualified contractor the construction is not a problem, but that because of wave action, some damage may occur to the tubes during minor storms. This damage causes leakage of the tubes, and sand will flow out of the tube. The final result is some slumping of the tubes, and consequently the tube is not able to fulfill its function any more in a proper way (in this case the function of the tube was to protect an artificial beach).

The exact cause of the damage is not fully understood. Probably it is a combination of rocking of the structure itself, causing a movement of sand inside the tube, in combination with some scouring under the tube. This may cause extreme tensions in the geotextile, leading to ruptures.

Geo-tubes, like other geotextile structures, are vulnerable to damage, both natural and man-induced. It is essential that damage be repaired as soon as possible. Recently a method has been developed by Heilman and Hauske (2003) to repair such structures, using HDPE repair plates. Although this works very well from a technical point, it requires a good management of the structure. The structure has to be monitored very regularly, and repair has to be done immediately after ascertaining the damage.

6.7.2 Others

There are a number of other coast protection techniques that are used and are given below.

- Artificial seaweed
- Seaweed planting
- Bubble barriers
- Alternative breakwaters
- Sunken vessels
- Tyre revetments
- Interlinked concrete block mattresses
- Bitumen spraying

Artificial seaweed

There have been several attempts at placing artificial seaweed mats in the near-shore zone in an effort to decrease wave energy by the process of frictional drag.

The field trials have generally been inconclusive as regards wave energy attenuation. The most successful trials have been in areas of very low wave conditions, low tide range and relatively constant tidal current flows, when some sedimentation was found to take place.

On open coast sites there have been major problems with the installation of systems and the synthetic seaweed fronds have shown very little durability even under modest wave attack. The synthetic seaweed has tended to flatten under wave action, thereby having minimal impact upon waves approaching the coast.

Field trials in the United Kingdom have been unsuccessful and the experiments were abandoned in all cases, due to the material being ripped away from the anchorage points.

In the Netherlands, experiments were more successful with synthetic seaweed been placed in relatively deep water, where sedimentation up to 0.35 m took place soon after installation, although this would result in only a very minor decrease in shoreline wave conditions.

The cost of the artificial seaweed is low but the cost and frequency of maintenance works make this option not worth pursuing in an exposed coastal environment, where it would be subject to severe wave conditions and would become damaged rapidly.

Seaweed planting

Seaweed planting can be considered as an alternative to the installation of synthetic seaweed, and works on the same principle of dissipating wave energy by friction. Artificial planting of Posidonia in relatively protected water is now well understood. However there are problems with applying this technique in open coastlines including growth time and creating sufficient plant area. The technique is unproven as far as the significant damping of open coast waves and is unlikely to be use in dune management.

Bubble barriers

The principle behind the bubble barrier technique is the creation of the continuous curtain of bubbles rising from the seabed to dampen wave energy. The concept was developed with the aim of stilling wave energy at the mouths of harbours, where it would be possible to create suitable conditions over a short distance. The installation costs of such techniques are high, and the maintenance problems are likely to be difficult.

The bubble technique is inappropriate for an open coast location where the costs of installation over hundreds of meters or greater would be considerable. The technique is very much in an experimental stage with respect to shore protection.

Alternate breakwaters

A considerable amount of research has been carried out on the potential performance of various types of breakwater including:

- Layered plate frameworks
- Floating breakwaters
- Perforated caissons

These techniques involve the attenuation of wave energy by means other than providing a direct barrier. The numerous designs that have been tested or built are usually specific to a particular wave environment, and are usually aimed at vessel protection over relatively short distance. Design, construction and management costs are high. None have been shown to be practical as far as dune protection is concerned.

Sunken vessels

Another method of shoreline protection involves the placement of vessels hulk (hull of ship wreck) parallel to the shoreline to dissipate incoming wave energy. Parts of the east coast of the UK are fringed by marshes,which are particularly sensitive to changes in the wave climate, changed sediment supply, etc.

On the borders of the Dengie peninsula at the mouth of the Thames Estuary these are extensive salt marshes affected by erosion. Attempts have been made to create conditions conducive to regeneration of salt marsh growth by grounding a line of barge hulks several hundred meters off the shore on shallow mud flats.

The cost of protection and maintenance is relatively low for this from of protection. However, this method does not easily lend itself to the protection of dune system, if only because of the various adverse impacts that may be encountered. The hulks act like a series of breakwaters having a strong influence on the coastal processes. Not only is wave energy dissipated, but littoral transport is strongly affected. The inability to fine-tune such structures means that the adverse impacts down coast may be severe when compared to any local beneficial impacts. The hulks are also very intrusive on the coastal landscape and may be unstable during the high wave energy conditions found off many Scottish dune systems.

Tyre revetments

Because of the availability of scrap tyres, a number of trials have been undertaken in the U.S.A to use them as low cost shoreline protection. Much of the shoreline in the U.S.A is in private ownership, hence there is a need for the development of solutions utilizing cheap material and simple to construct installation methods.

The intended function is to dissipate wave energy by means of the porosity characteristics of the tyre structures. This is not easily achievable due to problems with holding tyres together adequately.

This system is recommended for only sheltered conditions. Scrap tyres are not recommended for general use. Tests made in U.S.A. categorized the wave height range (below 0.6 m)under which tyres could be used. The main problem with tyre revetment is that the individual tyres are much stronger than the interconnections between them.

A revetment constructed of scrap tyres will be visually intrusive. The tyres are almost indestructible, hence there is a potential for adding a highly unattractive element to the shoreline if they come loose.

Interlinked concrete block revetments

Patented concrete block mattress systems are widely used for protection along estuary and river banks, and for protecting the face of earth embankments. The individual blocks are linked to form flexible mattress, often using flexible cables, allowing large surface area to be covered rapidly.

These mattresses are not suitable for use as dune face protection in situations, where wave attack is experienced. They require a well laid and compacted base to prevent hydraulic uplift forces form buckling the mattress, and they require solid fixing at the crest, toe and ends to prevent slumping or outflanking. Neither of these criteria can be met in most dune situations.

Bitumen spraying

Various surface stabilizing sprays, including bitumen, have been trailed in the U,K and elsewhere with the aim of reducing wind erosion of dunes,. The sprays temporarily fix the dune surface and allow newly transplanted grasses to become rooted if they are placed in very mobile sand. Any surface distribution will quickly break through the surface layer leaving the sand in its original form.

This approach may have some benefit to backshore blowout management, but will not have any benefit to an eroding seaward face.

6.7.3 Innovative Methods of coastal Protection work used in India

Seawalls with chains of concrete blocks

A concept of seawall constructed by placing chains of concrete block is developed. For forming the chain of concrete blocks small irregular shaped concrete blocks weighing up to 50kg and having a through-hole in the block are "woven" ie., passed over a nylon rope. Many such chains are placed side by side, along the slope of the rubble mound of 5 to 25 kg stones already placed on the beach. In case of chains the interlocking and resistance to wave action is provided by the nylon rope as weight of blocks acting together as a single block of heavy weight. Since the "chains" act as a single block of a much heavier weight, than a single stone or concrete armour unit, the armour layer does not get dislodged. In the conventional seawalls normally the stones or armour blocks have to be placed in double layer in order to achieve interlocking while in case of chains, a single layer of chain is sufficient as the interlocking is achieved with the nylon rope and the heavy weight of chain. Another advantage of seawall with chains is that the weight of the core stones (5 to 25 kg) and that of the concrete blocks used to form the chain is less than 50 kg. It is, therefore, possible to use only a couple of persons to handle, transport and construct this seawall at the beach site. This type of structure is used at Udwada (Gujarat and Dahanu (Maharashtra) successfully.

Seawalls with Gabions

The Gabions are either flexible or box type. Flexible gabions are fabricated by a net of 10 mm diameter polypropylene ropes or GI wire mesh and formed into a bag of 1m x 1m x 1m size with a suitable mesh opening size of about 100mm x 100 mm or 80mm x 80mm.In this flexible bag, stones of 15 kg to 35 kg i.e., one man stone are filled and the top cover is closed by securely tying with polypropylene rope.

In case of box type gabions, these are widely used for preventing erosion of the river banks, strengthening road embankments, channel linings, etc. These are readily available in the market. These box type gabions are fabricated using mild steel wire, with a coating of PVC or zinc compound. These boxes are available in different sizes of 1m x 1m x 1m, 1m x 1m x 2m and 1m x 1m x 3m. These boxes are filled with stones of 15 to 40 kg, and the top cover is closed securely with the help of wires. These boxes weigh from 1.5 t to 5 t depending upon the box size and the specific gravity of rock minerals of the filler rocks. These gabions-flexible-bags and boxes are used in the armour layer by placing them on the rubble mound of small (5 to 25 kg) stones, to construct the seawall.

Use of concrete pipes in the coastal structures

The purpose of rubble mound Anti Sea Erosion (ASE) bunds or seawalls is to dissipate energy of incident waves on the coast and protect the coast from the erosion. In the absence of stones for construction, other suitable materials, which would be readily available,needs to be used. In view of this, concrete pipes of suitable sizes are proposed to be used in construction of coastal structures. Concrete pipes of various sizes- 0.3 m to 1.0m diameter and 2 to 4 m length are readily available in the market and can be transported to the beach site. It would be easier to handle and place such pipes in position than heavier stones. The proposed ASE bund/ seawall section using 4 number of concrete pipes of one meter diameter tied to each other. For supporting the pipes on the lee side and protecting the seaward end from erosion; small stones (5 to 30 kg) have been used as toe.

Similarly, the pipe-structure could also be used as a detached, submerged bund for coastal protection- called offshore pipe breakwater O.P.B. The OPB is formed by typing 4 pipes side by side and placing them as a submerged structure. The pipes are placed over a bedding layer of sand- filled gunny bags or bedding layer of small stones.

Seawalls with coir bags

Use of coir ie., the cordage made from husk of coconut was used in the seawalls in Kerala state, in the form of coir matting as filter/bedding layer below the seawall. It was felt at that time the coir would be suitable to be used I marine environment. The Central Coir Research Institute, Coir Board, Kerala, which was promoting the use of coir, had offered to produce two types of coir bags for use in seawalls. The first type of coir bag is of 1.2 m x 0.9m size formed with coir mesh and the other type is 1.8 m x 1.2 m or 1.2m x 0.9m size with the interior faces of the bag rubberized to reduce the pores of the fabric. The bags are manually filled with locally available sand and are stitched by coir and placed on the slope of the sand-mound. The 1.8 m x 1.2 m size rubberized bags were used on the cover layer for constructing the seawall section. This bag weighs about 1000 kilograms.

Detached Seawall at Udwada, Valsad, Gujarat

Udwada is a hamlet in district Valsad, situated on the southern coast of Gujarat. The village is located at about 20 km south of Valsad town. The "Agyari", the holy temple of eternal fire, scared to the Parsee community, is located in Udwada which makes Udwada a headquarter of Parsees in India. For many years the beach in front of Udwada has been suffering gradual erosion and the eroding shoreline has reached within 25 m from the houses/ hotels/ school building constructed along the beach. After inspection of the site and analysis of field data, it was decided to construct detached seawall in theinter tidal zone. In order to prevent the erosion of the beach, wave flume studies were conducted to evolve design of the detached seawall sections. Based on these studies, the following three on these alternatives were suggested:

a) Section using stones up to 300 kg
b) Section using hollow concrete blocks each weighing about 220 kg
c) Section using chains of cement concrete blocks (up to 50 kg)

Each of the above alternatives was studied in the wave flume for the following Design conditions:

i. The design wave height considered was the breaking water waves (H_b=1.4 m) at higher water level of 98.5 m for the seawall with wave period of 9 to 11 s.
ii. The test was conducted at low water level as +9.23 m to check the stability of toe portion.

In addition to the seawall sections, the nourishment of the eroded beach by using the sand from river Kolak was also suggested. As a secondary measure, plantation of trees/ sea-grass on the beach and formation of committee for creating awareness amongst local residents was suggested. The feasibility of these measures along with the cost comparison of the three alternatives was made and out of these alternatives. The detached seawalls were constructed at the site using chains of concrete blocks as armour.

Each seawall segment was 67.2 m in length with a gap of 10 m left in between the adjacent segments. Construction of 6 detached seawalls was completed in 1997 and the 7th one was constructed during the year 2001. It was observed that the system of detached seawall is functioning as anticipated and considerable deposition of beach material was noticed behind the detached seawalls. It resulted in formation of beach of about 35 m width.

Seawall at Tithal, Gujarat

Village Kosamba is located 6 km north of Valsad on the southern coast of Gujarat and has a population of large number fisherman. The Swami Narayan temple, is located in village Kosamba near Valsad town. The temple is beautifully constructed and maintained. For the last 15 years, the beach in the front of the village has been suffering gradual erosion in varying degrees. Severe erosion was noticed during the monsoon of 2000, resulting in shifting of the shoreline landwards within about 25 m from the temple. The erosion was of vertical cliff type and it was feared that if such a degree of erosion continues during the next monsoon also, it may cause some damage to the temple itself. It was noted that the severe erosion was mainly due to monsoon waves of the order 2 m or so breaking waves on the coast. A typical design of seawall was supplied by the Damanganga project circle, government of Gujarat for protecting the eroded shore line. Considering various site constraints such as non-availability of heavier stones, construction machinery like crane etc. and the time span in which the work was to be completed in view of the impending erosion, the design was suitably modified by conducting model studies.

6.8 Model studies

6.8.1 Numerical modeling

Numerical modeling is a technique whereby the physical environment of the coast can be investigated through mathematical formulation using computers. It is widely used for studying coastal processes, sediment transport pattern, structural design and prediction of shoreline changes due to proposed coastal protection measures.

During the recent years, wide ranges of new models have been developed considering the rapid advancement in the computational speed and data storage capacity of the computers. These new models generally include better representation of the physical processes that cause sediment transport and change in morphology of beaches and shallow water areas. But there are limitations of the model in representing the physical process due to complexity of coastal processes. The theoretical basis for sediment transport along the shoreline and offshore is not fully developed. Applying the models supported by reliable long-term field data can bridge the gap in prediction of sediment transport. The data on wave height, period and direction in surf zone covering different seasons is required to predict the shoreline changes. Numerical models have the advantage of simulating shoreline response to time varying wave conditions.

Wave modeling results provide information on wave propagation across the continental shelf to the shoreline. It will provide the areas of increased wave energy and in turn the areas vulnerable to erosion.

Problems like testing a breakwater section for percentage damage are not carried out through numerical modeling due to very high complexity and therefore, physical models are usually employed.

6.8.2. Physical modelling

Physical models can be used as a predictive scale mode for the prototype or as a verification model for a mathematical one. At present mathematical modelling is studying the coastal processes and arriving at the design parameters.

Physical modelling is used when aspects related to run-up, overtopping, toe scour or rock movements have to be verified.

For most of the design problems, mathematical model will be the economical and efficient option.

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Annexure: Glossary

Accretion: deposition of sediment at a particular point either naturally or artificially.

Along-shore: Parallel to and near the shoreline, usually termed as long-shore.

Armour unit: A rock or concrete block designed as the outer protective layer for a seawall or breakwater.

Artificial nourishment: The process of replenishing the beach with material (usually sand) from another area.

Artificial reef: A man-made marine habitat constructed for the purpose of improving fisheries or to reduce the wave action on coast.

Atoll: A ring shaped coral reef that grows upward from a submerged volcanic peak and encloses a lagoon.

Back beach: Beach portion towards land from the high water mark to the point where there is an abrupt change in slope or material; also referred to as the backshore.

Backfill: Material used to build up and consolidate the land behind a seawall or similar structure.

Bar: Fully or partly submerged mound of sand, gravel, or other unconsolidated material formed on the bottom in shallow water by waves and currents.

Barrier beach: Deposit of sand, parallel to the shore, the crest of which is above normal high water level. Also called barrier island, offshore barrier.

Barrier lagoon: A bay roughly parallel to the coast and separated from the open ocean by barrier islands.

Barrier reef: A coral reef that is parallel to the shore but is separated from the landmass by a large lagoon or by several kilometers of open water.

Bathymetry: Measurement of depths of water in oceans and estuaries; also information derived from such measurements.

Bay: A recess in the shore or an inlet of a sea between two headlands or capes. Bay is larger than a cave but smaller than a Gulf.

Beach berm: Nearly horizontal part of the beach or backshore formed by the deposit of material by wave action.

Beach fill: Sand or gravel placed on a beach by mechanical methods.

Beach nourishment: Artificial process of replenishing a beach for recreational and/ or shore protection purposes with material from another source.

Beach profile: Intersection of the ground surface with a vertical plane that may extend from the top of the dune line to the seaward limit of sand movement.

Beach scarp: Nearly vertical slope along the beach due to erosion.

Beach: Region consisting of sand or gravel extending from the low water line to a point landward where either the topography abruptly changes or permanent vegetation first appears.

Beach-face dewatering: A technique whereby water is continuously pumped away from the beach-face, thereby lowering the water table under the beach.

Beach-face: Upper surface of the beach.

Benefit-to-Cost (B/C) ratio: Determined by dividing the value of the annual benefit by the annual cost. It is used to assess the overall efficiency of a plan.

Berm crest: Ridge of sand or gravel deposited by wave action on the shore just above the normal high water mark.

Berm: Nearly horizontal portion of a beach with an abrupt face, formed from the deposition of material by wave action at high tide.

Bluff: Cliff composed primarily of soil.

Bore: A very rapid rise of the tide in which the advancing water presents an abrupt front of considerable height.

Boulders: Large stones with diameters over 300 mm. Larger than gravels.

Breaker zone: Area in the near-shore where the waves break.

Breaker: A wave as it spills, plunges or collapses on a shore, natural obstruction, or man-made structure.

Breaking depth: Water depth at the location where the waves loses its shape and break.

Breakwater: A structure protecting a shore area, harbour, anchorage or basin from waves. Most common breakwaters are in the form of a sloping wall protected by rocks or concrete armour units.

Bulkhead: A structure (like seawalls and revetments) that retains or prevents sliding of land or protects the land from wave damage.

Chart Datum: The level to which soundings (or elevations) or tide heights are referenced. To provide a safety factor for navigation, some level lower than mean sea level is generally selected for hydrographic charts, such as mean lower low water or Indian springs low water or lowest astronomical tide.

Clay: Fine-grained soil with individual particles less than 0.002 mm in diameter.

Cliff: Same as bluff.

Cohesive sediment: Sediment particles with small diameters (usually less than 0.02 mm) and for which the attractive forces between particles are larger than gravitational forces.

Continental shelf: The zone bordering a continent and extending from the low water line to the depth (usually about 200 m) where there is a marked or rather steep descent toward a greater depth.

Coral reef: Complex tropical marine ecosystem dominated by soft and stony (hard) corals, anemones and sea fans. Stony corals are microscopic animals with an outer skeleton of calcium carbonate that form colonies and are responsible for reef-building.

Coral: The skeletal remains secreted by small marine polyps.

Crest: Upper edge or limit of a shore protection structure. For a wave, the portion that is displaced above the still water line; often used to refer to the highest point of the wave.

Cross shore transport: The displacement of sediment perpendicular to the shore (onshore or offshore), usually into a berm (onshore) or into an offshore bar (offshore).

Current: Flow of water in a given direction.

Cusp: One of a series of low mounds of beach material separated by crescent-shaped troughs spaced at more or less regular intervals along the beach face.

Cyclone: An intense tropical storm in which winds move in near circular paths, spiraling inward towards a calm centre of low atmospheric pressure. Maximum surface wind velocities (10 minutes average) equal or exceed 33.5 m/s (65 knots). Also known as Hurricane or Typhoon in different parts of the world.

Deep water: Water sufficiently deep not to affect the propagation of surface waves. Generally, a point where the depth is greater than one-half the surface wavelength.

Deep-water waves: An ocean wave that is traveling in water depth greater than one-half its wavelength.

Delta: An alluvial deposit, roughly triangular or digitate in shape, formed at a river mouth.

Deltaic shoreline: Shoreline formed by the deposition of sediment at the mouth of large sediment-laden rivers.

Deposit: Something dropped or left behind by moving water, as sand or mud.

Diffraction: Phenomenon by which energy is transmitted laterally along a wave crest.

Diurnal: Cycle lasting approximately one day. A diurnal tide has one high and one low in each cycle.

Down-drift: In the direction of net long-shore transport.

Dredging:Removal of sand, silt, rock or sea bottom material.Dredging is usually undertaken to maintain a navigation channel.

Dune: Accumulations of wind-blown sands in ridges or mounds that lie landward of the beach and usually parallel to the shoreline.

Ebb current: Current away from shore or down a tidal stream. Usually associated with the decrease in the height of the tide.

Ebb tide: Part of the tidal cycle between high water and the next low. The falling tide.

Emergence shoreline: Shoreline formed by sea level lowering or land rising (due to tectonic change, for example), characterized by a straight shoreline and mild beach profiles.

Environmental impact assessment: Detailed studies, which predict the effects of a development project on the environment. They also provide plans for mitigation of the adverse impacts.

Erosion: The removal of sediment from a particular location by the action of wind or water. Wearing away of land by action of natural forces.

Estuary: Semi-enclosed body of water having a free connection with the open ocean where fresh water from land runoff mixes with seawater.

Fetch: The uninterrupted distance over which the wind blows (measured in the direction of the wind) without a significant change of direction.

Fill material: Any material used for the primary purpose of replacing an aquatic area with dry land or for changing the bottom elevation of a water body. This includes both natural materials (silt, sand, gravel, rock, and wood) and artificial materials (concrete, plastic, steel, treated wood).

Filter cloth: Synthetic textile with openings for water to escape, but which prevents passage of soil particles.

Filter material: Layer of fine gravel used in slope stabilization structures that allows water to escape and retains soil particles.

Flood current: The tidal current towards shore or up a tidal stream. Usually associated with the increase in the height of the tide.

Flood tide delta:Deposit of sand found on the bay or river side of an inlet and usually formed by tidal currents.

Flood tide: Part of the tidal cycle between low water and the next high water. The rising tide.

Fore-dune: The first dune behind a beach formed by deposition of sand blown from the beach by wind. Also known as frontal dune.

Foreshore: The part of the shore, lying between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low-water mark, that is generally traversed by the uprush and backrush of waves as tides rise and fall.

Freeboard: The additional height of a structure above design high water level to prevent overflow. Also, at a given time, the vertical distance between the water level and the top of the structure.

Fringing coral reef: Coral reef closely associated with the land; it may be joined directly to the beach or separated from the beach by a shallow lagoon. A coral reef attached directly to an island or continental shore.

Gabions: Wire mesh rectangular containers filled with stones or concrete.

Geomorphology: That branch of both physiography and geology which deals with the form of the Earth, the general configuration of its surface, and the changes that take place in the evolution of landform.

Groyne field: Series of Groynes acting together to protect a section of beach.

Groyne: A shore protection structure built (usually perpendicular to the shoreline), installed singly or as a field of Groynes, designed to trap sand from the littoral drift system or to hold sand in place.

Headland: Rocky outcropping jutting from a shore; often perpendicular to the shore and usually with an associated shoal.

High water mark: The highest reach of the water at high tide. It is sometimes marked by a line of debris, e.g. sea-grass, pieces of wood.

Higher High Water: The higher of the two high waters of any tidal day. The single high water occurring daily during periods when the tide is diurnal is considered to be a higher high water.

Hind-cast: To generate wave statistics from historical wind data using computer wave models.

Igneous rock: Created when melted rock, called magma, gets trapped in pockets deep inside the Earth. When the magma cools and hardens it is known as igneous rock. Granite is an example of igneous rock.

Indian Spring Low Water: The approximate level of the mean of lower low waters at spring tides, used principally in the Indian Ocean and along the east coast of Asia.

Jetty: A structure projecting into the sea for the purpose of mooring boats/vessels; also solid structure projecting into the sea for the purpose of protecting a navigational channel.

Lagoon: A shallow body of water, separated from the sea by sandbars and coral reefs.

Land reclamation: Process of creating new, dry land on the seabed.

Lateral stream migration: Change in position of a channel by lateral erosion of one bank and simultaneous deposition on the opposite bank.

Lee: Sheltered.

Leeward coast: Coast sheltered from the waves.

Leeward: The lee side.

Littoral current: Any current in the littoral zone caused primarily by wave action; e.g., long-shore current.

Littoral drift: The sediment moved in the littoral zone under the influence of waves and currents.

Littoral zone: In beach terminology, an indefinite zone extending seaward from the shoreline to just beyond the breaker zone.

Long-shore bar: Offshore ridge or mound of sand, gravel or other loose material running parallel to the shore which is submerged (at least at high tide) and located a short distance from the shore.

Long-shore current: Current in the breaker zone moving essentially parallel to the shore and usually caused by waves breaking at an angle to shore. Also called alongshore current.

Long-shore transport rate: Rate of transport of littoral material parallel to shore. Usually expressed in cubic meters per year.

Long-shore transport: Movement of material parallel to the shore, also referred to as long-shore drift.

Long-shore: Same as alongshore.

Low tide: Minimum elevation reached by each falling tide.

Low water mark: The highest reach of the water at low tide.

Lowest Astronomical Tide: The lowest tide level which can be predicted to occur under average meteorological conditions and any combination of astronomical conditions.

Mangrove: A group of tropical plant species that grow in low marshy areas; they have extensive root systems and produce much organic detritus to create a unique coastal environment for marine life.

Marsh: Area of soft, wet, or periodically inundated land, generally treeless, and usually characterized by grasses and other low growth.

Mean High Water: Average height of the daily high waters over a 19 year period.

Mean High Water Neaps: Long term average of the heights of two successive high waters when the range of the tide is least, at the time of first and last quarter of the Moon.

Mean High Water Springs: Long term average of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest, at full and new moon.

Mean Higher High Water: Average height of the daily higher high waters over a 19 year period.

Mean Low Water: Average height of the low waters over a 19-year period.

Mean Low Water Neaps: Long term average of the heights of two successive low waters over the same period as defined for Mean High Water Neaps.

Mean Low Water Springs: Long term average of the heights of two successive low waters over the same period as defined for Mean High Water Springs.

Mean Lower Low Water: Average height of the daily lower-low waters of a 19-year period.

MeanSea Level: The average height of the surface of the sea for all stages of the tide over a 19-year period.

Median diameter: The diameter which marks the division of a given sand sample into two equal parts by weight, one part containing all grains larger than that diameter and the other part containing all grains smaller.

Migrate: To change location periodically, usually seasonal.

Mixed tide: A tide in which there is a distinct difference in height between successive high and successive low waters. For mixed tides there are generally two high and two low waters each tidal day. Mixed tides may be described as intermediate between semidiurnal and diurnal tides.

Mud-banks: A geological phenomenon serving as a natural barrier for waves and is peculiar to the Kerala Coast from ancient times.

Neap tides: Tides with decreased ranges that occur when the moon is at first or last quarter.

Near-shore: In beach terminology, an indefinite zone extending seaward from the shoreline well beyond the breaker zone.

Non-cohesive sediment: Sediment particles with large diameters (usually greater than 0.02 mm) and for which the attractive forces between particles are less than gravitational forces.

Offshore breakwater: A structure parallel to the shore, usually positioned in the sea that protects the shore from waves.

Offshore transport: Movement of sediment or water away from the shore.

Offshore: In beach terminology, comparatively flat zone of variable width extending from the breaker zone to the seaward edge of the continental shelf.

Onshore transport: Movement of sediment or water toward the shore.

Overtopping: Passing of water over the top of a structure as a result of wave run-up or surge action.

Perched beach: A beach or fillet of sand retained above the normal profile level by a submerged breakwater or reef.

Pile: Long heavy section of timber, concrete or metal, driven into the earth or seabed to serve as a support or protection.

Plunge point: The final breaking point of the waves just before they rush up on the beach.

Pocket beach: A beach, usually small, in a bay or between two littoral barriers.

Promontory: A coastal protrusion or headland, high and bordered by cliffs or bluffs usually smaller than a Cape.

Retaining wall: Wall built to hold back the earth.

Retreat:Movement backwards towards the land.

Return period: The average time interval between occurrences of an event of a given or greater magnitude, usually expressed in years.

Revetments: Structure built to separate the land from the water to prevent erosion and other damage. Revetments are designed to protect shorelines and waterways from erosion by currents and small waves.

Riprap: Rocks or broken pieces of concrete often placed in areas where the flow of storm water is expected to cause erosion. The riprap serves as "armor" for areas of channels and detention basins to minimize the occurrence of erosion.

Rubble-mound structure: A mound of random-shaped and random-placed stones protected with a cover layer of selected stones or specially shaped concrete armour units.

Run-up: The rush of water up a structure or beach on breaking of a wave. Amount of run-up is the vertical height above still water level that the rush of water reaches.

Sand bar: Deposit of sand formed across a river mouth or bay by wave action and joined to the shore at both ends.

Sand bypassing: Hydraulic or mechanical movement of sand from the accreting up-drift side to the eroding down-drift side of a structure, inlet or harbour entrance.

Sand spit: Low tongue of land or a relatively long, narrow shoal extending from the land.

Sandbag: Cloth bag filled with sand or grout and used as a module in a shore protection measure.

Scarp: Elongated and comparatively steep slope separating flat or gently sloping areas on the seafloor or on a beach.

Scour: Removal of underwater material by waves or currents, especially at the toe of a shore protection structure.

Sea level rise: Apparent rise in average sea level of the ocean measured relative to a landmass.

Seasonal deposition: Accumulation of sand or other beach material, usually layered, resulting from variations in coastal processes.

Seasonal erosion: Loss of sand or other beach material resulting from variations in coastal processes.

Seawall: Structure built along the shore to prevent erosion and other damage primarily due to wave action.

Semidiurnal Tide: A tide with two high and two low waters in a day, each high and each low approximately equal in stage.

Setback: Prescribed distance landward of a coastal feature (e.g. the line of permanent vegetation), within which all or certain types of development are prohibited.

Shallow water: Commonly, water of such a depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depths less than one-twentieth the surface wavelength as shallow water.

Sheet Pile: Pile with a generally slender, flat cross section driven into the ground or seabed and meshed or interlocked with like members to form a diaphragm, wall, or bulkhead.

Shoal: Elevation of the sea bottom comprising and material except rock or coral (in which case it is a reef) and which may endanger surface navigation.

Shore: Narrow strip of land in immediate contact with the sea, including the zone between high and low water lines. A shore of unconsolidated material is usually called a beach.

Shoreline: Intersection of a specific water height with the shore or beach, e.g. the high water shoreline is the intersection of the high water mark with the shore or beach.

Sill: Low offshore barrier structure whose crest is usually submerged, designed to retain sand on its landward side.

Silt curtain: Fine, meshed material suspended in the water to prevent silt escaping from a construction site.

Silt: Generally refers to fine-grained soils having particle diameters between 0.002 and 0.075 mm. Intermediate between clay and sand.

Siltation: Deposition of silt-sized particles.

Soil erosion: Processes by which soil is removed from one place by forces such as wind, waves and construction activity and eventually deposited at some new place.

Spit: Deposit of sand or stones located where a shoreline changes direction, formed by wave action and joined to the shore at one end only.

Still water level: Elevation that the surface of the water would assume if all wave action were absent.

Storm surge: Rise above normal water level on the open coast due to action of wind on the water surface. Storm surge resulting from a cyclone also includes the rise in level due to atmospheric pressure reduction as well as that due to wind stress.

Storm tide: Water level resulting from the combined effect of a storm surge and the normally occurring astronomical tide.

Submergence shoreline: Shoreline formed by sea level rise or land subsidence, characterized by irregular features and steep beach profiles.

Surf zone: The area between the outermost breaker and the limit of wave uprush.

Suspended load: The material moving in suspension in a fluid, kept up by the upward components of the turbulent currents.

Swamp: Low-lying areas that are frequently flooded and support vegetation adapted to saturated soils e.g. mangrove swamps.

Swash zone: The region on the beach face delineated at the upper level by the maximum uprush of the wave and at its lower extremity by the maximum down-rush.

Swell: Wind-generated waves that have travelled out of their generating area.

Tidal current: Alternating horizontal movement of water associated with the rise and fall of the tide caused by the astronomical tide-producing forces.

Tidal inlet: A river mouth or narrow gap between islands, within which salt water moves landwards during a rising tide.

Tidal range: The difference between the height of high tide and the next succeeding or preceding low tide.

Tide: Periodic rising and falling of large bodies of water resulting from the gravitational attraction of the moon and sun acting on the rotating earth.

Toe protection: Material, usually large boulders, placed at the base of a sea defense structure like a seawall to prevent wave scour.

Tombolo: A bar or spit that connects or "ties" an island to the mainland or to another island.

Topography: The configuration of a surface and the relations among its man-made and natural features.

Training wall: A wall or breakwater constructed to direct current flow in a river or estuary.

Tsunami: A long-period wave caused by an underwater disturbance such as a volcanic eruption or earthquake.

Up-drift: Direction opposite to the predominant movement of littoral materials in long-shore transport.

Uprush: The rush of water up onto the beach following the breaking of a wave. Also called swash.

Wave cut platforms: Near horizontal platform just below the sea level at the base of a cliff that has been progressively cut back by waves.

Wave height: Vertical distance between a crest and the preceding trough.

Wave length: The distance in a periodic wave between two points of corresponding phase in consecutive cycles.

Wave period: The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.

Wave refraction:Process by which the direction of approach of a wave changes as it moves into shallow water.

Wave setup: A localized increase in still water level from the point of wave breaking, across the surf zone and to the shoreline.

Wave spectrum: Distribution of wave energy in a given wave record as a function of frequency.

Wetlands: Low-lyingareas that are frequently flooded and which support vegetation adapted to saturated soils e.g. mangrove swamps, marshesand bogs.