सत्यमेव जयते

भारत सरकार
जल शक्ति मंत्रालय
जल संसाधन, नदी विकास और गंगा संरक्षण विभाग
Government of India
Ministry of Jal Shakti
Department of Water Resources,
River Development & Ganga Rejuvenation

Technical Memorandum on

OVERVIEW OF PORT PLANNING AND DESIGN : PRINCIPLES, PRACTICES, AND THE ROLE OF CWPRS

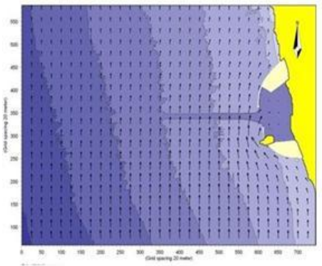
By
Rajeev Kumar Chaudhari, Scientist - C
Dr. M. Phani Kumar, Scientist - D

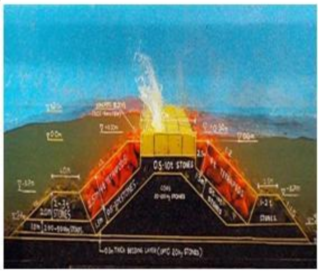
November, 2025

Dr. Prabhat Chandra
Director

केन्द्रीय जल और विद्युत अनुसंधान शाला, खडकवासला
CENTRAL WATER AND POWER RESEARCH STATION, KHDAKWASLA

Government of India
Ministry of Jal Shakti
Department of Water Resources
River Development and Ganga Rejuvenation
CENTRAL WATER & POWER RESEARCH STATION
Khadakwasla, Pune – 411 024





Technical Memorandum

on

OVERVIEW OF PORT PLANNING AND DESIGN: PRINCIPLES, PRACTICES, AND THE ROLE OF CWPRS

By

Rajeev Kumar Chaudhari, Scientist- C
Dr. M. Phani Kumar, Scientist- D

Dr. Prabhat Chandra
DIRECTOR

FOREWORD

The development of ports is one of the most ancient engineering endeavours known to humankind. In recent years, ocean transport has gained even greater importance due to its cost-effectiveness, calling for advanced and innovative approaches in port engineering. The Central Water and Power Research Station (CWPRS), Pune, India, a premier institute in the field of applied hydraulic research, has been contributing significantly to port development and coastal engineering studies for more than seven decades.

CWPRS made its humble beginning in the early 1950s by undertaking port development studies for Madras, Kandla, Kolkata, and Mumbai Harbours. Subsequent to the liberalization of the Indian economy, private port development gained momentum. More recently, under the flagship “Sagarmala” programme of the Government of India, port-led development has been initiated through modernization of existing ports, development of six mega ports under public–private partnership (PPP) schemes, and the creation of coastal economic zones.

Over the years, CWPRS has made strong imprints on the development of all major and minor ports in India, as well as on various coastal infrastructure projects. The institute has provided innovative, sustainable, and cost-effective solutions for coastal protection along the Indian coastline. Its expertise extends beyond ports and harbours to studies related to maintenance of coastal ecology, flood mitigation, effluent intake and outfall systems, and cooling water circulation systems for several nuclear power projects. CWPRS has also extended its consultancy services to several coastal projects abroad. Presently, CWPRS has been providing it's expertise to many on-going projects like New-Mangalore Port, Kalpasar, Varsha, Porbandar port, Vadhvan, ICTP at Andaman and Nicobar, Vasco Bay development, Ramayapatnam port, Kakinada Port and Greenfield port at Murbe etc.

With its vast experience, CWPRS continues to play a vital and significant role in the development of major and minor ports, passenger terminals, and fishing harbours across India. The organization is equipped with state-of-the-art facilities for both physical and mathematical hydraulic modelling, supported by modern laboratory and field instrumentation for data collection and analysis, at par with international standards.

The present Technical Memorandum on “Overview of Port Planning and Design: Principles, Practices, and the Role of CWPRS” is a consolidated document that reflects CWPRS’s extensive experience in the field of coastal and port engineering. It is envisaged that this memorandum will serve as a useful reference for design engineers, planners, and field professionals engaged in the planning and design of ports and harbours.

CWPRS, PUNE-411 024

Dr. Prabhat Chandra
Director

INDEX

List of Figures

CHAPTER I

INTRODUCTION

India’s port and shipping industry plays a crucial role in sustaining the nation’s trade and economic growth. With a coastline of about 7,517 km, India ranks as the sixteenth largest maritime nation in the world. Port planning on open coast and in tidal and estuarine regions requires an integrated understanding of coastal hydraulics, sediment transport, and environmental processes. It demands specialized technical approaches to ensure the functionality, safety, and sustainability of proposed layouts. This memorandum presents the theoretical background, technical challenges and application tools required to conduct hydraulic model studies in modern port planning. It also emphasizes the need for site-specific dredging, disposal, breakwater design strategies and the role of CWPRS in the planning and development of ports and harbours.

1.1 The Strategic Importance and Function of Ports

Ports and harbours are critical infrastructure essential for global trade, maritime transportation, and economic development. They function as vital nodes in the global supply chain, seamlessly connecting sea and land transport networks and facilitating the worldwide movement of goods and people. As gateways between land and sea, they play a pivotal role in supply chain efficiency, economic development, and geopolitical influence. A port or marine terminal is designed to offer facilities for the trans-shipment of cargo between vessels, as well as for cargo transported to and from inland locations via rail, road, inland waterways, and pipelines.

Strategically located ports enhance a nation's competitiveness by reducing logistics costs, attracting foreign investment, and supporting industrial growth. Beyond their economic function, ports also hold significant military and security importance, serving as key hubs for naval operations and humanitarian aid distribution. Their ability to handle large volumes of cargo, integrate with multi-modal transport systems, and adapt to technological advancements—such as automation and green port initiatives—determines their long-term sustainability and relevance. By understanding their functions and challenges, stakeholders can better leverage ports as engines of growth in an increasingly inter-connected world.

1.2. Challenges and Uncertainties in Port Facility Planning

Port facility planning must account for future demands while navigating significant uncertainties, particularly from dynamic and unpredictable environmental forces. Ports are continuously exposed to variable and often extreme natural conditions including wind, tides, currents, and waves which can disrupt operations and inflict structural damage. These risks manifest in multiple ways, such as flooding, extreme water level fluctuations, wind-induced damage, erosion, and sedimentation, all of which can compromise efficiency, safety, and long-term viability.

To ensure resilience, port facilities must be designed with robust risk mitigation strategies, minimizing the likelihood of critical failures or operational disruptions. Key challenges include:

- **Operational Disruptions in Cargo Handling** – Flooding and wave action can halt loading and unloading operations, leading to costly delays and supply chain bottlenecks.

- **Restricted Vessel Access and Berthing Challenges** – Adverse wind, extreme water levels, strong currents, and waves may prevent ships from safely accessing or remaining at port facilities, forcing evacuations or diversions.
- **Structural Damage to Protective Infrastructure** – Breakwaters, seawalls, and other protective structures are vulnerable to degradation from persistent wave forces, currents, and high winds.
- **Quay and Berth Damage from Ship Movements** – Moored vessels subjected to environmental forces can collide with or strain quays and berthing platforms, increasing maintenance costs and downtime.

Addressing these challenges requires advanced modelling, adaptive design, and proactive maintenance to ensure port infrastructure remains functional, safe, and economically sustainable in the face of growing climatic and operational uncertainties.

1.3 Design Parameters and Probabilistic Risk Assessment

The selection of design probabilities for critical port events should be informed by rigorous cost-benefit analysis whenever practicable. This evaluation must balance the additional costs of enhanced structural resilience against the long-term economic benefits of reduced operational disruptions and infrastructure damage. In certain cases, when coastal infrastructure is planned at river mouth, joint probability analysis is required to decide upon the critical model boundary conditions considering fluvial flows and sea tidal levels. In the era of climate change, consideration of additional components like storm surge and sea-level rise is also essential over and above the normal tidal levels in the model simulations to arrive at 'design water levels' and 'safe-grade elevations' of various reclamations and berthing structures.

Key design parameters, determined through probabilistic risk assessment, include:

- **Extreme High Water:** Potential for flooding of quays, leading to interruption of cargo handling, damage to cargo, and harm to fixed installations.
- **Extreme Low Water:** May necessitate ships leaving berths or prevent entry into the port.
- **Extreme Wind Conditions:** Can cause:
  - (i) Interruption of cargo handling operations.
  - (ii) Ships being forced to leave berths or being unable to dock.
  - (iii) Damage to port buildings and superstructures.
- **Extreme Currents:** Can lead to:
  - (i) Interruption of ship arrival and departure.
  - (ii) Erosion damage to submerged structures and channel beds.
- **Extreme Wave Action:** May result in:
  - (i) Damage to breakwaters and coastal defences.
  - (ii) Interruption of cargo handling operations.
  - (iii) Ships being forced to leave berths or being unable to dock.
  - (iv) Siltation of basins and/or access channels.

This structured approach enables designers to prioritize mitigation measures where they yield the highest return on investment, ensuring optimal allocation of resources while maintaining operational reliability.

1.4 Strategic Considerations for Port Development and Expansion

The need for new ports or the expansion of existing ones typically arises from increased traffic volumes or the emergence of entirely new types of cargo and vessel traffic. When a choice of location exists, new ports and port extensions should ideally be sited to minimize the total sea and land transportation costs for the national economy, considering the cargo's various origins and destinations. This decision is influenced not only by the geographical location of the port site but also by the differing construction costs associated with various potential sites.

1.5 Evolving Shipping Trends and Their Impact on Port Requirements

Ports are crucial for global supply chains, handling diverse cargo. Global trends in 2024 show containerization dominance (over 90% of maritime trade), larger vessels requiring deeper ports, and a push for decarbonization and digitalization for resilience. India is focused on expanding port capacity via the Sagarmala Programme, with JNPA and Mundra being key players, and developing waterways under the Maritime India Vision 2030 to reduce logistics costs. Port inefficiency is costly, but India is improving turn-around times through initiatives like DPD at JNP. Technological advancements include mega-vessels necessitating deeper ports (e.g., Colombo), automation and digitalization for smart ports (e.g., PCS 1x in India), and specialized terminals (e.g., LNG terminals). Future challenges involve decarbonization (green ports), geopolitical risks (e.g., Red Sea crisis), and automation impacting labor. India is addressing these with green initiatives, strategic port development (Chabahar, IMEC), and skill development. Ultimately, modern ports must become smart, sustainable, and resilient, and India's Maritime India Vision 2030 aims for global leadership, contingent on execution.

1.6 Core Physical Functions of a Port

The main physical functions performed within a port include:

- Ship and vehicle handling (berthing, mooring, traffic management).
- Loading and unloading of cargo.
- Stacking and unstacking of cargo.
- Transfer of cargo between modes of transport and within the port.
- Physical form change (e.g., bagging, packaging, light processing).
- Temporary storage and warehousing.
- Consolidation and deconsolidation of cargo.
- Environmental control and protection.
- Inspection, surveying, and marking of cargo.
- Inventory management.
- Documentation, customs clearance, and cargo control.

1.7 Classification of Port

Ports, vital nodes in global trade, exhibit diverse roles and operational characteristics categorized by several criteria:

1.7.1 Location

- Coastal/Open Sea Ports: Situated on coastlines, handling major international traffic and larger vessels.
  - (i) Natural: Located in sheltered areas (bays, estuaries).
  - (ii) Artificial: Constructed with breakwaters and dredging for protection.
- Inland Ports: Located on rivers, lakes, or canals, connecting inland economies to sea routes, often facilitating inter-modal transport.

- Estuary Ports: At river mouths meeting the sea, benefiting from river depth and sea access.

1.7.2 Function and Cargo Handling

- Single-Terminal (Specialized) Ports: Designed for specific cargo types:
  (i) Container Ports: Handle containerized cargo with specialized cranes and storage.
  (ii) Bulk Cargo Ports: Handle unpackaged commodities (coal, grain, liquids) using conveyors, grab unloaders, and pipelines.
  (iii) Break-Bulk Ports: Handle non-containerized/bulk general cargo (machinery, palletized goods).
  (iv) Ro-Ro Ports: For wheeled cargo (vehicles, trailers).
  (v) Passenger Ports: Serve ferries and cruise ships with passenger facilities.
  (vi) Fishing Ports: Infrastructure for the fishing industry (berthing, processing).
- Multi-Terminal (Multi-purpose/Composite) Ports: Handle various cargo types across specialized terminals, offering operational flexibility.

1.7.3 Ownership and Governance

- Public Ports: Government-owned and operated, focused on public service and trade facilitation.
- Private Ports: Privately owned and operated, with a commercial focus on profitability.
- Public-Private Partnership (PPP) / Landlord Ports: Public sector owns land/infrastructure, private sector operates terminals.
- Tool Ports: Port authority owns all assets and directly employs labour.
- Service Ports: Port authority owns and operates the entire port, providing all services.

1.7.4 Size/Scale and Connectivity

- Major Ports (Hub Ports): Large, deep-draft ports accommodating large vessels (ULCVs), serving as transhipment hubs connecting main and feeder routes.
- Minor Ports (Feeder Ports): Smaller ports handling lower volumes, serving regional needs or acting as feeders to major hubs.
- Regional Ports: Primarily serve the trade needs of a specific geographic area.

1.7.5 Definition of a Terminal

A dedicated, specialized facility within a port equipped for efficient handling, storage, and transfer of specific cargo types. A port can contain multiple terminals.

This classification highlights the multi-faceted nature of ports, each tailored by location, function, ownership, and scale to fulfil specific roles within the complex global maritime network.

1.8 Modern Analytical Techniques in Port Planning

Contemporary port planning utilizes advanced analytical methods like mathematical programming, game theory (often within input-output frameworks for market demand forecasting), deterministic transportation networks, stochastic flow graph models (for traffic modelling), and stochastic network simulation (for capacity and efficiency evaluation). These techniques enhance strategic decision-making and port adaptability.

1.9 The Indian Port Sector: An Overview

India has a vast coastline with 12 major and over 200 minor ports, crucial for its economy. Total cargo handled grew significantly from 334 MT in FY 1999-2000 (major: 272 MT, minor: 62 MT) to 1540.23 MT in FY 2023-24 (major: 819 MT, minor: 721 MT). Provisional data for FY 2024-25 indicates a 4.3% growth in major port cargo to 855 MT, driven by increased container, POL, fertilizer, and miscellaneous commodity throughput. This growth reflects infrastructure development, capacity expansion, efficiency improvements, investments, and supportive policies strengthening India's maritime trade position.

1.10 Scope of the Technical Memorandum

This technical memorandum provides fundamental guidelines and a comprehensive overview for the strategic planning and engineering design of major port infrastructure. It is organized into nine chapters covering key aspects of port planning, design, and operations. Chapter 2 provides the basic terminology of the sector and the points to be considered for selection of site for port development. Chapter 3 describes various aspects of the design of approach channels, basins and navigational aids. Various coastal parameters to be considered in the design are given vide Chapter 4 along with the details regarding equipment required for field data collection. In Chapter 5, various hydraulic model studies essential for port planning viz. Physical and numerical modelling aspects are covered including desk studies. Breakwater details and conceptual design are included in Chapter 6. Berthing structure features like mooring systems and fendering arrangements etc. along with offshore terminals are given vide Chapter 7. Chapter 8 includes dredging and disposal related content. Salient features of various ports and the contribution of CWPRS are given in Chapter 9.

CHAPTER II

BASIC TERMNOLOGY AND SELECTION OF SITE

2.1 Definitions

A ***harbour*** is a water area partially closed and protected from storms as to provide safe and suitable accommodation for vessels seeking refuge, supplies, refueling, repairs or the transfer of cargo.

A ***natural harbour*** is an inlet or water area protected from the storms and waves by the natural configuration of the land. Its entrance is so formed and located as to facilitate navigation while ensuring comparatively quiet within the harbour. Natural harbours are located in bays, tidal estuaries and river months.

A***rtificial harbour*** is the one which is protected from the effect of waves by means of breakwaters or one which may be created by dredging

A ***semi-natural harbour*** may be an inlet or river sheltered on two sides by headlands and requiring artificial protection only at the entrance. Next to a purely natural harbour, it forms the most desirable harbour site, other things being equal.

A ***port*** is a sheltered harbour where marine terminal facilities are provided, consisting of piers or wharves at which ship berth while loading or unloading cargo, transit sheds and other storage areas where ships may discharge incoming cargo and warehouses where goods may be stored for longer periods while awaiting distribution or sailing. Thus the terminal must be served by railheads, highway or inland waterway connections and in this respect the area of influence of the port reaches out for a considerable distance beyond the harbour.

A ***marine terminal*** is that part of a port or harbour which provides docking, cargo handling and storage facilities. Where only passengers embark or disembark along with their baggage and miscellaneous small cargo generally from ships devoted mainly to the carrying of passengers it is called a passenger terminal. In many cases, it will be known as bulk cargo terminal where such products as petroleum, cement and grains are stored and handled.

An ***offshore mooring*** is provided usually where it is not feasible or economical to construct a dock or provide a protected harbour.

An ***anchorage area*** is a place where ships may be held for quarantine inspection, await docking space while sometimes removing ballast in preparation for taking a cargo or await favourable weather conditions.

A ***turning basin*** is a water area inside a harbour or an enlargement of a channel to permit the turning of a ship. When space is available the area should be at least twice the length of the ship to permit either free turning or turning with the aid of tugs, if wind and water conditions require.

A ***breakwater*** is a structure constructed for the purpose of forming an artificial harbour with a water area so protected from the effect of sea waves as to provide safe accommodation for shipping, but occasionally, they serve a dual purpose by becoming part of a pier or supporting a roadway.

A ***dock*** is a general term used to describe a marine structure for the mooring or tying up of vessels, for loading and unloading cargo, or for embarking and disembarking passengers.

A ***wharf or quay*** is a dock which parallels the shore. It is generally contiguous with the shore, but may not necessarily be so. On the other hand, a bulkhead or quay wall while similar to a wharf is backed up by ground.

A ***pier or jetty*** is a dock which projects into water. A pier may be more or less parallel to the shore and connected to it by a mole or trestle, generally at right angles to the pier.

Dolphins are marine structures for mooring vessels. They are commonly used in combination with piers and wharves to shorten the length of these structures and are a principal part of the fixed mooring berth type of installation.

Displacement tonnage is the actual weight of the vessel or the weight of water it displaces and may be either `loaded' or `light'. Displacement loaded in the weight in long tons of the ship and its contents, when fully loaded with cargo, to the Plimsoll mark or load line painted on the hull of the ship.

Dead weight tonnage (DWT) is the carrying capacity of the ship in long tons and the difference between displacement light and the displacement when loaded to Plimsoll mark. It is the weight of cargo, fuel and stores which a ship carries when fully loaded down to the load line as distinguished from loaded to her space capacity.

The ***gross tonnage*** is the entire internal cubic capacity of a ship and net tonnage is the gross tonnage less the space provided for the crew, machinery and engine room and hull. Measure of the overall size of a ship determined in accordance with the provisions of the International Convention on Tonnage Measurement of Ships, 1969. No units required as it is a non-dimensional quantity.

The ***draft*** of a ship, expressed in relation to the displacement as being loaded or light draft, is the depth of the keel of the ship below water level for the particular condition of loading.

Ballast is the weight added in the hold or ballast compartments of a ship to increase its draft after it has discharged its cargo and to improve its stability. It usually consists of water and is expressed in long tons.

Aids to Navigation (A to N)*:* Device external to a vessel designed to assist in the determination of its position and its safe course or to warn of changes or obstructions. In the case of channels such devices include buoys, piled beacons, leading lights, sector lights, radar reflectors, etc.

Air draught: Vertical distance measured from the ship's waterline to the highest point on the ship.

Air draught clearance: Vertical distance measured from the highest point on the ship up to the underside of an overhead obstruction (such as a bridge or power cable).

Bank effects: Hydrodynamic effect caused by the proximity of a ship to a bank. Asymmetrical pressures acting on the ship may cause it to be sucked towards, and turned away from, the bank. Bank effects depend on speed, distance off, ship size, bank geometry and water depth/draught ratio.

Bend Angle: Angle between two legs of a channel which meet at a bend. Usually expressed as the change of heading for a ship using a bend, so that a '45° bend' means that a ship's track heading must change by 45° when navigating the bend.

Bend Radius: Radius from the centre of the bend to the centre-line of the channel.

Concept Design: Preliminary design of channel width, depth and alignment using data given in this report, together with other relevant data relating to ships and environment.

Differential GPS (DGPS): Method of improving the accuracy of GPS by means of ground stations at known locations.

Detailed Design: Additional design process involved in refining and exploring aspects of the approach channel design once the initial width, depth and alignment have been determined.

Downtime: Period(s) of time for which the channel cannot be used. This may be due to maintenance, accidents, congestion, insufficient water depth (due to low tide height), excessive wind, waves or current for safe navigation, or other met-ocean conditions (visibility, ice, etc.).

Fairway: Navigable waterway defined by the fairway buoys. This may or may not have a width equal to that of the channel (Figure 2.1).

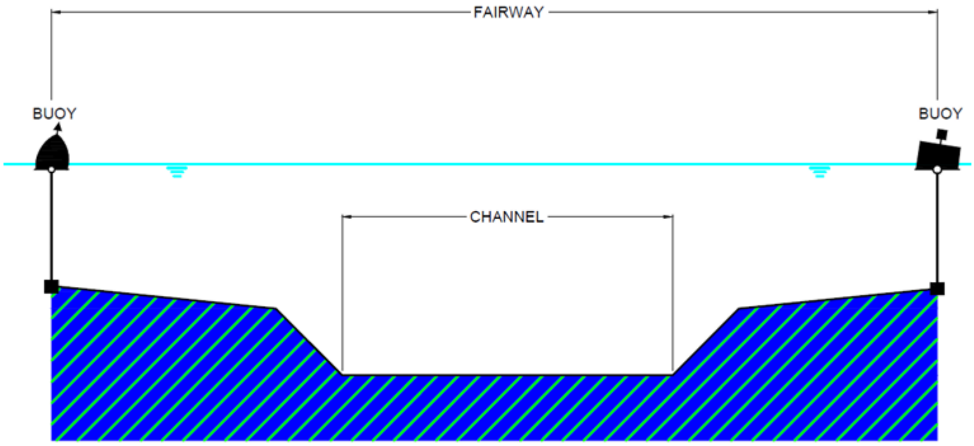


Figure 2.1: Fairway of Approach channel

Froude Depth Number: Most important dimensionless parameter is the depth Froude Number F_{nh}, which is a measure of the ship's resistance to motion in shallow water. The F_{nh} expresses the ship's speed as a fraction of a critical value $\sqrt{gh}$,which is the maximum velocity of a disturbance propagating in a free surface of unrestricted shallow water with depth h.

Grounding*:* Grounding occurs when a vessel under way comes into contact with the bed of waterway, berth or bank of a fairway, canal or river.

Impact: Impact occurs when a vessel under way, or drifting, hits an immovable object such as a jetty.

Interaction: Hydrodynamic effect induced on a ship when close to another ship or a bank. It causes asymmetric forces and moments to act on the ship which can cause it to move off course.

Marine impact assessment (MIA)*:*Multi-disciplinary method of assessing the effect of a change in the marine environment brought about by channels, new reclamations, changes in marine traffic, etc. The effect on marine risk is of paramount importance.

Manoeuverability Margin (MM): Manoeuverability Margin is the critical value of net under- keel clearance that will allow the ship to maneuver safely. A value of UKC less than the MM may result in unstable and dangerous conditions for a ship in transit.

Met-ocean conditions*:* Environmental conditions due to wind, wave, current, etc.

Navigation aid: Instrument, device, chart, etc. carried on board a vessel and intended to assist in its navigation.

Prevailing wind/current: Commonly occurring wind or current obtained from current and wind records. Currents will include tidal streams and wind-induced currents.

Risk*:* Product of the probability of a hazard resulting in an adverse event, times the severity (or possibly cost) of the consequence of that event.

Sea or Wind Sea*:* Wind waves are waves generated and affected by the local winds. These waves are characterized by short periods (typically more than 3 s and smaller than 8 s) and have a short-crested, irregular sea surface.

Sheer *:* Tendency of a ship to deviate from its chosen course. Usually this is caused by ship-ship interaction, bank effects, waves, high velocity local cross-currents, or wind squalls.

Stranding: Consequence of a grounding in which the ship is left high and dry.

Striking*:* Striking occurs when a ship underway hits a drifting floating object, such as a ship at anchor, floating dock or buoy.

Swell*:* Swell waves are wind-generated waves that have travelled out of their generating area. Swell has more well-defined and flatter crests than wind waves. Swell wave periods are very regular, ranging from 8 to 30 s, although 15 to 30 s periods are rare.

Swept track*:* Track swept out by the extremities of the ship when manoeuvering. It will generally be greater in bends than straight sections and in cross winds and currents. It will also be greater in deep water, under a given set of conditions, compared to shallow water.

Trade-off study*:* Study in which various (often competing) options are weighed against each other with the view to achieving an acceptable compromise solution.

Trim : Trim is the difference between draught forward and the draught aft, measured in metres (or sometimes degrees). Trim by the stern (i.e. deeper at the stern) is defined as positive.

Window*:* Time period for which a channel is available for use (typically due to tide height).

Vessel Traffic Service (VTS): Advisory service for mariners regarding ship operations in a port provided by an administration or Port Authority.

2.2 Site Selection

The selection of a site for port or harbor development is a critical process that ensures the facility meets its intended functions and serves the diverse needs of port users, including navigation, cargo handling, and safety. Key considerations include environmental, geotechnical, and operational factors, balanced against economic and future development requirements. Site selection is heavily influenced by exposure to waves, currents, and sediment transport. To minimize maintenance and ensure operational efficiency, marine structures should ideally be located in naturally sheltered areas, such as:

- Behind islands, shoals, or breakwaters to reduce wave impact.
- Within deep natural bays, fjords, or sheltered lagoons.
- At tidal entrances or estuaries with minimal exposure to extreme hydrodynamic forces.

Littoral drift, the movement of sediment along the coast, must be carefully assessed to prevent unintended shoreline changes or excessive dredging. General guidelines include:

- Avoid down-drift locations near large sediment sources (e.g., rivers, estuaries, or eroding shores) to prevent rapid sediment accumulation.
- Favor up-drift sites to minimize interference with natural sediment transport.
- Locate ports in neutral drift zones where sediment movement is balanced in both directions or rather in the zones with minimal differential drift rates.
- On open coasts with littoral drift:
  - (i) Prefer convex shores, which reduce drift due to their alignment against wave energy vectors. Ports should be placed as far downdrift as possible on such shores.
  - (ii) Avoid concave shores, where drift increases, unless the shoreline angle exceeds the maximum drift point (40°–60°), allowing placement either far up-drift (minimal drift) or beyond the accumulation zone.
- Select sites with coarse sediment (e.g., sand, gravel) on exposed shores, as these are more stable and require less dredging compared to fine sediment areas (e.g., silt, clay).
- Position ports downdrift of accumulation shoals in oceans, lagoons, or estuaries, while avoiding interference with local wave and current patterns.
- Where strong longshore currents exist, design streamlined breakwaters to minimize eddies and subsequent shoal formation.
- On headlands, the updrift side may be steep, potentially requiring sediment bypassing to maintain shoreline stability. The downdrift side may offer suitable sites for coarse sediment shores but could face challenges with shallow depths or excessive shoaling in fine sediment areas, necessitating significant dredging.

Site selection must account for environmental conditions that impact port operations, as outlined by PIANC's ICORELS committee. These include:

- Astronomical tides and their range.
- Wind patterns and their impact on navigation and mooring.
- Meteorological effects, such as storm surges and negative surges, which alter water levels.
- Wave characteristics (amplitude, period, direction) to minimize ship motion and mooring forces.

- Currents, which affect navigation and sediment transport.
- Visibility, critical for safe vessel operations.
- Ice conditions, where applicable, to ensure year-round functionality.
- Topographic, hydrographic, and soil conditions, which influence foundation stability and dredging requirements.

To optimize berth orientation, avoid broadside exposure to waves, winds and currents, as such conditions increase ship motion, mooring forces, and fender stress, hindering cargo operations. Dredged channels in open seas should ideally be perpendicular to depth contours to minimize dredging volumes, provided hard materials are avoided. In rivers or tidal inlets, channels should align parallel to the deepest contours to leverage natural depths. Where possible, align channels with predominant currents, particularly near tidal inlets or rivers, to reduce sedimentation. Geotechnical Considerations i.e. Geotechnical investigations viz. seismic reflection/ seismic refraction studies are essential for assessing sub-bottom profiling / sub-base strata and ensuring structural stability. Key data to collect include:

- Bedrock characteristics, including origin, formation, and properties like crushing strength.
- Geological discontinuities, such as faults, fissures, or folds, which could compromise foundations.
- Soft strata below foundation level, requiring detailed study via subsurface soundings (e.g., Standard Penetration Test, SPT).
- For dredging, boreholes should extend to a known geological formation or at least 5 meters below the design dredged depth, whichever is shallower.

Given the significant capital investment in port infrastructure, site selection must consider future developments, such as increasing ship sizes (e.g., bulk and container vessels) and climate change impacts like sea-level rise and intensified storms. Hydraulic and mathematical modelling are powerful tools for evaluating site suitability and optimizing layouts. These models help assess wave, current, and sediment dynamics, ensuring minimal environmental disruption and long-term sustainability. Effective site selection balances natural protection, minimal environmental interference, and operational efficiency while accommodating future growth and resilience. By integrating hydrodynamic, geotechnical, and operational data with advanced modeling, port planners can identify sites that ensure safety, functionality, and economic viability. Generally, crescent shaped bays will provide larger shelter area with minimal length of breakwaters thus giving better cost-benefit ratio. Thorough understanding of site-specific conditions is essential before finalizing any site for the development of port infrastructure.

2.3 Port Development in Gulfs and Creeks

Port development in gulfs and creeks requires careful consideration of complex hydrodynamic, environmental, and ecological factors, as guided by PIANC and IMO recommendations, to ensure safe navigation, operational efficiency, and environmental sustainability. Oceanic tides, driven by gravitational forces, propagate as shallow-water gravity waves, causing vertical and horizontal water movements and periodic oscillations in adjacent seas, gulfs, creeks, bays, and estuaries. These tides, comprising diurnal, semidiurnal, and quarter-diurnal constituents, undergo significant transformations in shallower coastal regions due to decreasing depths, varying channel widths, and bottom friction, potentially amplifying water levels through resonance in geometrically constrained gulfs, as noted by PIANC's ICORELS committee. Tidal currents, while weaker in the open ocean compared to wind-driven currents, dominate in confined water bodies like creeks and estuaries, with flow patterns complicated by flow separation at headlands, eddy formation in embayments, and slack water zones along fringes.

In estuaries, river discharges enhance ebb currents, diminish flood currents, and govern salinity intrusion alongside tidal dynamics, leading to well-mixed, partially mixed, or stratified conditions.

Port development in gulfs and creeks can be highly beneficial as these locations provide natural sheltered waters that reduce exposure to harsh sea conditions and lower infrastructure as well as maintenance costs. Such developments boost trade and commerce by facilitating imports and exports, attracting allied industries, and creating significant employment opportunities, while also supporting fisheries, cold storage, and tourism activities. Strategically, ports in creeks offer safe anchorage, shorter approach channels, and can serve defense and coast guard operations, thereby enhancing maritime security. They also improve regional connectivity through coastal shipping and inland waterways, easing pressure on land transport systems, and foster urban growth in surrounding areas. Additionally, these ports support the blue economy by enabling offshore oil and gas exploration, aquaculture, renewable energy logistics, and transshipment hubs for international trade. However, since gulfs and creeks are ecologically sensitive zones with mangroves, tidal flats, and rich biodiversity, port development must be planned with proper environmental safeguards to balance economic growth with long-term ecological sustainability.

2.4 Port Development in Rivers and Delta Regions

2.4.1 Riverine Ports

Riverine ports, located in non-tidal inland environments, encounter unique hydraulic and morphological challenges distinct from estuarine and coastal settings, in line with PIANC and IMO guidelines. Riverbeds are typically composed of cohesion-less sand and silt, facilitating sediment transport analyses yet complicating channel stability due to highly dynamic bed morphology. Seasonal variation in river discharge most pronounced in monsoon-influenced rivers such as those in India is critical for maintaining navigable depths, but is often further constrained by upstream dam regulation, which can severely reduce dry season flows. Such fluctuations frequently result in insufficient natural depths for large-scale port infrastructure, while extreme floods may mobilize significant sediment, shifting shoals, sand bars, and navigation channels and thus posing operational hazards.

Seasonal water level variability complicates siting of jetties; positions suitable during low flows are prone to inundation during floods, while infrastructure such as barrages and bridges often restrict navigation, necessitating costly locks with complex operational requirements as recommended by PIANC for inland waterway design. Consequently, large-scale riverine port development is generally economically prohibitive, though localized river stretches with reliable depths may support smaller barges, mechanized vessels, and passenger craft. The Inland Waterways Authority of India (IWAI) facilitates such operations through flow-training works, dredging, and establishment of river terminals to enhance navigability.

Advanced planning and design require mobile bed physical hydraulic models and high-resolution numerical simulations to assess sediment transport, channel dynamics, and optimize river training works and lock operation. These tools are critical for aligning riverine port design with IMO's sustainability objectives for low-carbon transport and PIANC's emphasis on resilient, adaptive infrastructure. Ultimately, these modelling approaches help minimize environmental impact, promote safe operations, and support efficient inland water-borne transport in highly dynamic riverine environments.

Riverine ports in India are not just remnants of the colonial trade era; they are integral to modern logistics, multimodal connectivity, inland waterway development, and regional growth.

With government initiatives like Sagarmala and Jal Marg Vikas, their role is expected to expand, making them crucial nodes in India's port and shipping sector.

2.4.2 Port Development in Delta Regions

Port development in delta regions, where rivers discharge water and sediment into coastal waters at open coasts, gulfs, or bays, is complex due to dynamic interactions between riverine sediment transport, tidal influences, and wave- and current-driven processes.

These confluence zones are dynamic environments characterized by significant deposition of river-borne material, influenced not only by river discharge but also by tidal forces, waves, and coastal currents.

Small rivers generally form single sand bars at their mouths, whereas large rivers give rise to extensive deltaic systems comprising multiple distributary channels, shoals, and islands formed by long-term sediment deposition. While tidal action contributes to local sediment dynamics, the overall sediment balance in deltas is primarily governed by river discharge.

Deltaic regions can extend over hundreds of square kilometers, creating intricate channel networks and unstable morphologies that pose considerable challenges for large-scale and fully integrated port development. As a result, port development in such settings is typically limited to localized interventions, including the construction of spurs and training walls, channel dredging, and the selective use of naturally stable waterways. These approaches generally support the establishment of isolated jetties or minor port facilities rather than major port complexes.

On the Indian coast, prominent delta systems occur at the mouths of rivers such as the Mahanadi, Krishna, and Godavari on the east coast, while on the west coast, the Narmada and Tapi rivers debouch into the Gulf of Khambat. The Narmada mouth is characterized by extensive shoals and islands, though the strong tidal currents in the Gulf inhibit the development of a large delta. Similarly, the Tapi mouth features complex deltaic channels and islands, which currently accommodate localized jetty-based port infrastructure. Understanding the riverine dynamics and sediment budgeting is the key for planning of port based infrastructure.

Delta regions in India present a strategic opportunity for port-led development, despite natural challenges of siltation and cyclones. With modern dredging, coastal protection works, and environmental management, deltaic ports can enhance India's trade capacity, strengthen the Sagarmala initiative, and support the vision of India becoming a global maritime and logistics power.

Chapter III

DESIGN OF APPROACH CHANNELS, BASINS AND NAVIGATIONAL AIDS

3.1 Approach Channel

The design and development of approach channels are critical for ensuring the safe and efficient movement of vessels between the open sea and port facilities. According to international best practices (PIANC, 2014; IMO Guidelines), the location and alignment of approach channels should be based on a balanced consideration of navigational safety, economic viability, environmental sustainability, and operational efficiency.

Where possible, channels should not be located downdrift of major sources of littoral drift to minimize sedimentation. The preferred alignment is perpendicular to seabed contours, unless this results in excessive dredging of hard strata or higher long-term maintenance due to wave or current-induced sediment transport. The final choice of channel depth and width should be governed by a life-cycle cost approach that accounts for both capital dredging and forecast maintenance dredging, discounted over the project horizon.

Modern port planning emphasizes optimization of the overall transport chain economics, including an acceptable return on investment (ROI) in port infrastructure and equipment, while meeting stringent environmental and regulatory requirements. The increasing deployment of larger vessels, driven by scale of economies in global shipping, has intensified pressure on port authorities to design channels that:

- Minimize ship transit time in the approach channel.
- Provide accessibility under all tide and weather conditions, or at least minimize operational restrictions.

An approach channel is broadly defined as the navigable stretch connecting the open sea to the port's berths and basins. Two primary types are recognized:

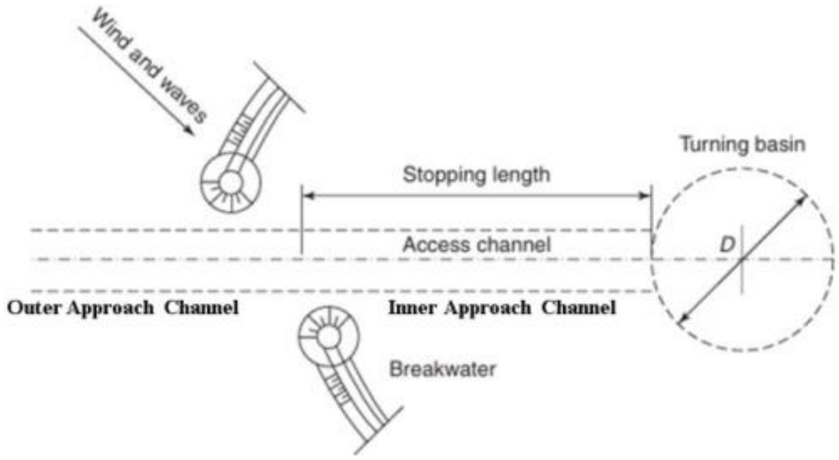


Figure 3.1: Typical Arrangement of approach channel

- Outer channels, located in exposed waters, where waves can induce significant ship motions (heave, pitch, roll).
- Inner channels, typically sheltered from wave action, but still subject to tidal flows, sedimentation, and vessel interaction effects.

(a) Location and Orientation of Approach Channel

The location and orientation of an approach channel directly influence navigational safety, dredging effort, environmental impact, and port performance. Selection should be based on an integrated analysis involving hydrographic surveys, numerical and physical modeling, ship manoeuvering simulations, and environmental impact assessments, in line with PIANC and IMO recommendations.

- **Natural Topography and Bathymetry**

Areas with naturally deeper depths are preferred to reduce capital dredging. Channels should avoid submerged obstructions such as reefs or rocky outcrops. Hydrographic and geotechnical surveys form the baseline for selecting routes with minimal excavation requirements/ rock blasting.

- **Wave and Current Climate**

Channel orientation must account for prevailing wave and current regimes to reduce cross-waves, ship yaw, and lateral drift during navigation. Alignment with dominant wave approach reduces agitation and enhances safety. State-of-the-art numerical models (e.g., MIKE 21, Delft3D, TELEMAC) are recommended to simulate wave-current-ship interactions.

- **Sediment Transport and Littoral Drift**

Sediment transport studies are crucial to anticipate siltation and future maintenance. High littoral drift zones should be avoided where feasible; otherwise, engineered measures such as sand bypassing systems, groynes, or training walls may be applied. Tools like LITPACK and coupled hydrodynamic-sediment models are commonly employed.

- **Navigation and Vessel Safety**

Channel dimensions (depth, width, bend radius, and turning basins) must accommodate the port's design vessel, considering under-keel clearance, squat, and manoeuvering margins as recommended by PIANC (2014). Ship-handling simulations and full-mission bridge simulators are widely used to validate channel geometry under realistic operating conditions.

- **Environmental and Regulatory Compliance**

Channel sitting should avoid ecologically sensitive areas such as coral reefs, mangroves, and fish breeding grounds. Compliance with Environmental Impact Assessment (EIA) frameworks, IMO guidelines, MARPOL regulations, and national Coastal Regulation Zone (CRZ) notifications is mandatory. Mitigation measures should be incorporated at the planning stage.

- **Economic and Operational Considerations**

Design decisions should minimize life-cycle costs, including dredging, breakwater protection, aids to navigation, and maintenance. Integration with port terminals, hinterland connectivity, and multimodal logistics corridors is essential for operational efficiency. Cost-benefit analysis should reflect both direct maritime costs (channel construction/maintenance) and indirect economic benefits (reduced freight costs, improved trade competitiveness).

The location and orientation of approach channels must be determined through a multi-disciplinary, data-driven process integrating engineering, environmental, navigational, and economic assessments. Alignment with international standards (PIANC, IMO, UNCTAD) and national guidelines (Sagarmala, IWAI, CRZ norms) ensures not only safety and efficiency but also long-term sustainability and resilience against climate change impacts such as sea-level rise and extreme events.

3.2 Elements of Channel Dimensions

The planning and design of navigational channels are fundamental to ensuring the safe and efficient passage of vessels to and from a port. Channel dimensions - including depth, width, and side slopes - must be meticulously determined based on the characteristics of the design vessel, prevailing environmental and hydrographic conditions, as well as operational and safety requirements. Properly optimized channel geometry minimizes navigation risks, reduces dredging and maintenance costs, and enhances the port’s long-term sustainability.

3.2.1 Approach Channel Depth

Definition: Channel depth is defined as the vertical distance between a standard water level reference (typically a chart datum, such as Lowest Astronomical Tide (LAT) or Lowest Low Water Springs (LLWS), as specified by national hydrographic offices) and the natural or dredged channel bed. This depth constitutes the minimum available clearance for safe vessel transit.
Channel depth selection requires balancing the costs associated with achieving and maintaining the design depth against operational benefits, such as reduced vessel waiting times and the ability to accommodate larger, more economical ships.

Key Determining Factors:

- **Design Vessel Draft**: The draught of the largest vessel anticipated to use the channel under fully loaded conditions sets the initial basis for depth determination.
- **Under-Keel Clearance (UKC)**: The vertical safety margin between the vessel’s keel and the channel bed, accounting for uncertainties caused by vessel motions and environmental factors. PIANC guidelines recommend a UKC of at least 10–15% of vessel draft in sheltered waters and up to 20% in exposed or dynamic conditions.
- **Squat Effect**: Ships moving through shallow water depress further into the water column due to hydrodynamic effects; the magnitude of squat increases with vessel speed, size, and proximity to channel banks or bed.
- **Wave Allowance**: Additional clearance must be provided in areas exposed to significant wave action, accounting for heave and pitch motions of the vessel.

- **Siltation Allowance**: An extra depth margin to compensate for anticipated sedimentation between dredging or maintenance cycles.
- **Water Level Variation**: Fluctuations due to tide, meteorological effects, or river inflow must be considered when establishing the design depth reference plane.

Required channel depth is typically expressed as:

Required Channel Depth= Design Draft+ UKC+ Squat+ Wave Allowance + Siltation Margin

The balance of capital dredging cost versus operational benefits (reduced vessel waiting time, accommodation of larger ships, lower freight costs) must guide final decisions. Regular hydrographic monitoring and maintenance dredging are essential to sustain design depth.

Increasingly, ports are integrating adaptive dredging strategies, real-time monitoring, and dynamic UKC management to reduce costs while ensuring compliance with IMO and PIANC safety standards.

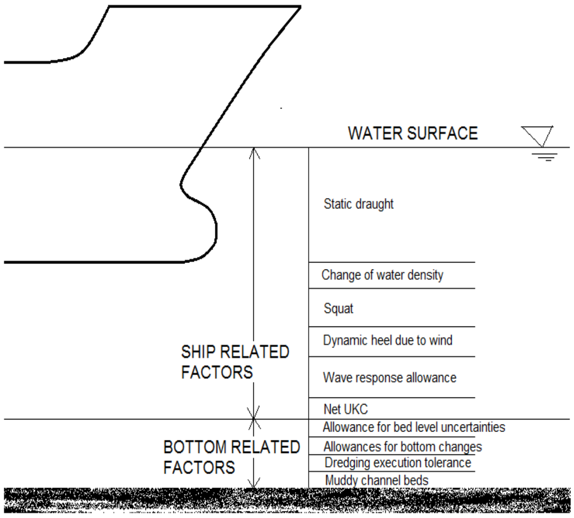


Figure 3.2: Factors of the Approach Channel Depth

3.2.2 Approach Channel Width

Definition: Channel width is the horizontal distance across a navigational channel that ensures safe and efficient vessel transit, accommodating the largest design vessel while accounting for environmental and operational factors. Properly designed channel widths, as guided by PIANC's Working Group 49 and IMO's navigational safety standards, minimize collision risks, enhance maneuverability, and optimize port accessibility, particularly in India's dynamic coastal and riverine environments. Key Factors Influencing Channel Width:

- **Beam of Design Vessel:** The width (beam) of the largest vessel expected to use the channel forms the baseline for determining channel width, ensuring sufficient clearance for safe passage.

- **Traffic Configuration**:
  - (i) **One-way traffic:** Requires a width of 3–5 times the beam of the design vessel, as per PIANC guidelines, to accommodate safe navigation and maneuvering under normal environmental conditions.
  - (ii) **Two-way traffic**: Requires 5–7 times the beam to allow simultaneous passage of vessels, accounting for increased risk of interaction.
- **Environmental Conditions:**
  - (i) Strong crosswinds, currents, or wave actions, common in India's monsoon-affected coastal regions, necessitate wider channels to counteract drift and maintain control.
  - (ii) Reduced visibility (e.g., fog, night navigation) requires additional width to mitigate navigational risks, as recommended by IMO.
- **Maneuvering Allowance**: Additional channel width is provided to account for ship handling during turning in the approach channel, as well as for drift caused by currents, steering inaccuracies, and tug operations particularly in confined or high-traffic navigation areas.

According to PIANC (Permanent International Association of Navigation Congresses) recommendations, the minimum channel width for a one-way approach channel is determined as a multiple of the vessel beam, with adjustments made to account for prevailing environmental and operational conditions.

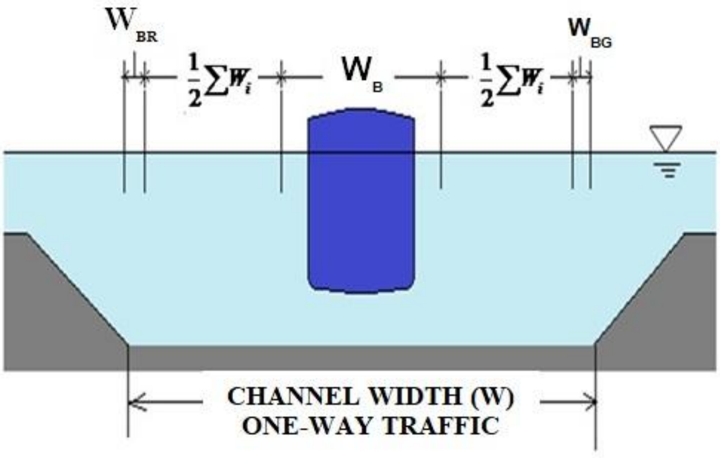


Figure 3.3: Channel width for one-way traffic

The bottom width (*W*) of one-way channel (Figure 3.3) is determined from the following equation:

$$\boldsymbol{W = W_B + \sum_{i=1}^{n} W_i + W_{BR} + W_{BG}}$$

Where

W_{BM} = width of the basic manoeuvering lanes a multiple of the design ship's Beam

$\sum_{i=1}^{n} W_i$= additional widths to allow the effects of wind, wave and current etc

W_{Br} , W_{Bg} = bank clearances on the 'red' and 'green' sides of the Channel

Optimal channel width is established through detailed assessment of vessel traffic, site-specific hydro-meteorological conditions, operational safety margins, and conformity with international best-practice (PIANC) guidelines. Channel width calculations should be validated through advanced simulation and navigational risk assessment to ensure effective and safe port operations under all anticipated conditions.

3.2.3 Approach Channel Side Slopes

Definition: Side slopes of an approach channel define the inclination of the surfaces extending from the dredged channel bed up to the surrounding natural seabed or ground level. They are critical to ensuring the structural stability of the channel and minimizing risks of slope failure, excessive sedimentation, and frequent maintenance dredging.

Importance of Side Slopes

- **Stability:** Adequately designed side slopes prevent collapse or sloughing of the channel edge, particularly following dredging in unconsolidated or low-strength materials.
- **Hydrodynamic Response:** Slope geometry affects local current patterns and sediment transport, influencing both navigability and channel longevity. Long approach channels with their side slopes will have significant bearing on the basin tranquillity by reducing the wave flux entering inside.
- **Sediment Control:** Gentle side slopes reduce the rate of sediment infill and scouring, sustaining channel dimensions over longer intervals.
- **Navigational Safety:** Proper slopes afford vessels a safer buffer during manoeuvering, reducing risk in shallow or constricted approach channels.

Key Factors Influencing Side Slope Design

- **Soil Type:** Cohesive soils (e.g., clay) can support steeper slopes (up to 1:2), while non-cohesive materials (sand, silt) require flatter slopes (e.g., 1:3 to 1:5) to maintain stability.
- **Wave and Current Action:** Greater hydrodynamic energy from waves and currents necessitates flatter slopes to prevent erosion and bedding failures.
- **Dredging Equipment:** Some dredging techniques allow for steeper slopes (e.g., cutter suction dredgers), while others require more gradual slopes.
- **Channel Depth:** As channel depth increases, flatter slopes may be essential due to higher lateral soil pressures and stability concerns.
- **Maintenance Strategy:** Flatter slopes may be adopted in erosion-prone areas to minimize the need for recurring maintenance.
- **Slope Protection:** Engineered slope defenses, such as riprap or geotextile armoring, may permit slightly steeper inclinations, particularly in cohesive substrata.

Typical Side Slopes (Horizontal: Vertical)

Material Type	Typical Side Slope (H:V)
Rock	1:1 to 1.5:1
Cohesive clay	2:1 to 3:1
Sand/Silt	3:1 to 5:1
Soft clay/muck	5:1 or flatter
With protection	2:1 to 3:1

Design Recommendations

- **Preliminary Slope Stability Analysis:** Should be performed using geotechnical investigation and modeling, with a recommended factor of safety typically exceeding 1.3.
- **Allowance for Over-dredging/ Slumping:** Consider inevitable post-dredging slope adjustment due to natural soil behavior.
- **Monitoring and Maintenance:** Channel slopes are subject to progressive degradation; regular hydrographic surveys and sediment monitoring are necessary for timely interventions.

Side slope design is a critical aspect of approach channel engineering, requiring a balance between geotechnical feasibility, dredging practicality, maintenance economy, and navigational safety. Optimal slopes should be determined from detailed site-specific investigations, supported by PIANC and IMO design guidelines.

3.3 Turning Basins

The turning circle of a ship is the path it follows to complete a full 360-degree turn, a critical manoeuver ensuring navigational accuracy and safe vessel handling within confined port areas. This maneuver typically comprises several phases: initial heading change, steady turning, and final realignment to the intended course.

The design of turning basins is a critical aspect of navigational safety and efficiency, ensuring that vessels especially large tankers, container ships, and LNG carriers—can manoeuver safely under prevailing environmental conditions.

The turning basin or turning area is generally located centrally within the harbour basin to facilitate unobstructed vessel manoeuver. The required size of the turning basin is primarily a function of the design vessel's length and Maneuverability characteristics, the available time for executing the turn, and environmental protections such as shelter from waves and strong winds.
Notably, vessels in ballast condition exhibit reduced turning performance and require larger turning areas. A fundamental design principle is that the shorter the allowed time for the turn, the larger the basin must be to safely accommodate the manoeuver. Optimally configured turning basins minimize reliance on tug assistance, reducing operational costs and improving efficiency.

Turning Basin Size Classifications:

1. **Optimum Size:** An ideal turning basin has a diameter approximately **four times (4L)** the length of the longest design vessel using the basin. This size allows easy, controlled turns with minimal power and manoeuvering skill.
2. **Intermediate Size:** Basins with diameters around **two times (2L)** the vessel length result in more challenging turning manoeuver requiring longer execution times. Successful turns depend on judicious use of vessel power, skillful steering, and often the assistance of tugboats.
3. **Small Size:** Basins with diameters less than **two times the vessel length (<2L)** demand complex manoeuver such as dragging the ship's anchor and significant tug intervention to effect the turn.
4. **Minimum Size:** The smallest functional turning basin has a diameter approximately **1.2 times (1.2L)** the vessel length. Here, the vessel pivots around a fixed point such as a dolphin, pier, wharf, or anchored object located on the turning circle's perimeter.

The design of turning basins requires balancing among available harbour space, vessel Manoeuverability, and operational safety. While optimum basins (≈ 4L) provide the best navigational conditions, intermediate and smaller basins may be used where space is restricted, provided sufficient tug assistance and pivot structures are available. Site-specific simulations and PIANC/IMO guidelines are recommended for finalizing basin dimensions.

3.4 Additional Clearances

Proper clearances are essential for the safe and efficient navigation of vessels in waterways, especially in confined or controlled environments such as inland waterways where overhead structures and bank stability are critical considerations.

- **Vertical Clearance**

Vertical clearance refers to the vertical distance between the water surface at the designated navigational water level and any overhead obstruction such as bridges, power cables, or communication lines. This clearance must accommodate the air draft (the height above the waterline) of the largest vessels operating in the waterway, including allowances for wave action, vessel motions, and seasonal water level fluctuations. Regulatory bodies such as the Inland Waterways Authority of India (IWAI) specify minimum vertical clearances to ensure uninterrupted passage of vessels, typically ranging from 4 to 7 meters depending on vessel size and waterway classification.

- **Bank Clearance**

Bank clearance is the lateral safety buffer between the vessel's navigational path and the physical edges of the channel or riverbank. This clearance prevents vessel grounding and mitigates risks of bank erosion caused by hydrodynamic forces generated by passing vessels, such as pressure differences and wave impacts. Appropriate bank clearance is critical in maintaining the structural integrity of the channel banks and preventing frequent maintenance dredging or bank reinforcement.

Additional clearances in both vertical and lateral directions are integral to channel design and must be carefully evaluated based on vessel dimensions, hydrodynamic effects, and site-specific constraints. Adequate allowances ensure not only safe vessel passage but also long-term stability of the channel infrastructure.

3.5 Berthing Area

The size of the berthing area and individual berths is determined primarily by the dimensions of the largest vessel expected to use the harbour and the total number of vessels anticipated to be accommodated simultaneously. The berth layout is influenced by multiple factors, including the size of the harbour basin available for vessel manoeuvering, the efficiency of ship arrivals and departures, vessel-specific features such as bow rudders and bow thrusters, availability and capability of tug assistance, and prevailing environmental conditions like wind, wave direction, and current strengths.

The berthing area, located in front of the berthing structure, must be sufficient to accommodate the design vessel(s) and any attendant craft. When dredging is required in this area, the following guidelines apply:

- The length of the dredged berthing area should be at least 1.25 times the length of the largest vessel when tug assistance is available, and at least 1.5 times the vessel length without tug assistance.
- The dredged width should be no less than 1.25 times the beam of the design vessel, with additional allowance added for the beam(s) of associated attendant craft.

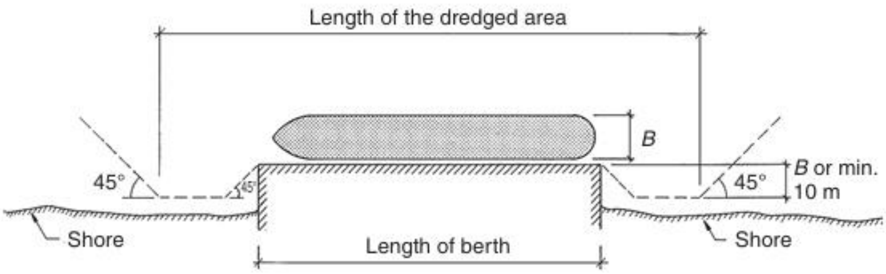


Figure 3.4: Dredged area around a berth

- A finger-type berth design maximizes berthing space relative to the shoreline length. For a single-berth finger pier, the clear water width between two piers should be approximately 2 times the beam of the largest vessel plus 30 meters to enable tug operations. For double-berth finger piers, this clearance should increase to roughly 4 times the vessel beam plus 50 meters. The length of a single finger pier generally equals the length of the ship plus an additional 30 to 50 meters for safe mooring and operational space. For extensive single-berth piers, the clear water width between piers should be adjusted to about 2 times the vessel beam plus 50 meters.
- To allow vessels to swing freely into berths, the required width depends on the berth angle relative to the shore: 1.5 times vessel length for berths angled at 45 degrees and 2 times vessel length for perpendicular (90-degree) berths.

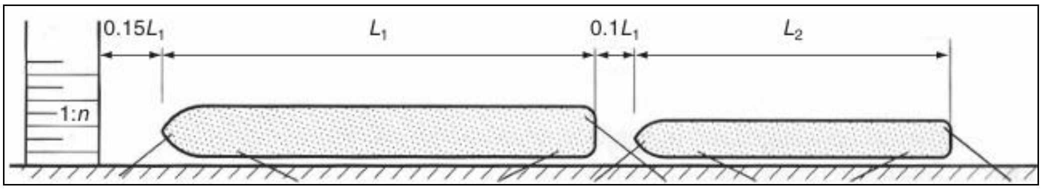


Figure 3.5: Clearance between ships at berth

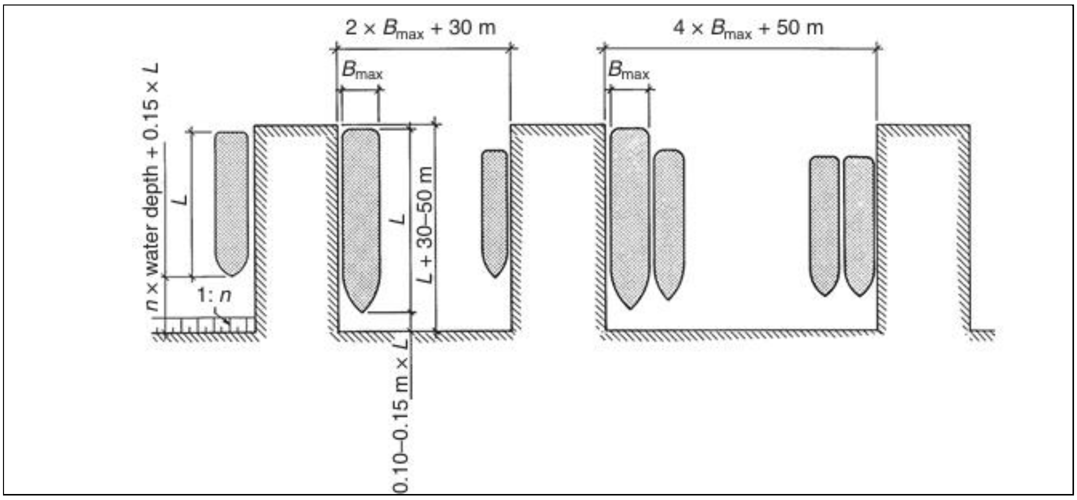


Figure 3.6: Layout of single piers

Passage and Manoeuvering Area

This zone extends beyond the berthing area, providing sufficient space for the passage of vessels and tugs, enabling ships to approach or depart their berths safely.

- **Apron Width**

(i) General cargo berths with one-way traffic typically require about **6.5 meters**.
(ii) Two-way traffic necessitates around **8.0 meters**.
(iii) Container berths generally demand **40 meters** clearance for container handling equipment.

- **Deck Elevation:**

The deck or apron elevation is commonly set at the Highest High Water Springs (HHWS) level plus half the characteristic wave height, with an additional 1 meter clearance to accommodate wave overtopping and operational safety.Inthe era of climate change, additional components like storm surge and sea level rise are also being considered for finalising the safe deck elevation.

- **Minimum Land Area Behind Berths**

(i) General cargo berths require approximately 2.5 to 3.0 hectares.
(ii) Container berths need larger space, about 8 to 12 hectares, reflecting container handling and storage demands.

Basin Layout Considerations

The harbour basin should be shaped to minimize disturbing wave action and, where possible, direct wave propagation along the longitudinal axis of moored vessels. Waves aligned in this direction typically cause the least interference with ship motions, mooring forces, and cargo handling.

The basin length just inside the harbour entrance must be sufficient to allow ships arriving at reasonable speeds to decelerate and stop safely. As a rule of thumb, the basin length should be at least five times the length of the largest ship using the harbour.

It is also important to identify and mitigate natural resonance periods of the basin, moored ships, and other harbour structures to avoid amplification of long-period waves and surf beats, which may adversely affect port operations and infrastructure.

The design of the berthing area must balance navigational safety, operational efficiency, and harbour space optimization. Properly dimensioned basins, finger pier configurations, and apron layouts ensure safe manoeuvering, minimize tug dependency, and reduce downtime due to environmental loads. Special attention must be paid to basin resonance, dredging requirements, and integration with overall port traffic flow.

3.6 Navigational Aids

Navigational aids (NAVAIDs) are essential components of safe maritime operations in rivers, channels, harbours, and along coastal waters. Their primary functions are:

- To warn ships of hazards, such as rocks, shoals, sand bars, and channel bends.
- To guide vessels safely along coasts, through waterways, and into harbours and berths.
- To support efficient and reliable navigation during both day and night, and under adverse weather conditions.

Navigational aids comprise floating, fixed, and electronic systems, each serving distinct roles in improving maritime safety.

3.6.1 Types of Navigational Aids

- **Floating Buoys**

Anchored floating markers are used to delineate navigable channels and harbour entrances. Buoys may be unlighted or fitted with lights, radar reflectors, and audible warnings (bells, horns) depending on their location and function. They are colour-coded and shaped according to international buoyage systems (e.g., IALA), including types such as spar, can, nun, spherical, and sound buoys.

- **Fixed Structure Channel Markers**

These are lighted beacons mounted on structures fixed to the seabed, such as piles or concrete foundations. Positioned strategically along channel edges, breakwaters, or harbour entrances, these markers are designed to be above tidal ranges and storm wave crests to remain continuously visible.

- **Navigation Lights on Piers, Wharves, and Dolphins**

Marine beacon lights are typically installed at both ends of these structures to clearly define their limits and aid vessel maneuvering near berths.

- **Fixed Structure Beacon Lights on Shore and Breakwaters**

Metal-framed towers equipped with marine beacon lanterns are erected on breakwater extremities, prominent headlands, and other key navigational points to signal hazards and guide shipping movements.

- **Lighthouses**

Lighthouses are constructed as tall, masonry or reinforced concrete towers with high-intensity marine beacon lights at their apex. Positioned on coastal promontories, reefs, or other hazardous zones, lighthouses provide long-range visual guidance, with heights ensuring visibility over the horizon.

- **Lightships**

Employed where construction of permanent lighthouses is unfeasible, lightships function similarly by maintaining position via anchoring and are equipped with distinctive lights, radio beacons, and fog signals.

- **Range Light Installations**

These paired shore-based lights, aligned along channel centerlines, provide unidirectional guidance through narrow or winding harbour entrances and channels. The rear range light is elevated and set back to allow mariners to maintain a safe course by aligning both lights vertically.

- **Radar Reflectors**

Attached to various aids including buoys, fixed markers, and range towers, radar reflectors enhance vessel radar detection by reflecting signals back to the ship, highlighting the position of navigational hazards or channel boundaries.

- **Marine Beacon Light Lanterns**

Constructed with metal frames and encased in durable glass or plastic, these lanterns operate using electric or acetylene light sources, designed for continuous maritime use.

- **Moorings for Floating Aids**

The safe and reliable positioning of floating navigational aids depends on robust mooring systems, typically comprising steel or wrought iron chains and anchors (concrete, cast iron, or mushroom-type). Mooring designs account for tidal, wave, and wind forces as well as the weight of the mooring components.

3.6.2 Advanced Navigational Technologies (ICORELS Group IV Recommendations)

- Radar with anti-collision systems for vessel traffic monitoring.
- Echo sounders providing accurate under-keel clearance in shallow waters.
- Doppler logs indicating vessel speed and movement across the ship’s breadth.
- Rate-of-turn indicators for precise manoeuvering.
- Radial setting systems enabling ships to follow curved trajectories smoothly.
- VHF radios with selective calling for reliable communication.

- Seamarks including various buoy markings and leading lights.
- Shore-to-ship radio telephone communication links.
- Supervisory radars monitoring port traffic conditions.
- Radio location systems for highly accurate ship positioning.

3.6.3 Improvements Achieved Through Navigational Aids

- Enhanced positional accuracy of channel marking buoys.
- Reliable day/night leading lights extending over long distances.
- Improved general VHF communication reliability.
- High-precision radar contouring for exact ship location determination.
- Cooperative radio-location systems offering position fixes within a few meters.

Navigational aids form the backbone of safe port operations, reducing the risk of collision, grounding, and navigational errors. A modern system integrates traditional aids (buoys, beacons, lighthouses) with advanced electronic systems (radar, radio, AIS, VTS) to ensure safe, efficient, and reliable vessel traffic management.

CHAPTER IV

COASTAL ENGINEERING PARAMETERS AND DESIGN LOADS

Physical planning in coastal and port engineering involves the systematic collection, processing, and application of environmental data to guide site selection, location, and orientation of major port components.The selection of an appropriate site is critically influenced by natural conditions, as comprehensively addressed by PIANC's ICORELS Committee No. 1.

The assessment of operational limit conditions that is, the environmental thresholds within which a port can function safely and efficiently requires detailed evaluation of the following coastal engineering parameters:

- Astronomical tide
- Wind
- Changes of water level caused by meteorological conditions, in particular storm surges and the so called negative surges
- Waves (Amplitude, period, direction)
- Currents
- Visibility
- Ice

4.1 Meteorological Conditions

4.1.1 Wind

Wind is a critical environmental factor in port and harbour design, influencing both the layout of berths and the operational safety of vessels. The wind climate—defined by speed and directional patterns—varies greatly by region. For planning purposes, berths are generally oriented parallel to the prevailing wind direction, except in situations where strong currents act at a different angle, in which case current effects may dominate.

Wind forces are particularly significant for light or high-sided vessels, where a large portion of the hull is exposed above the waterline, while current forces are more influential on heavily loaded ships with greater submerged hull area. The forces induced by wind on ships are also central to the design of bollards and mooring systems.

Useful wind data may be obtained in two different forms, as wind statistics providing average frequencies of occurrence of wind speeds and directions, and in the form of synoptic weather maps. Wind statistics are useful for evaluation of local wind climates and it is normally possible to find such wind data based on actual measurements rather than visual observations.

Where topography may create special wind conditions, local measurements by means of a recording anemometer for a period of one to two years, but sometimes by necessity a shorter period may be used to correlate local short term statistics to long term statistics from a location at some distance.

Synoptic weather maps obtainable from meteorological centers are used for calculations of wave conditions through so called hindcast methods and for calculation of surges and currents generated by wind and barometric pressure effects.

The wind forces acting on a ship may vary considerably, as do the current forces, with both the type and size of the ship, and should therefore best be established by testing in a hydraulic institute. This is especially so for the wind forces acting upon a ship with a large windage area on the side; for example, fully loaded container ships or large passenger ships are influenced greatly, while very large oil tankers have large variations in the longitudinal forces depending upon the shape or design of the bow. Generally, the wind effects on port and harbour operations are more important than those of the wave and current. In this chapter, different methods and national standards and regulations for calculation of the wind forces are compared against each other. It should be noted that in important evaluations these standards and regulations should only be used as a guide to the magnitude of the forces on the ship. The magnitude of the wind velocity Vw to be applied in design varies from place to place, and has to be assessed in each case. The design wind velocity should correspond to the maximum velocity of the gusts that will affect the ship, and not only to the average velocity over a period of time. A 30 m/s average wind velocity is recommended for use in the wind force equations for mooring analyses. The gust velocities can be about 20% higher than the average velocity. In the case of moored ships, the gust duration must be sufficient for the full mooring line or fender strains to develop, taking into account the inertia of the ship. This can lead to a reduced design wind speed. It should also be taken into account that the wind area is not symmetrical about the mid-ship line, which implies the development of a moment of rotation. Figure 4.1 shows the relationship between wind pressure and wind velocity over a 10 min period. When reading the wind pressure, the curve with the gust factor V + 20% should be selected to account for the wind gust factor. A wind velocity lower than 30 m/s– after the Beaufort scale– with a gust factor of 1.2 should not be assumed for the design of berth structures (i.e. the minimum wind pressure should be 0.81 kN/m^2).

Cross winds will affect the ship at all speeds but will have its greatest effect at low ship speeds. It will cause the ship to drift sideways or to take an angle of leeway, both of which increase the width required for manoeuvering. It is unlikely that a ship will be able to maintain a steady course at low speeds in a cross wind; the ship-handler will have to steer the ship slightly into the wind, resulting in the ship developing a drift angle and a slightly oscillatory course. Ship course changes under strong wind conditions.

Cross wind effects depend on;

- Ship speed
- Windage of the vessel (relative to lateral submerged area)
- Depth/draught ratio (because a ship's resistance to lateral motion increases as the depth/draught ratio approaches unity since wind causes less drift at small under Keel clearances)
- Wind speed and direction relative to the ship.

Some width allowance, over and above that needed for basic manoeuvering, must therefore be made for wind effects.

Information on wind speeds and directions for the area under consideration is needed. Wind effects become significantly larger at low ship speeds, such as in harbour areas, and even at high ship speeds for high-sided vessels. To keep a straight course in the channel under cross winds, counter helm is required to generate a suitable drift angle to compensate for leeway. These features are due to the balance of hydrodynamic forces (hull forces and rudder forces) and aerodynamic forces acting on the ship. The channel width requirement for cross winds is estimated by taking this obliquely running condition into account. The Beaufort scale is an empirical scale that relates wind speed to observed conditions at sea or on land. It was developed in 1805 by Sir Francis Beaufort, a British admiral, to help sailors estimate wind force without instruments.

Figure 4.1: Graph showing the Beaufort Scale plotted against wind speed in km/h. Each point represents a Beaufort number with its corresponding wind speed and description (e.g., "Calm", "Gale", "Hurricane")

the wind velocity increases above about 25–30 m/s, the ship would normally either leave the berth or take in ballast to reduce its wind area. It is very important to note that the wind force is proportional to the square of the wind velocity.

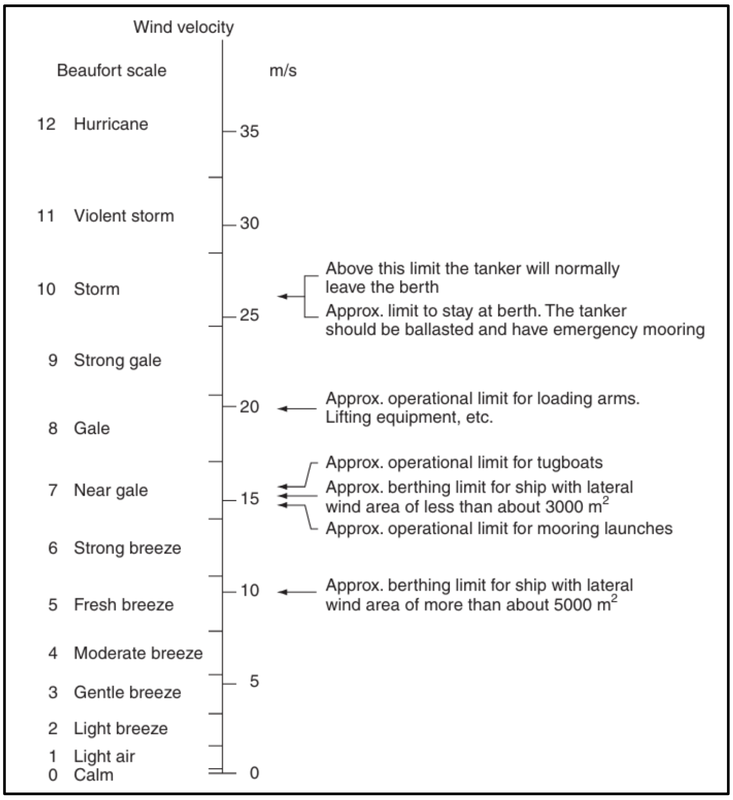


Figure 4.2 Operational wind speed for the vessel (Oil Tankers) operation at the berth

4.1.2 Temperature, rainfall and humidity

Extreme temperatures, rainfall and humidity adversely affect port operations and may be major reasons for low cargo handling rates and interruptions of cargo handling. Further, temperatures above 30^{o} C and below 5^{o} C require special precautions for pouring and curing of concrete. Extreme rainfall governs the design of storm drains and sewers.

4.2 Oceanographic Conditions

Waves, tides and currents, constitute the most important environmental conditions for planning and design.

4.2.1 Waves

Waves exert forces directly on breakwaters and exposed terminal structures and determine major features of harbour layout through indirect action by generating movements of moored ships with mooring lines and fender forces and by generating or greatly influencing littoral drift, erosion and accumulation. These effects are of over-riding importance for determination of harbour layouts and for design of its structures. Waves will also naturally influence the channel depth design as a result of the ship's vertical motions (pitching, heaving and rolling). However, they may also have effects on the width design. The ship generally makes a yawing motion in waves due to unsteady wave forces. Therefore, the channel width should include the drift due to such yawing. In addition to unsteady wave forces, there are steady 2nd-order wave drift forces, which are similar to wind forces. In the following waves, course instability may occur (which may result in broaching) in the case of long waves and relatively small vessels. These wave drift forces may be considered depending on the local wave conditions

Waves are traditionally, and for practical reasons, classified into the following different types:

- **Wind waves or locally generated waves**. These are generated by winds that are acting on the sea surface bordering on the port site.
- **Swell or ocean waves.** These are normally also wind-generated waves, but are created in the deep ocean at some distance from the port site, and the wind that created them may be too distant to be felt in the port or may have stopped blowing or changed its direction by the time the waves reach the port.
- **Seiching or long waves.** Waves of this type have very long periods– typically from 30 s up to the tidal period 12 h 24 min– and are mostly found in enclosed or semi-enclosed basins, such as artificial port basins, bays or fjords.
- **Waves from passing ships**. Ship waves may pose significant problem in certain ports, especially since they are generated by a moving source and may appear in areas where large waves are not expected. Ship waves may also be very complex in nature.
- **Tsunamis and waves** created by large, sudden impacts, such as earthquakes, volcanoes or landslides that end up in the ocean.
- **Breaking waves.** These types of waves' impacts are short waves creating high-pressure impulses to the vertical structure, and can exert considerable forces of the order of 150 and 600 kN/m2.

Waves are also classified according to the ratio of the water depth d in which they occur to the wave length L:

- **Deep-water waves,** for which d/L > 0.5.
- **Intermediate-water waves**, for which 0.04 < d/L < 0.5.
- **Shallow-water waves**, for which d/L < 0.04.
- **Breaking waves** are those which, for example, fall forward since the forward velocity of the crest particles exceeds the velocity of the propagation of the wave itself.

In deep water this normally occurs when L<7H, and in shallow water when d is approximately equal to 1.25H and H is wave height. The still-water depth, where the wave breaking commences, is called the breaking depth. Wind-generated waves are defined by their height, length and period. The height, length and period are dependent on the fetch (the distance the wind blows over the sea in generating the waves) and the velocity, duration and direction of the wind. The wave characteristics for deep-water waves are shown in Figure 4.3

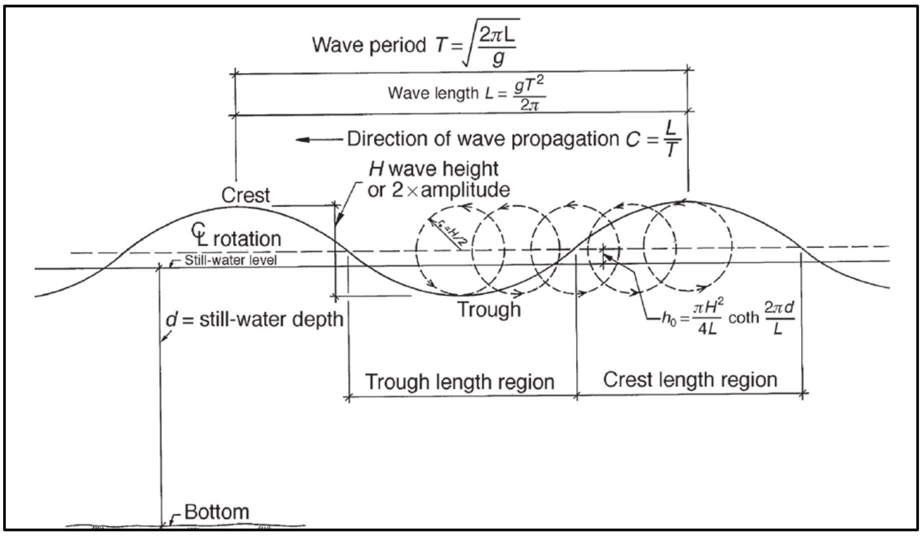


Figure 4.3 Wave Characteristics in deep water

The wave period is the time between successive crests passing a given point. The wave steepness is defined as the wave height divided by its length. As the waves propagate in water, it is only the waveform and part of the energy of the waves that move forward. The wave heights H may be defined as follows:

Hm =arithmetical mean value of all recorded wave heights during a period of observation = 0.6Hs
Hs =significant wave height, which is the arithmetical mean value of the highest one-third of the waves for a stated interval
H1/n =average value of the 1/n highest waves in a series of waves, usually of length 15–20 min commonly used values of n are 3 (significant wave height), 10, 100
H1/10 = arithmetical mean value of the height of the highest 10% = 1.27Hs
H1/100 = arithmetical mean value of the height of the highest 1% = 1.67Hs
H_{max} =maximum wave height = 1.87H = 2Hs when a high risk of danger is present, or if storms of long duration are to be considered.

The variables in wind wave height computations are: V_{10} =wind speed at 10 m above sea level, usually taken as a 10 min mean, which is representative of the entire fetch and the entire duration of the situation F =fetch length, t =duration of the wind

A natural wave trend may be described as a series of individual waves of different heights, periods (wave length), and limited crest lengths. The energy in the wave train is spread over a certain sector of directions. Thus all the properties of the waves in a wave train (height, period and direction) varying within certain intervals and therefore can be realistically described by their statistical distribution. The height (H) of the individual wave is measured from trough to crest and its period (Tz) is the time between two subsequent downward crossings of the mean surface level. The distribution of wave heights in the natural wave trains in deep water, as well as in shallow water seaward of the breaker zone may normally described by Rayleigh distribution.

$$p\left(\frac{H}{H}\right) = e^{-\left(\frac{H}{H}\right)^2}$$

where p is the probability of wave heights exceeding H and H is the mean wave height. However, the height used to describe the wave train is its significant height H_s which is defined as the average of highest one third of the waves. This apparently arbitrary parameter has been chosen because experience has shown that it represents fairly well what is estimated as "the wave height" by a visual observer. From the Rayleigh distribution the following values may be calculated.

$H_s = 1.6$ H and $H_{max} = 1.86\ H_s \sim 3.0$ H

where H_{max} is defined as the height that is exceeded one in 1000 waves. One thousand waves occur within a period of about three hours during which the wave train usually changes because of transient nature of generating wind. In principle, the statistical distribution of wave train, like any of the existing parametric description, rests on the assumption that the sea state is stationery.

The majority of the wave related problems are dynamic i.e. the effects of waves are not caused by the wave generated water surface elevations as such but by their variations in time and space. Proper analysis of wave trains should include correlation between wave heights and periods.

(a) Wave spectra

Another way of describing a natural wave train is by determining a spectrum (Bettjes 1978 and Houmb 1981). A wave spectrum is a powerful tool for describing a natural wave train, which is a complex combination of many different waves. It's based on the idea that any observed wave train can be considered a superposition of numerous small, regular, sinusoidal waves, each with a specific height and frequency. The wave spectrum shows how wave energy (or variance density) is distributed across frequencies:

(i) The horizontal axis represents frequency, *f* (Hz).

(ii) The vertical axis represents variance density, *S(f)*, typically expressed in units of m^2/Hz.

The variance density is the variance divided by the width of a differential frequency interval. Thus the horizontal axis in the spectrum shows the frequency measure in Hz and the vertical axis shows the variance density measured in length unit in the second power divided by Hz.

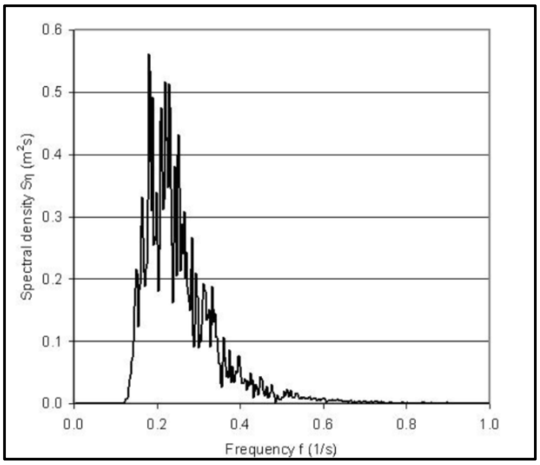


Figure 4.4: Wave Spectrum

The variance is proportional to energy and that is why the spectrum, often is called an energy spectrum. The spectrum is conveniently obtained from the wave recording by a Fourier analysis using a fast fourier transform routine on a digital computer. The spectrum is used to calculate a number of characteristics parameters for the wave train. These calculations are based on moments of the spectrum defined by -

$$m_n = \int_0^\infty f^n S(f)\,df$$

where , m_n is the nth movement of the spectral density function S(f) and f is the frequency. As in the zero crossing analysis, the primary parameters determined are characteristics wave heights and periods. For a Rayleigh wave height distribution $H_{mo} = 4\ m_o$ and it may be shown that it is equal to H_s . Another wave period derived from the spectrum is the peak period T_p which is calculated as $1/f_p$ where f_p is the peak frequency i.e. the frequency of maximum density. Standard forms of wave spectra are used if only the characteristic wave height and period are available and as reference for measured spectra. Recently the most widely used was the Pierson - Moskowitz (PM) spectrum which represents full developed wave in deep water. This spectrum may be written in which α = 0.0018 (Phillips constant) and g is the acceleration of gravity.

$$S(f)_{pm} = \alpha\, g\,(2\pi)^{-4}\ f^{-5}\, e - ^{5}\!/_{4}\left(^{f}\!/_{f_p} \right)^{-4}$$

(b) Wave groups

While a wave spectrum provides detailed information about the characteristics of the wave train, it is not a complete description. First of all, it does not describe any three dimensional characteristics as it assumes unidirectional waves with infinitely long crests. Moreover, the spectrum description assumes that the wave train is a random combination of individual monochromatic waves. However, real wave trains exhibit a more or less pronounced tendency towards occurrence of its higher waves in groups with certain periodicity. This group effect may be expressed as a result of a certain phase correlation between the higher wavelets used in the spectrum description. The grouping of waves is of considerable importance to various design problems.

For example the armour layer stability of rubble mound breakwaters has been shown to depend significantly on the way in which the high waves of the train follow upon each other, i.e. on the ratio of wave groups. Another effect of wave groups, which is of great importance, is the so called radiation stress, which is proportional to second power of the wave height (Lundgren, 1963). Seaward of the breaker zone, the radiation stress generates a set down of the water level, whereas shoreward of the breaker zone, it results in a set up of the water level. When the high waves occur in a group, this results in water level oscillations with a period corresponding to the period of occurrence of the wave groups and an amplitude proportional to the second power of the wave heights. Shoreward of the breaker zone, this phenomenon has been observed long ago and is known under the term `Surf beats'.

The period of the wave groups is in the order of five to ten times the wave period. The periods of the water level oscillations generated by the wave groups thus lie in the range from 30 to 120 seconds, which means that such oscillations may be amplified by resonance effects of harbour basins. Moreover, this range covers resonance periods of certain oscillations of large moored ships, notably surge. Thus, these phenomenon may produce dangerous movement of ships even in a port that is otherwise well protected against wave disturbance. Analysis of wave records purpose, where long period oscillations may be matter of concern, should include a description of the wave groups.

Regardless of whether short period or long period waves, the problem of resonance is very important. Wind waves or swells of 10 to 20 seconds may cause a resonance effect in shorter harbour basins, e.g. when the period T of a free oscillation having its mode at the entrance and its loops at the end equal $4L/\sqrt{gD}$ where L is the length of basin and D is depth of basin or $2L/\sqrt{gD}$ for a partly closed entrance. Long period waves, particularly those of 2-4 minute periods may be responsible for considerable surge action in ports which is of great nuisance to vessels at berth. They occur during storms as well as during calm weather seasons but do not need to be kept up by external effects, although they are always started by oscillation coming from the sea. Most harbour Seiches do not exceed a few centimeters but they rise above 1 ft when resonance occurs because of the geometry of the harbour basin. Adverse affects by long period waves in port basins may be eliminated to a considerable extent by avoiding natural conditions and basin geometry which will encourage resonance phenomenon. The nautical depth in channels with a muddy bottom has been defined as depth (below datum) at which $\rho_B = 1.2$ g/cm^3 is first encountered. In offshore regions, where mud banks occur, it is found that wave induced re-suspension is significant for mud layers with densities less than 1.2 g/cm^3. For densities greater than 1.2 g/cm^3, vessels experience increased drag due to retarding influence of the mud. The nautical depth may be determined based on the difference between the echo of 33 KHz and 210 KHz signals.

(c) Design Wave Characteristics

One of the most important tasks of the designer of facilities exposed to wave action is the determination of design wave characteristics, especially the significant wave height to be used to determine the dimensions of the structure concerned. For this purpose, a satisfied description of the wave climate at the site must be established. The designer will actually have to base his evaluation of design wave heights on wave recordings of only one to two years duration, which makes extrapolation of the frequency of occurrence for very rare events highly uncertain. Wherever possible, such wave recordings of relatively short duration should, therefore, be supplemented by hindcast of extreme wave conditions covering a much longer period which is often possible since reasonably reliable meteorological charts covering a period of 10 to 30 years are often available. By combining actual wave records with calibrated hindcast covering a longer period of time, the designer will obtain the best evaluation of extreme conditions that can be achieved by present technology. It is reasonable to choose design conditions as those that will occur with a probability of 10% during the expected useful life of the structure.

Design waves should of course be chosen with due regard to consequences of excess condition. Some structures, such as traditional rubble mound breakwaters, may suffer only limited and repairable damage by experiencing a small excess of design conditions, while other structure may collapse entirely in such case. The economic optimum would correspond to lowest value of the sum of the discounted capital, maintenance and repair cost over the expected useful life of the breakwater.

4.2.2 Tides, Storms, Surges, and Seiches

Tides are primarily generated by the gravitational attraction of the moon and sun, resulting in highly regular and predictable water level oscillations in coastal regions. Because of their periodic nature and the reliability of observation methods, tidal behaviour has been accurately measured, analyzed, and forecasted for centuries. However, actual coastal water levels often deviate from purely astronomical tides due to meteorological influences—chief among them wind stress and changes in atmospheric (barometric) pressure.

(a) Storm Surges

In shallow seas and estuaries, storm surges—caused by intense wind forcing and low pressure during cyclonic weather events—can significantly elevate water levels above predicted astronomical tides. The “inverse barometer effect” dictates that low atmospheric pressure causes a local rise in water level, typically of the order of 1 cm per 1 hPa pressure drop; high pressure suppresses water levels accordingly. These meteorological effects can add several decimetres to water levels during storm events, compounding the hazard for ports and coastal infrastructure.

Where long-term tidal records exist, it is possible to statistically separate the astronomical tidal signal from meteorological surges and apply rigorous analyses to estimate extreme water levels for design purposes. This enables the derivation of robust design criteria for quays, breakwaters, and other critical structures, accounting for both typical and extreme conditions.

(b) Seiches

Seiches are standing wave oscillations in semi-enclosed water bodies—like harbours, lagoons, or bays which occur when an external event (e.g., atmospheric disturbance, swell group, or passage of a pressure front) excites the basin’s natural resonant frequency. The period of a seiche depends on the geometry and depth of the water body, and often falls between those of wind waves (seconds) and tides (hours).

Seiches may be generated by:

- Long-period components of wind and wave activity (“infragravity” or group-forced waves)
- Rapid changes in atmospheric pressure
- Remote excitation, such as seismic activity or passing storms

In stratified water bodies, internal seiches can also develop along the density interface (pycnocline), further complicating water level dynamics within the port. Persistent seiche activity within harbours can lead to oscillatory water level motions that resonate with the natural periods of port basins or moored ships, potentially amplifying vessel motions and producing hazardous mooring conditions. In extreme cases, these effects when combined with tides and storm surges have led to infrastructure overtopping and operational disruptions.

Therefore, modern harbour design requires integrated analysis of:

- Astronomical tides (from harmonic prediction)
- Storm surges (via statistical and dynamic modelling)
- Seiche risk (using basin resonance theory and spectral analysis)

Mitigation strategies involve optimizing harbour geometry, establishing robust freeboard allowances, and providing real-time water level monitoring to reduce vulnerability to compound extreme events.

4.2.3 Currents

Currents are a fundamental hydrodynamic parameter for port and harbour design, influencing vessel manoeuvering, mooring loads, sediment transport, and the long-term stability of port infrastructure. All vertical movements of the water surface, by continuity, are inherently tied to the presence of currents. In addition, wind-induced shear, estuarine freshwater inflow, and density stratification can generate complex and spatially variable current systems.

(a) Engineering Relevance:

- While direct current forces rarely threaten port structures, their impact on navigation safety, ship handling especially at low speeds and mooring arrangements is significant.

- Currents play a decisive role in sediment transport, often dictating the rates and patterns of erosion or deposition within navigation channels, turning basins, and harbour entrances. Failure to account for these can result in high maintenance dredging costs or loss of navigable depth.

(b) Types and Measurement:

- Tidal Currents: Display regular, predictable variations in line with astronomical tides and can generally be characterized using short-term measurements correlated with tidal cycles.
- Wind-generated and Barometric Currents: Typically secondary unless astronomical tides are weak. However, wind-driven currents in stratified waters can amplify circulation via density differences and should be assessed where applicable.
- Comprehensive field data supplemented with validated numerical or hindcast models are essential for mapping current patterns and predicting extreme scenarios.

(c) Harbour Seiches and Induced Currents:

The most critical effect of Seiches (standing oscillations within the basin) is the generation of low-frequency currents. These currents can cause substantial ship movement at berth, intermittently loosening and tightening mooring lines, which increases the risk of line failure and operational hazards. Vertical oscillations are mainly a concern for quay design, rarely impacting structures otherwise unless amplitudes are unusually high.

(d) Influence on Ship Operations:

Currents, even of moderate velocity, have a more pronounced impact than wind on slow-moving vessels—particularly during approach, berthing, and departure manoeuver. Cross-currents at harbour entrances and within basin approaches can complicate navigation and demand increased channel width or tug assistance.
Unlike oscillatory wave motion, persistent current flow consistently pushes ships off course, requiring compensatory helm adjustments and careful piloting.

(f) Littoral Currents and Sediment Transport:

Littoral Currents: Generated mainly by oblique wave action in the surf zone, these currents drive littoral drift, transporting sediment along the coastline. At harbour entrances, they can modulate the near-shore current field, influencing both sedimentation and navigability.

Coastal sediment transport processes are thus tightly linked to local current regimes—a critical consideration in designing for shoreline stability and minimizing port siltation.
Inadequate accounting for current-driven sediment transport can lead to costly and frequent maintenance dredging or to unwanted accretion and reduced water depths.

4.2.4 Sediment Transport

Sediment transport processes are central to coastal engineering and port planning, directly impacting navigation, shoreline stability, and long-term maintenance. On sedimentary coasts and in estuarine environments, sediment movement is governed by a complex interplay among waves, currents, tides, and the physical characteristics of the seabed.

(a) Mechanisms of Sediment Transport

- **Bed load Transport:** Sediment grains roll, slide, or hop (saltate) along the bed, driven primarily by bed shear stress from currents or waves. Bed load is especially significant for coarser particles and in environments with strong unidirectional flows, such as river channels and tidal inlets.

- **Suspended Load:** Fine particles—such as sand and silt—are lifted into suspension by turbulent eddies and transported within the water column. In high-energy flows, particularly in estuaries and coastal channels, suspended load typically far exceeds bed load and is a principal contributor to port siltation. Direct measurement requires specialized techniques, such as Acoustic Doppler Current Profilers (ADCPs) or water sampling.

- **Wash Load:** Extremely fine-grained materials (silts and clays) remain largely in suspension with minimal interaction with the seabed and are often associated with freshwater or riverine inflows. These materials can bypass traditional bed sampling efforts but may settle rapidly in quiescent waters (e.g., port basins).

- **Estuarine and Coastal Influences:** At the river–sea interface, flocculation of clay particles under the influence of salinity creates larger aggregates with enhanced settling rates, intensifying siltation problems in port basins, dredged fairways, and navigation channels. These effects are compounded by **density-driven exchange currents** across the salinity gradient, which can greatly increase sediment import during tidal cycles.

(b) Wave Action and Littoral Transport

- **Wave-induced Transport**

Within the breaker zone, waves generate strong turbulence and oscillatory flows at the seabed, mobilizing both suspended and bed load sediment. The interaction of waves with tidal currents enhances overall sediment transport capacity, particularly for dredged areas, leading to high re-sedimentation rates after dredging operations.

- **Littoral Drift (Longshore Transport):**

The most critical wave-induced process is littoral drift, wherein breaking waves approach the shore at an angle, generating longshore currents that transport sediment parallel to the coastline. This mechanism shapes coastal morphology, governs sediment supply to beaches, and strongly impacts harbour sedimentation and coastline accretion / erosion patterns. Direct measurement of longshore sediment transport is rarely feasible at scale. Net and gross littoral transport can sometimes be deduced from changes in shoreline form or from sediment accumulation patterns at structures (e.g., jetties). In the absence of sufficient field data, empirical formulae and morphological studies are used to estimate littoral drift magnitude. Port engineers must account for these dynamic processes in site selection, channel alignment, and maintenance planning. Effective sediment management relies on Comprehensive site-specific monitoring (including both hydrodynamic measurements and sediment sampling) Numerical and physical modelling of transport processes, and Adaptation of efficient design and dredging strategies to minimize siltation and to maintain navigable depths. A predictive understanding of sediment transport—across both bed load and suspended load regimes, and considering wave, current, and salinity effects—is critical for the safe, economical, and sustainable operation of coastal and port infrastructure.

4.2.5 Ice Conditions

Harbour structures built in regions with frequent ice formation have to be designed for ice forces. Generally speaking, horizontal ice forces are exerted on structures either from drifting ice sheets which have gained velocity as a result of shear forces transmitted from winds and temperature expansion of ice.

Ice occasionally piles up on the sloping breakwaters and may even overtop the structure with danger of damage to its superstructure. Vertical face breakwaters are usually sufficiently strong to withstand ice forces. A harbour without protecting breakwater or piers on an open coast will be subject to the full loads of drifting ice.

4.2.6 Topography and Hydrographic Conditions

For efficient port development, large areas of level land adjacent to deep-water zones are generally required. Earthwork operations such as removal, transport, and placement of large volumes of soil or rock are extremely costly, while dredging may also result in high long-term maintenance expenses for artificially created depths. Therefore, site selection typically begins with an assessment of available data on land topography and near-shore hydrography to identify locations offering favourable natural conditions.

Existing maps and hydrographic charts usually provide adequate guidance for preliminary site identification. Available aerial photography and satellite imagery also can supplement these resources by offering broader spatial insights. For detailed investigations, modern hydrographic surveys are commonly employed, using fully automated systems that integrate electronic positioning with continuous echo-sounding. The collected data can be processed directly to generate accurate digital charts, ensuring reliable evaluation of site suitability.

4.2.7 Coastal Field data Collection

Hydraulic model studies for port development require intensive coastal data. Detailed data collection programs are essential to arrive at economic design of any project scheme. The research and testing programs conducted by CWPRS in both the field and laboratory have resulted in enormous savings of money, time and in the improvement of coastal structure design. The following coastal parameters are collected by CWPRS data collection team

- Wave height, direction and period
- Tidal Currents
- Tidal levels
- Depth, Temperature
- Positioning System.
- Suspended Sediment Size Analyzer
- River Discharge
- Ancillary-Acoustic Releases, Mooring etc

To collect these data CWPRS uses the instruments mentioned below;

(a) Wave height, direction and period recording equipments

- Wave rider buoy (transmitting unit)
- Rx-D (receiving unit)
- Standard mooring system

Waves are the result of disturbance of the water surface. Waves are generated in the offshore region by the interfacial shear extended by wind blowing over the sea surface as such they are also called a wind waves. The parameters which govern the wave generation process are fetching of water surface which is subjected to wind (F), wind speed (V), duration of wind (t).

Normally wind waves are short waves with period varying between 1 and 30 sec, height 0.5 to 5 m, and wave length is of order of few hundred meters. However, during the sever cyclones the wave heights may be up to 10 m or higher. As restoring force for this kind of wave is gravity these are also known as gravity waves.

Figure 4.5: Wave-rider Buoy with Mooring Material

(b) Tidal Current:

In coastal environment, the currents vary spatially and temporally in both magnitude and direction. Knowledge of currents is essential in assessing siltation in channels and harbour waters, aligning coastal structures, in understanding geomorphic changes taking place etc. Measuring current magnitude and direction is useful in proper understanding of sediment transport in the near shore zone under action of wave induced littoral currents and locating dumping ground in the vicinity of breakwater. To collect the current strength and direction in the near shore coastal region following instruments used in CWPRS.

- Impeller type Direct Reading & In-situ Current meters**.** Electromagnetic Current meters
- Acoustic Doppler Current Profiler –ADCP

Impeller type Direct Reading & In-situ Current meters:
The instrument is manufactured from titanium and polymers, giving excellent resistance to corrosion. This instrument features speed and direction parameters as standard, with further options of temperature and depth. Data (logged or real time) is compatible with dedicated Data Log software.

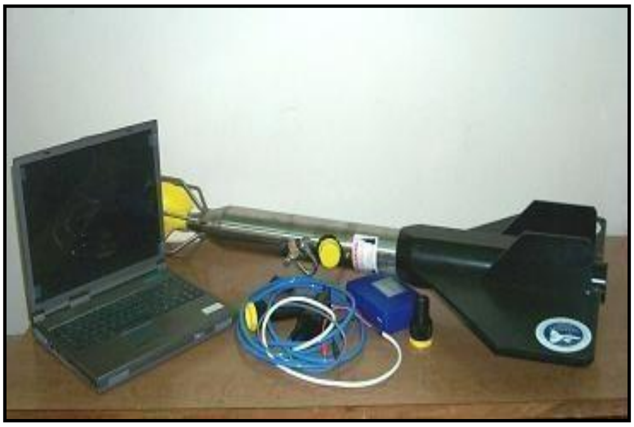


Figure 4.6 Impeller Type Current Meter

(i) Electromagnetic Current Meters

The S4 family consists of self-contained, spherical current meters equipped with advanced solid-state electronics for data acquisition, processing, and output. Data retrieval is accomplished via a serial interface without the need to open the instrument.
The S4 measures both the magnitude and direction of horizontal water currents. It operates on the principle that as water flows through the electromagnetic field generated by the instrument, an induced voltage is produced, which is directly proportional to the velocity of the water. This voltage is detected by two pairs of titanium electrodes positioned symmetrically along the equator of the spherical housing, enabling accurate and reliable current measurements.

Figure 4.7: S4 Electro-magnetic Type Current Meter

(ii)` Acoustic Doppler Current Profiler (ADCP)

The *Sentinel Workhorse* is a versatile Acoustic Doppler Current Profiler that can operate as a direct-reading or self-contained instrument, whether moored or deployed from a moving platform. It provides high-precision current profiling data in real time or for long-term deployments. Designed to meet both research and commercial needs, this four-beam configuration ensures enhanced reliability, accuracy, and data quality. With its internal battery and data recorder, the Workhorse Sentinel is capable of several months of autonomous operation, making it ideal for oceanic, near-shore, and harbor current measurements.

Figure 4.8: Acoustic Doppler Type

(c) Tidal Levels Measuring System

The rhythmic rise and fall of sea water levels over a tidal day (approximately 24 hours and 50 minutes) is known as the tide. The rising of the water level is termed flood tide, while the lowering is referred to as ebb tide. When the Sun, Moon, and Earth align in a straight line, the gravitational forces combine to produce the maximum tidal range, known as a spring tide. Conversely, when the Sun and Moon are at right angles to the Earth, the tidal range is at its minimum, known as a neap tide.

(i) Tides can be classified based on their frequency:
(ii) Diurnal tide – one high and one low tide per day.
(iii) Semi-diurnal tide – two high and two low tides per day.
(iv) Mixed tide – a combination of diurnal and semi-diurnal characteristics.

Tidal level measuring systems are deployed in the sea for continuous monitoring of tides, typically for periods ranging from 7 days to 3 months. The recorded data are vital for the development of mathematical and numerical models used to study tidal propagation and siltation mechanisms. This information is also crucial for assessing the impact of future port developments, including channel deepening and harbour expansion.

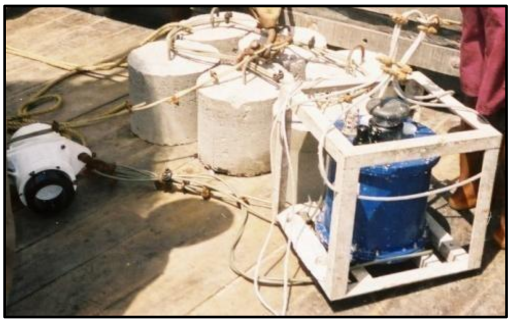


Figure 4.9: Tide Gauge with Acoustic Release

(d) Temperature and Depth

The temperature sensors are associated with the current meters as well as directional wave-rider buoy. Temperature is measured at the point of contact with the ocean waters. The ADCP comes along with the pressure sensor to measure the depth of the overhead water columns.

(e) Positioning System

The Global Positioning System (GPS) serves as essential support equipment for accurately locating coordinates during all measurement activities. The *Mobile Mapper 50* handheld GPS device records a time series of position and depth data in real time and displays it on an integrated LCD screen. Positioning is achieved using the built-in GPS receiver. This Android-based system also supports geo-tagging through its inbuilt camera, making it highly effective for hydrographic surveys and spatial data acquisition.

Figure 4.10: GPS-Mobile Mapper 50

(f) Suspended Sediment Size Analyzer

Laser diffraction is one of the most advanced and efficient techniques for determining sediment particle size distribution. The method measures the scattering of laser light at multiple angles caused by sediment particles of varying sizes (ranging typically from 1 to 500 microns). Based on the scattering patterns, the system computes the particle size distribution (PSD) across defined size classes after estimating the concentration in each range.

Modern analyzers are equipped with integrated depth and temperature sensors, providing essential data for interpreting sediment distribution and transport mechanisms. The laser diffraction and scattering analysis operates in real-time, allowing on-site estimation and immediate data visualization through dedicated software.

This method eliminates the need for extensive sample collection and prolonged laboratory analysis processes that often take weeks or months when using traditional techniques. The Suspended Sediment Size Analyzer is thus ideally suited for in-situ measurements in rivers, streams, ports, harbors, coastal areas, and oceans, supporting studies in sediment transport, environmental monitoring, and biological assessments.

Figure 4.11: Laser In-Situ Scattering and Transmissometer

(g) River Discharge (RADCP) Measurement:

Accurate measurement and analysis of river discharge are fundamental tasks in hydrological studies. Traditional methods of discharge estimation have been largely replaced by advanced techniques that employ modern acoustic technologies. Among these, Acoustic Doppler Current Profilers (ADCPs) have become widely adopted due to their precision, efficiency, and versatility. The River Discharge ADCP (RADCP) utilizes the principle of acoustic signal Doppler shift to measure water velocity profiles across the river cross-section. This allows for accurate determination of discharge under varying flow conditions. The system can be deployed in rivers, streams, and estuarine environments to measure flow characteristics, support sediment transport studies, and provide essential data for hydrodynamic model calibration and validation.

The CWPRS employs the River Pro 1200 kHz ADCP, which is specifically designed for shallow to medium-depth applications. It provides high-resolution, real-time discharge measurements with enhanced accuracy and reliability, making it an invaluable tool for hydrological and environmental monitoring.

Figure 4.12: River Pro 1200 kHz ADCP along with Trimaran Boat and GNSS antenna

4.3 Design Loads and Forces

The design of dock and harbour structures shall include consideration of all relevant load categories in accordance with IS 4651: Part I (1974). Guidance from PIANC and OCIMF Berthing and Mooring standards has also been reflected where applicable.

4.3.1 Dead loads

All dead loads of and on structures relating to Docks and harbours should be assessed and included in the design.

4.3.2 Live loads

Surcharge due to stored and stacked material, such as general cargo, bulk cargo, containers and loads from vehicular traffic of all kinds, including trucks, trailers, railway, cranes, containers, handling equipment and construction plant constitute vertical live loads. The berths should be generally designed for the truck loading and uniform loading relevant to IRC code of loading like AA, A, B etc.

4.3.3 Berthing load

Berthing energy, when an approaching vessel strikes a berth (Figure 4.13), a horizontal force acts on the berth. The magnitude of this force depends on the kinetic energy that can be absorbed by the fendering system. The reaction force for which the berth is to be designed can be obtained and deflection or reaction diagrams of fendering system chosen.

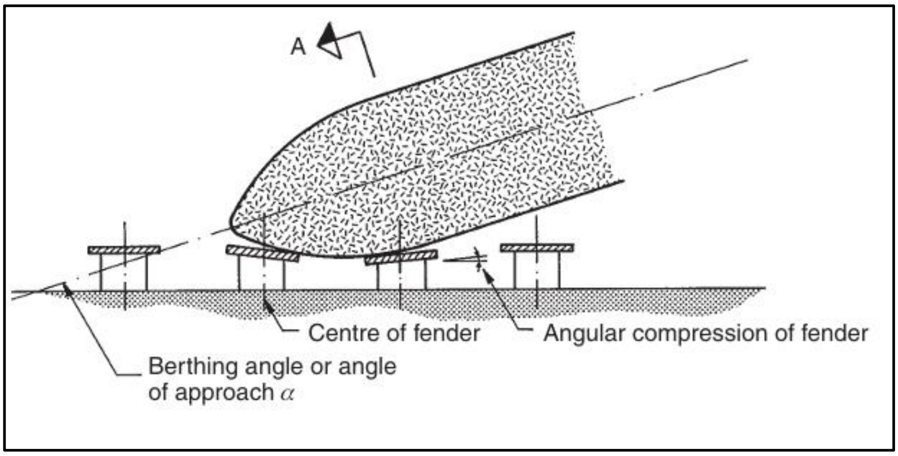


Figure 4.13: Berthing Loads

The kinetic energy E, imparted to a fendering system, by a vessel moving with velocity V, m/sec is given by

$$E = W_o \frac{V^2}{2g} C_m\, C_e\, C_s$$

W_D = DWT in tones,
V = velocity of vessel in upstream normal component of approach velocity
C_m = mass coefficient, C_e = eccentricity coefficient, C_s = softness coefficient
C_m =(1 + 2 D/B) or if L>> B
C_m = 1 + (π/4) D^2 / W_D
$C_e = (1 + (L/r)^2 \sin^2\theta) / (1 + (L/r)^2)$
C_s = normally between 0.9 to 0.95

Berthing load and, therefore, the energy of impact is to be considered for pier, dolphin and the like, with no backfill. In the case of continuous structures with backfill this may not form a governing criterion for design because of enormous passive pressure likely to be mobilized.

4.3.4 Mooring load

The mooring loads are the lateral loads caused by the mooring lines when they pull the ship into or along the dock and hold it against the forces of wind and currents. The maximum mooring loads are due to the wind forces on exposed area on the broad side of ships in light condition

$F = C_w A_w P$

Where,

F = force due to wind in kg
C_w= shape factor = 1.3 to 1.6
A_w = Windage area in sq. m
P = Wind pressure in kg/sq. m to be taken in accordance with IS 875-1974

The windage area can be defined as follows -

$A_w = 1.175 L_p (D_M – D_L)$

Where,
L_p = length between perpendicular in m
D_M = molded depth in m
D_L = average light draft in m

when the ships are berthed on both sides of a pier, the total wind force acting on the pier, should be increased by 50% to allow for wind against second ship.

The appropriate load on the bollard shall then be calculated which depends on the layout of harbour, position of bow line, stern line, spring line and breasting lines; for guidance the bollard pulls independent of the number of laid - on - hawsers, since the hawsers are not fully stressed simultaneously -

Bollard Pull

Displacement Tonnage	Line Pull (tonnes)
20000	60
50000	80
100000	100
200000	150

4.3.5 Combined Loads

The combination of loadings for design is dead load, vertical live loads plus either berthing load or live pull or earthquake or wave pressure. If the current and alignment of berth are likely to give rise to live pull in excess, provisions for such extra pull in combination with likely wind should be made. The worst combination should be taken for design.

Earthquake forces will have to be considered if the project is situated in an area of seismographic disturbance. The horizontal forces may vary between 0.025 and 0.10 of the acceleration due to gravity times the mass, applied at its center of gravity, which can be expressed as 0.025 to 0.10 of the weight, respectively. The weight to be used is the total dead load plus one half of the live load.

4.3.6 Forces due to currents

Pressure due to current will be applied to the area of the vessel below the water line when fully loaded. It is approximately equal to $wv^2 / 2g$ (sqm) of area, where v is the velocity in m/s and w is the unit weight of water in t/cum. The ship is generally berthed parallel to the current.

OCIMF Publication Prediction of Wind and Current Loads on VLCCs reports on the research undertaken by the industry to develop wind and current shape coefficients. It provides information on wind shape coefficients for both cylindrical and conventional bows as well as for ballasted and loaded tankers. Current shape coefficients for varying water depth to draft ratios and for the effects of both cylindrical and conventional bows are also given.

The equations for determining the wind and current loads for the hand calculation are as follows:

Equations for computing wind loads

Longitudinal wind force (ton) $F_{xw} = C_{xw} (\rho_w /7600) Y_w^2 A_T$
Lateral wind force at (ton) $F_{YAw} = C_{YAw} (\rho_w /7600) V_w^2 A_L$

Aft perpendicular

Lateral wind force (ton) $F_{YFw} = C_{xw} (\rho_w /7600) V_w^2 A_L$
Forward perpendicular

where,

C_{xw} = Non-Dimensional longitudinal force coefficient
C_{Yw} = Non-Dimensional transverse force coefficient
M_{xYw} = Non-Dimensional yaw moment coefficient
ρ_w = Density of air (kgs^2 / m^4)
V = Velocity of wind at 10m elevation , knot
A_T = Transverse (head on) area, m^2
L_{BP} = length between perpendiculars, m
F_{xw} = Longitudinal wind force, ton
F_{Yw} = Lateral wind force, ton
M_{Xyw} = Yaw moment , ton-m

Equations for computing current loads
Longitudinal current force (ton) $F_{xc} = C_{xc} (\rho_c /7600) V_c^2 TL_{BP}$
Lateral current force (ton) $F_{YAc} = C_{xAc} (\rho_c /7600) V_c^2 TL_{BP}$
At aft perpendicular

Longitudinal wind force (ton) $F_{YFc} = C_{YFc} (\rho_c /7600) V_c^2 L_{BP}$
At forward perpendicular

The nomenclature for current is similar. The main difference being that the subscript ‘c’ is substituted for ‘w’ and the introduction of the term ‘T’. ‘T’ is the draft of the vessel in meters. ‘Vc’ is also different in that it represents the average current acting over the draft ‘T’ of the vessel. The force coefficients for wind and current are shown in Figures 4.14, 4.15 & 4.16.

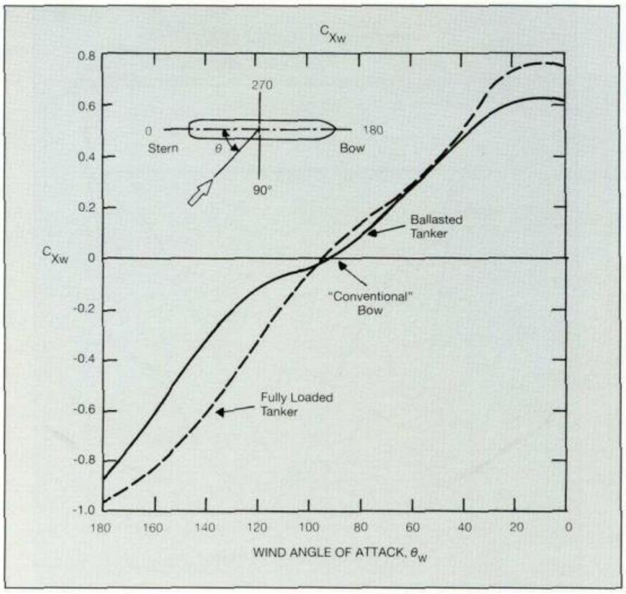


Figure 4.14: Longitudinal Wind Force Coefficient

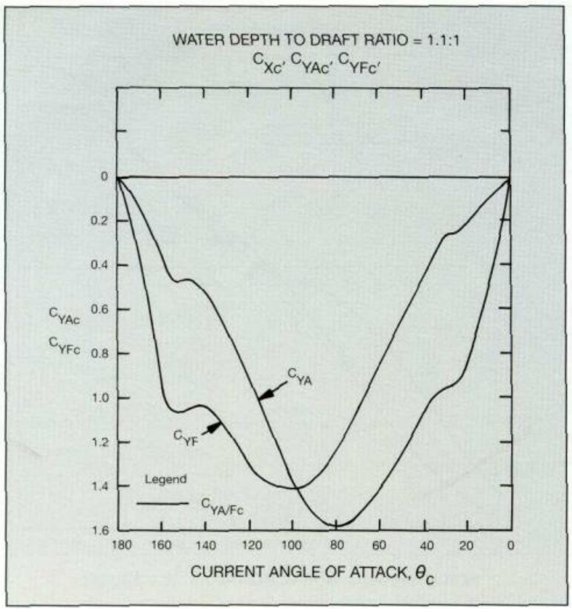


Figure 4.15: Lateral current Force Coefficient

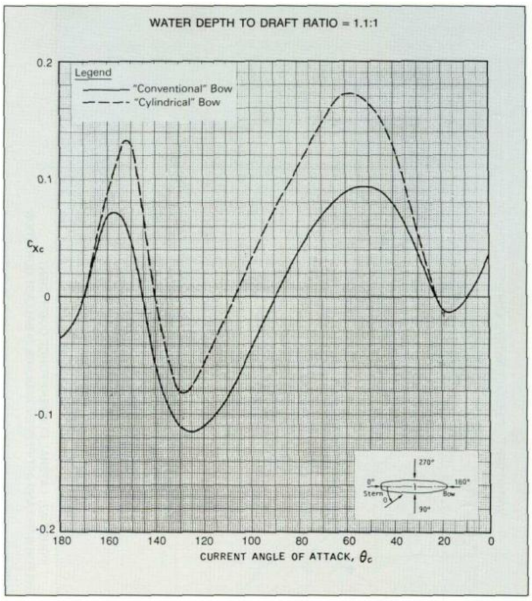


Figure 4.16: Longitudinal Current Force Coefficient

Current forces may 'exception wise' cause very strong tensions in mooring ropes. In case the current does not run parallel to the pier front, strong yawing forces may occur.

4.3.7 Wave forces

a) Non breaking waves
b) Breaking waves
c) Broken waves

Non breaking waves

When depth of water against the structure is greater than about 1 and 1/2 times, the maximum expected wave height, forces are eventually hydrostatic which are to be computed using "Sain flow method".

Breaking waves

Cause both static and dynamic pressure and to be obtained by using "Minikin's method"

Wave forces on vertical cylindrical structures such as piers

1) Forces due to drag
2) Forces due to inertia

Drag Force , $F_{DM} = (1/2)\, C_d \rho\, D\, H^2 K_{DM}$ and $C_d = 0.53$
Inertial Force , $F_{IM} = (1/2)\, C_m \rho\, D\, H^2 K_{IM}$ and $C_m = 2.0$ for vertical circular
$F_M = F_{DM} + F_{IM}$
The wave forces are smallest for piles of cylindrical cross section. For piles with flat or irregular surfaces, such on concrete and H pipes, very little is known.

4.3.8 Ship-shore cargo transfer limits (Tranquility/Workability)

When motions of moored vessels become too great, cargo handling operations have to cease to prevent damage to the vessels and cargo handling equipments. Motions of moored ships are mainly induced by waves (i.e. swells) and by long period waves (over 30 sec period). If waves approach at an angle with the vessel, yawing may occur. This also sets up surge, sway and other angular movements like roll and pitch. For operational reasons it is important that these movements are limited to values acceptable for operation and safety at berth.

Maximum acceptable wave conditions for operations are dependent on ship size, type and wave condition at the berth. The initial limit is lowest for beam sea and highest for head sea. The maximum significant wave height (Hs) for different wave directions before loading/ unloading operations will have to be stopped are summarized in Table 2 as per PIANC's recommendations:

TABLE 2: Ship Shore Cargo Transfer Limits

Type of ship	**Limiting wave height Hs (m)**	
	0^o (head on or stern on)	**$45^o – 90^o$**
Container Ship	0.5	-
Dry Bulk Carrier • **Loading** • **Unloading**	 1.5 1.0	 1.0 0.8 – 1.0
Tanker 30000 DWT **30000 – 2000000 DWT**	1.5 1.5 – 2.5	- 1.0 – 1.2 2.0
Break Bulk Cargo	1.0	0.8

As per IS 4651 (Part V) – 1980, as a general rule the wave disturbance within the harbour should not exceed the following limits as given in Table 3

TABLE 3: Limits for Wave disturbance

Type of Ship	Maximum Significant Wave Height in m		
	At berths	Turning basin	Offshore mooring
General Cargo	0.65	0.90	1.50
Bulk Cargo	0.90	1.20	1.50 for berthing 2.50 for operation
Container Cargo	0.65	1.20	-
Passenger Vessel	0.65	-	-
Trawler and Fishing boats	0.60-0.90	-	-
Deep Sea Tugs	-	1.20	-
Dredgers	-	0.45-2.00	
Supervisor's Boats	0.60	0.60-1.20	-

4.4 Choice of Construction Material

The basic criteria adopted in the general choice of construction material, such as availability, easy working, mechanical properties suited to the purpose for which it is to be used and economic consideration hold equally good for dock and harbour structures. The durability under the environmental condition, however, is of particular importance in the marine structures. The aggressive action of sea water and/ of the marine environment of the principle construction material, such as, steel, concrete and timber require special attention. The IS 4651 (Part IV): 1989 recommends following guidelines for use of construction material for marine construction:

4.4.1 Steel

Unless otherwise specified, the steel confirm to IS 226: 1975 or IS 2062: 1984.

The corrosion of steel varies in different conditions of sea air or sea water exposure. Severe corrosion, however, occurs in saline water and under marine growth, especially in the splash zone and in the reaches of the tidal range with alternate wetting and drying. Steel buried in is also subjected to corrosion under certain conditions. Any one or a combination of the following remedial measures may be taken against the corrosion:

a) Protective coatings

Protective coatings for a barrier to the environmental exposure and thereby delay in the corrosion. These barriers invariably break down after a number of years, specially under the suction and growth of barnacles. The choice of coatings, method of application, thickness of coats, possibility of re-coating etc. are important in ensuring optimum performance of coatings.

b) Cathodic Protection

Corrosion of steel completely immersed underwater or buried in ground (where possibility of electrolytic corrosion exists) can be substantially eliminated and corrosion of steel alternatively exposed to wet and dry condition can be significantly protected by Cathodic protection using an impressed current system or sacrificial anode system.

c) Increased Section / Reduced Stresses

Where the above mentioned measures are not practical or their maintenance a doubtful, extra thickness of metal or section may be considered for providing an economic solution.

The actual recommendations as to the minimum metal thickness depend upon the nature of the structure and its projected life. As a general rule, it may be considered that any mild steel used in marine structure, should have a minimum thickness of 6 mm when Cathodic protection is provided and a minimum thickness of 10 mm when Cathodic protection is not provided. In any case, no structural steel should be used in marine conditions without protective coatings.

d) Use of Special Steel

Special alloy steels, such as, like those with 2 percent copper content can significantly arrest corrosion.

e) Jacketing with Concrete or Other Suitable Synthetic Material

Special care has to be taken in the splash zone where the protection could be given by a concrete lining applied by jacketing with suitable synthetic material.

4.4.2 Concrete

Concrete is extensively used in harbour structures such as dock walls, jetties, wharves, and breakwaters. When used in aggressive marine environments, it is crucial that the concrete is made highly impermeable to prevent the ingress of seawater and its corrosive constituents. The densest concrete provides the best protection.
To ensure durability, a minimum concrete grade of M 30 for reinforced concrete (RCC) and M 40 for pre-stressed concrete is recommended. For mass concrete construction, the minimum grade should be M 15.

The type of cement is also important. Sulphate-resistant cement or blast furnace slag cement is preferred for marine structures. If ordinary Portland cement is used, a higher grade of concrete is required. Minimum cement content of 400 kg/cum and a maximum water-cement ratio of 0.45 should be maintained for all RCC and pre-stressed concrete. For plain cement concrete, minimum cement content of 310 kg/cum and a maximum water-cement ratio of 0.5 should be used.

Minimizing cracks is essential. It is recommended to reduce the stresses in concrete and steel to ensure cracks do not form, or to check the structure against crack formation. As a guide, the surface width of cracks nearest to the main reinforcement should not exceed 0.004 times the cover of the reinforcement.

An adequate thickness of cover is also vital. For structures immersed in seawater, in the splash zone, or exposed to a marine atmosphere, the cover thickness should be 25 mm more than the standard specified.

Using precast concrete elements is a preferred option for marine structures because they are manufactured under strict quality control, making them more resistant to the destructive effects of the marine environment.

4.4.3 Timber

Timber has a wide range of uses in dock and harbour structures, including sheet piles, jetties, fenders, and structural members in buildings. The main hazards for timber in these environments are attack by fungi and insects on land, and by marine borers in seawater. When used in dockside buildings, the design should follow relevant standards for protection against fungi and insects. For timber used in marine structures, especially in areas with fluctuating tides, it is highly susceptible to marine borer attacks and requires preservative treatment. An effective preservative treatment is creosoting, which is typically applied using a pressure impregnation process.

Chapter V

HYDRAULIC MODEL TESTING

Hydraulic Model Testing is a physical simulation technique used in hydraulic engineering to study and analyze water flow behavior and its interaction with structures such as breakwaters, ports, harbors, rivers, and coastal systems. It involves constructing scaled-down physical models of water systems in a controlled laboratory environment to replicate and study real-world conditions.

The purposes of hydraulic model tests in relation to Port planning and design are -

a) Investigations of the stability of breakwater cross sections and of their armour layers
b) Investigations of wave disturbances and flow conditions in ports in order to determine general layout of breakwaters and basin
c) Investigations of littoral drift, erosion and sedimentation, beach nourishment in
Movable bed models

The state of art of relatively new discipline of computer programmed mathematical modeling of water motion in ports and coastal areas allows the following principal applications -

- Wave hindcasting from synoptic weather charts, including shallow water effects such as
- refraction, diffraction and friction for evaluating design wave heights through extreme value analysis of wave data including cyclone waves at the development site.
- Tides and currents in coastal waters and associated transport phenomenon (suspended
- sediments, pollutants etc.)
- Water levels and currents in river and canal systems
- Wave disturbance in port basins; and
- Simulation of ship manoeuvering in approach channel and ship motions at berth with
- thorough dynamic mooring analysis
- Alongshore sediment transport, siltation aspects and shoreline management
- Identification of safe-grade elevations for reclamations and other port infrastructure
- Identification of suitable dumping ground locations through hydrodynamic modelling and dredge spoil dispersion studies.

5.1 Hydraulic Physical Model

Hydraulic scale models are based on the fact that in a large number of hydraulic problems, the number of important types of forces is limited to two, so that when the ratio between the two types of forces is kept the same in model and in nature (prototype), the flow pattern in the model becomes geometrically similar to that of the prototype. In hydraulic modelling of port problems, most processes are governed by gravity and inertia forces or forces similar in form to inertia forces, such as turbulent drag forces, while viscous friction plays a fairly insignificant role.
In such cases, the model scales may be derived from Froude model law, which says that when the Froude number -

$$F = \frac{v}{\sqrt{gd}}$$

where v represents velocity, g the acceleration of gravity and d linear dimension, is the same in model and prototype, then the ratio between gravity and inertia forces is also the same. From this, it may be seen that the velocity scale of a Froude model is equal to the square root of linear scale, whereas the force scale equals the linear scale to the third power. Elastic mooring and fenders forces are reproduced by the stiffness according to the length scale in the second power.

This type of hydraulic model provides a very accurate representation of most wave effects such as wave disturbance in ports and wave forces on structures, as well as many of the current related effects. Inaccuracies and indeed limitations arise when the influence of the two other types of forces, viscous friction and surface tension which are always present begin to play a significant role or when turbulent drag forces in nature go beyond the region of constant drag coefficient i.e. at very high Reynolds numbers.

5.1.1 Wave Models

Wave models are generally constructed for determining port layouts so that proper tranquility conditions are ensured at the berths, breakwater alignment, length etc. Besides the layout of breakwater system, orientation / alignment of berthing structures can be finalized based on the wave approach conditions. Model studies are also essential to decide upon the type of structure like whether it is a structure on caissons or on piles etc. Wave models are also used to study littoral drift problems including design of sand traps and bypassing system, selection of dumping ground for dredged material etc, the navigational aspects ship motions etc. To evolve the configuration and the efficacy of sand traps on rigid bed model, tracer material injection studies are to be conducted. Wave generators are so aligned in the wave basin so that the waves are generated from predominant wave directions observing the vulnerability to the conceptual layout. For physical wave models, geometrically similar scales (means both horizontal and vertical scales are same) are to be adopted as all the wave phenomena are depth- dependent also and thus any vertical distortion will give rise to improper simulation of wave propagation and poor model-prototype conformity.

Model scales, design

From prototype wave data analysis collected for atleast one year covering all seasons, predominant direction, height and period of waves are decided. As per the norms, the wave generator / model boundary is to be located at about 8 to 10 wave lengths away from the structure to avoid any reflections that may alter boundary condition. Model bed is laid as per the latest hydrographic survey chart of the area to the desired level of accuracy as the errors made in model construction will be multiplied according to the selected scales while obtaining model results and converting to prototype parameters.

(a) Reflection

The phenomenon associated with wave action, generally are reflection, refraction, diffraction, attenuation, breaking. These phenomena would be properly simulated in a geometrically similar model. If vertical exaggeration is adopted, then there will be steeper side slopes in the model and due to that, reflection would be considerably in excess of that obtained with undistorted slope.

(b) Wave celerity `C'

The wave model is derived from wave celerity condition -

$$c^2 = \left(\frac{gL}{2\pi} + \frac{2\pi\sigma}{\rho L} \right) \tan h \frac{2\pi d}{L}$$

where,

L = wave length
G = acceleration due to gravity
σ = surface tension
ρ = density of water
d = depth of water from still water level

For deep water conditions (h/L > 0.5), tan h (2πd /L) = 1, and effects of surface tension is negligible, hence,

$C^2 = gL / 2\pi$ $C_o^2 = gL / 2\pi$

(subscript `o' refers deep water)

Shallow water,
tan h (2πd /L) tends 2πd /L

$C^2 = gd$

Hence, `C' is a function of L in deep water and d in shallow water

For deep water $T_r = L_r$

For shallow water $T_r = L_r / d_r$

for vertically exaggerated model.

In the models for coastal engineering application, both deep and shallow water zones are to be reproduced. There will be some difficulty regarding time scale if model is to be vertically exaggerated. But in case of G.S. model, Time scale $T_r = L_r$

(c) Wave diffraction

Wave diffraction depends upon depth and alignment and geometry of obstruction. In distorted models, depths are exaggerated resulting in improper wave diffraction phenomenon in the model. This can be avoided with a G.S. model

(d) Surface tension

For L/d > 0.3, the effect of surface tension is considered to be nil (L is wave length and d is water depth)

(e) Effects of scale distortion

If $L/d \le 3$ Distortion is generally allowed since this is deep water zone
If $3 \le L/d \le 30$ Model should be G.S. as both shallow and deep water effects are equally predominant

If $L/d > 30$ Distortion is generally allowed since only shallow water effects prevail

The effects of scale distortion are shown in Figure 5.1.

(f) Model friction

From Manning's formula, it can be seen that for a G.S. model

$N_r = L_r^{1/6}$

If we take a scale of 1:244, then

$N_r = (1/244)^{1/6}$ = ½.5 $n_m = n_p/2.5$

i.e. the model finish should be very much smooth as compared to prototype. Models are generally constructed out of cement mortar.

Scale should be so chosen that it should be possible to measure the probable smallest wave height in the harbour model with adequate accuracy from available instrument.

5.1.2 Breakwater models

The scales generally adopted for sectional breakwater models are between 1:20 to 1:60 geometrically similar. The weight of the graded stone and the weight of the model armour unit is to be worked out from the following law –

$$\frac{(W_a)_m}{(W_a)_p} = \frac{(\gamma_a)_m}{(\gamma_a)_p}\left(\frac{L_m}{L_p}\right)^3 \left[\frac{(S_a)_p - 1}{(S_a)_m - 1}\right]^3$$

where subscript m denotes model, subscript p denotes prototype

W_a = weight of armour unit
Υ_a = specific weight of armour unit
S_a = specific gravity of an armour unit relative to water in which breakwater is situated
L = length scale

A typical test is required to run for about 2 to 4 hours. Afterwards damage for armour blocks and other layers is measured by actually measuring dislodged units and finding out its percentage to the total number of units in the test section. For very fine material like core material, it is not possible to measure actual number of units dislodged. Breakwater sections in a monochromatic wave flume are generally tested for design period maximum significant waves. However, they are also tested for worst conditions of breaking waves at low water and high water.

5.1.3 Tidal Model

Tidal model studies become important for development of estuaries, estuarine ports, berths, for locating cooling water inlets and hot water outfalls, flood control measures, siltation, flow patterns, alignments of bridges, reclamations, navigational aspects etc. The model boundaries should be decided considering the fact that both upstream and downstream areas are covered. The tide generator is located in such a way that the tide would approach the project site in the direction as observed in the prototype. Side creeks and upper reaches of the estuary are represented by labyrinths. Unlike wave models, the tidal models are generally distorted for the following reasons -

1) To avoid capillary effects in the model - Scales should be so chosen that the depths are sufficiently large and viscous and capillary effects become negligible
2) To avoid too long models - In case of estuaries, if scale is chosen to maintain certain depth for satisfying conditions, the length of geometrically similar model may become too long as prototype length of a few kilometers of the estuary would have to be reproduced
3) To get model velocity higher than the minimum measurable velocity of the Instrument
4) In G.S. models, bed movement would not be properly reproduced because of reduction in hydraulic forces
5) Since the prototype flow would be turbulent flow, the model should also have turbulent flow and hence Reynolds number should be greater than 2000 in the model. This again could be achieved by distorting the model.

Derivation of model scale laws

With equality of Froude number in tidal model, we have

$$\frac{V_m}{\sqrt{g\,D_m}} = \frac{Vp}{\sqrt{g\,Dp}} \quad \cdots \frac{V_m}{V_p} = \sqrt{\frac{d_m}{d_p}} \;\rightarrow V_r = \sqrt{d_r}$$

Other scale laws in terms of length and depth scale automatically came from this relationship such as

$$Time\ scale\ \ T_r = \frac{L_r}{V_r} = \frac{L_r}{\sqrt{d_r}}$$

Discharge scale $Q_r = A_r V_r = L_r\, d_r\, d_r^{1/2} = L_r\, d_r^{3/2}$

The depth scale is to be chosen in such a way so as to ensure that the flow in the model is turbulent by maintaining the Reynolds number (Re = vd/ν) above 4000.

Model friction

In case of distorted models, friction scale can be worked out as below –

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

hence, velocity ratio

$$V_r = \frac{1}{n_r} d^{2/3} \left(\frac{d}{L_r} \right)^{1/2}$$

$$n_r = \frac{1}{V_r} d^{2/3} \left(\frac{d}{L_r} \right)^{1/2}$$

$$n_r = \frac{1}{\sqrt{d_r}} d^{2/3} \left(\frac{d_r}{L_r} \right)^{1/2}$$

$N_r = (V.E.)^{2/3} L_r^{1/6}$

Thus friction depends upon vertical exaggeration and depth scale dr. If V.E. is very large say 10 or beyond, the friction in model increases (model bed has to be very rough). It is necessary to add artificial friction by placing barbed wire, cement concrete blocks, M.S. strips etc. in the model. Too much friction may disturb local flow pattern. To avoid all this, the V.E. is to be limited to 10, preferably around 4 to 5. The effects of model distortion and friction are shown in figure 5.2.

5.1.4 Mobile bed models

Movable bed models are needed to predict bed forms and bed material movements (erosion, siltation etc). It would generally be impossible to contain a material of reduced size as dictated by the model scales. Hence, low specific gravity material (even at times D 50 > prototype value) is used in the model. Since tractive force decides the extent of erosion / siltation, the criterion here is to simulate tractive force and to select a material which will move with the simulated critical tractive force.

The ratio τ/τ_c for model and prototype should be same

τ = γ d S
γ = specific weight of water
d = depth
τ = tractive force
τ_c = critical attractive force
S = slope of the channel

Hence V = (1.486/ n) $R^{2/3}$ $S^{1/2}$ and in ocean conditions R = d

Under wave conditions,

$$V_{\max} = H \frac{\pi}{T \sin h \frac{2\pi d}{L}}$$

$$\tau_c = 0.06\ \rho_w\ (S_s - 1)\, d_s$$

where

τ_c = critical tractive force

S_s = specific gravity of bed material

ρ_w = density of water

d_s = grain dia. in feet

For a given model scale, specific gravity of bed material required can be worked out. A bed material which is available and which has specific gravity sufficiently close to computed one can be chosen and model scale can be worked backwards. Sometimes Noda's criteria can be used to select the suitable tracer material in the model. Two equations involving Horizontal scale ratio (Hr), Vertical scale ratio (Vr), Grain size ratio (D_{50}r)& Specific gravity ratio (Sgr) are to be solved. For the selected scale and site specific sediment characteristics, suitable tracer material for the model can be decided.

For 3-D Shallow wave basins, typical scales of 1: 100 to 1;120 GS are adopted for wave propagation studies of various ports whereas distorted scales are adopted for tidal models. Photographs of some physical models are given below;

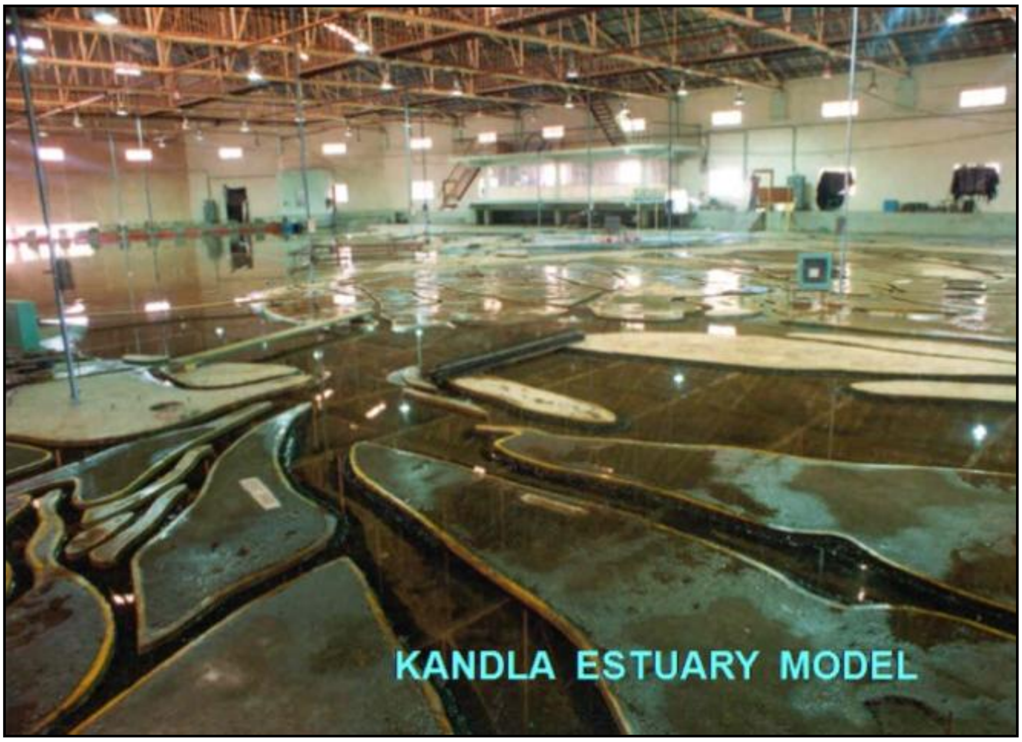


Figure 5.1 Tidal Model of Kandla Estuary system housed in a hangar

Figure 5.2 Physical Wave Model housed in a MS tubular structure equipped with RSWG system

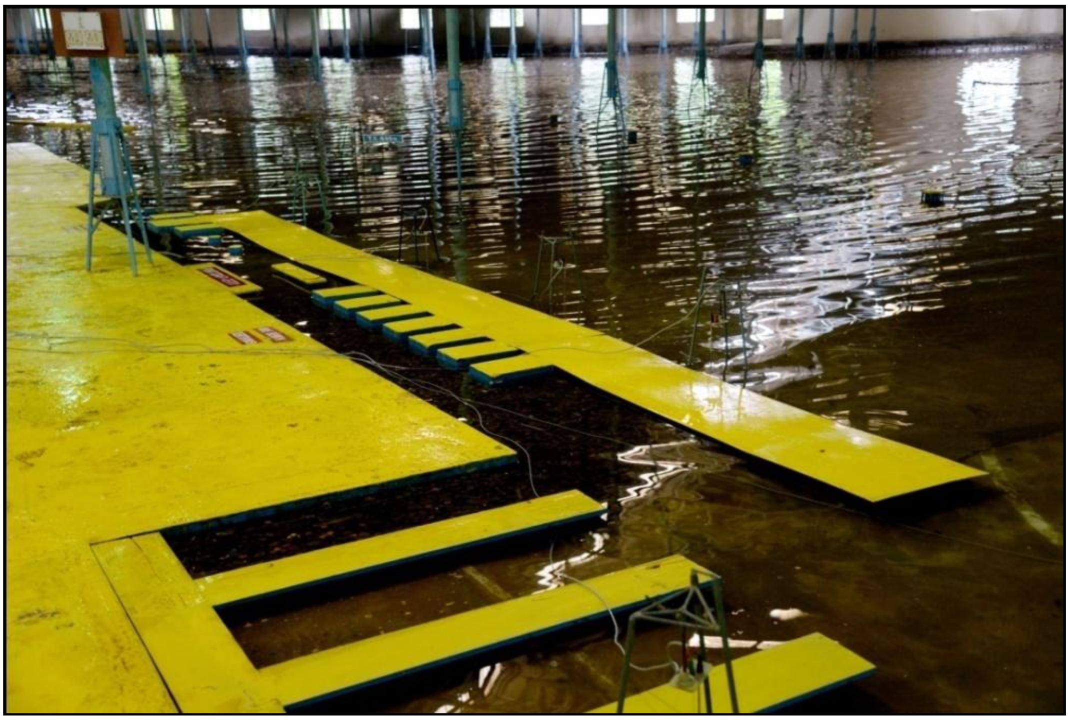


Figure 5.3: Wave tranquility studies for Mormugao Port

Figure 5.4: Physical Wave Model of Kamarajar Port at CWPRS

Figure 5.5 Tracer material injection studies for sand trap configuration on Physical Wave Model of Visakhapatnam Port

The Multipurpose Wave Basin Hangar(MPWBH) of size 60M x 75M at CWPRS is a unique research facility in Asian subcontinent and established for evolving layout of Ports and harbours located on open coast as well as in estuarine areas. The physical wave model at MPWBH is being engaged in carrying out wave tranquillity studies by artificial wave generation using mechanical wave boards operated by servo-hydraulic system and Hydraulic Power Pack of 75HP capacity. MPWBH has capability to generate waves from three different wave directions with wave paddle/ wave front of 21m long. The PC based multi-channel data acquisition system is used for measuring wave heights at multiple points by using capacitance type wave sensors or probes in a geometrical similar physical wave model with rigid bed. Different coastal engineering projects viz. fishing harbours at Colachel, Poompuhar, Tamilnadu, Moplabay, Kerala, Mega container terminal and Dry bulk cargo terminal at Tuna-Tekra in Gulf of Kutch, Kandla port as well as studies for development of Bhagwatibundar, Ratnagiri, Maharashtra, inner and outer harbour development of VOC port, Tuticorin and many more. The wave tranquility studies for developing an all-weather deep water multi-purpose Gateway port at Kakinada, Andhra Pradesh are also completed.

The hydraulic model studies for studying wave reflection effects due to proposed 3 Km long Vizhinjam Sea port breakwater on the existing fishing harbour at Vizhinjam, Kerala have also been studied at MPWBH for five predominant wave directions in two phases. Studies for development of Porbandar port are recently completed and wave tranquillity studies for International Container Transshipment Port are under progress.

Figure 5.6: Outer View of Multi-Purpose Wave Basin Hangar at CWPRS, Pune

Figure 5.7: Wave tranquility studies conducted in MPWB for fishing harbour at Vizhinjam Port, Kerala

5.2 Mathematical Models

The most important new development in hydraulic engineering of recent times is undoubtedly the development of mathematical modeling, made possible by advanced digital computers. A mathematical model is in principle nothing more than a mathematical formulation of a physical process, such as for instance the Navier-Stokes equation. However, it was only after the arrival of large capacity digital computers that such mathematical expressions could be handled in the form of a discrete numerical model and used for sufficiently detailed practical application.

The advantages of mathematical models over physical models are many and important. First and foremost, the mathematical model can take into any physical phenomenon that can be described in mathematical form. Outstanding examples of this are Coriolis force and wind effects. Wind effects have important impact on currents and water levels in shallow regions and on ship manoeuvering at slow speed. In a physical model it would be impossible or very costly to simulate wind effects in a realistic way for such purposes, while in a mathematical model it is a very simple matter. Errors, may of course be introduced by simplifications in the mathematical equations describing the natural processes and this might perhaps be called a scale effect, the model grid made too coarse, thereby smoothing out important features of the region described. But contrary to scale effects in physical models, this type of `scale effect' is not a matter of principle, rather a matter of cost. Finally, the mathematical model has the obvious advantage that it can be stored and remobilized at insignificant cost. Until recently, near-shore wave studies have been carried out either by means of physical models or through the use of idealized mathematical models, such as pure refraction on a gently sloping bed or pure diffraction. Development of two - dimensional hydrodynamic models to incorporate the influence of vertical accelerations in short wave motions has made it possible to describe the combined effects of refraction, diffraction and reflection on short period wave phenomenon in an arbitrary near-shore bathymetry.

The limits of application of mathematical models once set by insignificant knowledge in terms of quantitative description of physical processes to be modeled (e.g. wave breaking and some aspects of sediment transport), inaccuracies in numerical solution techniques, insufficient input data (e.g. meteorological data for wave hindcasting) and by computer capacity and costs (e.g. for three dimensional modeling). The art of `computational hydraulics' is concerned with developing numerical solutions techniques with insignificant or at least acceptable inaccuracies within the whole range of application for a particular model.

The discipline of computational hydraulics focuses on improving numerical solution techniques to minimize inaccuracies across a wide range of model applications. In coastal engineering, the physical processes of interest include:

- Flow fields,
- Sediment transport,
- Short wave propagation,
- Ship navigation and motion,
- Pollution dispersion.

In reality, these processes are fundamentally three-dimensional, with water capable of moving in two horizontal directions and one vertical direction. The mathematical modelling of these processes is based on two fundamental conservation principles:

1. **Conservation of Momentum**, which states that force equals mass times acceleration.
2. **Conservation of Mass**, which assumes incompressibility for sea water.

Conservation of momentum basically states that force is a product of mass and acceleration and the important forces can be divided into two, primary which cause motion and secondary which result from motion. The primary forces are (1) gravitation including pressure forces (2) wind stress which may act tangential to sea surface (3) atmospheric pressure (4) seismic resulting from sea bottom movement. The secondary forces which came into being when water starts to move are (5) coriolis force, an apparent force on moving body when its motion is observed relative to rotating earth and (6) friction acting at the boundary of the fluid and tending to oppose its motion. In words, it can be written,

Acceleration = (Pressure + gravity + tidal + Coriolis+ frictional) force / unit mass

Accordingly, the equation for x direction can be written as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - g\frac{\partial z}{\partial x} + f_v + \frac{\partial}{\partial z}\left(A\frac{\partial u}{\partial z}\right)$$

Similarly identifying forces in other two directions, the equation can be derived. It may be noted that gravity term only contributes in vertical direction. If the fluid is incompressible as may be taken to be the case for sea water, the mass conservation equation becomes

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

In the above equations u, v and w represent velocity, ρ = specific gravity, p = pressure, g = acceleration due to gravity, f = coriolis parameter, ε is eddy viscosity and ξ = tidal fluctuation.

In coastal engineering particularly in Ports and Harbours Engineering, two more aspects of studies are being added, i.e. wave tranquility and ship navigation and motion.

In wave transformation model, mainly the equation for conservation of wave energy is solved. The conservation of wave energy may be written in the following form -

$$\frac{\partial}{\partial x}(E_{flux}) = -E_{Diss}$$

where, E_{flux} indicates energy flux and E_{Diss} indicates energy dissipation.

5.3 Mathematical Model Studies for Port and Harbour Development

The fundamental purpose of a port is to provide a sufficiently tranquil or sheltered area for the safe berthing of vessels, facilitating efficient loading and unloading operations at jetties or wharves. The design of effective ports and harbors is inherently dependent on site-specific hydraulic parameters, including waves, currents, tides, and prevailing wind conditions. To accurately assess these parameters and their potential impact on a proposed port development, numerical model studies can play very important role, these studies may be very cost-effective approach too.

The primary mathematical model studies typically required for the development of ports and harbors include:

1. **Wave Tranquility Studies:** Assessing wave disturbance within the harbor area to ensure suitable berthing conditions and optimize breakwater lengths.

2. **Hydrodynamics and Sedimentation Studies:** Analyzing water circulation patterns, current velocities, and the transport and deposition of sediment within and around the port.
3. **Hydrodynamics and Dumping Ground Disposal Studies:** Setting up a basic hydrodynamic model and to ascertain the fate of disposed dredge spoil in the dumping ground area to assess the suitability of the location and disposal strategy.
4. **Littoral Drift and Shoreline Studies:** Evaluating the movement of sediment along the coast and its potential impact on harbor entrances, navigation channels, and adjacent shorelines.
5. **Storm Surge and Wave Hindcasting Studies:** Predicting extreme water levels and wave conditions during storm events to evolve the design of coastal protection structures and assess potential risks.
6. **Ship Navigation Studies:** Simulating vessel movements within the harbor and approach channels to optimize layout, turning basins, and channel dimensions for safe navigation.
7. **Ship Mooring Studies:** Analyzing the forces acting on moored vessels due to waves, currents, and wind to design safe and effective mooring systems.
8. **Shoreline Management Studies:** Shoreline management studies addressing morphological aspects to arrive at suitable anti-sea erosion measures (soft measures like formation of beach fills through sand nourishment and hard measures like sea walls, groynes etc.)

5.3.1 Wave Tranquility Studies

The primary objective of wave tranquility studies is to assess the degree of wave disturbance at the proposed port site. If the natural conditions do not provide sufficient tranquility for safe berthing and cargo operations, breakwaters are necessary. These studies help optimize the length and layout of breakwaters to achieve the desired sheltered conditions.

To conduct these studies, a mathematical model is developed using prevailing wave conditions at the site. Ideally, measured wave data spanning one to 33 years is required for accurate port layout design. However, this long-term measured data is often unavailable.

In such cases, near-shore wave characteristics can be derived from offshore wind-generated wave data (e.g., from the Indian Meteorological Department - IMD, or the ERA5 dataset from the European Centre for Medium-Range Weather Forecasts - ECMWF). This is achieved using wave transformation models, which simulate how offshore waves change as they propagate towards the coast. Spectral models are commonly employed for this purpose. The resulting near-shore wave data then serves as the boundary condition for detailed wave propagation models within the harbor, such as the Boussinesq wave model.

(a) Spectral Wave (SW) Model

As waves propagate from deep to shallow coastal waters, their direction and height change due to refraction and shoaling. The Spectral Wave (SW) model is a state-of-the-art third-generation spectral wind-wave model used to simulate this wave transformation. It accounts for:

- Wave growth due to wind action.
- Transformation due to refraction and shoaling resulting from depth variations.
- Wave decay due to white capping, bottom friction, and wave breaking.
- Effects of wave-current interaction.
- Non-linear wave-wave interaction.
- Time-varying water depth.
- Diffraction.

The model utilizes a flexible mesh, allowing for coarse spatial resolution offshore and high resolution in shallow water and along the coastline.

The dynamics of gravity waves are described by the wave action balance equation. For small-scale applications, this equation is typically formulated in Cartesian coordinates (x, y), while spherical polar coordinates are used for large-scale applications. In horizontal Cartesian coordinates, the conservation equation for wave action density, N (x, σ, θ, t), is given by:

$$\frac{\partial N}{\partial t} + \nabla.(\vec{v}\, N) = \frac{S}{\sigma}$$

where N($\vec{x}$, σ, θ,t) is the action density, t is the time, $\vec{x}$ = (x, y) is the Cartesian co ordinates, $\vec{v}$ = (C_x , C_y , C_σ , C_θ) is the propagation velocity of a wave group in the four dimensional phase space $\vec{x}$, σ and θ . S is the source term for the energy balance equation. ∇ is the four dimensional differential operator in the $\vec{x}$, σ and θ space.

Execution of the spectral wave model provides the magnitude of wave height and wave direction throughout the area of interest.

The main application of this software is mentioned below;

Wave Climate Simulation: Predicts wave fields in offshore, coastal, and port environments under various wind conditions.

Wave Transformation: Simulates refraction, shoaling, wave breaking, bottom friction, and depth-induced effects as waves move from deep to shallow waters.

Harbour Design: Used for assessing wave agitation inside harbours and the efficiency of breakwaters or port layouts.

Coastal Engineering Studies: Supports coastal protection planning, beach erosion studies, and impact analysis of structures.

Wind-Wave Generation: Simulates local wind-driven wave development and wave growth.

Input for Other Models: Provides boundary conditions for Boussinesq wave model and sediment transport models (e.g., LITPACK), hydrodynamic models (MIKE 21 HD), or morphological models.

Wave Statistics & Design Parameters: Generates wave roses, significant wave heights, peak periods for design or operation of marine structures.

(b) MIKE 21 Boussinesq Wave (BW) Model

The MIKE 21 Boussinesq Wave (BW) model is employed to study wave disturbance within harbors. This model is based on the time-dependent Boussinesq equations for the conservation of mass and momentum, derived by integrating the three-dimensional flow equations while retaining terms related to vertical acceleration. Operating in the time domain, it allows for the simulation of irregular waves and incorporates both non-linearity and frequency dispersion. The frequency dispersion is accounted for by considering the influence of vertical acceleration or streamline curvature on the pressure distribution.

The model simulates key coastal processes within a harbor, including:

- Shoaling.
- Refraction.
- Diffraction at breakwater tips.
- Bed friction.
- Partial reflections from boundaries, piers, and breakwaters.

While the classical Navier-Stokes equations describe all mechanisms of wave propagation, their solution can be computationally intensive. The Boussinesq equations offer an alternative by using a depth-averaged form of Euler's equations, retaining higher-order terms of vertical acceleration crucial for shorter waves.
Following are Boussinesq equations of motion:

- **Continuity Equation** :
- $\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0$
- **X Momentum Equation :**
- $\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + gh\frac{\partial \eta}{\partial y} + g\frac{\sqrt{p^2+q^2}}{c^2h^2}\, q = \frac{Dh}{3}\left(\frac{\partial^3 p}{\partial x^2 \partial t} + \frac{\partial^3 q}{\partial x \partial y \partial t}\right)$
- **Y Momentum Equation :**
- $\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \eta}{\partial x} + g\frac{\sqrt{p^2+q^2}}{c^2h^2}\, p = \frac{Dh}{3}\left(\frac{\partial^3 q}{\partial y^2 \partial t} + \frac{\partial^3 p}{\partial x \partial y \partial t}\right)$

Where p and q are fluxes in X and Y directions, D is still water depth, η is water surface elevation, h=D+η being water depth and c is Chezy coefficient.

These simultaneous, non-linear, hyperbolic equations capture important wave phenomena such as refraction, shoaling, diffraction, and reflections, along with non-linearity and frequency dispersion. The models solve for water surface elevation at each grid point over time, enabling the simulation of wave forms. Boussinesq equation models are applicable to a wide range of wave frequencies, making them suitable for studying wave disturbance in harbors due to both regular and random wave trains.

A major limitation of the simple form of the Boussinesq equations is the water depth restriction, typically breaking down for a depth to deep water wavelength ratio (d/Lo) greater than 0.12. Additionally, these models can require significant computational time and storage, and must satisfy the Courant-Friedrichs-Lewy (CFL) condition for numerical stability.

Key Applications of MIKE 21 BW Model:

Wave Transformation in Near-shore Zones
Simulates shoaling, refraction, and diffraction of waves.
Captures wave asymmetry and skewness near shore.

Wave Breaking and Energy Dissipation
Models wave breaking over reefs, bars, or slopes.
Useful for surf zone hydrodynamics and energy dissipation studies.

Harbour Resonance and Wave Penetration
Analyzes how long-period waves propagate into harbours or lagoons, including harbour oscillations.

Coastal Structure Interaction
Simulates wave interactions with breakwaters, jetties, groynes, and other structures.
Helps in optimizing structure designs for wave attenuation and scour protection.

Wave-Driven Currents and Setups
Models wave-induced currents, longshore currents, and wave setup which are critical in coastal sediment dynamics.

Design and Safety Assessments
Provides wave climate inputs for port/harbour design, offshore structures, and coastal defenses**.**

Flooding and Overtopping Studies
Assists in evaluating wave run-up, overtopping, and coastal flooding under storm conditions.

Limitations of the MIKE 21 BW Model

- Valid for shallow water with depth-to-wavelength ratio d/L0<0.12d/L_0 < 0.12d/L0<0.12
- Computationally intensive and sensitive to the Courant-Friedrichs-Lewy (CFL) criterion
- Despite their complexity, Boussinesq models offer a high-fidelity simulation of wave patterns, especially for wave disturbance studies in harbor basins.
- Computationally intensive: Due to high-resolution and nonlinear formulations, simulations can be time-consuming.
- Limited to shallow to intermediate water depths: Best suited for depths < 30 m; deep-water wave phenomena may require other models like MIKE 21 SW.
- Grid size restrictions: Requires fine meshes to resolve wave details accurately, increasing data and processing needs.
- Wave breaking parameterization: Calibration may be needed for realistic breaking and energy dissipation representations.

When to Use MIKE 21 SW

- Regional wave climate modeling
- Input for sediment transport and coastal morphology models
- Wind-driven wave generation in large open domains
- Wave statistics for offshore structures

When to Use MIKE 21 BW

- High-resolution near-shore wave modeling
- Wave run-up, overtopping, and structure interaction
- Harbor and lagoon wave dynamics (oscillations, penetration)
- Studies involving wave breaking, surf zone currents, and non-linear wave propagation

As per the practice, MIKE 21 SW is used first to simulate large-scale wave conditions and generate boundary conditions. Then, MIKE 21 BW is used locally in critical areas (like harbours or surf zones) for detailed analysis using the SW output.

For the simulations of SW a flexible mesh based bathymetry prepared for the larger domain (Figure) and by considering all the possible incident waves at boundary, near-shore wave data (wave height and direction) is extracted at the desired point.

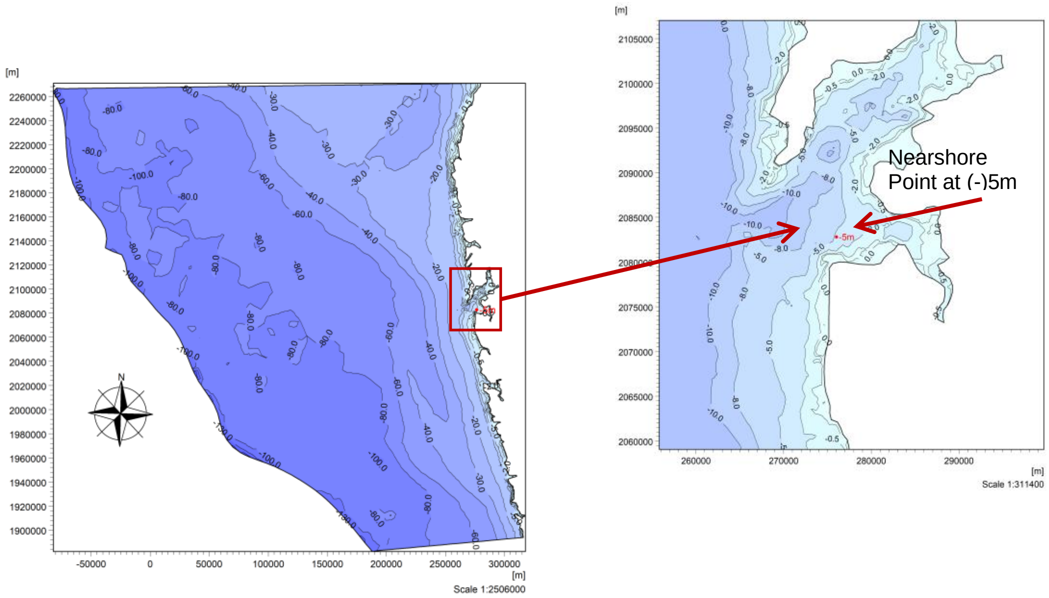


Figure 5.8: Bathymetry for the SW module

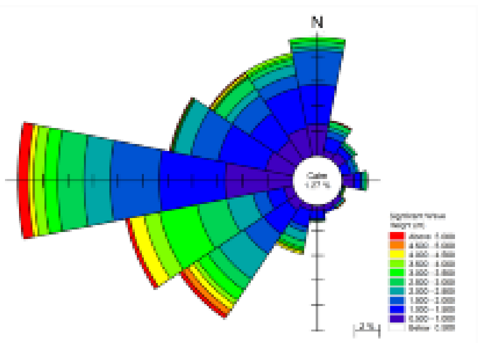


Figure 5.9: Offshore Wave rose diagram

After applying the ratio table get the near-shore wave rose diagram as below

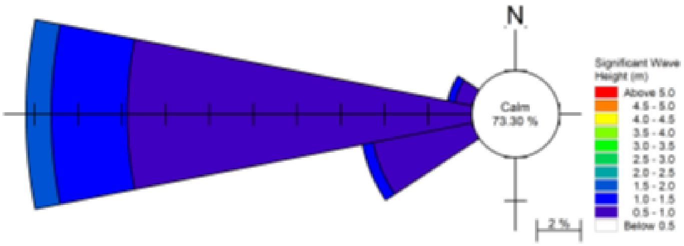


Figure 5.10: Near-shore wave diagram

These studies are very much effective in deciding the optimum port layout or any new port as well as refurbishment of existing port or harbour. A typical output of the MIKE 21 BW simulation is given below:

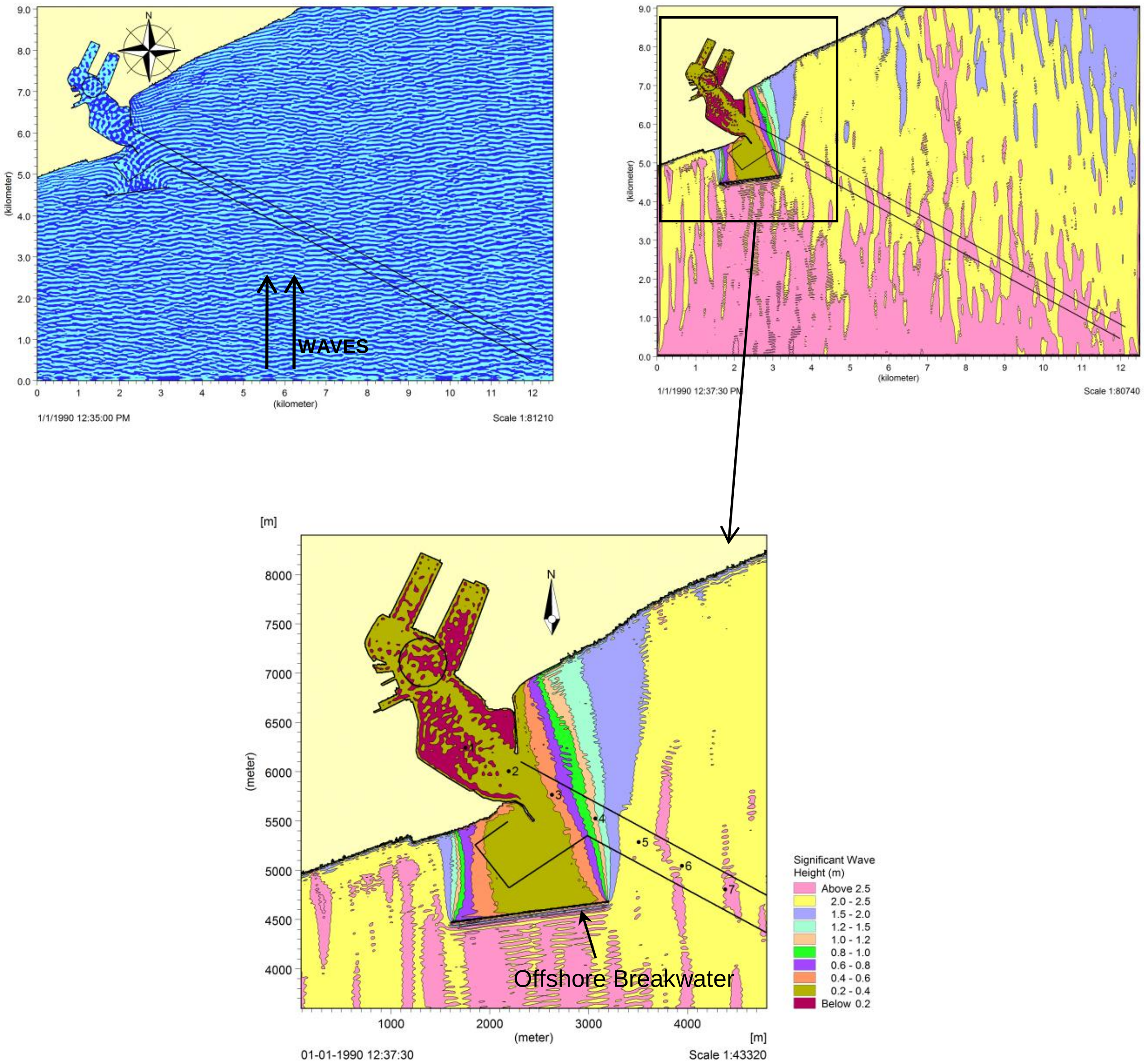


Figure 5.11: Wave propagation and Wave Height Distribution in the Harbour for Waves Incident from South direction (incident wave height: 2.75m)

From the above wave distribution plot, the effectiveness of the offshore breakwater can assessed to provide the wave tranquillity in the last stretch of the approach channel.

5.3.2 Hydrodynamics and Sedimentation Studies:

The MIKE 21 Hydrodynamic (HD), Sediment transport (ST) and Mud Transport (MT) modules are powerful tools for understanding and predicting water flow and sediment movement, which are crucial for the successful design and operation of ports and harbors. Here's a breakdown of their importance and uses:
Sedimentation studies are paramount for successful port and harbor development and operation for a multitude of reasons:

I. **Maintaining Navigational Depths:** Sedimentation directly impacts the depth of navigation channels, berthing areas, and turning basins. Unpredicted or excessive siltation can lead to reduced draft availability, restricting access for larger and more economical vessels, and necessitating frequent and costly dredging.
II. **Optimizing Dredging Strategies:** Understanding sediment transport pathways and accumulation zones allows for the development of efficient and targeted dredging strategies. This includes identifying optimal dredging locations, volumes, and timing, minimizing operational costs and environmental impact.
III. **Informing Port Layout and Design:** Sedimentation patterns are strongly influenced by the layout of port structures like breakwaters, jetties, and quays. Modeling sediment transport can help optimize these layouts to minimize siltation within critical areas and promote natural sediment bypassing where possible.
IV. **Ensuring Structural Stability:** Sediment erosion and deposition can impact the stability of coastal structures and underwater slopes within the port. Studies can help identify areas prone to erosion or excessive loading due to sediment accumulation, informing design considerations.
V. **Assessing Environmental Impacts:** Port development and maintenance activities (like dredging and disposal) can significantly alter sediment transport and suspension, impacting water quality, turbidity, and benthic habitats. Sedimentation studies are crucial for Environmental Impact Assessments (EIAs) and for designing mitigation measures like silt curtains or optimized disposal sites.
VI. **Predicting Long-Term Morphological Changes:** Ports are dynamic environments. Sedimentation studies can help predict long-term changes in bathymetry and shoreline evolution due to natural processes and port activities, allowing for proactive adaptation and planning.
VII. **Managing Siltation in Berthing Areas:** Tranquil berthing areas are susceptible to fine sediment deposition, potentially hindering operations. Modeling can help identify the sources of this siltation and evaluate the effectiveness of counter-measures.

Two-Dimensional hydrodynamic model MIKE 21 HD, sediment transport Models have been used to simulate the flow field and sediment transport in the existing and the proposed scenario under prevailing tidal and wave conditions. Brief description of scientific background of MIKE 21 HD model, MIKE-21 SW model and MIKE-21 MT model is given in following paragraphs as below.

MIKE 21HD Module

In order to simulate dynamics of cohesive sediment, it is necessary to initially compute the hydrodynamics of water body in terms of velocity and water level fluctuations. Appropriate governing equations for hydrodynamics in tidal areas are given by the shallow water wave equations. These two dimensional shallow water equations are derived from Navier Stokes equations of motion with the following simplified assumptions:

(i) The flow is incompressible
(ii) The flow is well mixed
(iii) Vertical accelerations are negligible
(iv) Bed stress can be modeled using a quadratic friction law.

The conservation of mass and momentum integrated over the vertical are used in the hydrodynamic model to describe the flow and water level variations

$$\frac{\partial H}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=\frac{\partial d}{\partial t}$$

$$\frac{\partial P}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial H}{\partial x}+\frac{gp\sqrt{p^2+q^2}}{c^2h^2}$$

$$-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})\right]-\Omega q-fVV_x+\frac{h}{\rho_w}\frac{\partial}{\partial x}(P_a)=0$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial H}{\partial y}+\frac{gq\sqrt{p^2+q^2}}{c^2h^2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{\partial}{\partial x}(h\tau_{xy})\right]+\Omega p-fVV_y$$

$$+\frac{h}{\rho_w}\frac{\partial}{\partial y}(P_a)=0$$

The following symbols are used in the equations:

h(x, y, t)	:	water depth(m)
H(x, y, t)	:	surface elevation (m)
d(x, y, t)	:	time varying water depth (m)
p,q(x,y,t)	:	flux densities in x and y directions [$m^3/(s.m)$]
c(x,y)	:	Chezy resistance ($m^{1/2}/s$)
g	:	acceleration due to gravity (m/s^2)
f(v)	:	wind friction factor
v, v_x, v_y(x,y,t)	:	wind speed and components in x and y direction (m/s)
Ω(x,y)	:	Coriolis parameter (s^{-1})
P_a	:	atmospheric pressure (kg/ms^2)
ρ_w	:	density of water (kg/m^3)
x, y	:	space coordinates (m)
t	:	time(s)
τ_{yy}, τ_{xy}, τ_{xx}	:	components of effective shear stress (N/m^2)

MIKE 21 Flow Model FM is based on a flexible mesh approach and it has been developed for applications within oceanographic, coastal and estuarine environments. The modelling system may also be applied for studies of overland flooding. The system is based on the numerical solution of the two- dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The spatial discretization of the primitive equations is performed using a cell-centered

finite volume method. The spatial domain is discredited by subdivision of the continuum into non-overlapping elements/cells. In the horizontal plane an unstructured grid is used while in the vertical domain in the 3D model, a structured mesh is used. In the 2D model the elements can be triangles or quadrilateral elements.
The typical mesh for 3-Dimesional model is given below.

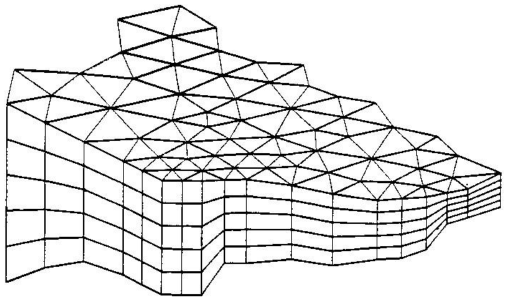


Figure 5.12 Flexible Meshes for 3-Dimensional Model

MIKE 21 MT Module

The sediment transport studies were carried out using MIKE 21 MT model. This model simultaneously solves hydrodynamic and sediment transport equations. The calibration of sediment transport model is difficult because morphological changes are too slow and temporal bed changes are too variable to measure anything significant for comparison. The sediment fluxes at various locations may differ and the following factors contribute for these variations:

- Unsteadiness of flow,
- Mixtures of sediment in suspension,
- Variability of supply of mobile sediment on the bed,
- Presence of sandy (non cohesive) sediment,
- Omission of depth variation,
- Effect of wave stirring.

The erosion, transport and deposition of silt, mud and clay particles under action of currents and waves can be best described by the multi-layers mode of the mud transport module of MIKE 21. The sediment transport module is dynamically coupled with the 2-dimensional hydrodynamic module, MIKE 21 HD. The module solves the primitive equations in two dimensions using finite difference methods by Alternating Direction Implicit technique and the Double Sweep algorithm. Following are the relationships used in the module.

The sediment transport formulations are built into the advection-dispersion module, MIKE 21 AD, which solves advection-dispersion equation:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = \frac{1}{h}\frac{\partial}{\partial x}\left(hD_x\frac{\partial c}{\partial x}\right) + \frac{1}{h}\frac{\partial}{\partial y}\left(hD_y\frac{\partial c}{\partial y}\right) + Q_L C_L\frac{1}{h} - S$$

The following symbols are used in the equation:

c	:	compound concentration (arbitrary units)
u,v	:	horizontal velocity components in x, y directions (m/s)
h	:	water depth (m)
D_x,D_y	:	dispersion coefficients in the x,y directions (m^2/s)
S	:	accretion/erosion term ($kg/m^3/s$)
Q_L	:	source discharge per unit horizontal area ($m^2/s/m^2$)
C_L	:	concentration of source discharge (kg/m^3)

The advection-dispersion equation is solved using an explicit, third-order finite difference scheme, known as the ULTIMATE scheme.

Importance of Hydrodynamics and Sedimentation Studies for Port Development

Hydrodynamic and sedimentation studies are crucial for successful port development due to the following reasons:

I. **Navigation Safety:** Understanding water depths, currents, and wave patterns ensures safe navigation for vessels of various sizes, minimizing the risk of grounding, collisions, and other accidents.
II. **Sedimentation Management:** Ports require sufficient water depths in navigation channels and berthing areas. Sedimentation studies help predict siltation rates, identify critical areas of deposition, and design effective dredging strategies and sediment disposal methods. This minimizes maintenance dredging costs and ensures operational efficiency.
III. **Coastal Morphology and Stability:** Port construction can alter local hydrodynamics and sediment transport patterns, leading to erosion or accretion in adjacent coastal areas. Studies help assess these impacts and design mitigation measures like breakwaters, groynes, and beach nourishment to maintain coastal stability and protect infrastructure.
IV. **Structural Design and Stability:** Hydrodynamic forces from waves and currents exert significant pressure on port structures like quays, jetties, and breakwaters. Accurate hydrodynamic modeling is essential for designing stable and resilient structures that can withstand these forces.
V. **Environmental Impact Assessment:** Port development can affect water quality, marine habitats, and sediment composition. Hydrodynamic and sediment transport models are used to predict the dispersion of pollutants, changes in salinity and turbidity, and the impact on benthic ecosystems, aiding in environmental impact assessments and the development of mitigation strategies.
VI. **Operational Efficiency:** Optimizing port layout, channel design, and vessel maneuvering areas based on hydrodynamic and sedimentation characteristics can improve operational efficiency, reduce turnaround times, and enhance overall port capacity.
VII. **Climate Change Adaptation:** Rising sea levels and altered storm patterns due to climate change pose increasing risks to port infrastructure. Hydrodynamic modeling can help assess these vulnerabilities and design adaptation measures to ensure long-term resilience.

Limitations of Hydrodynamic mathematical models:

While powerful, these models have limitations in the context of sedimentation studies:

I. **Data Requirements:** Accurate sediment transport modeling requires detailed and high-quality data on bathymetry, hydrodynamic forcing (tides, waves, currents), and crucially, sediment properties (grain size distribution, settling velocity, critical erosion stress, bed erodibility, consolidation parameters for mud). Obtaining this data can be challenging and expensive.

II. **Complexity of Sediment Behavior:** Sediment transport is a highly complex process involving various physical, chemical, and biological factors that are often simplified in models. For example, the effects of vegetation, bioturbation, and flocculation (especially for cohesive sediments) can be difficult to fully capture.

III. **Calibration and Validation Challenges:** Calibrating and validating sediment transport models is often more challenging than hydrodynamic models due to the difficulty in obtaining comprehensive field data on sediment fluxes and bed level changes.

IV. **Modeling Mixed Sediments:** Many port environments contain a mixture of cohesive and non-cohesive sediments. While MIKE 21 offers modules for both, accurately modeling their interaction and combined transport behavior can be complex.

V. **Representation of Bed Morphology:** Morphological changes (bed erosion and deposition) can feedback on the hydrodynamics, requiring morphdynamic modeling. While MIKE 21 has capabilities for this, long-term morphological simulations can be computationally intensive and prone to uncertainties.

VI. **Small-Scale Processes:** Models with coarser grid resolutions may not accurately capture small-scale flow features and their influence on localized erosion or deposition around structures.

VII. **Assumptions and Simplifications:** Models inherently involve simplifications of reality. For example, assumptions about sediment homogeneity or steady-state conditions might not always hold true.

VIII. **Modeler Expertise:** Setting up, calibrating, and interpreting the results of these complex models requires significant expertise in hydrodynamics, sediment transport processes, and numerical modeling techniques.

IX. In conclusion, sedimentation studies using MIKE21 HD, ST or MT are essential for sustainable port design and operation. They provide critical insights into sediment dynamics, allowing for optimized layouts, efficient dredging, and effective environmental management. However, it's crucial to acknowledge the inherent limitations of these models and to rely on high-quality data, careful calibration and validation, and expert interpretation to ensure reliable and meaningful results.

5.3.3 Hydrodynamic and dumping ground disposal studies

Model study is required to be conducted by setting up basic 'Hydrodynamic' and allied 'Mud Transport' modules to assess the spread of the disposed dredge material in the dumping ground area and thereby to arrive at suitable disposal strategy for the proposed development project. Total Bed Thickness Change (TBTC) and suspended sediment concentrations (SSC) in and around the disposed location can be obtained through model simulations for the pre-decided dumping cycle / disposal rate. Dump rates are to be arrived at based on the capital dredging quantity and schedule as well as the type of dredger being deployed. Spread in the longitudinal and transverse directions can be observed from model results. If necessary, the sub-domains are to be earmarked to adopt best management practice for dredge material disposal. This strategy of changing the sub-domain would keep the benthic thickness below the permissible limit for the safety of fauna. Suspended sediment concentration values around the dumping location, during the disposal period shall need to be as per norms.

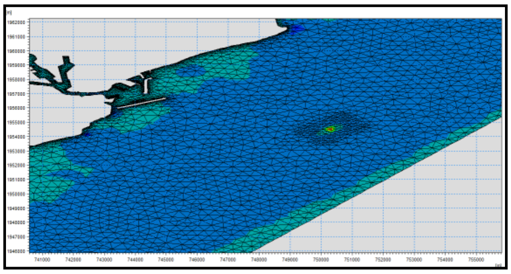


Figure 5.13: Hydrodynamic model set up with Mesh for Dumping Ground Disposal

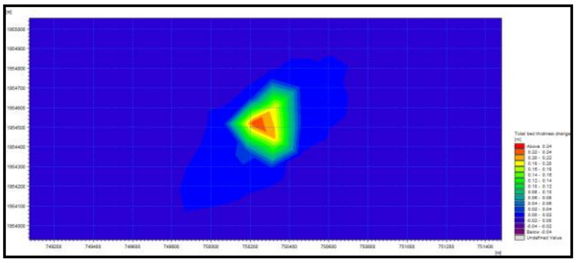


Figure 5.14: Spreading Pattern for Total Bed Thickness Change (TBTC) in Dumping Ground Area after 30 Days disposal in Mud Transport model

5.3.4 Littoral Drift and Shoreline Studies:

Littoral drift, also known as longshore drift, is a fundamental geological process involving the transportation of sediment (such as sand, pebbles, and shingle) along a coast parallel to the shoreline. It's the primary mechanism by which beaches and coastal areas either erode or accrete (grow).

Here's a breakdown of how it works:

- Wave Approach: Ocean waves rarely hit the shoreline head-on (perpendicularly). Instead, they typically approach the coast at an angle.
- Swash and Backwash:
- Swash: As a wave breaks and rushes up the beach (swash), it carries sediment with it at an angle, following the direction of the incoming wave.
- Backwash: As the water loses energy, it flows back down the beach (backwash) due to gravity, usually at a right angle to the shoreline.
- Zigzag Movement: This combination of angled swash and perpendicular backwash creates a "zigzag" or sawtooth pattern of sediment movement. Each wave pushes the sediment slightly along the coast in the direction of the wave's approach.
- Longshore Current: The continuous repetition of this zigzag motion, coupled with the momentum of the breaking waves, generates a persistent current flowing parallel to the coastline within the surf zone. This is called the longshore current.
- Sediment Transport: Littoral drift is essentially the sediment that is carried by this longshore current. It's like a "river of sand" flowing along the coast, moving material from one area to another.

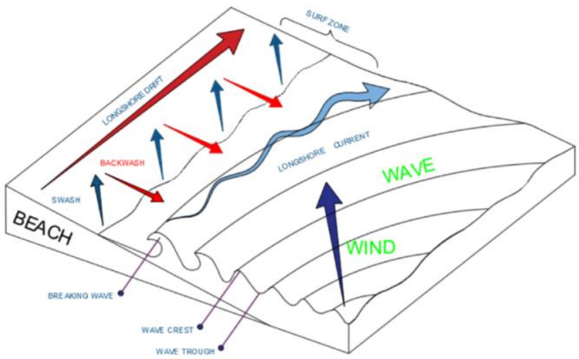


Figure 5.15: Sketch showing LST based on coastal waves

Key Factors Influencing Littoral Drift:

1. **Wave Height and Period:** Larger waves and longer periods generally generate more significant sediment transport.
2. **Wave Angle:** The angle at which waves approach the shoreline is the most critical factor determining the direction and magnitude of littoral drift.
3. **Sediment Characteristics:** The size, shape, and density of the sediment influence how easily it's transported.
4. **Coastal Morphology:** The shape of the coastline, presence of headlands, bays, or offshore bars, can affect wave patterns and sediment transport.
5. **Currents:** Besides wave-driven currents, tidal currents and other ocean currents can also contribute to or oppose littoral drift.

Littoral drift is a major factor in coastal erosion, accretion, and the formation of coastal landforms like spits, bars, and tombola.

Mathematical models are essential tools for understanding and predicting littoral drift and shoreline changes, which are complex processes driven by wave action, currents, sediment characteristics, and coastal morphology. These models range in complexity and application, from simplified empirical approaches to highly detailed process-based simulations.

Key Concepts in Littoral Drift and Shoreline Change

- **Littoral Drift (Longshore Sediment Transport):** The movement of sediment along the coast, primarily driven by waves breaking at an angle to the shoreline, generating a longshore current. It can be net (overall direction and quantity) or gross (total amount transported, regardless of direction).
- **Shoreline Change:** The erosion or accretion of the coastline over time, which is directly linked to the balance of incoming and outgoing sediment due to littoral drift and cross-shore transport.
- **Depth of Closure:** The offshore depth beyond which significant wave-induced sediment transport does not occur, defining the active coastal profile.

LITPACK Modeling System

The LITPACK software suite was used to compute littoral drift and simulate shoreline changes resulting from the construction of breakwaters. LITPACK is a professional coastal engineering tool developed for modeling non-cohesive sediment transport under the combined action of waves and currents, as well as for analyzing coastline evolution and beach profile development along quasi-uniform shorelines.

LITDRIFT Module

The LITDRIFT module simulates the cross-shore distribution of wave height, wave setup, and longshore currents across an arbitrary coastal profile. It provides a deterministic description of longshore sediment transport under both regular and irregular wave conditions, taking into account varying bathymetry.

Key features include:

- Solution of longshore and cross-shore momentum balance equations to compute the longshore current and wave setup.
- Modeling of wave breaking and wave decay, either using an empirical formulation or the Battjes and Janssen model.
- Calculation of net and gross littoral transport rates over a specified design period.
- Inclusion of key hydrodynamic linkages between sea state, water level, and beach profile.

LITLINE Module

Based on the outputs from LITDRIFT, the LITLINE module simulates shoreline evolution by solving the sediment continuity equation in the littoral zone. It accounts for gradients in longshore sediment transport capacity caused by both natural features (e.g., headlands) and man-made structures (e.g., groynes, jetties, and breakwaters).

Key aspects:

- Incorporates the effects of coastal structures, including sources and sinks of sediment.
- Accounts for wave diffraction in the lee of breakwaters and other offshore structures.
- Predicts long-term changes in the shoreline position based on transport gradients.

Modeling Limitations and Application Scope

LITPACK is inherently a one-dimensional (1-D) modeling system, making it ideal for assessing alongshore sediment transport but not suitable for resolving complex 2-D circulations around coastal structures such as breakwaters. In particular, flow patterns around breakwaters involve multi-directional currents and eddies that cannot be fully captured by a 1-D model.
However, for the purpose of modeling shoreline evolution, the primary impact of an offshore breakwater is its sheltering effect. In the shadow zone between the breakwater and the coastline, wave energy and the resulting longshore current are significantly reduced—and may even reverse depending on the geometry and dimensions of the breakwater. This leads to a localized reduction in longshore sediment transport, a phenomenon effectively modeled in LITLINE.

The annual sediment budget is estimated by aggregating transport contributions from all incident wave conditions over a representative year. The total annual drift is thus calculated as the sum of sediment transport rates corresponding to each wave event, providing a comprehensive assessment of long-term coastal stability.

Its primary role in coastal engineering is to:

1. **Quantify Littoral Drift:** LITPACK provides detailed calculations of the longshore sediment transport rates along a stretch of coastline. Unlike simpler empirical formulas, it employs a more deterministic approach, considering complex interactions between waves, currents, and sediment properties. It can account for:

- o Waves and currents at arbitrary angles.
- o Breaking and non-breaking waves.
- o Different bed conditions (plane, ripple-covered).

- Uniform or graded bed material.
- Effects of bed slope and streaming.

2. **Predict Shoreline Evolution:** A key capability of LITPACK is its ability to simulate how the coastline will change over time (e.g., years to decades) due to the gradients in littoral drift. Where more sediment comes in than goes out (accretion), the shoreline advances; where more goes out than comes in (erosion), the shoreline retreats.

3. **Assess Impacts of Coastal Structures:** Engineers use LITPACK to predict the influence of various coastal structures on sediment transport and shoreline stability. This includes:

Groynes: Structures built perpendicular to the shore to trap sand. LITPACK can simulate the accretion up-drift and erosion down-drift of groynes.

Jetties/Breakwaters: Structures at harbor entrances or offshore. LITPACK can help understand how they affect harbor siltation, navigational channel stability, and adjacent coastlines.

Revetments/Seawalls: While primarily erosion protection, LITPACK can help assess their indirect impacts on sediment dynamics.

Beach Nourishment: Simulate the effectiveness and longevity of artificial beach replenishment projects.

Support Coastal Management and Planning: LITPACK assists in:

I. Climate Change Impact Assessment: Analyzing how changes in wave climate and sea level rise might affect coastal sediment dynamics and inform adaptation strategies.
II. Coastal Erosion Strategies: Evaluating the effectiveness of different schemes to combat erosion.
III. Optimizing Designs: Helping coastal engineers optimize the design and placement of coastal structures by predicting their long-term morphological effects.
IV. Harbour Siltation Studies: Providing insights into sediment behavior to address siltation problems in harbors and navigation channels.

Advantages of LITPACK:

I. Deterministic Approach: Provides a more physically rigorous and detailed calculation of sediment transport compared to simpler empirical formulas.
II. Integrated System: The modular structure allows for complex simulations by linking different processes seamlessly.
III. Versatility: Applicable to a wide range of coastal engineering problems, from regional studies to localized impact assessments.
IV. Industry Standard: Widely recognized and used by coastal engineers and researchers globally.
V. In essence, LITPACK serves as a vital tool for coastal engineers and managers to understand, predict, and manage the dynamic changes occurring along coastlines due to the powerful forces of waves and currents and the resulting littoral drift.
VI. In addition to LITPACK, several other numerical software tools are widely used for modeling littoral drift, shoreline evolution, and coastal sediment dynamics. Each has its own strengths depending on the complexity of the coastal environment, available data, and modeling objectives.

At CWPRS, littoral drift studies have been conducted for almost all coastal states of India. These studies indicate that the east coast experiences significant littoral drift, making it a major concern. The primary cause of this is the intense wave action along the eastern shoreline. Additionally, all the perennial rivers in India discharge into the Bay of Bengal along the east coast, contributing further to the sediment load and drift.

Several other factors also influence littoral drift along the east coast, making it more pronounced than on the west coast. The general direction of sediment transport on the east coast is predominantly northward.

In contrast, the west coast experiences relatively lower sediment transport. Moreover, the direction of littoral drift along the west coast varies depending on the local coastal geometry and wave climate. One case study of the littoral drift included in this document is related with stabilizing the river mouth for the fishing activities at Hejemadi kodi in Karnataka.

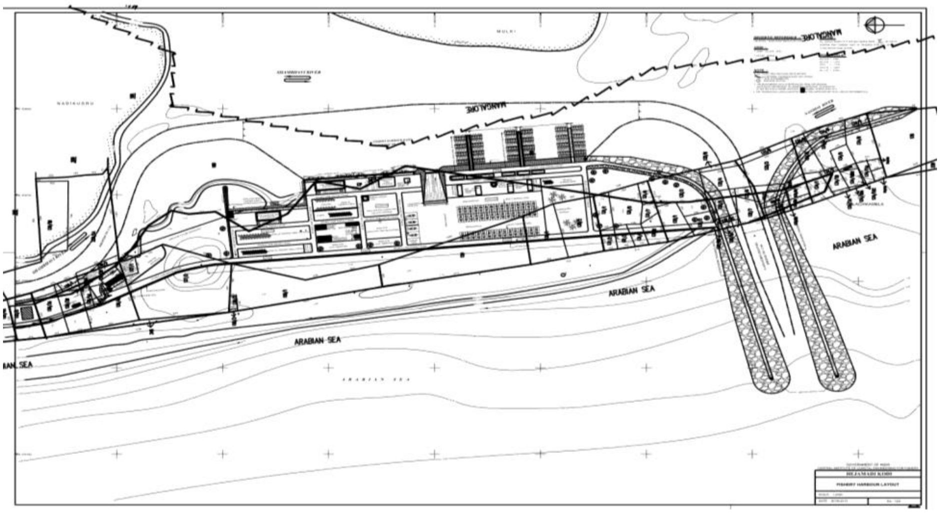


Figure 5.16: Proposed layout of Hejamadi Kodi Fishery Harbour

LITPACK model was used to estimate annual littoral drift rates and its distribution on the profile. Normal to the shoreline i.e. 257^0 N. Figure 5.17 shows the cross shore profile near the Hejamadi fishing harbour, used for drift computation.

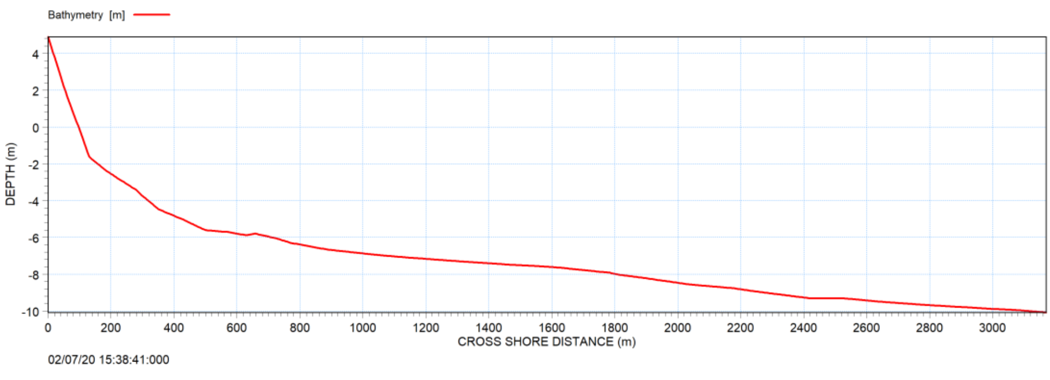


Figure 5.17 Cross shore Profile

The profile covers a distance of 3.2 km extending up to about -10m depth contour (with respect to chart datum) as shown in Figure 5.17 .The profiles were discredited with grid size of 5 m. Grain size distribution, fall velocity and roughness coefficient over the profile were required for computation of littoral drift. At the site, grain size is observed to be of the order of 0.25 mm. The model was calibrated using bed roughness to get the annual net transport of the order of 0.047 x 10^6 m^3/year. The model was run for annual near-shore wave climate given in Tables 5. Annual northward and southward drift distribution across the cross shore profile is shown in Figure 5.18 and in Table 5.1. The northward drift is plotted positive while southward drift is plotted as negative.

Table 5.1: Littoral Transport Rate (m^3)

Northward	Southward	Net *	Gross
93100	140700	-47600	233800

Note*: '-ve' Southward '+ve' Northward for the Net Drift

Net transport in a year is of the order of 0.047million cum and is towards south and gross transport is of the order of 0.23 million cum.

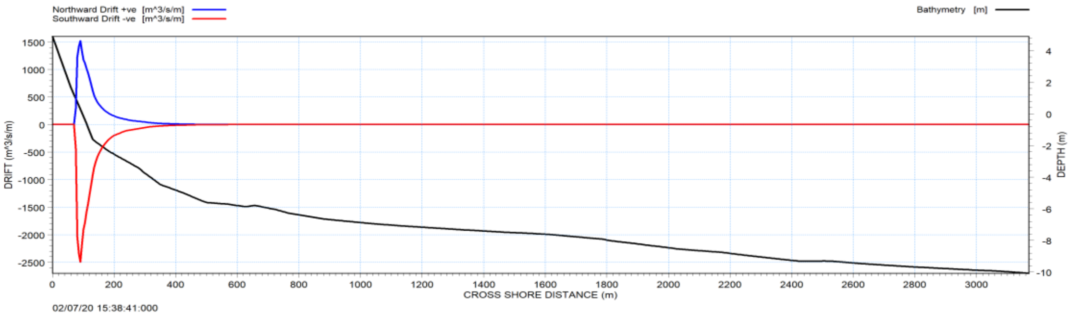


Figure 5.18: Cross shore Distribution of Northward and Southward Littoral Drift during entire year

According to cross shore distribution plot (Figure 5.18) the maximum transport occurs at about 40 m from the shoreline (i.e. High Water Line) at 0.29 m depth contour. The sediment transport occurs between 1.2 m and (-) 5.8 m depth contours

Shoreline Evolution

In order to assess the impact of the shore connected breakwaters on the coastline, LITLINE module of LITPACK software was used. It may be noted that LITPACK is a 1-D model, in which the shore connected breakwaters are assumed as obstructions which are perpendicular to shoreline. Therefore, projections of the breakwaters were considered in the simulation. The model was run for 1, 2, 4, 6, 8 and 10 years with proposed North and South breakwater as shown in Figure 5.19.

The length of the shoreline considered for the studies is 6 km, extending about 3 km towards north of the breakwater and about 3 km towards south of the breakwater. It is divided into 1200 grid points of grid size 5 m. Two shore connected breakwaters of lengths 395 m (Southern) and 360 m (Northern) were included perpendicular to the shoreline the length of the breakwaters are measured from the MHHW Line the separation distance between two breakwater is considered as 120m.

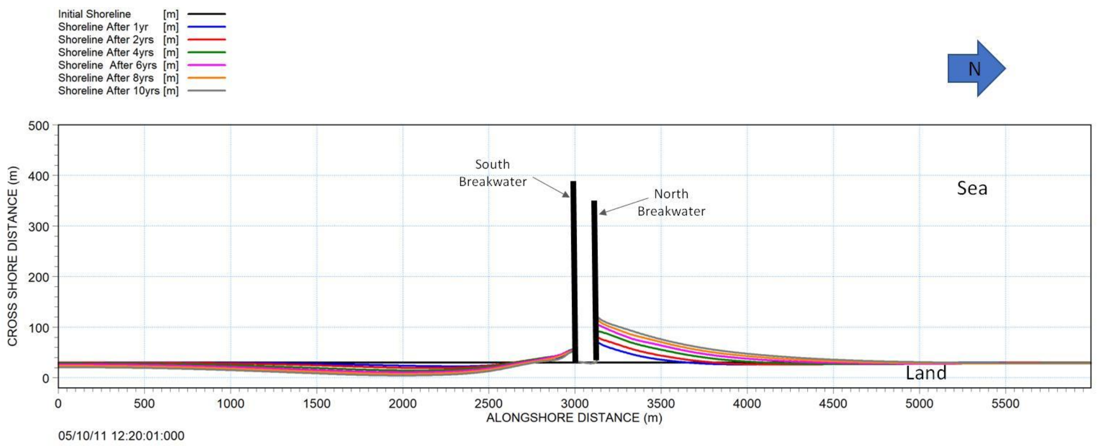


Figure 5.19: Shoreline Changes Plot with proposed North and South Breakwater

The LITLINE model was run for 1, 2, 4, 6, 8 and 10 years with the proposed breakwater.

It is estimated from the model that shoreline will advance by 41 m, 50 m, 62 m, 74 m, 85 m and 91 m North of Northern breakwater in 1, 2, 4, 6, 8 and 10 years respectively. The shoreline erosion on south of southern breakwater was also observed from the model results.

It is estimated that shoreline would erode by 6 m, 11 m, 16 m, 19 m, 23 m and 26 m on the south of Southern breakwater in 1, 2, 4, 6, 8 and 10 years respectively.

5.3.5 Storm Surge and Wave Hindcasting Studies

Waves and storm surges are complex oceanographic phenomena that can have significant impacts on coastal communities and coastal hydraulic structures. The design and operational efficiency of any marine structure depends mainly on environmental parameters such as waves, wind and current and surge. Wave is the most influential parameter in the design of any marine structure. The underestimation of design wave condition will lead to failure of structure, while overestimation results in uneconomical design. The operational condition of marine structure is governed by normal wave condition, while the stability of the structure is governed by storm wave condition. The waves in the ocean are formed due to blowing of wind over the surface of sea. The wind may be locally generated over a smaller area or due to formation of storm over the larger area in deep sea. The waves generated in the sea due to wind are random in nature i.e. wave height and period of every individual wave is different. By meticulously reconstructing historical wave conditions and predicting potential storm surge scenarios, researchers and policymakers can gain valuable insights into coastal vulnerability. This knowledge, in turn, becomes instrumental in crafting robust strategies for mitigating the impact of natural disasters, informing urban planning, and safeguarding coastal communities against the escalating challenges posed by climate change. In this context, the exploration of wave hindcasting and storm surge studies not only contributes to scientific understanding but also plays a pivotal role in fostering a proactive approach towards coastal hazard management.

The Indian coasts are characterized by monsoon wave climate and tropical storms. The monsoon wave climate is less severe in comparison to storm waves. As such, in the extreme value analysis for determining the design wave conditions for certain return periods, it is necessary to consider the storm wave climate. Several storms occur on the East and West coasts of India every year, particularly during the periods from April to June and October to January, due to typical meteorological conditions in the oceans.

On the West coast, the frequency of occurrence of cyclones is low (about 2 per year); whereas on the East coast, the cyclones are more frequent (about 5 per year).

Ideally, the design wave height for any marine structure is the extreme wave height that a structure should withstand without significant damage and its determination is site specific and depends on extreme wave climate at the site, life of the structure, risk, cost etc. Ideally, the determination of design wave height should be based on the statistical analysis of long-term extreme wave height measurements which occur during the storm conditions, but these observed data are seldom available. Hence, the extreme value analysis is carried out using wave hindcasting and storm wave data for estimating the design wave and surge conditions using empirical and Numerical Method.

(a) Wave Hindcasting:

Wave hindcasting is a method of prediction of surface waves on water body (Ocean) for a past wind event (storm). Wind hindcasting requires following parameters

- Wind speed
- Duration of wind (Storm)
- Distance over which the wind blows, called 'fetch'
- Distance between point of observation & face of fetch called as ‘decay distance’

Wave hindcasting can be done using empirical formulae, or with the help of Numerical method. Simplified methods for estimating wave conditions from the above parameters have been established by various researchers. A combined empirical-analytical procedure was developed by Sverdrup and Munk, which were revised by Bretschneider, based on empirical data. This wave prediction system is called as the "Sverdrup-Munk-Bretschneider (SMB) Method". Using the SMB method for hindcasting of storm waves, the significant wave height (H_s) and the peak wave period (T_p) could be predicted for a particular site. The data regarding wind speed, wind duration, fetch length and decay distance is obtained from the storm tracks and the synoptic charts.

The wind speed is determined from the pressure gradient and the latitude of the fetch area. The pressure gradient is determined from the isobar spacing shown on the synoptic chart. The details of the SMB method are described in the Shore Protection Manual -1984. Wave hindcasting can be assessed with Numerical methods in which the previous storms can be generated and their impact on wave and be assessed for design wave height for breakwater or any other coastal hydraulic structures.

(b) Storm Surge

Storm surge is the temporary rise in the water level at the coastline during the cyclone. This temporary rise in the water level takes place only when the cyclonic wind blows over the continental shelf and pushes the water against the coastline. Cyclones are not only associated with high winds, but are also associated with torrential rains that lead to flash flooding and abnormally high waves and storm surge. Each of these alone can pose a serious threat to life and property. Their combined effect is capable of causing enormous loss of life and widespread destruction. Severity of the storm i.e. wind speed, pressure gradient as well as water depth, width of continental shelf etc. establishes the magnitude of the surge. The determination of the storm surge is site specific and depends on extreme storm climate in the vicinity of the site. Ideally, determination of extreme storm surge values should be based on the statistical analysis of surge values.

Since the measurements of surges, which occur during the storm conditions, are not available, the extreme value analysis is carried out using past storm data for estimating the design storm surge. Surge hindcasting is usually done to obtain surge data from the major storms over 30 to 50 years or longer. In order to determine the extreme water level at the shore, the predicted maximum storm surge is to be superimposed over the Highest Astronomical Tidal Water Level (HATWL).A storm surge is a complex phenomenon in which current, tide, and waves interact with each other. Even if the wind is the main force of driving the surge, waves and tide are also key factors that affect the momentum and mass transport during the storm surge.

The main parameters, which govern the storm surge, are:

1) Wind speed
2) Duration of wind
3) Distance over which the wind blows, called 'fetch'
4) Isobaric pressure gradient
5) The width of the continental shelf
6) Water depth at the edge of the continental shelf
7) Water depth at the observation site

The storm surge at or near the shoreline is due to two main components viz. (a) inverted barometric pressure effect and (b) onshore wind stress effect.

i) Inverted Barometric Effect:

The inverted barometric effect is the tendency for the water surface to be sucked upwards in regions of low atmospheric pressure. During the storm conditions, the water surface rise is centered at the eye of the storm and depends directly on the central pressure relative to normal sea-level pressure.

The surge due to inverted barometric effect (S_a) is given by (Silvester, 1974):

Sa=0.01(Pn- Po) in meters

Where,P_n = Pressure of the isobar at the boundary of storm, in mb

P_o = Pressure at the central Pressure

The central pressure (Po) is generally not mentioned on the synoptic charts. However, it can be computed using Hydromet-Rankin Vortex Model for the cyclones [Herbich, 1990]. The pressure profile of a cyclone in Hydromet-Rankin Model is given by :

$$\frac{P_r - P_0}{P_n - P_0} = e^{-R/r}$$

Where,

R=Radial distance of maximum cyclostrophic wind from the centre of storm in km

r= Radial distance from centre of storm in km

Pr= Pressure at radial distance ‘r’ in mb

The set of the values of Pr and r can be obtained from the synoptic chart and equation (2) can be solved for Po and R.

ii) Wind Stress Effect:

Generally, the larger component of any storm surge is that due to the wind stress on the water surface. The storm surge at the shoreline of an open ocean (i.e. storm surge over the continental shelf) due to static wind field is given by Silvester (1974) as :

$$S_w = \frac{kU^2L}{g(d_1 - d_2 - S_w)} \ln\left(\frac{d_1}{d_2 + S_w}\right)$$

S_w =Storm surge due to wind stress in meters

K= Wind stress co-efficient

= 0.000003 for open ocean,

= .0000033 for enclosed/semi enclosed water bodies

U = Surface wind speed in m/sec

L= Length or Fetch over which wind is blowing in meters.

(Taken as width of the continental shelf if fetch is larger than the width of the continental shelf)

g= Acceleration due to gravity (9.81 m/sec^2)

d_1= Depth of the water at the edge of the continental shelf in m

d_2= Depth of the water near the coast in meters

MIKE 21 CYCLONE WIND GENERATION TOOL

Storm winds are generated over the study region using parametric storm wind models. The MIKE21-cyclone wind generation tool was used with parametric inputs like position of cyclone's eye, radius of maximum winds etc, obtained from synoptic Chart and IMD daily weather report. Several Cyclone parametric models are included in the tool. The Young and Sobey parametric model was used to generate wind field. Following Yound and sobey (1981) the rotational wind gradient speed V_g at a distance r from the centre of the cyclone is given by

$$V_g(r) = V_{max} \cdot \left(\frac{r}{R_{mw}}\right)^7 \cdot \exp\left(7\left(1 - \frac{r}{R_{mw}}\right)\right) \quad \text{for } r < R_{mw}$$

$$V_g(r) = V_{max} \cdot \exp\left((0.0025R_{mw} + 0.05)\left(1 - \frac{r}{R_{mw}}\right)\right) \quad \text{for } r < R_{mw}$$

Where R_{mw} is the radius to maximum wind V_{max} is the maximum wind speed

Following the shore protection Manual (1984) the pressure p is given as

$$p(r) = p_c + (p_n - p_c) \cdot \exp\left(-\frac{R_{mw}}{r}\right)$$

Where

p_c is the pressure at the storm centre or central pressure

p_n is the ambient surroundings Pressure field or neutral pressure

The data used to this parametric wind model includes following Parameters

1. Longitude of the centre of the cyclone (E positive and W negative)
2. Latitude of the centre of the cyclone (N positive and S negative)
3. Radius to maximum wind speed R_{max} (or $R_{max,1}$, given in km)
4. Maximum wind speed V_{max} (in m/s)
5. Central pressure P_c in hPa
6. Neutral pressure Pn (the pressure outside the area influenced by the cyclone, in hPa)

MIKE Extreme Value Analysis (EVA) tool

Extreme value analysis (EVA) is a statistical tool to estimate the likelihood of the occurrence of extreme values based on a few basic assumptions and observed /measured data. For evaluating the risk of extreme events a parametric frequency analysis approach is adopted in EVA. This implies that an extreme value model is formulated based on fitting a theoretical probability to the observed extreme value series. The main distribution function used in this analysis are Gumbel distribution, Weibull distribution,Log-Normal distribution.

Vital inputs used for these studies are cyclone tracks of various storms (Figure 5.20) and synoptic charts of storms. a typical synoptic chart is shown in the Figure 5.21 below.

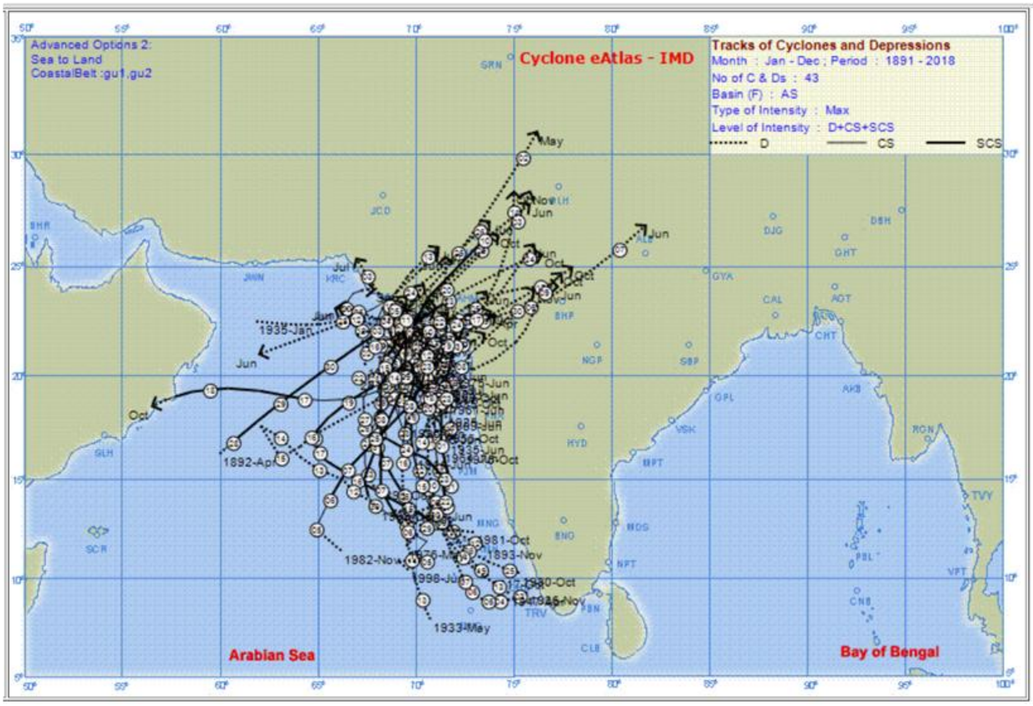


Figure 5.20: Cyclone tracks passed through Maharashtra and Gujarat

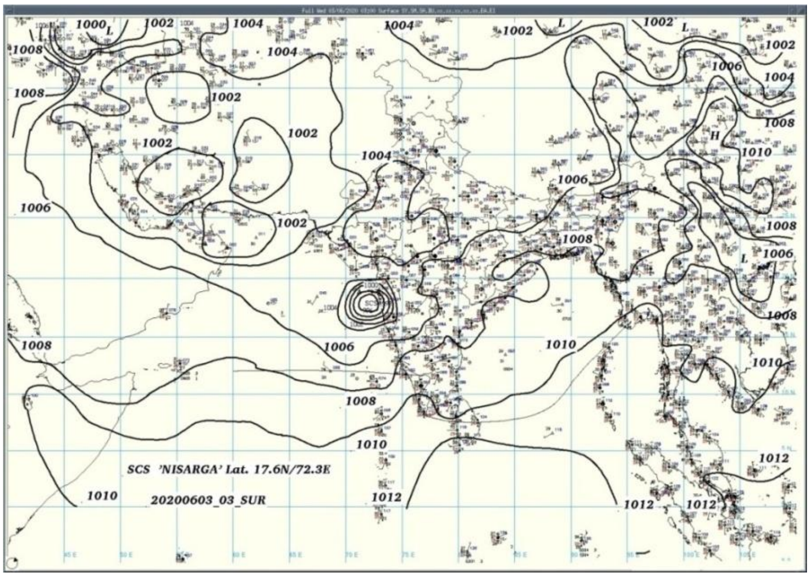


Figure 5.21: Synoptic chart for Cyclone Nisarga

Wind and pressure data generated by a tropical cyclone can often be described by simple parametric models based on few parameters like position of the cyclone's eye, radius of the maximum winds, etc. In order to compute wind and pressure data due to tropical cyclone, MIKE 21 Cyclone Wind Generation tool can be used. Some of necessary parameters were taken from IMD daily weather publications and other parameters were derived by the synoptic charts based on wind or pressure measurements. The simulations were carried out using the two-way coupling of wave and hydrodynamic models (MIKE 21 SW + MIKE 21 HD) to compute the wave characteristics and water levels during the various considered cyclones.

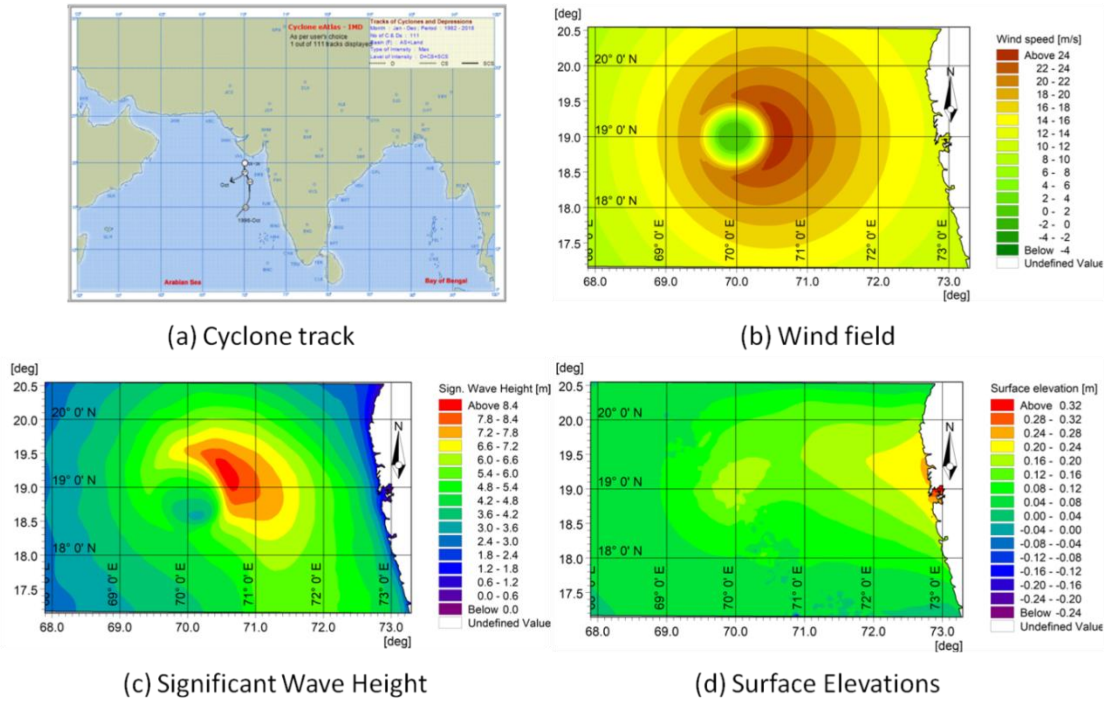


Figure 5.22: Mathematical model simulation results for a typical storm

Wave hindcasting and storm surge studies emerge as indispensable tools in our efforts to comprehend and address the complex dynamics of coastal hazards. Through meticulous analysis of historical wave conditions and predictive modeling of storm surges, these studies empower us with the knowledge needed to enhance disaster preparedness, inform resilient infrastructure development, and mitigate the impact of natural calamities. As our coastal environments face escalating challenges from climate change, the insights gained from these studies become even more crucial. By embracing the findings and incorporating them into adaptive strategies, we can build a more resilient future, better equipped to navigate the uncertainties of our changing coastal landscapes. These studies are cost effective and very much efficient and valid to provide the waves and storm surge levels of various return periods required for the design of breakwaters and determination of safe-grade elevation.

5.3.6 Ship Navigation Studies

Ship navigation studies are essential for the safe and optimized design of port approach channels. The fundamental objective is to ensure safe vessel manoeuvring and efficient port operations. The design process begins with the port authority or terminal operator defining the desired cargo throughput, which determines the type and size of design vessels. The designer then translates these requirements into a channel layout through iterative analyses, balancing safety, operational efficiency, and economic feasibility.

Once safety criteria are established, alternative layouts are assessed to identify the most suitable option while ensuring compliance with defined safety standards. The channel design must also consider future variations in ship size and cargo type. For instance, channel depth is determined based on tides, waves, and dredging economics, but the decision should affect only the channel's operational availability, not navigational safety.

The design process represents a trade-off between investment, port efficiency, and availability, but not between investment and safety, as minimum safety standards must always be maintained.

Design Tools and Methodology

Approach channel design tools are broadly classified as:

- **Analytical models** – used to analyze wind, waves, currents, and probabilistic aspects of marine traffic.
- **Numerical models** – computer-based simulations of hydrodynamics, ship manoeuvring, and traffic flow.
- **Physical models** – laboratory-scale models used where mathematical understanding or validation is limited, such as wave propagation and seabed interactions.

Channels are generally categorized as one-way or two-way. Shorter channels with limited traffic may adopt a one-way configuration, while longer or busier channels often require two separate lanes or designated passing areas.

Key Design Considerations

Determination of channel configuration and dimensions depends on:

- Vessel size, manoeuvrability, and tug assistance requirements.
- Availability and accuracy of navigational aids.
- Physical and geometrical characteristics, including siltation, erosion, and sediment transport.
- Environmental and safety constraints.

Since the design is centered on the vessel's manoeuvring behavior under the influence of wind, waves, and currents, a clear understanding of hydrodynamic responses is vital. Sediment transport and its impact on siltation and coastal processes must also be evaluated to minimize maintenance dredging.

Determining Channel Dimensions

Methods used for defining channel width and horizontal layout include:

- Empirical methods
- Fast-time navigation simulations
- Real-time navigation simulations
- Physical model investigations

The design process typically involves two stages:

1. **Conceptual Design** – Preliminary estimation of channel width, depth, and alignment based on empirical relations and available data. This stage emphasizes rapid evaluation of alternatives and integration of navigational aids. Simulator-based risk analyses may be conducted to test configurations. The output is a reliable, conservative design concept that balances safety, functionality, and cost, serving as the basis for further refinement.
2. **Detailed Design** – A comprehensive phase that validates and optimizes the concept design through advanced numerical and physical modeling. This stage refines dimensions, verifies safety and manoeuvrability, and defines operational rules related to weather, vessel size, tug assistance, and piloting. Real-time simulations and risk analyses ensure the final layout meets both safety and operational standards.

ship navigation studies integrate safety, hydrodynamics, and operational efficiency into a systematic design process. The ultimate goal is to develop a channel configuration that ensures safe, efficient, and sustainable navigation while maintaining compliance with international standards and accommodating future port developments.

In CWPRS the Navigational studies carried out generally with the desk studies based on PIANC and other international guidelines and recommendations besides a fast time mathematical model NAVIGA developed at CWPRS used to carry out the simulation studies of ship maneuvering along the approach channel to the Port. The model is based on Abkowitz (1964) formulation and upgraded based on the latest literature on ship hydrodynamics. The mathematical model computes the track of the center of gravity, heading angle and the required rudder action in small time steps. The model accounts for the influence of winds, waves and currents. The environmental loadings tend to deviate the ship from the desired path. In order to maintain the course under the influence of winds, waves and currents and also in channels having bends, proper steering actions are necessary. In this mathematical model, the captain’s actions are reproduced by a mathematical auto pilot which computes the desired rudder action for effective course and track keeping.

The Governing equations of motion are as follows,

$$m(\dot{u} - v\dot{r} - x_G \dot{r}^2) = X_{HULL} + X_{RUDDER} + X_{WIND} + X_{WAVE} (surge)$$
$$m(\dot{v} + ur + x_G \dot{r}) = Y_{HULL} + Y_{RUDDER} + Y_{WIND} + Y_{WAVE} (sway)$$
$$I_Z \dot{r} + m x_G (\dot{v} + u\dot{r}) = N_{HULL} + N_{RUDDER} + N_{WIND} + N_{WAVE} (yaw)$$

where m is the virtual ship mass, I_Z is the moment of inertia of the ship about z-axis through CG, u is the forward ship speed, v is the drift velocity, r is the yaw rate and x_G is the x-co-ordinate of the ship CG. The dots represent the derivatives of the corresponding variables. X and Y denote the components of the respective forces in x and y directions. N denotes the moment of the respective forces about z-axis.

The left hand sides of the equation are standard Newtonian terms containing mass, moment of inertia, ship velocity and acceleration terms. The right hand sides contain the hydrodynamic interaction forces between ship hull and surrounding water, disturbing forces from waves and wind and controlling forces from rudder and propeller. The effect of current is included in the velocity terms. The typical output of model simulation shown in Figure 5.23.

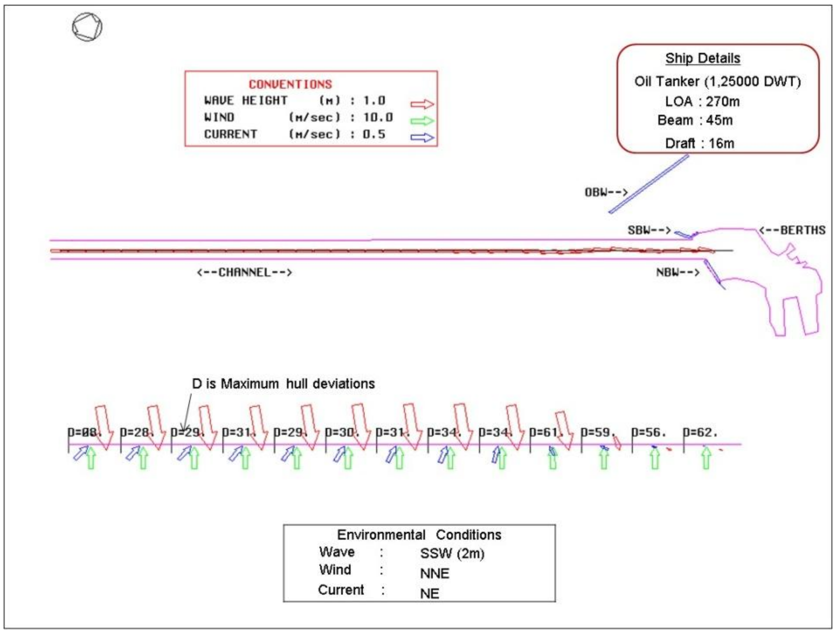


Figure 5.23 Trajectory Of Oil Tanker, Showing Maximum Hull Deviation For Waves From SSW Direction for Paradip Port, Odisha

This mathematical model can be utilized to:

- Optimize the width of the approach channel
- Determine the most suitable alignment of the navigation channel
- Assess the navigability of the channel under varying conditions
- Identify the limiting environmental or climatic conditions for safe vessel maneuvering
- Define the safe maneuvering speed for different vessel types and operating scenarios

5.3.7 Mooring Studies

Mooring analysis Studies at CWPRS generally carried out using desk and numerical model. Desk studies are generally carried out to access the berthing energy and suitable fender the final mooring arrangement based on the dynamic numerical simulations This dynamic simulation software evaluates the motions and loads of a moored vessel under combined environmental conditions such as wind, waves, and currents.

The model uses vessel hull geometry and gyrostatic data to determine frequency response characteristics and compute vessel motions in relation to mooring lines and fenders.

A floating vessel experiences motions in six degrees of freedom three translational (surge, sway, heave) and three rotational (roll, pitch, yaw) as shown in Figure 5.24.

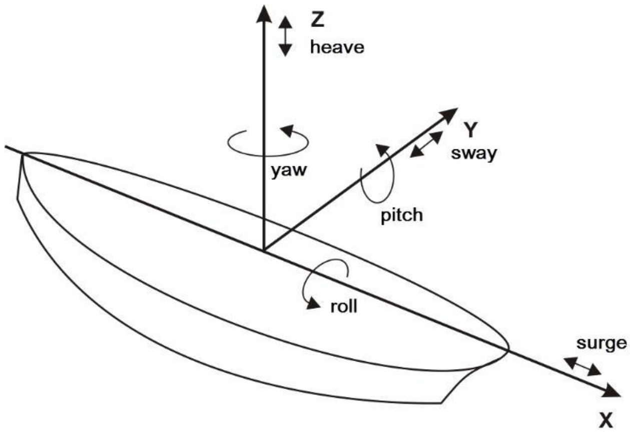


Figure 5.24: Ship Motions in Six Degrees of Freedom

The numerical simulation is performed in three main steps:

1. **Frequency Response Computation:**
   The vessel's frequency response characteristics are obtained using the diffraction/radiation panel program (FRC) based on hull geometry, hydrostatics, and inertia data.
2. **Equilibrium Displacement:**
   The model determines an initial static position that results in a uniform pre-tension distribution among all mooring lines.
3. **Time-Domain Simulation:**
   Dynamic simulations are run for different combinations of wind, wave, and current conditions to compute vessel motions, mooring line tensions, and fender deflections.

.

The MIKE 21 Mooring Analysis module was used to simulate the motions of the design vessel and evaluate:

- Maximum displacements in surge, sway, heave, roll, pitch, and yaw
- Mooring line tensions under dynamic loading
- Fender deflections at the berth

The model was initially run in convergence mode to establish the equilibrium vessel position under constant or low-frequency loads, followed by full dynamic simulations for the prevailing site conditions. Figure 5.25 illustrates the mooring line configuration used in the study.

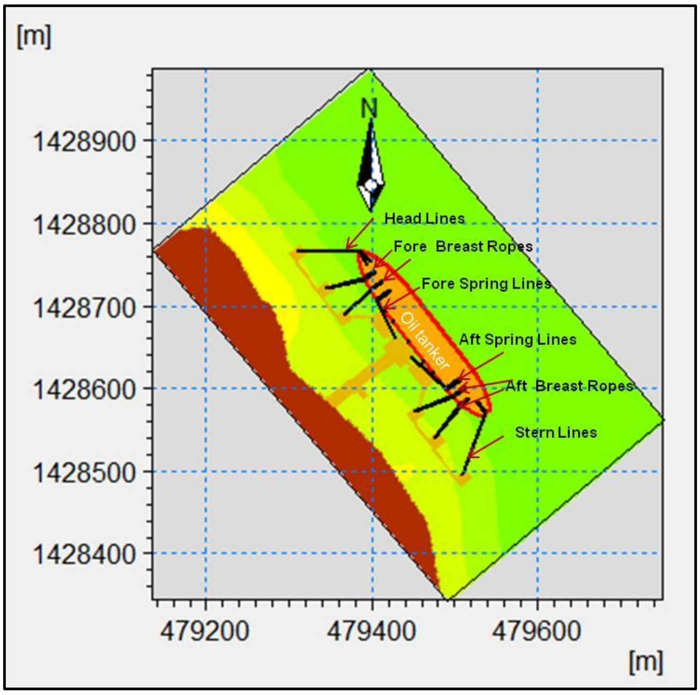


Figure 5.25: Mooring Line Description and Arrangement

MIKE 21 MA is primarily used to assess the safety and efficiency of moored vessels and their associated infrastructure. Its main applications include:

- **Port and Harbour Design:** It helps engineers evaluate different port layouts and breakwater designs to ensure that wave conditions inside the harbour basin are suitable for safe mooring.
- **Mooring System Design:** The model is used to design and optimize mooring configurations, including the number, type, and arrangement of mooring lines and fenders, for specific vessels and berths. This helps prevent line failure and vessel damage.
- **Vessel Response Analysis:** It simulates the motions (surge, sway, heave, roll, pitch, and yaw) of a moored vessel under various environmental loads, such as waves, currents, and wind. This is crucial for ensuring that vessel motions remain within safe limits for cargo operations.
- **Evaluation of Extreme Conditions:** The model can be used to test mooring arrangements under extreme weather events, like storms, to determine if the system can withstand the forces and ensure the safety of the vessel and the port infrastructure.
- **Passing Vessel Effects:** It can simulate the complex hydrodynamic forces created by a passing vessel (drawdown waves) and their impact on a moored ship, helping to determine safe passing speeds and distances.
- **Operational Planning:** Ports can use the model's results to develop operational guidelines, such as limiting the size of vessels that can berth during specific weather conditions or for optimizing cargo loading/unloading schedules.

5.3.8 Integrated Coupled Model Studies for Beach Fill Design

In order to avoid the delicate coast-line conditions at Visakhapatnam, in the context of non-availability of sufficient sediments for regular beach re-nourishment and impinging severe cyclones. It is opined that additional sand buffers are required to be planned with appropriate beach fill and feeder beach concept so as to suit the prevailing conditions. In view of this, in order to evolve a suitable beach fill shape, an integrated coupled numerical model study is carried out and the results are analysed to identify the shape of the beach fill and feeder beach locations as well.

Two-dimensional Integrated mathematical model is set up using the MIKE21 software by developing Flexible Mesh (FM) Finite Volume based model. Hydrodynamic (HD) and Spectral Wave (SW) modules are coupled along with sediment transport (ST) module to understand the effect of various seasons on the northern coastline of the port area.

The main features of the Coupled Model FM are as follows;

- Dynamic coupling of flow and wave calculations
- Fully feedback of bed level changes on flow and wave calculations
- Easy switch between 2D and 3D calculations (hydrodynamic module and process modules)
- Optimal degree of flexibility in describing bathymetry and ambient flow and wave conditions using depth-adaptive and boundary-fitted unstructured mesh coupled model can be used for investigating the morphological evolution of the near-shore bathymetry due to the impact of engineering works (coastal structures, dredging works etc.). The engineering works may include breakwaters, groins, shore-face nourishment, harbours etc.

It is most suitable for medium-term morphological investigations over a limited coastal area. The typical dimensions are about 10km in the alongshore direction and 2km in the offshore direction. The computational effort can become quite large for long-term simulations, or for larger areas.

The model domain is taken big enough for appropriate simulation of hydrodynamics by suitably imposing the tidal boundaries including long coastline and sea portion north and south of the Outer Harbour(Figure 5.26). The extant of the model on north and south side of the port area is about 6 Km. East side boundary is situated beyond 40m depth at a distance of about 4.5 Km from the coastline. Data available at the research station regarding bathymetry, stream discharges, currents, wave data etc. are utilised to set up and calibrate the model to the desired degree of accuracy and the results obtained from the model are processed to derive the inferences pertaining to the northern coastline. Through the coupled model studies, a suitable beach- fill (Figure 5.27) is designed along with the identification of 'feeder beach locations' (Figure 5.28) for disposal of annual beach nourishment to stabilise further down-drift coastline.

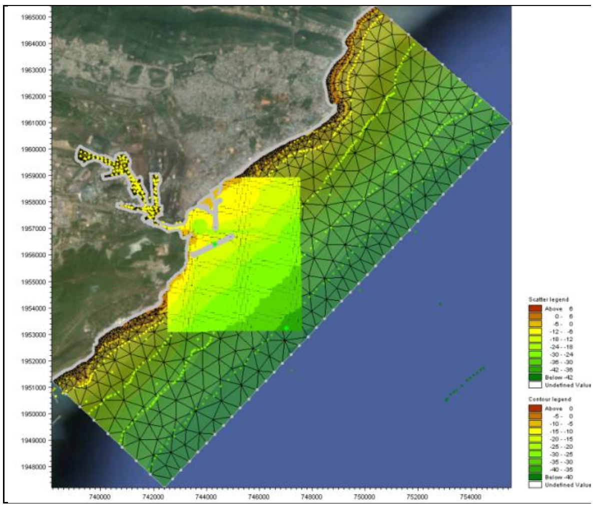


Figure 5.26: Coupled model for Beach fill study at Visakhapatnam

Figure 5.27: Beach fill Design using Coupled model

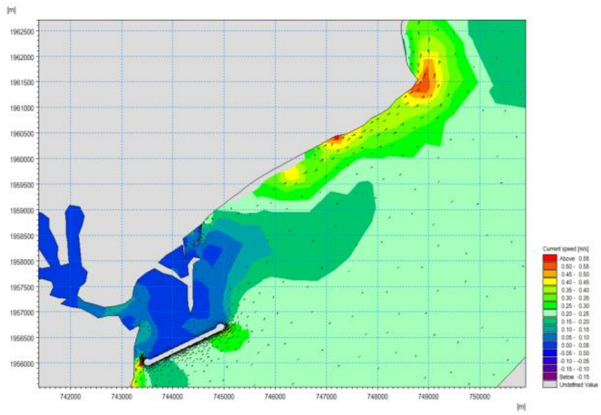


Figure 5.28: Identification of feeder beach locations using coupled model

5.4 Desk Studies

Besides the Physical /Mathematical model studies and field studies, desk studies are also carried out at CWPRS. Sometimes, Desk studies form the foundation of any port or harbour development project. They involve the collection, review, and interpretation of all existing data and information related to the proposed site before conducting any field investigations or design work. Reviewing existing port facilities, navigation channels, and utilities helps determine the extent of upgrading or integration needed with new development works. By compiling and analyzing available reports, satellite imagery, hydrographic charts, and previous studies, desk studies help identify missing information that needs to be collected through field surveys and investigations. Early review of historical data, environmental records, and navigation incidents assists in identifying potential risks such as erosion, siltation, flooding, or operational hazards, enabling planners to propose preventive measures. Information gathered during the desk study stage supports feasibility assessments, site selection, and conceptual layout planning for the port or harbour.
The desk studies carried out for Navigational risk studies for development plays a significant role towards the safety of vessel and Port. Through detailed analysis of prototype data, coastal processes can be analysed pre and post construction stages.

5.4.1 Navigational Risk Analysis

This study includes the risk analysis associated with tug failure during vessel assistance, engine failure conditions, and other environmental abnormalities that may affect vessel operations. The study also encompasses hazard identification and risk assessment related to potential incidents such as ship parting, collision, and similar operational hazards.

Methodology of Risk Analysis Study

Risk is defined as the frequency of occurrence of a negative event (such as an accident, incident, or damage) multiplied by the severity of its consequences. According to IMO guidelines, a *hazard* is "something with the potential to cause harm, loss, or injury," the realization of which may result in an accident. When the likelihood of a hazard's occurrence is combined with the estimated or known consequence of its outcome, the result is termed *risk*. Hence, risk is a measure of both the frequency and consequence associated with a particular hazard.

Risk analysis is a logical and systematic approach aimed at minimizing losses while maximizing safety, reliability, serviceability, and the overall economic and social benefits of a project. It seeks to identify potential hazardous events, prevent their occurrence, and mitigate the consequences should they occur. This process involves identifying, analyzing, assessing, monitoring, and communicating the risks associated with any activity, function, or process of the project. In the context of channel and harbour projects, risk assessment specifically focuses on incidents involving vessels and their cargo.

Risk analysis forms a critical component of the overall risk management process. It systematically uses all available data to estimate the frequency with which different incidents may occur and to assess the magnitude of their potential consequences. The calculated risk expressed as the product of frequency and consequence is then compared against defined acceptance or rejection criteria. Based on this comparison, decisions are made regarding the acceptability of the risk and whether mitigation measures are required to reduce it to an acceptable level.

Risk analysis methodologies may be qualitative, quantitative, or a combination of both, depending on the nature and stage of the project. Quantitative analyses are generally more complex and resource-intensive. Therefore, a simplified qualitative assessment is often performed initially to gain an overall understanding of the risk profile. If warranted, a more detailed quantitative analysis can then be undertaken for critical or high-risk scenarios.

The Matrix Method is one of the commonly used qualitative tools, allowing identification of the most unfavourable cases and their treatment according to predefined decision-making rules. However, this method can lead to fragmentation into individual cases each acceptable in isolation, yet potentially unacceptable when considered collectively. To mitigate this limitation, the analysis should avoid excessive subdivision into minor scenarios. A combined assessment approach ensures that the overall level of risk remains within acceptable criteria.
The most effective risk assessment approach typically integrates both qualitative and quantitative methods. This combined strategy allows the identification of specific high-risk events contributing most to the total risk, while maintaining a holistic perspective on overall project safety.
A Simplified Qualitative Matrix (SQM) Method has also been developed for use during the preliminary (concept design) stages of a project. This approach helps to quickly eliminate scenarios that pose very low levels of risk or those where the required safety levels are not critical during detailed design.

The risk assessment process involves the following key stages:

- Collection of Relevant Information and Data
- Hazard Identification
- Frequency Estimation
- Consequence Estimation
- Risk Evaluation

Risk Estimation

The risk analysis is based on the consequences of the outcomes of Hazard identification, frequency analysis and consequence assessment. The risk estimation is based on two aspects considered in the assessment Matrix are frequency of occurrence and severity of consequences of the risk events.

Risk = Consequences x Frequency

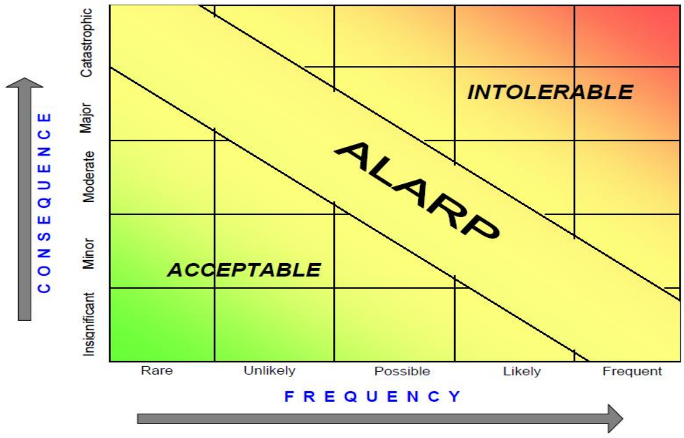


Figure 5.29: Conceptual diagram for understanding the risk estimation

Finally, the SQM Risk assessment is calculated and the following assessments are assigned for each event:

- Unacceptable/ Intolerable (NA) = An investigation of corrective measures which will reduce the risk and classify this risk event as acceptable is required.
- Correctible (C) = An investigation of corrective measures to reduce the risk 'as low as reasonably possible' (ALARP) is required.
- Acceptable (A) = No need to develop corrective measures

Risk can be defined as the product of the probability of an event is occurring and the consequences following from it. Thus an event that occurs infrequently and has a low level of consequence constitutes a lower risk than one which occurs more frequently and has a higher consequence. The analysis for each hazard requires the establishment of probability of occurrence, and the consequences reasonably expected to be associated with that level of probability

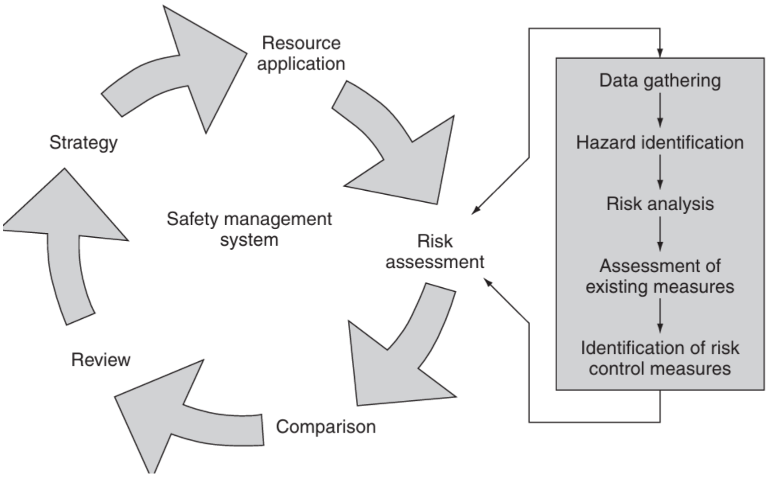


Figure 5.30: Relationship between the SMS and risk assessment

Once the risk assessment is completed and appropriate control measures are identified, the Safety Management System (SMS) can be established or updated accordingly. These risk control measures become an integral part of the SMS. Since the SMS framework includes mechanisms for performance measurement, auditing, and periodic review, the implemented control measures are continuously monitored, verified, and improved. The frequency of these reviews may be predetermined or adjusted based on the level of risk identified.

5.4.2 Beach Profile Analysis

The analysis of the data pertaining to dry beach, inter-tidal beach and deep contour bathymetry would identify the surf zone beach details in response to various conditions and thereby to decide better strategy for beach nourishment. The profiles of the immediate northern stretch i.e. CS 10 to CS 16 (Figure 5.31) that are being surveyed regularly every month since the commissioning of outer harbour have been used for detailed analysis. The typical profiles as surveyed by Marine Department of Visakhapatnam Port are shown in Figure 5.32. The long-term analysis observing the advancement and recessing trends of coastline along with volumetric approach helped in understanding the behavior of the beach under the influence of artificial sand nourishment. The offshore distances of HWL (+1.5m) and LWL (0 m) from a reference line are extracted for all cross sections from the survey profiles of every month. The beach indices (position of HWL and position of LWL) along with inter-tidal slope (between HW and LW) are extracted from the prototype data covering different periods and the efficacy of on-shore disposal / shore-face disposal are assessed.

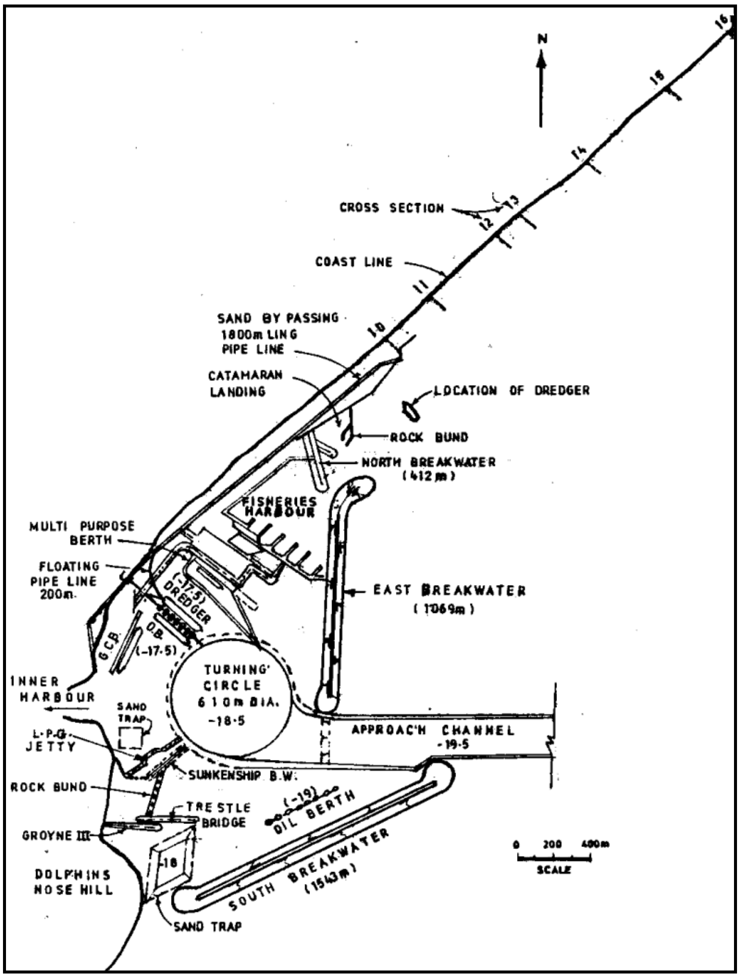


Fig 5.31 Outer Harbour Layout showing Sand By-Passing Pipe-Line for Beach Nourishment & Locations of Immediate North Profiles (CS10 to CS16)

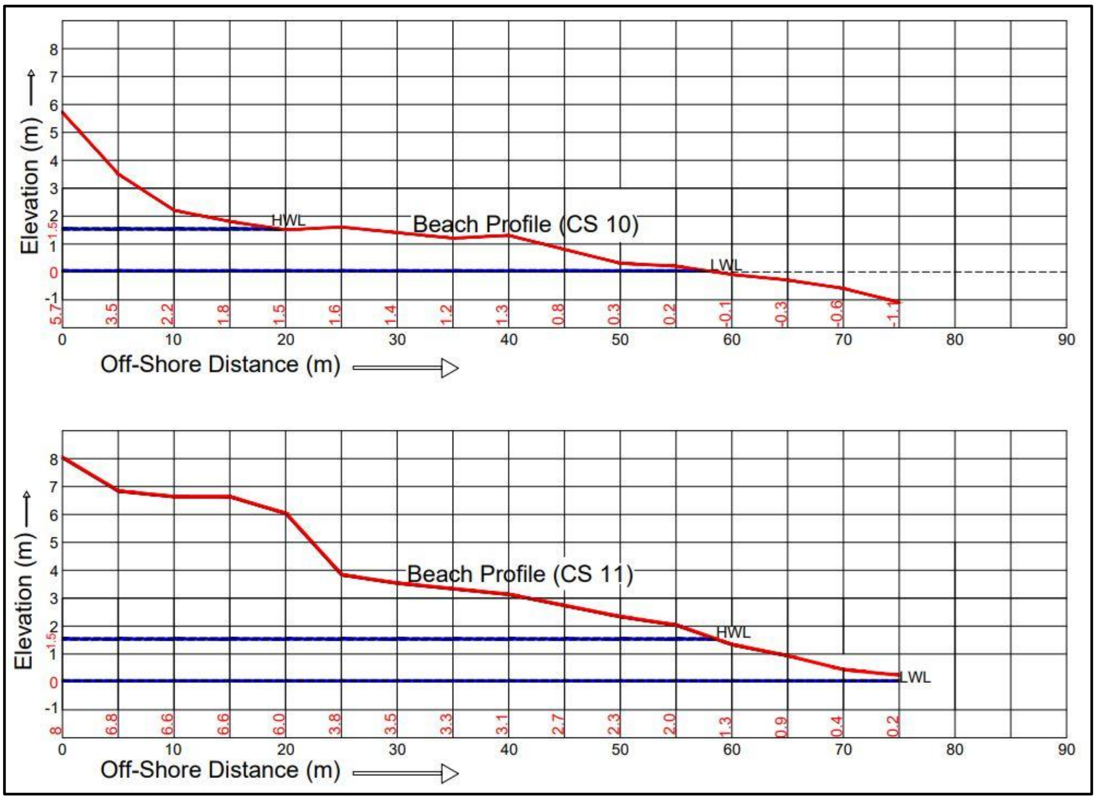


Figure 5.32 Typical Beach profiles (CS-10: KGH Down, CS-11: Jaipur Palace) surveyed at Visakhapatnam Coast

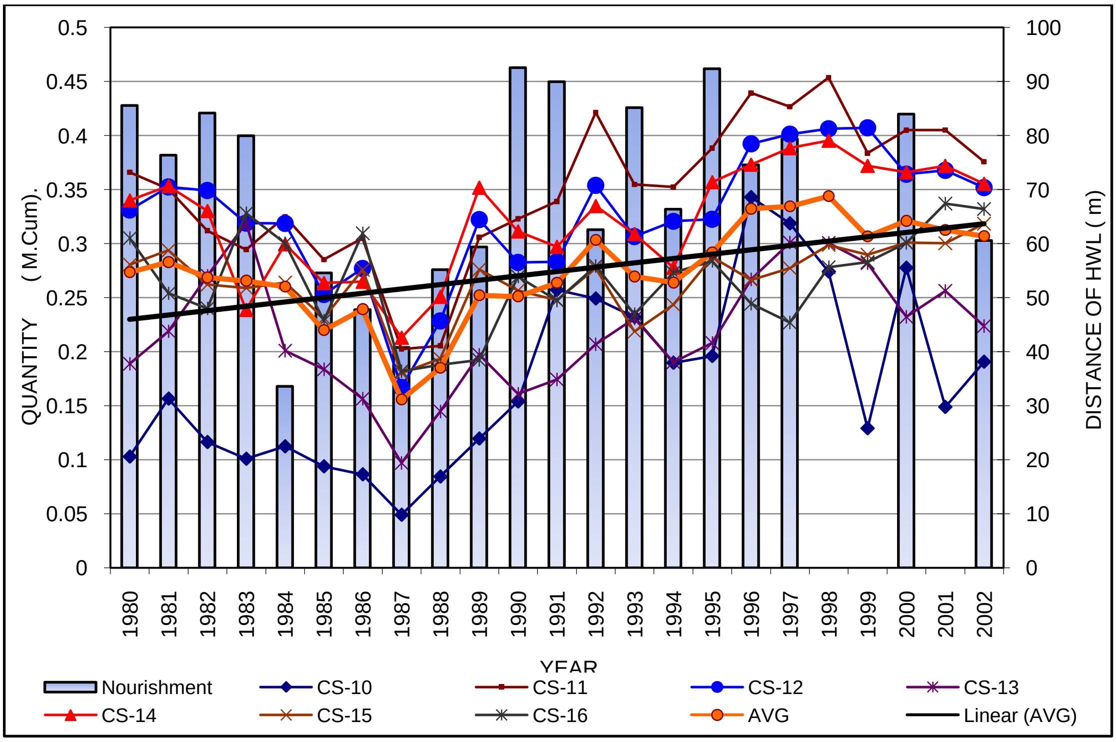


Figure 5.33 Annual Nourishment versus Position of HWL at various cross sections during On-shore disposal period (1980-2002)

Chapter VI

DESIGN OF BREAKWATER

In cases where there are two or more potential sites for a port on an open coast, the breakwater requirements may have considerable influence on site selection because of relatively high cost of constructing breakwater.

In order to minimize breakwater costs, the following factors should be considered -

1. Total length of breakwaters to be as small as possible
2. Depth along breakwaters to be as small as possible
3. Availability of rocky material
4. Suitable foundation condition to avoid excessive settlements etc.
5. Production and transport of caissons

The locations and alignments of the breakwaters are determined by -

- Size of port area to be protected
- Degree of shelter required at berths
- Ship manoeuver requirement in basins
- Influence of breakwaters on currents
- Influence of breakwaters on harbour resonance
- (Long period waves and tsunamis)
- Influence of breakwaters on sediment transport, as well as
- on accumulation and erosion

6.1 Types of Breakwaters

There are three main types of breakwaters, characterized by their seaward faces:

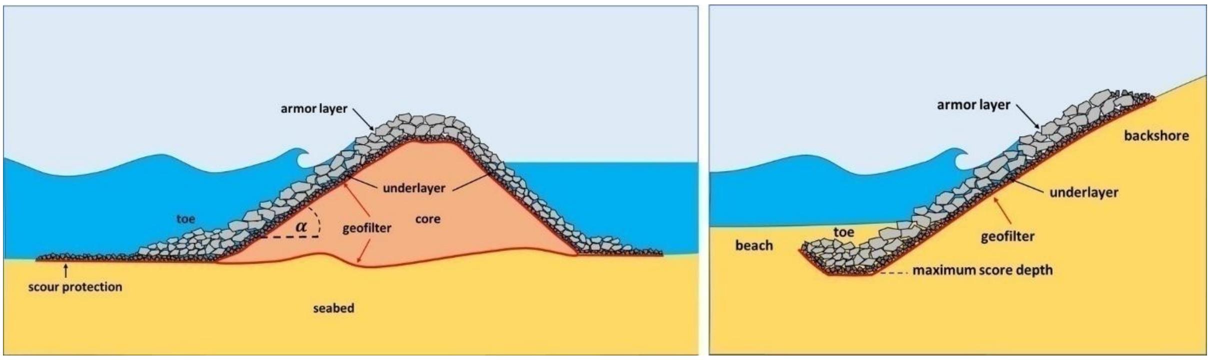


Figure 6.1 Type S called sloping breakwater because its seaward face has a slope of 1 on 1 or flatter

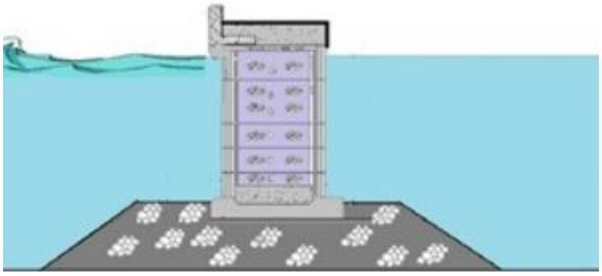


Figure 6.2 Type V called vertical breakwater because it has a vertical or near vertical seaward face, generally called caisson breakwater

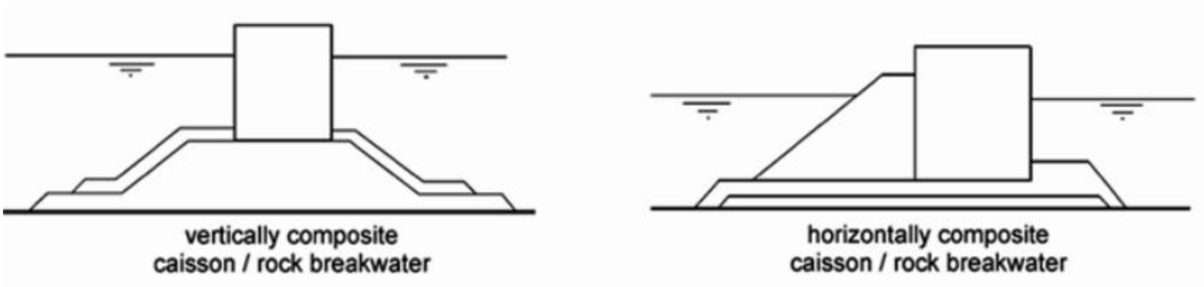


Figure 6.3 Type C called composite breakwater consisting of a vertical breakwaters, placed on a foundation with slopes on both sides

The above terminology is independent of harbour side, which may be vertical (quay wall), sloping or horizontal (reclaimed area).

The large majority of sloping breakwaters consists of rock and concrete blocks and hence the widely used name rubble mound breakwaters.

Choice of Type

To choose the right type of breakwater at an early stage of the design process required great experience. The choice between type S, V and C depends mainly on:

(a) Availability of rock
(b) Water depth
(c) Wave height Hs, the typical significant height of the design storm

If good rock is available at reasonable cost, the choice is likely to be roughly as follows:

Hs < 3m - Type S without superstructure

Hs > 3 m and D > 20 m - Type S with superstructure

3 m < Hs < 6 m and D > 20 m - Type S with superstructure

Hs > 6 m and D > 20 m - Type S with superstructure or Type C

If good rock is not available, the choice is likely to be roughly as follows:

D < 15 m - Type V

D >15 m - Type C

provided that foundation is reasonably good.

Several other factors than the availability of rock may have an influence on the choice. Bad weather all year or rapid changes from acceptable to poor wave conditions almost invariably will lead to a caisson solution (Type V) because it is possible to progress considerably during a good weather period by placing one or more long caissons.

An offshore breakwater with berths for dry bulk on the leeside should be built of caissons because it would be too expensive to transport all the material for a rubble mound breakwater (Type S) by barges.

The relative cost of equipment and labour may sometime be decisive. Rubble mound breakwaters require a good deal of heavy construction equipment and relatively little labour, whereas caisson breakwaters require much more labour and less equipments. Therefore, if labour is relatively cheap but sufficiently skilled, there will be a tendency to prefer caissons and vice versa. Short breakwaters should be of Type S, because caisson breakwaters have high initial cost.

With regard to climatic, oceanographic and hydrographic conditions, the design of breakwater cross section is in particular a function of:

- Wave heights
- Wave directions; and
- Water levels

Each of these factors has its statistical distribution. Therefore, the results of model tests have to be considered with a risk analysis, which combines these three distributions.

6.2 Design of Rubble mound Breakwaters

Main elements

The simplest form of a rubble mound breakwater is one consisting entirely of loose materials (quarry rock / or concrete blocks) without concrete superstructure (Fig.6.4). Design of such involves determination of the following -

- Crest elevation
- Side slopes
- Sizes and layer thickness for crest and lee side armour units
- Top level for main armour layer
- Bottom level for main armour layer
- Type and size of main armour units
- Dimensions and rock size for toe berm
- Top level for filter layer
- Filter stone sizes; and
- Core material requirements

The values of the above parameters are determined by one or more of the following criteria -

- o Functional requirement
- o Hydraulic stability
- o Availability of construction material
- o Construction ability
- o Geotechnical stability

These criteria are of course interlinked and the final choice of solution is always a matter of cost optimization among various alternatives.

Rubble mound Hydraulics

Incident waves may be reflected and / or overtop the breakwater and / or transmitted through the breakwater. In breakwater design, both overtopping and transmission have to be limited to acceptable levels to prevent excessive wave disturbance behind the breakwater. Transmission is limited by having enough small stone sizes in the core and thus reducing permeability.

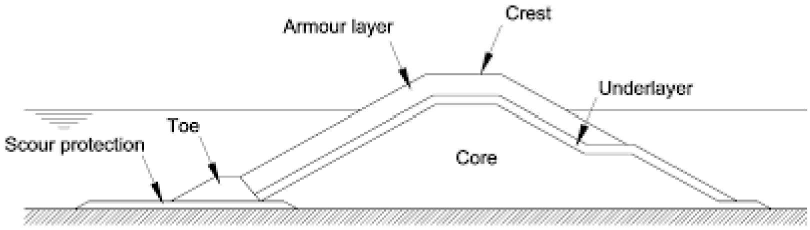


Figure 6.4: Different elements in Cross section of the Breakwater

Waves will generate up-rush over and in the main armour layer as well as in the filter layer below. The up-rush water exerts forces on the superstructure and may overtop the breakwater and exert forces on the crest and the leeside on the armour layer. The down-rush water over and in the main armour layer as well as in the filter layer below governs the stability of armour units for normal front slope of 1 in 1.5 to 1 in 3.0. Only for slope flatter than 1 in 3.5 is up-rush governing. Down- rush is also governing for the berm which supports the main armour layer and for the toe protection. Further water flows in and out through filters and in and of the core in varying directions. This means that a standard filter criterion for unidirectional flow perpendicular to layer surface becomes invalid for breakwater filters.

In general, less stringent filter criteria may be applied to normal breakwater slope. An important exception to this is the case of rubble mound structure used to contain reclamation. In this case, the finer material resting upon coarse breakwater material requires extremely stringent filter criteria and the solution should normally include the use of the filter sheet.

Hydraulic damage to a rubble mound breakwater may occur in various ways. The most common mode of damage occurs when the force generated by the down-rush (or up-rush) on a main armour layer unit exceeds the stabilizing effect of gravity and interlocking between the units which are dislocated from their original positions and rock and slide down the slope, most often all the way to the toe berm or to the sea bottom.

For main armour layer, down-rush is the governing for rubble mound breakwaters with slopes varying from 1 in 1.5 to 1 in 3.0. Only for slopes flatter than approximately 1 in 3.5, up-rush govern the stability.

The submerged weight of the armour unit is proportionate to $g(\rho_s - \rho_w)\, d^3$

where, ρ_s is the specific gravity of the armour unit material. Thus,

1) The dislocating force is proportional to $\rho_w\, d^2 gH$ and
2) The stabilizing force is proportional to $g\,(\rho_s - \rho_w)\, d^3 F(\alpha, \varphi, I)$

where α is the slope angle, φ is the angle of friction of the armour unit and I represents the interlocking effect, which especially for artificial units may be very significant, but hard to determine and describe in mathematical term.

Based on experimental results, Hudson suggested the following formula for armour units

$$W = W_r\, H^3 / K_D\, (S_r - 1)^3 \cot\theta$$

Where W= weight of armour units (kg)
W_r= unit weight of armour block (kg/cum)
H = wave height at the location of proposed structure
S_r = specific gravity of armour units
θ = angle of breakwater slope measured with the horizontal
K_D = coefficient which varies with the type of armour unit (which takes into account roughness, sharpness of edges, quality of interlocking etc.)

Hudson had considered in his experiments wave periods varying from 0.8 to 2.65 sec and the armour layer slope from 1/1.25 to 1/5. All the experiments were conducted for non overtopping and non breaking monochromatic waves. The values for different type of stones may be given as below for slopes 1 in 1.5 and 1 in 2.0

Quarry stones	1.0 - 4.0
Cubes	2.0 - 7.0
Tetrapods	3.0 - 8.0
Dolos	6.0 - 15.0

The lower values correspond to initiation of damage and very long waves (low steepness) while the higher values correspond to high steepness and acceptable damage in the order of 5 percent after exposure to the given wave conditions for duration in the order of 3 hours. The different types of blocks for breakwater armour section are shown in fig.11.

The new armour block `ACCROPODE' developed by SOGREAH France has advantage over other concrete blocks. Accropodes are designed to be used on steeper slope of 1 in 1.33 in a single layer (as against double layer for other blocks), thus effecting about 40% saving in concrete cost. Values of about 10 to 12 for breaking and non breaking waves have been formulated considering uncertainty in design wave height and other constraints at site.

The choice of design wave conditions for structural stability as well as functional performance of a rubble mound, near-shore structure at any time depends critically on the water level at the site. A given structure may be subjected to non breaking, breaking and broken waves during different stages of a tidal cycle. Generally, the coastal structures are designed for breaking wave conditions which exert maximum force on the structures. The breaking wave height can be obtained from the depth of water at the structure by the relation $d_s/H_b = 1.28$

If breaking in shallow water does not limit the wave height, a non breaking condition exists. As a rule of thumb, the design wave height is selected as follows -

For a rigid structure like sheet pile wall a concrete caisson, where a high wave within the wave train might cause failure of the entire structure, the design wave height is normally H_{max} or H_1 ($H_1 = 1.67 H_s$ = average of highest 1 percent of all waves). For semi-rigid structure, the design wave height is selected from a range of H_5 to H_1(H5 = 1.37 H_s = average of highest 5 percent of all waves). For flexible structure such as rubble mound or riprap structures, the design wave height usually ranges from H_{10} toH_s ($H_{10} = 1.27$ Hs = average of highest 10 percent of all waves). Selection of a design wave height between $H_s$and H_{10} is based on the following factors-

a. Degrees of a structural damage tolerable and associated maintenance and repair cost

b. Availability of construction materials and equipment

c. Reliability of data used to estimate wave conditions

Though, theoretical formulae are available for designing rubble mound structures, they can be only used for conceptual design to determine the weight of armour units. Hydraulic stability of these structures has to be tested in physical models (wave flume) to arrive at a final design.

6.2.1 Filter layers under armour layers

The purpose of filter layers is to prevent core material from being washed out through the armour layer. Published criteria for filter stability are shown as below where (a) refers to armour sizes and (f) refers to filter material size.

Filter Criteria

	$\frac{d_{15,a}}{d_{85,f}}$	$\frac{d_{50,a}}{d_{50,f}}$	$\frac{d_{15,a}}{d_{15,f}}$
Terzaghi and Peck (1967)	≤ 4 to 5	-	≤ 20 to 25
U. S. Army Costal Engineering Research Center (1977)	~ 2.2	~2.3	~2.5
Thomson and Shutler (1976)	≤ 4	≤ 7	≤ 7

Filter layers should be few and thick rather than many and thin for construction reasons when large artificial armour are used, quarry stones are used as filter layers or secondary armour layer.

6.2.2 Core

The core normally consists of quarry run, which should not be so coarse that wave action is transmitted through the breakwater. Sometimes a minimum stone size is specified, to avoid wash out of core material which could cause settlement of the structure and perhaps accumulation of core material in dredged area.

6.2.3 Berm

The seaward berm acts as toe support for the main armour layer and may catch units dislodged from the armour layer, whereby the slope of the latter becomes more gentle and its stability improves as some damage develops. The berm should be sufficiently wide to compensate for construction inaccuracy and to allow for some damage during extreme wave action. The most critical conditions for deciding the stone weight for berm are low water and large waves.

6.2.4 Filter on sea bed and toe protection

On a sandy bottom, a toe protection layer is traditionally used to protect the breakwater from undermining. The toe protection material is normally so coarse compared with the sea bottom material that it does not conform to standard filter criteria. A filter layer is often used between the core and the bottom material. Very thin and/or geometrically complex multilayer filters are sometimes used as toe protection.

After the selection of suitable type of breakwater, the conceptual design is made based on site-specific conditions or using Hudson/ Van der Meer formulae for rubble-mound type breakwater and further structural stability of cross sections of breakwater (trunk portion) at different depths will be tested in 2-D wave flume. The round head design will be tested in 3-D hammer head of flume facility.

Chapter VII

MOORING, FENDERING, DOLPHINS AND OFFSHORE TERMINALS

7.1 Moorings

Mooring systems are critical for safely securing vessels to berths, protecting both the ship and the port infrastructure. The primary function of a mooring system is to counteract forces exerted by environmental factors such as wind, current, short-period waves, and long-period waves (typically with periods ranging from 60 seconds to several hundred seconds).

(a) Forces on Moored Vessels
The interaction between water particle kinematics, ship motion, and mooring system response is complex. Wave forces on moored ships manifest in two primary components:
.
Linear Oscillatory Forces These forces occur at the frequency of the incident waves. They arise from the varying water pressures acting on the submerged portion of the hull. To accurately determine these forces, diffraction theory must be employed, as the ship's presence significantly modifies the incident wave train. The oscillating ship scatters waves, which propagate away from the hull and contribute to the damping of the oscillations.
The hydrodynamic coefficients of added mass and damping, which are crucial for characterizing ship motion, vary for each of the six degrees of freedom and are dependent on the oscillation frequency. In shallow water, the water depth-to-draught ratio or the vessel's under-keel clearance significantly influences these coefficients. Buoyant restoring forces can induce heaving and/or pitching oscillations at the system's natural period.

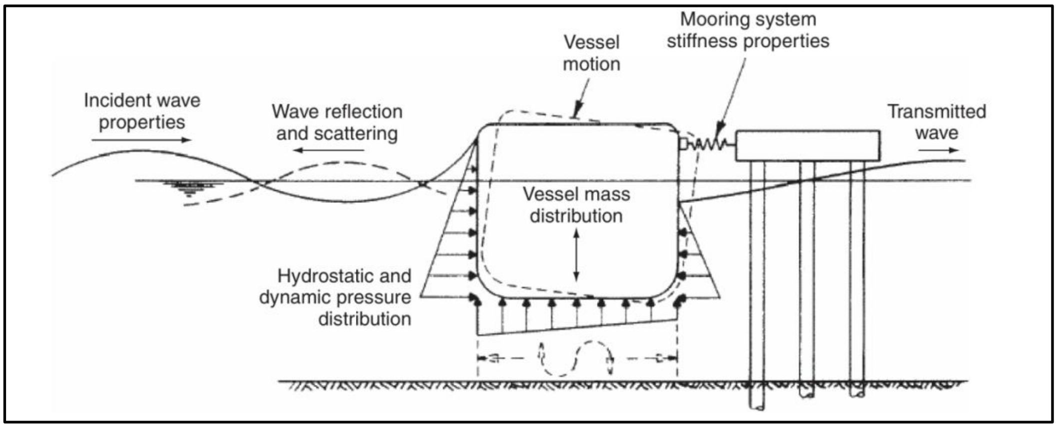


Figure 7.1: Wave Force Distribution on a Moored Vessel in Beam Sea

Non-linear Drift Forces These forces are non-linear in nature and are primarily a consequence of irregular sea states, specifically wave grouping and set-down effects. The momentum flux and radiation stress generated by progressive groups of higher and lower waves result in a net force in the direction of wave propagation.

The drift force is a steady force in regular waves, but becomes a slow-varying or low-frequency force in irregular waves. This low-frequency component is particularly critical because damping is relatively low at these frequencies, and the typical period range of 20–100 seconds often coincides with the natural periods of moored ships. Consequently, slow-varying drift forces can lead to overstressing of mooring lines and excessive fender forces.

(b) Ship Motions in Moored Conditions

Understanding ship motions is fundamental to effective mooring design. Vessels exhibit six degrees of freedom: three translatory motions (surge, sway, heave) and three rotational motions (roll, pitch, yaw).

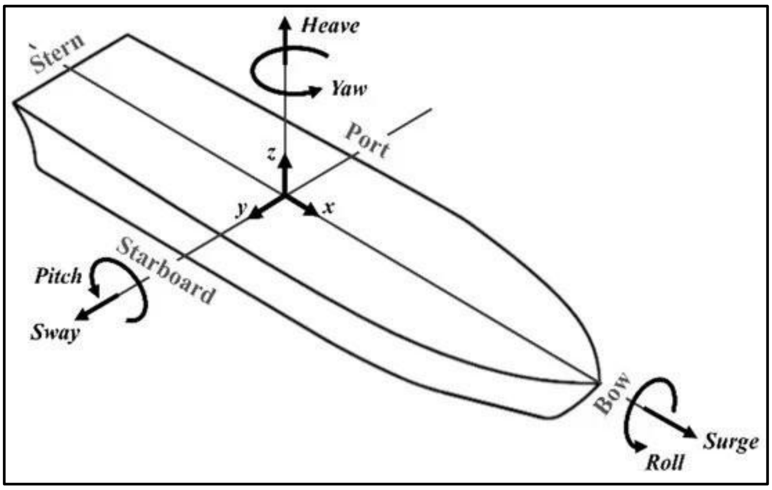


Figure 7.2: Six Degrees of Freedom of Ship Motion

Natural Periods of Roll, Pitch, and Heave:

These periods are predominantly governed by the ship's inherent characteristics and cannot be significantly influenced by mooring or fender systems. Buoyant restoring forces are the primary drivers for these motions

.

Natural Periods of Surge, Sway, and Yaw: For restrained ships, these periods are largely governed by the berth structure (e.g., solid wall or open pile-supported deck) and, crucially, by the mooring and fender systems.

- o **Surge:** Primarily influenced by the mooring lines.
- o **Sway and Yaw:** Influenced by both mooring lines and fenders.

(c) Mooring System Components and Materials

Mooring is achieved by wires or ropes attached to bollards, capstans, or rings, which are typically fastened to concrete blocks or other heavy elements within the quay wall.

- **Line Types and Function:**
  - o **Bow, Stern, and Breast Lines:** Primarily keep the vessel alongside the quay.
  - o **Spring Lines:** Crucial for hindering surge motion parallel to the quay.

- **Force Absorption and Line Geometry:** Mooring lines are designed to absorb forces exerted by winds, currents, and waves (short-period for smaller vessels, long-period for larger vessels, and occasionally anomalous waves like tsunamis or ship waves). To optimize force absorption, mooring cables should be positioned as horizontally as possible. This can be challenging in areas with significant tidal ranges.

- **Mooring Line Materials:** Mooring ropes are available in various constructions and materials:

- **Steel Wire Ropes:** Composed of individual wires woven into strands, which are then formed into ropes. Wires may have different strength grades and can be galvanized for corrosion protection. A typical steel wire rope consists of 6 strands, each containing 19, 24, or 37 individual wire filaments built around a fiber core.

- **Natural or Synthetic Fiber Ropes:** Typically consist of three strands (plain-lay), but can also be found in four-strand (shroud-lay) or nine-strand (castle-lay) constructions. Common fiber materials include Manila, sisal, coir, nylon, saran, dacron, rayon, and prolene.

- **Nylon:** Provides additional elasticity to mooring lines, which can significantly reduce loads under dynamic conditions. This elasticity allows the ship to respond more favorably to combinations of wind, wave, and current, as well as to passing ship effects.

- **Mooring Tails:** Often used to provide this additional elasticity and distribute loading more evenly. However, tails can introduce a "weak link" into the mooring system that may not be immediately apparent to the ship operator.

(d) General Guidelines for Mooring Design (Based on OCIMF, 1978)

While originally developed for tanker moorings, the following guidelines are widely applicable to other ship types and are particularly important for berth designers:

- **Symmetrical System:** The mooring system should be symmetrical to ensure balanced load distribution.
- **Spring Line Direction:** Spring lines should be aligned as closely as possible to the ship's longitudinal direction to effectively restrain surge.
- **Breast Mooring Angle:** Breast moorings should be approximately perpendicular to the ship's hull to provide effective lateral restraint.

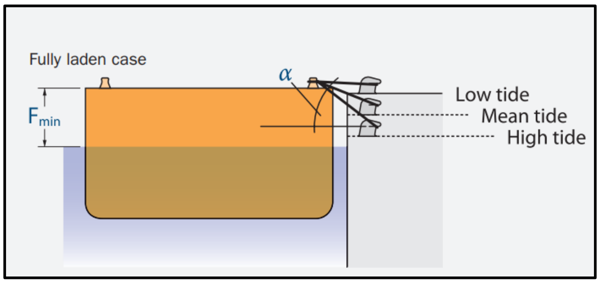


Figure 7.3: Berthing Angles in fully Loaded Condition

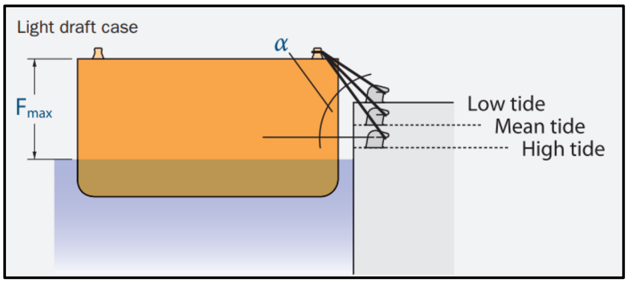


Figure 7.4: Berthing Angles in Light draft Condition

d. **Bow and Stern Moorings:** While traditional, bow and stern moorings may not be strictly necessary if other mooring points are suitably designed and arranged.

e. **Vertical Mooring Angle:** The vertical angle of mooring lines should be as small as possible, and ideally not exceed 30 degrees, to maximize the horizontal component of the restraining force.

f. **Line Uniformity:** All lines, especially those in the same direction, should ideally be of the same type, diameter, and, if possible, length to ensure consistent load sharing.

g. **Tail Uniformity:** For lines utilizing mooring tails, the same type of tail should be used for lines of the same type.

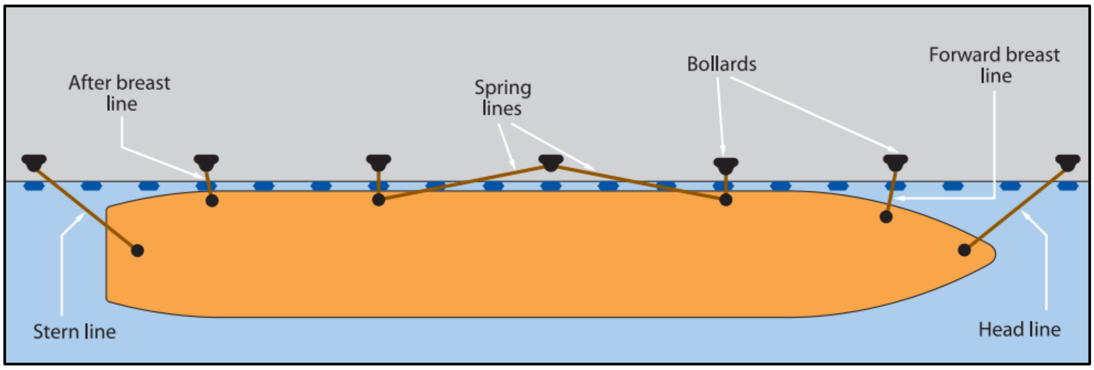


Figure 7.5: Image showing the typical mooring arrangement for a vessel at berth

7.2 Bollards

Bollards and mooring rings are essential components of quay infrastructure, providing secure points for a vessel's mooring lines. Their design and placement are critical for safe and efficient berthing operations.

(a) Placement and Types

Bollards and rings are typically positioned just inside the front edge (cope line) of the quay. While their specific shape can be influenced by local experience and aesthetic preferences, cast steel bollards are a standard feature of modern quay outfitting due to their strength and durability. (figure) Mooring rings are generally installed in pairs, anchored by hairpin-shaped foundations.

(b) Structural Integrity and Load Transfer

A fundamental design principle for bollards is that their structural integrity, or that of their anchorage, should fail *before* the stability of the quay structure itself is compromised. This ensures that in extreme loading scenarios, the localized failure of the mooring point occurs, preventing catastrophic damage to the entire quay.

The calculation of forces transferred from a ship's mooring lines to a bollard must be based on the maximum anticipated environmental forces acting on the ship, primarily wind and current.

(c) Spacing and Location Guidelines

According to Indian Standard IS: 4651 (Part V) – 1980, for general cargo berths, specific guidelines apply to the spacing and location of bollards:

- **Spacing:** Bollards for spring lines and breast lines should be spaced at intervals of **25 to 30 meters** along the length of the berth.
- **Location:** These bollards should be located approximately **0.15 meters (150 mm)** behind the cope line of the berthing structure. This offset provides adequate clearance for mooring lines and reduces chafing against the quay edge.

(d) Specialized Bollards and Adaptability

Larger fittings or corner posts may be installed at the offshore corners of a pier or wharf. These are specifically designed for handling the extreme loads exerted by bow and stern mooring lines, which often experience higher tension due to their critical role in vessel positioning.

It is important to note that while general guidelines exist, the spacing of bollards may need to be varied to accommodate special conditions. These could include:

- **Specific vessel types:** Berths designed for very large vessels (e.g., VLCCs, container ships) may require different bollard arrangements.
- **Environmental conditions:** Locations prone to severe winds, strong currents, or significant wave action may necessitate closer bollard spacing or higher capacity bollards.
- **Operational requirements:** Specialized cargo handling or unique berthing manoeuvres might influence bollard placement.

(e) Cleats: Mooring Points for Smaller Vessels and Harbour Crafts

Cleats and mooring rings serve as essential mooring points for smaller vessels, such as harbour crafts, tugs, service boats, and leisure craft. They complement the primary bollard system by providing additional, suitably sized attachment points along the length of a pier or wharf.

- **Complementary Mooring:** Cleats and rings are specifically installed *between* the main mooring bollards. This ensures continuous availability of mooring points for smaller vessels that may not utilize the heavy-duty bollards designed for larger ships.
- **Accessibility for Smaller Vessels:** Their smaller size and often lower profile make them more practical and accessible for the lines typically used by smaller craft.

(f) Location and Elevation Guidelines

For effective and safe use, specific guidelines apply to the placement and elevation of cleats and rings:

- **Alignment:** Mooring cleats are typically located in alignment with the row of primary bollards, maintaining a consistent line along the quay edge.
- **Elevation:** Mooring rings should be positioned approximately **50 cm (0.5 meters)**above the mean high water level (MHWL). This elevation is crucial for:
    - **Ease of Use:** Allowing crew members to easily reach and secure mooring lines from small vessels, even during high tide conditions.
    - **Preventing Submersion:** Ensuring the rings remain above water during most tidal cycles, preventing marine growth and making them readily visible and accessible.
    - **Optimizing Line Angle:** Contributing to a suitable upward lead angle for the mooring lines, which helps to secure the vessel effectively against the quay.

7.3 Fendering

Fenders are critical components of marine infrastructure, serving multiple vital functions in protecting both vessels and quay structures during berthing, mooring, and unmooring operations.

Fenders are installed for one or more of the following principal reasons:

i). **Preventing Direct Contact (Protection/Rubbing Fenders):** To physically separate the vessel from the quay structure, thereby preventing direct contact, chafing, and potential damage to both surfaces while the vessel is moored alongside.

ii). **Mitigating Resonant Motion:** To reduce the risk of a moored vessel moving in resonance with incoming waves or wave groups, which can lead to excessive motion, loading, and operational disruptions.

iii). **Absorbing Berthing Impact Energy:** To safely absorb the kinetic energy generated during the berthing manoeuvre, preventing structural damage to the vessel hull and the quay.

(a) Classification of Fenders

Fenders can be broadly categorized based on their primary function:

i). **Protective/Rubbing Fenders:** These are designed to provide continuous protection against minor impacts and rubbing between the vessel and the quay while the vessel is alongside. They mitigate damage caused by vessel movements due to wind, water level variations, and waves generated by wind or passing vessels.

Traditional Types: Originally, rubbing fenders commonly consisted of vertical and horizontal timber elements fixed directly to the quay wall, or timber piles supported at the top by the quay wall, either directly or via a wale.

Modern Examples: Small cylindrical hollow rubber fenders, often suspended or fixed along the wall, also fall into this category.

Note: Energy-absorbing fenders will also inherently function as rubbing fenders due to their presence and material properties.

ii). **Impact Fenders:** These are specifically engineered to absorb significant kinetic energy, particularly during the berthing manoeuvre. They are crucial in minimizing impact forces and preventing structural damage during vessel approach.

iii). **Fenders for Mooring Condition Improvement:** This category encompasses fenders designed to actively improve the dynamic behaviour of a moored vessel.

(b) Fenders and Mooring System Dynamics

A moored vessel, together with its mooring lines and fenders, constitutes a complex physical system with inherent natural frequencies. If these natural frequencies are close to the frequency of incident waves or wave groups, the vessel can enter a state of resonance.

- **Consequences of Resonance:** Resonant motion leads to significantly increased amplitudes of vessel movement. This can:
    - Impede or halt cargo loading/unloading operations due to excessive motion.
    - Cause mooring line forces and fender forces to reach unacceptable, potentially damaging, values.

- **Mitigation through Fender Characteristics:** In such resonant scenarios, it may be possible to radically alter the system's dynamics by modifying the characteristics of the elastic elements (fenders or mooring lines). This can involve:
    - **Changing Fender Deformation Characteristics:** Adjusting the force-deflection ratio of the fenders to shift the system's natural frequency away from the excitation frequency.
    - **Energy Dissipation:** Utilizing fenders that dissipate energy (e.g., through internal friction or material hysteresis) rather than primarily storing and returning it to the vessel. Energy dissipation helps to damp down oscillations.
- **Design and Testing:** Determining the precise requirements for fenders relative to moored vessel movements often necessitates the use of physical hydraulic models. While introducing specific elasticity requirements can improve dynamic response, it may limit the fender's overall energy absorption capacity, representing a trade-off in design.

(c) Energy Absorbing Fenders

The paramount function of a fender system is to effectively absorb the kinetic energy generated during berthing impacts. This capability is crucial for safeguarding both the vessel and the quay structure.

For modern vessels, particularly those of considerable tonnage, any time spent in dry dock for repairs due to berthing damage translates directly into significant financial losses. These losses stem from:

- **Lost Revenue:** The vessel is out of service and unable to transport cargo or passengers.
- **Repair Costs:** Expenses associated with material, labour, and potential specialized equipment for hull or structural repairs.
- **Operational Disruptions:** Delays in supply chains, missed schedules, and potential penalties.

Therefore, investing in high-quality, effective energy-absorbing fendering systems represents a sound economic decision. Such an investment directly contributes to:

- **Reduced Downtime:** Minimizing the need for costly and time-consuming repairs.
- **Lower Repair Costs:** Preventing or significantly reducing the extent of damage to both ship and berth.
- **Enhanced Safety:** Protecting personnel and assets during berthing operations.
- **Improved Operational Efficiency:** Ensuring vessels can berth smoothly and quickly, maintaining schedule integrity.

In essence, energy-absorbing fenders are not just a protective barrier but a strategic asset that contributes significantly to the overall economic viability and operational resilience of port facilities and shipping operations.

(d) Types of Fenders: Materials, Mechanisms, and Performance Characteristics

The primary objective of a fender system is to absorb the kinetic energy of a berthing vessel. While various materials and designs have been employed, modern fendering largely relies on materials and mechanisms that can efficiently absorb and, ideally, dissipate this energy.

Common Fender Types and Materials

i). Rubber Fenders (Most Common) Rubber fenders are the most prevalent type due to rubber's inherent ability to undergo significant elastic deformation under load and subsequently return to its original shape upon unloading. This property allows them to effectively absorb and store kinetic energy.

- **Mechanism:** When a vessel impacts a rubber fender, the rubber compresses, temporarily storing the impact energy as strain energy.
- **Load-Deflection Characteristics:** The relationship between the applied load and the resulting deflection is a critical performance indicator for fenders.

ii). Pneumatic Fenders Pneumatic fenders consist of a rubber bag filled with air under pressure.

- **Mechanism:** Upon impact, the air inside the bag is compressed, increasing its internal pressure. This compression allows the fender to deflect and absorb energy. The controlled release of air (or slow return to original shape) contributes to energy absorption.

iii). Other Fender Types While less common today, other fender types have been utilized:

- **Gravity Fenders:** These systems absorb energy by lifting a heavy weight as the vessel berths. The potential energy gained by the lifted weight dissipates as the vessel moves away.
- **Torsion-Bar Fenders:** Energy absorption in these fenders is achieved through the elastic deformation (twisting) of steel torsion bars.

Common Principle: In most fender types, the kinetic energy of the berthing vessel (or a portion thereof) is temporarily stored within the fender material or mechanism. This stored energy is then more or less returned to the ship as the fender recovers its original shape or position.

(e) Fender Characteristics and Materials (IS 4651 Part IV – 1989)

Indian Standard IS 4651 (Part IV) – 1989 outlines various fender characteristics and acceptable materials:

- **Materials:** Fenders may be constructed from rubber, steel, timber, brushwood, rope, concrete, and similar materials. Rubber, however, has gained extensive use in modern fender systems due to its superior energy absorption and resilience.
- **Types:** Within the various material categories, fender designs include:
    - Hollow cylindrical or rectangular rubber fenders
    - Sandwich-type fenders (e.g., Raykin fender buffers)
    - Steel spring fenders
    - Wood spring-type fenders
    - Horizontal and vertical timber fenders
    - Fender piles

(f) Design and Installation Guidelines

- **Longitudinal Spacing:** As a general rule, the longitudinal spacing between fenders should not exceed 0.3 to 0.4 times the length (L) of the smallest ship expected to berth at the facility. This ensures adequate coverage and protection along the vessel's hull.
- **Vertical Disposition:** The vertical placement of fenders must be carefully designed to prevent damage to both the ship's hull and the berthing structure under all anticipated tidal conditions. This typically involves installing fenders at multiple vertical levels or selecting fender types with a large effective berthing range.

- **Expansion Joints:** For structures incorporating fenders, a sufficient number of expansion joints must be provided. A general recommendation suggests a length of 30 to 40 meters (e.g., 39 meters) between expansion joints to accommodate thermal expansion and contraction. These joints must be properly covered to prevent the washout of backfill material behind the quay wall.

(g) Recoil and Dynamic Considerations

A critical performance characteristic of fenders is their recoil behaviour:

- **Recoil Effect:** Many rubber fenders, after compression, exert strong "recoiling" or reflection forces as they return to their original shape. This can induce oscillating movements in the moored vessel.
- **Adverse Effects:** Excessive recoil, similar to the effects of overly stiff bow and stern mooring lines, can contribute to amplified vessel movements and potentially lead to resonance effects with environmental forces (e.g., waves).
- **Design Imperative:** To minimize undesirable vessel movements and prevent resonant conditions, there is a strong design requirement for "low recoiling" or "no recoiling" fender systems. Such fenders dissipate a larger proportion of the absorbed energy, reducing the elastic rebound and the subsequent dynamic response of the moored vessel.

7.4 Dolphins

Dolphins are auxiliary marine structures primarily used for mooring and for absorbing berthing impacts. They are often constructed in combination with piers and wharves to reduce the overall length of the main structure. Their key functions include:

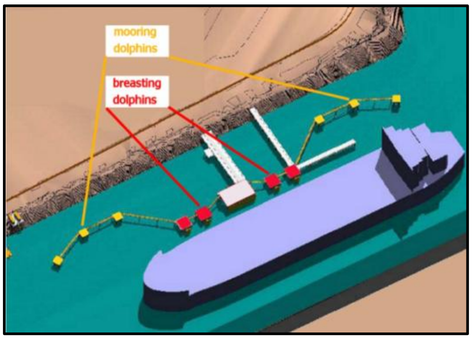


Figure 7.6: Typical mooring Platform for the Oil tanker

- **Breasting Dolphins**: Designed to absorb the berthing energy of vessels during docking and to hold ships against broadside winds. These are heavier and more robust since they must withstand significant impact forces. Heavy sheet pile dolphins are also used as turning dolphins for warping or manoeuvering vessels at the dock ends.
- **Mooring Dolphins**: Intended solely for securing mooring lines; they are not designed to resist berthing impacts. At oil terminals, a typical arrangement includes mooring dolphins, breasting dolphins, and spring line dolphins, as shown in Figure 7.6. Mooring dolphins are generally placed at a uniform distance from the dock face, approximately 45° off the bow and stern of a standard vessel, ensuring mooring line lengths between 200 and 400 ft.

Dolphins may also serve as navigational markers. Their construction may be either **flexible** or **rigid**. With the increase in ship sizes, modern breasting dolphins are frequently built as heavy reinforced concrete platform slabs supported by vertical piles, usually of steel or precast concrete, to provide greater strength and durability.

7.5 Offshore Terminals

Pipelines allow efficient transportation of liquid cargo, and specialized offshore terminals have been developed for handling these commodities.

7.5.1 Conventional Buoy Mooring (CBM)

This is the oldest offshore mooring system. The vessel is held in a fixed position by multiple chain anchor legs, sometimes supplemented by the vessel's own bow anchors (see Figure). The cargo is transferred through flexible rubber hoses connecting the vessel's midship manifold to a subsea manifold, which is linked to shore facilities by a submarine pipeline. When idle, the hoses rest on the seabed but remain attached to a marker buoy.

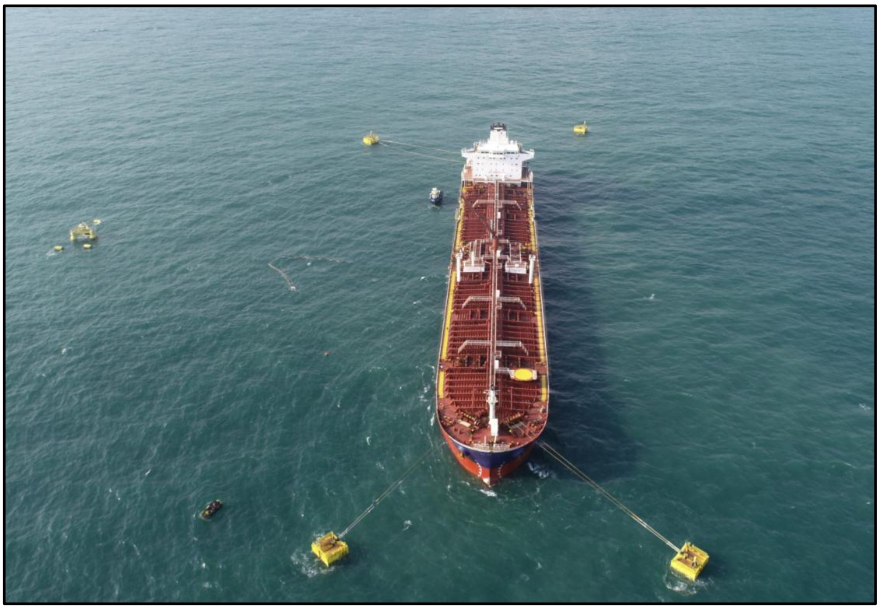


Figure 7.7 Conventional Buoy Mooring

CBM installations are relatively low in capital cost, but they present challenges in navigation and are highly sensitive to wave conditions, which can prevent safe tanker mooring and operation. Maintenance costs are also comparatively high. In some cases, floating hoses may be used to transfer cargo directly to shore, eliminating the need for a submarine pipeline.

7.5.2 Single Point Mooring (SPM)

In this system, the vessel moors by the bow only, allowing it to freely weathervane around the mooring point in response to wind, waves, and currents. This significantly improves operational safety, enabling vessels to remain moored under severe conditions. Cargo transfer is achieved via floating rubber hoses connected between the ship's midship manifold and a swivel on the mooring unit.

The main types of SPM are:

- **Catenary Anchor Leg Mooring (CALM):** A surface buoy anchored by multiple (5–8) chain legs. Submarine hoses transfer cargo from the pipeline to the buoy, while floating hoses connect the buoy to the vessel. CALM systems are the most common type, suitable for shallow water (≤30 m), though maintenance costs are relatively high.

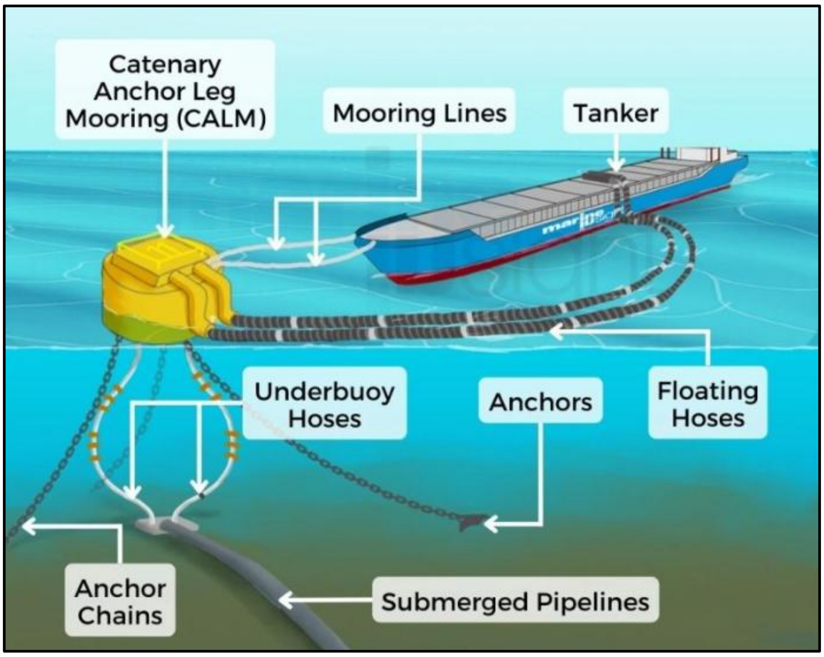


Figure7.8: Single Point Mooring

- **Single Anchor Leg Mooring (SALM):** A buoy connected to a single vertical anchor leg (chain or pipe). The system relies on a taut mooring under all conditions to prevent impact failures. Cargo transfer is via a submerged swivel and surface hoses. SALM is more cost-effective in deeper waters (see Fig. 17).

- **Tower Mooring:** Consists of a fixed tower or single pile structure, with the cargo swivel typically positioned above the water surface. This system is well suited for vessels with bow manifolds, eliminating the need for floating hoses.

SPM systems can, in theory, remain operable during extreme conditions (significant wave heights of 4 m or more). However, practical transfer operations are usually limited to Hs < 2 m due to constraints in securing floating hoses.

Use of SPMs for liquefied gas transfer has been explored but is generally feasible only for products with relatively high boiling points, such as propane. Major challenges include hose flexibility at low temperatures, thermal insulation requirements, and restrictions on LNG carriers when tanks are partially filled.

CHAPTER VIII

DREDGING AND DISPOSAL

Dredging is the process of excavating and removing soil, sediment, or rock from underwater locations using specialized equipment known as dredgers. Although dredging in its most basic form has been practiced since ancient times, it was initially carried out with primitive tools and limited to small-scale removal. By the early half of the 20th century, the advent of steam-powered dredging equipment allowed more effective operations, particularly in rivers and estuaries, to deepen shallow bars, construct tidal docks, and develop basins. Over the past five decades, dredging technology has advanced significantly through the adoption of diesel-powered vessels and mechanized equipment designed to withstand wave action, strong currents, and winds, enabling sustained, large-scale dredging activities over prolonged periods. Recent practices, following international guidelines such as those developed by PIANC (Permanent International association for Navigational Congress), IADC (International Association of Dredging Companies), and IMO (International Maritime Organization), emphasize not only efficiency but also environmental sustainability and safe disposal.

The primary purposes of dredging, aligned with both national coastal management policies and global standards, include the following:

1. **Material excavation** for navigation channel deepening, port maintenance, and inland waterway transport enhancement.
2. **Land reclamation and fill material** for infrastructure development, coastal defence structures, and climate resilience projects.
3. **Subsurface material replacement**, improving geotechnical stability and enabling construction on challenging foundations.
4. **Resource extraction** such as sand, gravel, and other materials for mining and construction industries in compliance with sustainable resource-use practices.
5. **Environmental enhancement**, including improving hydraulic flow, restoring aquatic ecosystems, managing contaminated sediments, and employing capping techniques to isolate pollutants.

8.1 Basic Dredging Processes

The physical mechanisms may be broadly classified as pretreatment, extraction, transportation and disposal.

8.1.1 Pretreatment

Pretreatment refers to the preparatory treatment of the seabed or ground before initiating dredging operations. Its purpose is to reduce the strength and compactness of hard formations, such as rock or cemented soils, to facilitate efficient excavation. While soft and normal soils are naturally disintegrated during the dredging process, consolidated or lithified materials generally require additional pretreatment. Two broad methods are employed: chemical and mechanical.

Chemical Methods

Chemical pretreatment predominantly involves the use of explosives or expanding gas cartridges to fracture hard materials prior to dredging. The standard practice is to drill a systematic grid of boreholes vertically into the material requiring treatment. Cartridges or charges are placed within these boreholes and detonated in controlled sequences, breaking the substrata into manageable fragments. The loading, stemming, and fixing of charges are typically done in grouped boreholes to ensure uniform fragmentation across the targeted area.

Such operations are most commonly performed from floating platforms or jack-up pontoons that provide stability during drilling and charge placement. In certain cases, specialized divers with submersible drills may carry out the borehole preparation and charge placement underwater. Internationally, strict safety protocols (as per IMO and PIANC guidelines) and environmental safeguards are required to mitigate impacts such as shock waves on marine ecosystems and dispersion of suspended sediments.

Mechanical Methods

Mechanical pretreatment, though now less frequently employed due to the efficiency of explosives, remains a viable option in specific conditions. The technique employs rock breakers, consisting of a floating pontoon equipped with a heavy chisel or needle. This tool is repeatedly hoisted and dropped vertically onto the seabed, delivering concentrated impact forces to fracture the rock or cemented material.

Fragmentation is achieved either through shear stress or compressive crushing, depending on the crystalline structure and hardness of the substratum. Although slower and less cost-effective than chemical methods, mechanical pretreatment has the advantage of minimizing underwater shock impacts and is preferred where explosive use is restricted by environmental, navigational, or safety considerations.

Both chemical and mechanical pretreatment approaches are evaluated through geotechnical investigations and risk assessments, ensuring compliance with national regulations (such as MoEFCC and CPCB in India) and international dredging practices. The method selected depends on geological conditions, environmental sensitivity, and project-specific requirements.

8.1.2 Extraction

The extraction process in dredging refers to the removal of soil or rock material from its natural or pretreated location and its transfer into a transportation system for disposal or reuse. Extraction generally involves a combination of two distinct operations: a primary operation that disintegrates or detaches the material, and a secondary operation that conveys and delivers it to the transport system. The primary operation is executed either mechanically or hydraulically, depending on soil conditions, equipment availability, and environmental considerations.

Mechanical Primary Extraction Methods

Mechanical primary extraction is primarily achieved through digging or cutting techniques. Digging involves the use of various types of buckets designed to penetrate the seabed, detach soil masses, and retain the material for removal. The effectiveness of this method depends on the power applied to the bucket and the cutting profile of the bucket rim. The most common mechanical dredging systems include:

- **Face shovel (dipper dredger)** – uses forward thrust to detach large portions of cohesive material.
- **Backhoe bucket (backhoe dredger)** – well-suited for precision excavation in confined areas.
- **Bucket chain (bucket dredger)** – continuous chain of buckets for sustained excavation, often used in stiff or compacted soils.
- **Grab bucket (grab dredger)** – a clamshell-type bucket ideal for silt, sand, or fragmented material.

Cutting techniques, on the other hand, employ rotating or slicing blades that chip or shear soil into manageable fragments. These dislodged particles are subsequently removed by a secondary extraction method. Mechanical processes are particularly effective for compacted soils, clays, or rock-like formations where hydraulic methods may be less efficient.

Hydraulic Primary Extraction Methods

Hydraulic primary extraction relies on the movement of water to erode, suspend, and transport soil particles. Water movement may either flow towards the dredger (suction-based) or be directed away from it (jet-assisted).

- **Suction dredging** employs a suction head to intake a mixture of soil and water from the seabed. Common suction head types include:
  - **Plain suction head** (used in suction dredgers for fine sediments).
  - **Drag head** (used in trailing suction hopper dredgers for loose or sandy soils).
  - **Dustpan head** (applied mainly on riverbeds with silt).
- To enhance performance, drag heads and dustpan heads are often supplemented with **water jets** directed away from the dredger, which agitate the seabed and keep sediments in suspension for easier suction. Specialized pneumatic dredging methods also utilize compressed air for similar sediment mobilization.

Secondary Extraction Methods

The secondary extraction process ensures the transfer of dredged material into the transportation system, either mechanically or hydraulically.

- **Mechanical methods** generally extend from the primary process, whereby a bucket or chain of buckets is lifted to the required elevation, shifted laterally, and emptied into barges, hoppers, or transport conveyors.
- **Hydraulic methods** depend on pumping and fluid mechanics to raise and convey the soil-water mixture. Four principal systems are employed:

1. **Centrifugal pumps** – the most common method, capable of both vertical lifting and horizontal transport of dredged material.
2. **Jet pumps** – used alongside centrifugal pumps to enhance efficiency. High-pressure jets inject water into the suction pipe stream, creating a venturi effect that increases lifting capacity and allows dredging at greater depths without oversized pumps.
3. **Air-lift systems** – among the simplest methods, where compressed air is released at the base of a suction pipe. The rising air column reduces density in the pipe, lifting water and entrained solids upward for discharge.
4. **Ejector systems** – variants that rely on pressurized fluid streams to entrain materials within a suction conduit.

Each extraction method is selected based on soil characteristics, depth, project scale, and environmental sensitivity. Adherence to modern dredging guidelines (e.g., PIANC, IADC, and national dredging policies) ensures that extraction techniques optimize efficiency while minimizing impacts such as turbidity, suspension of contaminants, and ecological disturbances.

8.1.3 Transportation

The transportation process refers to the movement of dredged material (spoil) from the dredging site to a designated disposal area or reuse location. This transfer may be accomplished by the dredging equipment itself or with the assistance of external transport systems. The choice of transportation method depends on the dredger type, dredging scale, distance to disposal area, and environmental restrictions.

Own Hold

When the dredger is equipped with its own hopper or hold, the spoil is stored onboard while dredging continues until the hopper is filled to capacity or reaches an economic load level. The dredger then suspends excavation, sails to the disposal site, discharges the material (by bottom opening, overflow, or pumping out), and subsequently returns to resume dredging operations. This method is common with trailing suction hopper dredgers (TSHDs).

Self-Propelled Barges

In this method, self-propelled barges operate alongside the dredger to receive spoil continuously. Once fully loaded, the barge sails to the disposal site while another barge takes its place, ensuring uninterrupted dredging. Barges are typically deployed in pairs or groups of three to maintain continuous transport cycles. This system is widely used with cutter suction dredgers (CSDs) or grab dredgers engaged in medium- to long-distance transport.

Dumb Barges

They are also known as non-propelled barges, function similarly to self-propelled barges, except they lack independent propulsion. They require towing by tugboats between the dredging and disposal sites. While less flexible, they are still cost-effective for short to medium distances where disposal points are easily accessible.

Pipelines

Pipelines are frequently employed to transport spoil as slurry (water-soil mixture) from the dredger to the disposal or reclamation site. The primary pumping unit is often integrated with the dredger's extraction system. For longer transport distances, booster stations are installed along the pipeline to maintain flow and pressure. Pipelines may take the form of:

- **Floating pipelines** – supported on pontoons across the water surface.
- **Submerged pipelines** – laid on or below the seabed for navigational safety.
- **Onshore pipelines** – transporting dredged material to reclamation areas, dyke construction, or confined disposal facilities.

Pipelines are also widely used in beach nourishment and land reclamation projects, as they allow precise placement of dredged material.

Natural Processes

In some cases, dredged spoil is transported through natural hydrodynamic processes such as currents or tides. Here, the dredger releases spoil directly into the water at or near the dredging site without engineered transport methods. This approach is limited to specific contexts, such as offshore disposal areas where natural dispersion is acceptable under environmental regulations.
All transportation methods are selected based on economic efficiency, distance, environmental safety, and project objectives, following international guidelines (PIANC, IADC) and national standards for sustainable dredged material management.

8.1.4 Disposal

The disposal process represents the final stage of dredging, where dredged material is released or placed at a designated site for either permanent containment or beneficial reuse. The selection of a disposal method is governed by the nature of the spoil (contaminated or uncontaminated), project objectives, environmental regulations, and logistics. Several disposal approaches are commonly practiced.

Bottom Discharge

Bottom discharge releases spoil from a dredger's hopper or hold directly into the water by gravity. This is achieved through mechanisms such as bottom opening doors, valves, horizontal sliding gates, or split hulls, but all systems achieve the same end result—rapid downward release into a disposal area. This method is typically used by trailing suction hopper dredgers (TSHDs) to deposit spoil at offshore disposal grounds.

Grab

A grab dredger or separate grab crane can be employed at the disposal point to unload spoil from self-propelled or dumb barges. In some cases, grab dredgers may also discharge their own hopper load directly into the designated dumping ground. This method is generally used for small to medium-scale disposal or when controlled placement of spoil is required.

Scrapers

Scrapers are integrated into certain self-propelled or dumb barges for unloading their cargo. The scraper mechanism feeds dredged material onto another conveyance system, such as a conveyor belt, for further transfer or controlled discharge. This method is particularly useful when mechanical handling is required for land disposal facilities.

Pipeline

Pipelines are widely used for disposal operations, particularly for land reclamation, beach nourishment, dyke strengthening, and contained disposal facilities (CDFs). Spoil in slurry form is pumped via floating, submerged, or onshore pipelines and deposited precisely at the reclamation site. In some cases, pipelines may discharge directly into the sea, though this method is increasingly regulated under environmental protection standards.

Land-Based Units

In projects where dredged material is intended for beneficial use (e.g., reclamation, landscaping, or construction), land-based suction pumps can remove spoil directly from the hopper and transfer it to designated placement areas or processing facilities. This approach allows for controlled handling and reuse of dredged material.

Natural Processes

In certain cases, disposal occurs through natural hydrodynamic processes. When spoil is released directly into the water at the dredging site, tidal and current movements disperse the dredged material across the seabed. While cost-effective, this approach is only permitted where environmental impact assessments confirm negligible adverse effects on ecosystems or navigation channels.

8.2 Types of Dredgers

Dredger types are many and most commonly used are given below:

1. Trailing Suction Hopper Dredger (TSHD)
2. Cutter Suction Dredger (CSD)
3. Hydraulic Backhoe Dredger
4. Grab Dredger
5. Bucket Dredger

8.2.1 Trailing Suction Hopper Dredger (TSHD)

TSHD (Figure 8.1) consists of a drag head, which is moved along the seabed by trailing connected by a pipeline to a large system of hoppers having bypassing, or overflow arrangements. TSHD is quite extensively used for capital and maintenance dredging operations for major ports; intermediate ports and hopper sizes ranging from 800 to 4500 cum are quite common. The dredger is able to dredge under wave action in the sea with wave height upto 2 to 3 m. Being a self contained dredging unit it can work independently. It is mobile during dredging operation and has minimal effects on shipping in the dredging areas and can easily phase out its activity. Due to its use of powerful pumps, it has ability to transport dredged material upto long distances in the sea for disposal or for reclamation or for open water disposal or even side cast dredging. The TSHD dredge has high rate of production. Dredging cycles of about 10 to 15 times per day are not uncommon. Even during the dredging operation in a day the dredger can use different disposal grounds, if required to take advantage of the phase of the tide and the local tidal flows. This dredger is suitable for soft clay, silt and sands, but it is not so suitable for dredging strong/hard materials. Due to the requirement of movement of the dredger over the dredging areas for its operation, it cannot work in very restricted areas near jetties or in anchoring areas. The dredging operation involves mixing soil with water by suction and jetting at the drag head. Therefore, energy is required to be used for pumping not only soil but also large quantities of mixing water in the hopper and for the over-flows thereby the net efficiency of the dredger is affected.

Figure 8.1: Trailing Suction Hopper Dredger (TSHD)

8.2.2 Cutter Suction Dredger

The cutter suction dredger consists of a cutting head attached to the rotating pipe which is lowered by ladder supported on a deck on which pumps are located. The dredger operates by rotating cutter on the pipeline on its axis and drawing soil water mixture by pumps. The delivery end is connected to pipeline. The mixture is discharged either through pipeline further or loaded in a hopper barge on the side of the dredger. The movement of the dredger is by a pair of spuds on the rear side of the dredger. One of the spuds is lowered and rested on the seabed (working spud) around which dredger rotates and then second spud (stepping spud) is lowered. The operations of these spuds are altered in such a way that the movement of the dredger takes place in forward direction and despite arc motion of the cutter head uniform dredging is achieved along the track. The cutter suction dredger does not have storage of dredging material onboard and has limited draft. Therefore, it can dredge in limited depths of 1 to 2 m's, if required. The allowable wave disturbance for operation of the dredger is comparatively much restricted in comparison to the TSHD and wave action more than 1 m can cause problems for small CSD. The bigger CSD may work upto 2m waves. The cutter suction dredgers are quite commonly used for dredging during the capital dredging operations for creating reclamation fills, dredging in small and intermediate ports, fisheries harbours, inland navigation schemes etc. The dredged material can be used for the beach nourishment, reclamation or disposed at suitable disposed ground or may be disposed by side cast dredging some distance away along long navigation channels. This dredger has an advantage that it can dredge a large range of material like soft clay, sand, gravel, and soft rock. The dredger, however, has limitation due to sensitivity to wave conditions, strong currents, wind etc. The dredging operation also involves dilution with the dredging material with surrounding water around the cutter head and in addition to soil, water is required to be pumped. The mobility of the dredger is limited and the region of dredging is required to be separated from navigation tracks of the other traffic.

Figure 8.2: Cutter Suction Dredger (CSD)

8.2.3 Grab Dredger

The dredger consists of a grab bucket (clamshell) which is lowered to the seabed for removal of the bed material and material is discharged into a hopper barge or in the hopper provided in the body of the dredger itself (Figure.8.3). The capacity of the grab can range 1 cum to 2 cum. The dredger has an advantage of removing the dredged material with minimum disturbance and dilution of the bed compared to the TSHD or cutter suction dredger. It can handle a variety of bed materials, can work in confined areas near jetties anchorage's and works in very shallow waters. The dredger has low rate of production, cannot accurately produce a desired level by dredging.

Figure 8.3: Grab Dredger

8.2.4 Bucket Dredger

The bucket dredger consists of buckets mounted on a rotating chain, which are lowered, to the bed and the whole assembly is mounted on a small vessel/barge (Figure 8.4). The bucket dredger has an advantage that continuous dredging process takes place unlike grab, with minimal dilution of soil unlike TSHD or CSD. Dredger can achieve uniform dredged level with good control over dredging fleet and dredging operation and output is not sensitive to small boulders. The dredger has disadvantage of requirement of large space for anchoring and can cause hindrance to navigation. Material cannot directly be transported to a distant reclamation area and cannot work in very shallow areas.

In addition to above dredgers the dredgers like Backhoe dredger, Crawl-cat, (it has been developed by M/s Tebma) and numerous other types are also used for dredging operations. In the recent years there are new types of dredgers being introduced like Water Injection dredger which uses technique in which a manifold with multiple water jets is lowered and jets are forced on the sea bed with large discharge which removes the soil to form a turbid fluid of clay, which moves to the deeper area by effect of gravity and ambient currents. This technique has been used and found to be useful for fine sediment like clay and silt and has been used by M/s HAM at Mumbai. Holland is leading in dredge building and most of the dredgers are manufactured in Holland itself or built in local shipyards based on the designs evolved by the Dutch dredging companies.

In India the majority of dredging is carried out by Dredging Corporation of India, whose head office is located in Visakhapatnam. The dredging requirement of the major ports is both for capital dredging for developments and maintenance dredging on regular basis for which TSHD of 2500 to 4500 cum hopper capacity are used. For dredging, foreign companies are also engaged at some of the major ports. There are many small Indian companies who operate small dredgers like cutter suction dredger, Crawl cat, grab dredger. All ports generally have at least one grab dredger for dredging in port areas. State governments have at least a couple of CSD for small craft fisheries harbours, intermediate ports etc.

Figure 8.4: Bucket Dredger

8.2.5 Agitation Dredging

In areas of high silt sedimentation, e.g. in the brackish water regions of tidal rivers and in the region of locks and harbours, jet pumps for flushing, harrows, overflow methods, boom and side casting dredging methods may be applicable under particular conditions (agitation dredging), but with varying success. Flushing and stir up methods are based on the principle that the removal of a particle resting on the bottom requires a higher stream velocity than is necessary thereafter for keeping the particle in motion for some time.

These methods are only appropriate if they are carried out in channels carrying strong ebb currents or in a basin with a high tidal range during the first phase of ebb tide and when a return of sediment can be avoided. It is, however, indisputable that under certain circumstances the use of flushing methods may lead to rapid success without great efforts.

The German `Hydraulische Egge', which is a dragline provided with water jets has proven to be very effective in major trials. It requires strong currents to carry the stirred up material away. It is partly controllable.

Air lift methods utilize perforated hoses releasing air bubbles placed down in the mud the mixture of air and water having specific gravity less than one carries silt with it up to the surface. Applied during an ebbing tide e.g. in a marine or harbour basin, silt laden water is carried away with the current. This method is controllable by varying the air pressure and thereby the air flow. This method is largely controllable.

The propeller method, which is also largely controllable, utilizes water that is either pushed down or lifted up by a propeller current. This current is produced in a cylinder or placed in a carrier which is moved over the bottom.

Agitation dredging will under favourable condition prove more economical than other methods. Environmental problems may arise, but they can usually be overcome by proper controls.

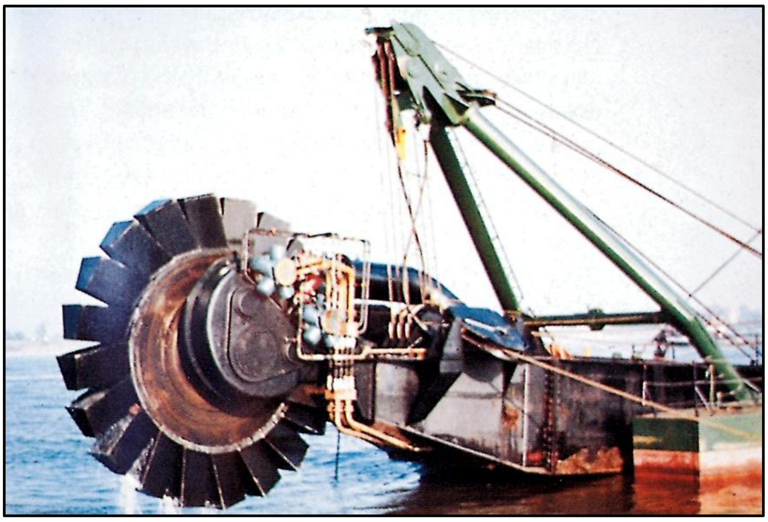


Figure 8.5 Bucket Wheel dredger

8.3 Disposal of Dredged Material

While dredger operators primarily focus on optimizing equipment performance and operational efficiency, the selection of disposal sites and the management of dredged material require active involvement of coastal and hydraulic engineers. The choice of a disposal ground must balance operational economy with environmental safeguards. Ideally, disposal areas should be located close to the dredging site to minimize transport time and cost; however, they must also be chosen to ensure that re-deposition of material into the dredged channel or harbor basin is avoided.

Since currents, tides, waves, and seasonal variations strongly influence the spread of discharged material, predictive modeling of sediment transport under different conditions is essential. In addition, the type of dredger and available transport means also influence disposal strategies. For example:

- A disposal ground at sea may be most suitable, but small hopper barges may be unable to reach it safely.
- Floating pipelines may face stability issues under high wave conditions, requiring disposal in sheltered areas.
- Tidal patterns in estuaries and creeks can be used advantageously, allowing selective disposal during ebb or flood tides.

The material's properties also dictate its reuse potential. While clays and silts are generally unsuitable for reclamation due to weak geotechnical strength, coarse material like sand is highly sought after for redevelopment projects, beach nourishment, and land reclamation. Therefore, different disposal strategies may be adopted even within the same port, depending on reach-specific soil composition and hydraulic conditions.

Each port or project presents unique disposal challenges, shaped by local wave climate, currents, sediment types, and development requirements, underscoring the need for a site-specific disposal strategy rather than standardized generic approaches.

Recommendations for Disposal

1. All countries should adopt and enforce controls designed to eliminate or minimize water pollution at its source as early as practicable.
2. Countries are encouraged to ratify and implement international conventions (e.g., London Convention/Protocol, MARPOL) and strengthen them locally to suit regional needs.
3. Each dredging and disposal project should be assessed on site-specific merits, as universal numerical criteria often fail to reflect local environmental realities.
4. Disposal approvals must consider transboundary impacts, taking into account potential effects on neighboring countries.
5. Continuous efforts should be made to improve forecasting, modeling, and monitoring of environmental changes resulting from dredging and disposal.
6. Research should focus on the soil-water interaction processes, sediment plume behavior, and ecosystem recovery dynamics.
7. Dredging equipment should be progressively automated and modernized to reduce environmental impacts, with special emphasis on noise abatement, fuel efficiency, and adaptive operational modes.

8. Selection of disposal areas must account for:
    - Disposal capacity and site size
    - Effluent characteristics
    - Levels of pollution
    - Presence of resident or transient marine flora and fauna
    - Human health and safety
    - Final land use and ecosystem impacts
9. Effluents from contained disposal facilities (CDFs) should be treated where pollution levels warrant intervention.
10. National regulations should explicitly recognize and control potential damage to highly productive wetlands from dredging, filling, or disposal activities.
11. Dredging for minerals and other near-shore resources should be subjected to strict environmental controls, ensuring long-term sustainability.

8.4 Dredging and Quay Design

The design of a quay depends on multiple interrelated factors, including required navigational depth, tidal range, vessel type, ground levels prior to dredging, seabed soil characteristics, relative costs of construction materials and labor, and availability of construction equipment. Dredging requirements and tolerances must be carefully coordinated with quay wall design to ensure stability, long-term performance, and cost efficiency. The four common types of quay construction are given below.

8.4.1 Open Pile Structures

For open pile quay structures, dredging is generally undertaken before pile installation, as forming the side slopes and dredged profile afterward is highly impractical. To accommodate future deepening requirements, the front row of piles must be driven or cast to adequate depths to ensure stability at the lowest planned dredge level. Similarly, the dredged slope should be cut to suit the ultimate design depth.

- In **hard ground**, the dredged toe is formed at the required depth from the outset. Over-dredging or fracturing must be avoided, as this can necessitate deeper piles.
- In **soft ground**, the slope toe will naturally adjust as additional dredging is carried out later.

Dredging tolerances are not usually critical in soft soils but require strict control in hard strata.

8.4.2 Caissons

Caissons are large watertight structures sunk through soil or water to form quay foundations or berthing faces. Different caisson types impose specific dredging requirements:

- **Open pneumatic caissons** and **monolith caissons** are open at the base, allowing dredging from within during sinking. They may be installed before basin dredging or manoeuvering areas are created.
- **Box caissons**, closed at the base, require a prepared seabed with uniform, compacted material. Dredging to form a level foundation bed must be completed prior to positioning.

Frequently, additional dredging around caissons is performed after installation, particularly in sheltered conditions where dredgers can operate efficiently to remove hard material. When caissons are used as a berthing face, they must be seated no higher than the deepest designed dredge level to prevent undercutting.

8.4.3 Sheet Piles

Sheet pile quay walls are widely used when it is necessary to retain backfill material behind the berthing face. Piles are driven before dredging begins, with careful consideration of:

- The maximum dredge depth, including allowable over-dredging tolerances.
- The embedment depth of pile toes, which directly affect wall stability.

Key precautions:

- Dredging alongside pile walls must be closely supervised. Over dredging can compromise the stability of the structure.
- If toe elevations are too low or soils unsuitable, original material may need to be removed and replaced with engineered fill before sheet piles are driven.
- In cases where backfill levels are insufficient to anchor piles, partial filling and anchorage must be established before dredging proceeds.

8.4.4 Diaphragm Walls

Diaphragm walls are reinforced concrete walls constructed within excavations supported by betonies or polymer slurry. This method requires soils capable of standing temporarily when supported by slurry. After the slurry-supported trench is cast with concrete, it forms a strong retaining wall suitable for quay construction.

In this case, dredging of the berth is carried out after the wall has been completed. Because diaphragm walls act as retaining structures, over-excavation below the dredged level is unacceptable, as it directly affects stability. The wall must be designed for the lowest planned dredge level, including tolerance for over dredging.

In sites where original ground is below water level, diaphragm wall construction may involve reclamation:

- The seabed is temporarily raised using hydraulic or other fill within a bund.
- The wall is cast in the reclaimed area at working level.
- After curing, the fill seaward of the wall is removed to restore berthing depth.

8.5 Present Dredging Scenario in India

India’s dredging scenario is a critical component of its maritime and coastal infrastructure management, characterized by extensive operations across major ports, intermediate ports, fisheries harbors, and urban flood mitigation schemes. In the 12 major ports, approximately 58 million cubic meters of dredging is undertaken annually, driven by both capital and maintenance dredging needs. Capital dredging, essential for new development projects, involves millions of cubic meters and primarily relies on Trailing Suction Hopper Dredgers (TSHDs) with hopper capacities of 4,500 cubic meters or more, valued for their high dredging rates and ability to operate in challenging conditions like waves and strong currents. Cutter Suction Dredgers (CSDs) are also widely used for capital dredging, while maintenance dredging predominantly employs TSHDs for their efficiency and access to distant disposal grounds. Additionally, CSDs with barges and grab dredgers are common for maintenance and improvement works near port structures. To prevent re-entry of dredged material into deepened areas, ports adhere to designated disposal grounds. However, dredging requirements vary significantly due to the diverse physiographical setups of ports, ranging from Tuticorin Port with minimal dredging needs to Calcutta-Haldia, where even 20 million cubic meters annually falls short of demand For intermediate ports, fisheries harbors, and urban flood mitigation schemes, dredging operations are typically smaller in scale and rely on CSDs with pipelines for disposal on beaches or land, alongside grab dredgers and proclainers for land-based disposal. Barges are rarely used due to operational challenges, such as limited availability and difficulties in navigating surf zones. Beach nourishment programs, though uncommon in India and often tied to nearby dredging projects, utilize CSDs with pipelines, as barge-based nourishment faces similar constraints. Coastal inlet improvement schemes also depend on CSDs with pipelines, but operations in shallow bars or surf zones are hampered by frequent equipment breakdowns, limited effective dredging time, and environmental challenges like large wave action. Fixed structures, such as piled trestles with sand pumps, have proven largely ineffective due to land-locking or wave-induced damage. Overall, India's dredging landscape reflects a blend of advanced technology and localized solutions, with ongoing challenges in equipment reliability, environmental management, and adapting to diverse coastal conditions.

8.6 Prevailing Conditions at the Major Ports of India

There are 12 Major Ports in India, six on the west coast and six on the east coast of India as shown in Figure 8.6.

Figure 8.6: Locations of the Major Ports in India (Courtesy: Google Earth)

Deendayal Port (Formerly known as Kandla Port)

The Kandla creek, along the west bank of which the present major port is located, has been maintaining the depths more than 10m below CD for more than 50 years and no major dredging was required to be carried out despite strong currents and some bathymetry changes. However, in the approaches to Kandla creek, the natural channel and shoal systems undergo very large scale changes due to the prevalent strong tidal flow conditions and for maintaining even 4.6 m depth below CD in critical region in the approach channel viz, Sogal channel, annual dredging of about 3 Million cum is required to be done in a reach of 2.3 km length. The dredging requirement of other part of the approach channel of about 23 km length is generally very marginal. The maintenance dredging in this critical reach, which is crossed by ships only at high water conditions, is required to be done continuously by deploying TSHD of 4500 cum hopper capacity. The reasons for siltation in the critical reach, its prevalence along only one edge and overall stability in other reaches are well established. The bed material encountered is fine sand which does not disperse after disposal and use of agitation dredging is difficult.

Mumbai and Jawaharlal Nehru Ports

These ports are located along the west and east banks of Thane creek respectively. The approach channel is maintained at –15 m by carrying out dredging once in four years. The advantage of natural tidal flow in maintaining the depths in the main channel has been taken by both these ports. The cross approach channels to various docks of the Mumbai Port, however, requires annual maintenance dredging. The annual maintenance dredging for the cross channels is about 2.5 Million cum whereas average yearly dredging in the main channel works out to equivalent of 1.2 Million cum and for all these TSHD is mainly used. In the recent years, use of water injection dredgers has been resorted mainly for improvement of depths along the berths along the docks. Water injection technique has also been used by M/s Mazgon Dock Ltd. for taking out the ships. Water injection technique has been used in the adjacent naval dockyards as well. Strong tidal currents adjacent to these areas and fine nature of the sediments would be the main reasons for successful use of this technique. In addition to above dredging is being done by the grab dredgers in the isolated pockets for the coolant water intakes of refineries. The dredged material is disposed at the main disposal ground specified by the Mumbai Port Authorities. Long turn-around time of the dredgers due to the distant disposal ground is one adverse aspect of dredging in the region.

In the case of JNPT, the regions near the port structures are not required to be maintained due to strong currents but some maintenance dredging requirement is in the cross channel Open water disposal at the designated site selected based on detailed studies is being resorted to for both the ports.

Mormugao Port

In the case of Mormugao port the depths of 13.7 m are maintained below CD in the 5 km long approach channel and 13.1 m in the major operational area of the port. The annual dredging requirement of this port is about 2.9 Million cum for which TSHD is used. The siltation in the dredged areas which consists of mainly clayey and silt, occurs mainly during the SW monsoon season. The disposal site is located at –14.7m contour, decided with the detailed studies. Maintenance dredging operation is completed within 2 months spell after SW monsoon season.

New Mangalore Port

This artificial lagoon type of port is connected by channel of 7 km length. The depth of –15.4 below CD is maintained in the channel and –15.1 m in major part of the port basin. The annual maintenance dredging requirement is about 6 Million cum out of which 4.3 Million cum is in the approach channel and rest in lagoon. The disposal ground is located on the south side of the outer channel at -25 m depth contour. Formation of very small hard patches is noticed on the side slopes which are due to mixture of sand / clay / silt and require special efforts by TSHD.

Cochin Port

The Cochin port is located in the estuarine backwaters where depths of about 12 m are maintained and the long approach channel of 10.5 km length with bed levels of 11.8 m have been provided. The annual maintenance dredging requirement at the port is about 12 Million cum. The siltation occurs not only during SW monsoon season but also during the non-monsoon season as well. Therefore, even though major dredging activity is carried out after SW monsoon season, some dredging is continued even thereafter. A new concept of 'Assured Depth' has been introduced by the Cochin Port in 2000-2001 for dredging to get the benefit of maximum depth. The siltation mainly occurs due to settlement of the suspended sediments crossing the approach channel and settlements in the backwaters and is of clay / silt with considerable flocculation effects.

V.O. Chidambarnar Port (formerly known as Tuticorin Port)

Due to absence of beaches and the littoral drift, the siltation in the Tuticorin Port is almost negligible even in the port basin protected by the long breakwater or in the approach channel. Due to existence of rock on the seabed, the main problem occurs during the capital development like deepening.

Chennai Port

Chennai Port has been created on open coast subjected to large littoral drifts by constructing breakwaters for enclosing the required port / harbour basin and its development have resulted in major shoreline changes over the last century. The main mechanism causing siltation is due to crossing of the littoral drift which is mainly from south to north. The main maintenance dredging requirement is in the sand trap and outer channel and is about 1.20 Million cum / year. The requirement of the droughts is met by dredging in the sand trap area on the east side of the outer breakwater or in the channel and very small quantities are required to be dredged from the dock area. The sand trap is dredged intermittently and the material is disposed off in deep sea rather than on the northern downdrift side beach. Due to progressive accumulation of sand on updrift side shoreline has advanced and siltation in the sand trap is increasing.

Visakhapatnam Port

The main mechanism causing siltation is in the outer harbour and is due to littoral drift from south to north. The total dredging requirement is about 1.2 Million cum / year. Major part of it is handled by using a sandtrap adjacent to the western tip of the south breakwater. The dredging of about 0.2 to 0.4 M.cum / year is being carried out in the sand trap by using TSHD and disposed off for nourishment of the beach on the north side. Rest of the material is disposed in sea at about –30 m contour. The length of the approach channel at Visakhapatnam is 2.6 km and the depth of 19 m is being maintained. The case of Visakhapatnam is an excellent example of regular maintenance dredging and the sand is used for beach nourishment optimally to ensure stability of the downdrift beach despite large rate of littoral drift in the region, by taking holistic approach.

Paradip Port

The length of the approach channel at Paradip is 2 km where the depth of -12.8 m is maintained. The annual maintenance dredging quantity at Paradip is about 2.5 Million cum, most of which is due to littoral drift from south to north. In the event of cyclones, enhanced siltation rates have been noticed. Due to inadequate bypassing of the sand to the northern shore, considerable erosion has occurred and the long sea wall has been provided to protect the coast. Effective dredging in the sand trap and bypassing to the northern shore are the main challenges for the dredging.

Calcutta-Haldia Port

These ports being located in the Hooghly estuary are required to be approached through very long approach channel within the estuary. The total length of the channel being 230km up to Calcutta and 80km upto Haldia. The approaches are marked by very shallow and unstable regions with prevalent shifts in the natural channel. The ruling depths in approaches to Calcutta on such shallow regions has been less than 3 m whereas in the approaches to Haldia, it has been less than 4m. Despite increasing the dredging to more than 15 million cum / year, no adequate increase in the depths of the channel had been achieved. This channel is therefore used by taking advantage of the increased water level at the high tide. Large scale re-shoaling rate has been the main menace for not achieving the desired depths in the navigation channel. The disposal is generally done in the estuarine waters in the eastern part of the estuary, involving long haulage distances.

Kamarajar Port (Formerly Ennore Port)

This port located on the Coromandal coast, north of Chennai on the east coast of India., This port is capable to handle large capsize vessels. Existing approach channel length 3775m, 250m width at straight portion channel while 300m at bed portion of the channel, outer approach channel has depth about (-)23m (CD), inner approach channel has (-)22m depth wrt CD. The port handles cargo like Coal, LNG, Containers and multipurpose goods with coal being the primary item shipped. Maintenance dredging conducted annually below 1 million cum at Kamarajar Port.

CHAPTER IX

SALIENT FEATURES OF MAJOR PORTS IN INDIA - ROLE OF CWPRS

9.1 Major Ports in India: Salient Features

Along the Indian coastline there are presently 12 major ports, representing a combination of natural, lagoon, artificial, estuarine, riverine and open protected harbors, and together with more than 200 minor and intermediate ports they form the backbone of the nation's maritime trade. While in 1999–2000 the traffic handled at the major ports was 271.92 million tones, by 2024–25 this figure has surged to over 835 million tonnes, reflecting more than threefold growth in two and a half decades. The major cargo components now comprise Petroleum, Oil and Lubricants (about 38–40%), coal (22%), containers (nearly 20%), and iron ore and others accounting for the rest, with container traffic growing at the fastest pace. At present, Deendayal (Kandla) Port and Paradip Port lead in total cargo traffic by crossing 140–150 million tones each, while Jawaharlal Nehru Port Authority remains the largest container hub handling over 6.5 million TEUs annually, followed by Chennai, Visakhapatnam and Cochin. The overall vessel traffic has also expanded from 15,462 vessels in 1999–2000 to over 23,000 vessels handled annually by 2025, supported by more than 260 modern berths, liquid cargo terminals, mechanized coal and iron ore handling systems, and upgraded draft depths of 14–18 metres to accommodate larger ships. Dredging requirements have similarly grown, with ports like Kolkata–Haldia and Paradip incurring the highest dredging expenditure in recent years due to heavy siltation. Financially, the major ports, whose total income in 1999–2000 was barely ₹4,049crore, now generate over ₹22,000 crore in revenues with a rising net surplus, enhanced further after the implementation of the Major Port Authorities Act, 2021 which conferred financial autonomy and operational flexibility. Minor and intermediate ports have witnessed remarkable expansion as well, with their combined traffic exceeding 600 million tones in 2024–25, surpassing the traffic at central government–owned major ports, with Mundra in Gujarat emerging as India's busiest port handling more than 160 million tones alone. Gujarat continues to dominate the minor port sector with roughly two-thirds share of total non-major port traffic. The development of these ports is propelled through flagship initiatives like the Sagarmala Programme and Maritime India Vision 2030, which integrate port-led industrialization, logistics efficiency and cargo diversification.

Research and technical input provided by the Central Water & Power Research Station (CW&PRS), Pune, remain crucial, as advanced studies are carried out in areas such as wave tranquility, berth alignment, breakwater design, morphological impacts, dredging methodologies, siltation estimation and littoral drift, supporting sustainable port expansion and planning of future port infrastructure across India. Role of CWPRS in Development of Ports and harbours sector is vast and historical growth and coastal engineering facilities available at the research station are given below in brief.

LOCATION AND TOPOGRAPHY: MAJOR PORTS

Port	Latitude	Longitude	Distance from Harbour Entrance (km)	Min Depth (m)	Min Width (m)	Turning Circle (No.)	Turning Circle (Diameter m)	Type of Dock/Port
Calcutta	22°33'N	88°19'E	232	3	200	2	190 / 288	Riverine with impounded docks and river side jetty
Haldia	22°02'N	88°06'E	115	6.7	467	1	549	Riverine
Paradip	20°15'N	86°40'E	2	12.8	160	1	520	Artificial lagoon port
Visakhapatnam (IH)	17°41'N	83°18'E	2.2	10.7	94–122	1	366	Natural harbour
Visakhapatnam (OH)	17°41'N	83°18'E	0.4	17.5	200	1	610	Natural harbour
Chennai (IH)	13°06'N	80°18'E	6.7	18.6	192	1	548	Artificial harbour with wet docks
V.O. Chidamba-rnar Port	8°45'N	78°13'E	4	10.4	162	1	488	Artificial harbour
Cochin	9°58'N	76°14'E	10.5	11.8	185	2	260	Lagoon port
New Mangalore	12°55'N	78°48'E	7.5	15.4	245	1	570	Artificial lagoon port
Mormugao	15°25'N	73°47'E	5	13.1	250	2	480	Open protected harbour
Mumbai	18°54'N	72°49'E	9.6	10.9	366	1	366	Natural harbour with impounded wet docks
JNPT	18°56'43"N	72°56'24"E	17	11	350	1	600	All-weather tidal port (Bulk berth south-west)
Kandla	23°01'N	70°13'E	25	4.6	200	-	-	Estuary port
Vadinar (OOT)	-	-	8	23.5	1500	-	-	Offshore Oil Terminal (Single buoy mooring system)

NUMBER OF BERTHS AVAILABLE
(Based on Re-assessment of Existing Port Capacities)
As on 2025

Port	POL & Other Liquid	Iron Ore	Coal	Fertilizer	Container	Gen./ Break Bulk	Total (Approx.)
Kolkata–Haldia (SMPK)	15 (including liquid jetties)	2	4	2	6	18	47
Paradip	6	4 (mechanized)	6	2	1	5	24
Visakhapatnam (VPA)	6	3	4	1	2	12	28
Chennai	4	1	2	1	7 (incl. private terminals)	10	25
Tuticorin (VOCPA)	3	-	3	2	4	10	22
Cochin	4	-	2	1	4 (ICTT Vallarpadam + feeders)	8	19
New Mangalore	7 (incl. petroleum & LNG)	1	2	1	1	8	20
Mormugao	2	3 (ore handling modernised)	2	-	1	4	12
Mumbai	7 (liquid + offshore jetties)	-	2	1	2	25	37
JNP	4 (incl. BPCL & liquid cargo jetty)	-	1	-	15 (incl. DP World, APMT, PSA Bharat)	3	23
Kandla (Deendayal)	8 (incl. SBM & OOT Vadinar connectivity)	2	3	2	3	15	33

TRAFFIC IN TERMS OF BROAD CATEGORY OF CARGO (in 000 Tonnes)

Port	Period	Dry Bulk	Liquid Bulk	Break Bulk	Container	Total Tonnage
Calcutta	1999-2000	-	70	6,199	1,927	10,313
	2023-2024	6,500	400	8,000	6,000	20,900
Haldia	1999-2000	4,462	3,207	11,678	932	20,713
	2023-2024	7,000	4,500	12,000	1,500	25,000
Paradip	1999-2000	2,640	7,846	3,018	132	13,636
	2023-2024	15,000	25,000	10,000	3,000	53,000
Visakhapatnam	1999-2000	7,206	14,145	15,946	262	39,510
	2023-2024	10,000	30,000	25,000	4,000	69,000
Chennai	1999-2000	6,259	14,364	11,613	1,230	37,443
	2023-2024	15,000	30,000	15,000	10,000	70,000
Tuticorin	1999-2000	3,580	2,129	986	1,665	9,993
	2023-2024	10,000	8,000	4,000	3,000	25,000
Cochin	1999-2000	359	386	10,217	588	12,797
	2023-2024	500	2,000	15,000	1,500	19,000
New Mangalore	1999-2000	6,680	727	9,589	605	17,601
	2023-2024	12,000	1,500	15,000	1,500	30,000
Mormugao	1999-2000	14,013	2,456	1,334	373	18,226
	2023-2024	20,000	4,000	2,000	500	26,500
Mumbai	1999-2000	-	913	18,582	4,761	30,413
	2023-2024	1,000	2,000	20,000	6,000	29,000
JNPT	1999-2000	1,287	691	2,171	147	14,975
	2023-2024	3,000	1,500	4,000	7,300	15,800
Kandla	1999-2000	-	4,223	38,002	2,944	46,303
	2023-2024	1,000	12,000	60,000	4,000	77,000
Total	1999-2000	46,486	51,757	1,29,335	16,655	2,71,923
	2023-2024	1,20,000	1,40,000	2,00,000	85,000	5,45,000

9.2 Role of CWPRS for development of Ports and harbours

The Central Water and Power Research Station (CWPRS), Pune, an apex Research and Development institution in the field of hydraulics and allied studies, has been serving the nation for over a century. Guided by its motto *"Service to the Nation through Research"*, CWPRS has played a vital role in the safe and economical planning and design of water resources structures covering River Engineering, Hydropower, Ports and Waterways projects.

The Coastal Engineering activities at CWPRS began in 1947, focusing initially on port navigability, estuarine training, and wave tranquility studies for ports such as Kolkata, Kandla, Visakhapatnam, Mangalore, and Chennai. With the establishment of the Tidal Hydraulics Division in 1958, studies expanded to include salinity intrusion, coastal erosion, and harbour development. The rapid growth of Indian ports during 1960's led to the creation of the Maritime Structures Division, focusing on the design and optimization of breakwaters, jetties, seawalls, and sediment management systems.

With the advent of computer-based modelling, CWPRS established strong mathematical modelling capabilities, complementing its physical laboratory expertise and grown as one of the most advanced Coastal & Offshore Engineering Laboratories in Asia,

The details of Laboratory facilities are given below;

3-D Wave/ Tidal physical models

- Chennai Port Model
- Visakhapatnam Port Model
- New - Mangalore Port Model
- Kamarajar (Ennore) Port Model
- Project Varsha Model
- Murmugao Wave Model
- Deendayal Port Tidal Model
- Mumbai & JN Port Model
- Cochin Port Model
- Kalpasar Project Model

General Facilities

- Multi-Purpose Wave Basin equipped with RSWG and SCDA Facility
- Multi-Purpose Tidal Basin equipped with ATG and SCDA Facility
- Random and Regular Sea Wave Generation Flumes

Mathematical Modelling Software:

- **MIKE 21 / MIKE 3** (2D and 3D hydrodynamics, sediment transport, wave modeling)
- **HEC-RAS, TELEMAC 2D, and SMS** for flow, sedimentation, and shoreline simulations

Broad Areas of Expertise

CWPRS undertakes end-to-end studies/ services for the Development of Ports and Harbours, including:

- Hydrodynamic modelling for berth/ channel alignment, reclamation impact, and siltation estimation
- Wave tranquility assessment in harbours
- Shoreline evolution and coastal protection design
- Ship motion, mooring, and navigation simulation
- Storm surge, wave hindcasting, and flood inundation mapping
- Determination of safe grade elevations and storm resilience
- Optimization of structures through integrated physical–numerical modelling
- Field data acquisition for waves, currents, tides, and bathymetry
- Thermal Dispersion modelling for cooling water intake and outfall locations

Significant Contributions

Visakhapatnam Port, Andhra Pradesh

- Physical and mathematical model studies for outer harbour, FSRU, fertilizer berth utilization, sand trap relocation, and beach nourishment.

Mumbai and Jawaharlal Nehru Ports

- Studies for capital dredging, reclamation optimization, and FSRU development in Mumbai Harbour.
- Wave tranquility and flow modelling for the proposed Vadhavan Mega Port.

Other Major and Minor Ports

- Comprehensive physical and numerical studies for Mormugao, Chennai, Kamarajar, Cochin Port, Paradip, JNPT, Mumbai Port, New Mangalore, and Deendayal Ports.
- Design optimization and flood corridor studies for a mega coastal project in Andhra Pradesh.
- Wave tranquility, sedimentation, and reclamation design for Tuticorin (VOC Port) and Ratnagiri.
- Development of Kalpasar Project (Gujarat) through an innovative 1:40 scale hybrid model integrating dam spillway and downstream wave basin.
- Model studies for Mumbai Trans-Harbour Link, JNPT container terminals, and Navi Mumbai International Airport.
- Coastal stabilization and wave tranquility studies at Shrivardhan, Mulagaon, and Anjarale fishing harbours and so many.

Through its rich legacy of scientific innovation and applied research, CWPRS continues to play a pivotal role in India’s port sector development. By combining physical modelling, numerical simulations, and field expertise, CWPRS provides reliable, site-specific solutions to complex coastal challenges. Details of studies conducted for major ports and benefits obtained there from are given below;

DEENDAYAL PORT, GUJARAT

Background

The Deendayal Port is located at the head of Gulf of Kutch along a tidal creek known as "Kandla creek" in the state of Gujarat. The Kandla creek is 140 km inside the gulf from the entrance. The region is dominated by high tidal range and strong tidal currents though wave disturbances in the approaches to Kandla creek are not much significant. The port is of strategic importance and is the nearest Indian port from the Middle East and Europe.

Studies Conducted

- CWPRS was approached for advice on various hydraulic related issues such as alignment of berths and jetties in Kandla creek, alignment and siltation of approach channel, dredging and disposal strategies in the approaches.
- The Physical tidal model (scale: 1/1000H and 1/100V) of Kandla estuary is used to study the flow conditions and patterns under different tidal conditions in the approaches to Kandla creek for assessment of siltation and to suggest dredging and disposal strategies.
- Additional Physical tidal model (scale: 1/300 H: 1/50 V) of Kandla creek is used to study flow conditions during flood and ebb tides to suggest suitable alignment of berths and jetties.
- Mathematical models are also setup using MIKE-21, HD/MT for studying tidal hydrodynamics, assessing the quantity of maintenance dredging and location of disposal grounds etc.

Location of Deendayal Port

Deendayal Port Model

Outcome and Benefits

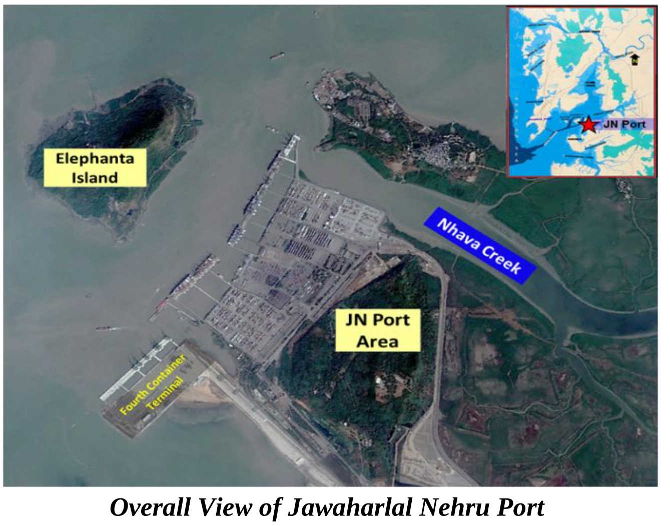
- As per the advice of CWPRS, the depth along the navigational channel at Deendayal Port has improved significantly to (-) 8.5m below Chart Datum from earlier (-) 3.5m and the port now caters to ships of upto 14.m draft
- The strategy of shifting the channel and identifying the critical reach of siltation has yielded very fruitful results. The annual maintenance dredging was correctly assessed as 7.0 Million cum.
- With the help of hydraulic model studies, it was possible to align the cargo berths and the oil jetties without significantly affecting the morpho-dynamics of Kandla creek. The port has 12 cargo berths to accommodate vessels of 11 m draft till recently. Now 4 more berths are being added to cater to vessels of 14 m draft. Apart from these, the port also has six jetties to cater to oil and liquid cargo.

Deendayal Port

JAWAHARLAL NEHRU PORT, MAHARASHTRA

Background

The Jawaharlal Nehru Port (JNP), a natural major port of India, is situated in Thane creek on the west coast of Maharashtra. The development of JNP was proposed as the port of Mumbai got congested due to significant increase in vessel traffic by mid 1970s. The location for port in front of Elephanta Island near Nhava-Sheva creek in Thane creek was identified such that the natural deeper depths in channel are available with minimum expenditure on capital dredging and no construction of breakwater was required for wave tranquility. The port facilities are being developed in stages to cater to the increasing demand of container traffic and presently it is the premier container port of India handling about 4.8 Million TEUs containers/annum. The depth of 14 m below CD is maintained by port as Phase-I deepening in main channel to allow smooth entry of 5th generation container carriers with the aid of tidal window. The Phase-II deepening of channel up to -16m is in progress. JNP has recently completed development of 2 km long mega container terminal known as Fourth Container Terminal (FCT) to increase its container handling capacity up to 10 Million TEUs.

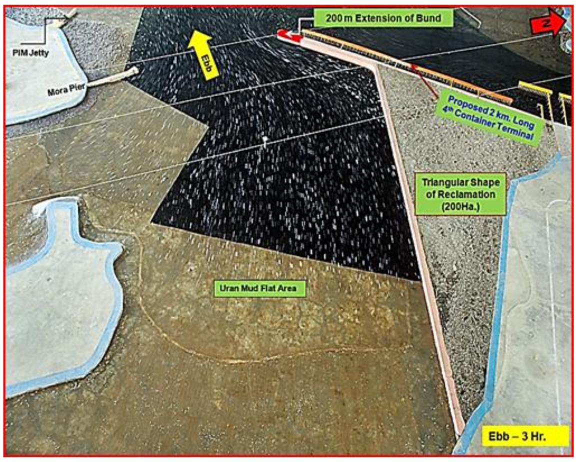


Overall View of Jawaharlal Nehru Port

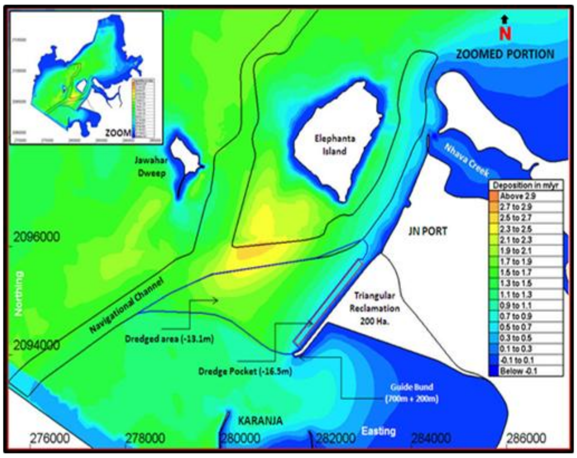
Studies Conducted

The well calibrated physical tidal model of the Mumbai Port constructed to a scale of 1:400 (H) and 1:80 (V) at CWPRS in association with mathematical model (Telemac software) are in use to study the various developments under consideration.

- More than 50 model studies including field investigations were carried out by CWPRS for JNP since its inception.
- Studies for Master plan development for the expansion of port were also carried out.
- Aspects such as alignment of jetties/berths,effect of shape of reclamation on the surroundings,alignment of navigational channel, design of channel cross sections etc, were studied and finalised to achieve safe navigation and berthing/de-berthing of shipping vessels at JN Port.
- The optimal alignment/length of guide bund to achieve desired flow conditions at container terminal proposed at the confluence of Nhava creek and Elephanta Deep was evolved considering the effect of reclamation in Nhava creek.
- The estimation of likely rate of siltation in navigational channel, berth pockets etc. to assess quantum of maintenance dredging was carried out using mathematical model.
- Since the capital dredging of main channel up to (-)16 m below CD was proposed by JNP in two phases, wherein the dredging quantity is about 85 Million m^3, the locations for disposal of dredged material were finalised based on the dispersion studies carried out using mathematical model.



Effect of Reclamation on Flow-Physical Model (FCT)



Estimation of Siltation- Mathematical model (FCT)

Outcome and Benefits

- The CWPRS studies provided optimum alignment/orientation of berths and navigational channel as well as effect of proposed developments on nearby waterfront structures.
- The dispersion studies provide environment compliant viable location of dumping grounds for the safe disposal of dredged material resulted from capital and maintenance dredging.
- The alignment & orientation of guide bund at the confluence of Nhava creek and Elephanta Deep wherein complex hydrodynamic flow conditions prevail was evolved to develop a new container terminal and it also allows safe movement of fisher folks in and out of Nhava creek.
- Recently, alignment of 2 km long mega container terminal along with suitable shape of 200 ha reclamation was evolved to have negligible impact on nearby waterfront facilities as well as to achieve smooth operability of container ships round the clock/year all along the entire berth length.
- The layout of various berths finalised through model studies carried out at CWPRS and constructed at JNP are operating smoothly without any interruption and the Port has achieved number one position in India in handling container traffic.
- No adverse impact of development is reported on surrounding area from morphological considerations.
- This has resulted in significant contribution of the Port in economic growth of the country by way of increase in export/import of goods.
- In near future the port will handle about 10 Million TEU container traffic at JNP.

Panoramic View of Jawaharlal Nehru Port

Background

Mumbai Port, one of the oldest British era ports of India, is situated in Thane creek on the west coast of India, on leeside of Salsette /Mumbai island. This is an all weather natural port and well protected from the fury of sea waves. The port has access to the Arabian sea through a navigational channel wherein tidal phenomenon is dominant with macro type of semi-diurnal tides having range of 5 m. The various marine facilities in the form of docks, jetties and oil terminals were built during pre-independence era. Since opening of Suez Canal in 1869, Mumbai Port had become the Principal Gateway to India and has played pivotal role in the development of the country's trade & commerce. The main docks viz. Indira, Princess and Victoria in use for berthing and ships, were plying towards deep waters of the Arabian sea by taking advantage of tidal window. After independence, various marine facilities like Oil berths at Jawahar Dweep, Chemical & POL berths near Pirpau, finalization of alignment of main navigational channel with its deepening/widening etc. were planned under master plan development. The various techniques such as field data measurements, physical tidal model (scale: 1/400 H, 1/80 V) and mathematical modeling, desk studies etc. were used to finalise the layouts/alignments of waterfronts, estimation of siltation at berths/channel, identification of dumping grounds for disposal of dredged materials. The port, however, has severe restriction in ship draft due to heavy siltation of the old Docks.

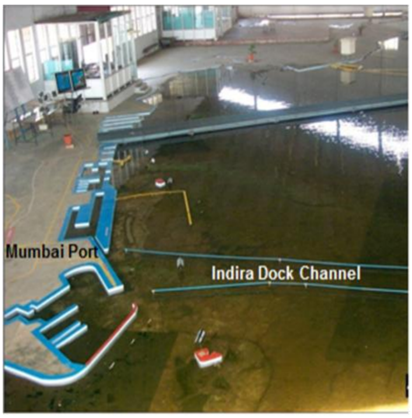
View of Mumbai Port

Physical Model of Mumbai Port at CWPRS (1953-1985)

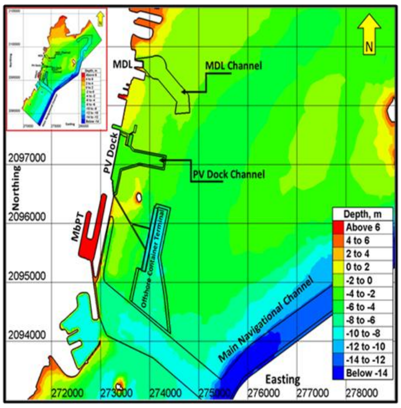
Studies Conducted

More than 150 studies were carried out since 1950s for the development of various marine infrastructures in Mumbai harbour using Physical and Mathematical modelling techniques.

- Field investigations for various oceanographic parameters were carried out to provide input data for simulation of prevailing flow phenomena in the models.
- Finalization of alignment of main navigational channel, berths/jetties and effect of reclamations on nearby waterfront facilities.
- Estimation of maintenance dredging quantity in navigational channel and at various waterfronts.
- Identification of dumping grounds for the safe disposal of dredged material.
- Both physical & mathematical (tidal/wave) models are being used as a hybrid modeling technique to finalise alignments of berths, navigational channel etc. in complex hydrodynamic regions.



View of Mumbai Port area on Physical Model(1985- till date)



Mathematical model showing Mumbai Port area

Outcome and Benefits

- The finalization of optimal alignment of navigational channel facilitated smooth movement of ships to and fro between port and the Arabian Sea along with significant reduction in siltation and thus appreciable decrease in maintenance dredging quantity.
- The appropriate alignment of marine facilities based on tidal/wave hydro dynamics, has simplified the herculean task of berthing/de-berthing of deep draft vessels at oil terminals near Jawahar Dweep as well as other ships at the port.
- In addition, predictions of reliable siltation in harbour by mathematical model studies provide guidance to the port authorities in planning and timely execution of maintenance dredging to enhance the operability of ships at berths.
- The shape of reclamations for various marine facilities like oil terminals, bunders etc. evolved through model studies does not have adverse impact on nearby waterfront facilities as well as on the marine environment.
- The suitable locations of disposal sites for dredged material resulted from capital/maintenance dredging are identified based on dispersion studies carried out using mathematical model studies. The material dumped at dumping/disposal site do not re-enter in to harbour area and in navigational channel.
- The comprehensive studies carried out provide the port authority a guidance to plan the future developments in the harbour area.

MORMUGAO PORT, GOA

Background

Mormugao Port is situated on the west coast of India at the entrance of Zuari estuary in Goa state. A breakwater of 525 m length and a mole of 270 m length were completed in 1930 and a total of seven berths were in operation till 1960s. The maximum draft of the vessels that could be accommodated at the berths was limited to 8.5 m. With the opportunities for large scale export of Iron ore it was considered necessary to develop the Port for big size ore carriers of 60,000 DWT size.

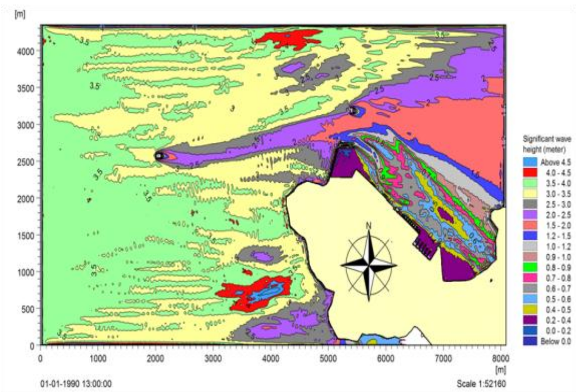
Studies Conducted

More than 80 studies were conducted since 1970 to cover the following aspects,

- Under stage-1 development in 1970s, it was proposed to dredge a 4km long approach channel to (-) 13.7 m; and construction of additional berths for iron ore export, oil berth, and a barge basin. An additional breakwater of 1000 m was proposed to provide wave protection to these berths. The CWPRS was approached to suggest suitable layout for Stage-1 development from the considerations of wave tranquility, flow conditions and siltation.
- Physical wave model (G.S.-1/100) was used to study wave tranquility conditions under the predominant incident wave conditions. Physical tidal model and mathematical models were utilized for studying hydrodynamic conditions, assessing the quantity of maintenance dredging, and location of disposal grounds.
- The challenges for the Stage-1 development were: ensuring adequate wave tranquility at the proposed berths as the port is exposed to direct waves from the Arabian Sea; assessment of the annual maintenance dredging against a capital dredging; identification of suitable locations of disposal grounds for capital as well as maintenance dredging under reversing tidal flow with prevailing wave climate.

Satellite Image Of Mormugao Port Region

View Of Mormugao Port Wave Model



Numerical Model results : Wave height distribution

Outcome and Benefits

- With the help of hydraulic studies at CWPRS, the ore, oil and barge basin were laid out in such a way that there was no need for additional breakwater for obtaining necessary wave tranquility at berths.
- The berths were laid along the existing water front and reclamation areas were created for storage of material and operation and, consequently, the hill cutting was avoided.
- The annual maintenance dredging was correctly assessed.
- Survey records show that all disposed material is transported to the deep sea in the north and no accumulation of the same is observed.
- CWPRS studies affected big savings in the project cost and eliminated recurring expenditure.

NEW MANGALORE PORT, KARNATAKA

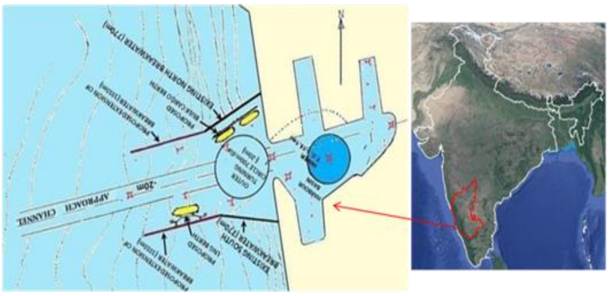
Background

New Mangalore Port is a deep-water, all-weather man made Lagoon type port at Panambur, Mangalore in Karnataka state of India. It is located to the north of confluence of Gurupura (Phalguni) river to Arabian sea. It consists of 7.5 Km approach channel, 570 m Turning circle with draft of 15.4 m & 15.1 m, two rubble mound type South & North Breakwaters each 770 m long.

Studies Conducted

More than 45 major studies during last 50 years covering the following aspects:

- The location of the site and initial planning of the port layout is based on model studies carried out at CWPRS. Initially, a physical model to scale 1:100 (GS) was developed.
- An important decision of port entrance facing west despite the waves being critical from this direction was taken after conducting many trials on this model. This decision helped in optimising the channel length for any given depth. It was very useful for further developmental stages of the port as well.
- A physical wave model having Random Sea Wave Generation system along with computerized Data Acquisition System was developed to a scale of 1:100 (G.S.) at CWPRS during 1994.
- A number of port expansion studies were conducted for the development of Southern Dock Arm berthing structure. Later, during 2004, model was upgraded by changing the scale to 1:120(G.S.) by simulating more areas for the developmental studies of Deep Draft Multipurpose Berth and Western Dock Arm.
- CWPRS was also involved in conducting a number of field studies including Radio Active Tracer studies for identifying disposal site for the dredged material.
- Mathematical model studies were carried for assessment of wave tranquility, tidal hydrodynamics, ship manoeuvring and ship mooring.



Location of New Mangalore Port

Physical Model : Testing for outer harbour development

Ship Moored at New-Mangalore Port

Outcome and Benefits

- Optimum alignment of approach channel normal to the bathymetry contours.
- Minimum length of breakwaters taking advantage of the phenomenon of wave attenuation along channel.
- Optimum alignment for various berthing structures under different stages of development.
- Identification of suitable disposal grounds for dredged material.
- Analysis and prediction of the formation of hard patches in the approach channel and suggesting preventive measures to avoid costly dredging activity

COCHIN PORT, KERALA

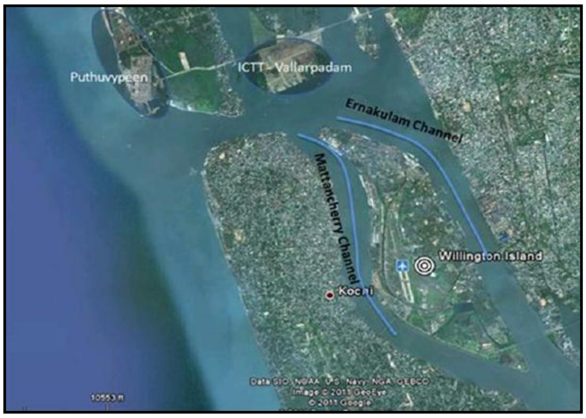
Background

Cochin port, an all weather port situated on the west coast of India, is located in the vast expanse of backwaters formed by confluence of two major water courses of the area viz. Vembanad Lake in the south and Periyar River in the north. Five different rivers from the south and two branches of Periyar River from the north debouch into the Arabian Sea through an opening in the shore called as Gut. Two peninsular lands Vypeen and Fort Cochin protect the harbour from waves approaching from the sea.

Studies Conducted

More than 50 major model studies including physical and mathematical models completed during last 70 years covering the following aspects.

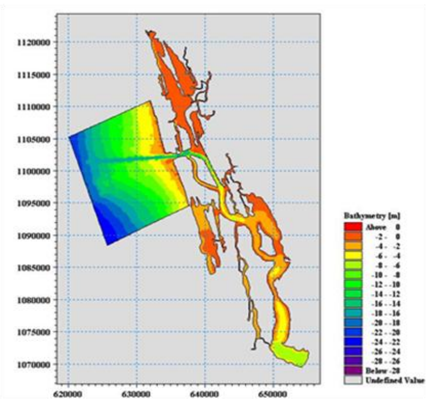
- Simulation of tidal currents of semi diurnal in nature on vertically distorted physical model on a scale of horizontal 1: 800 and vertical 1: 80 in 1984.
- The model is operated by computerized Automatic Tide Generated (ATG) system for the generation of tides in the model.
- Tidal reach of the model is up to prototype distance of 80 km to the south and up to 32 km to the north of Cochin Gut.
- Two dimensional mathematical model of Cochin port area with latest MIKE 21 Software.
- Reclamation of Ernakulam foreshore, extension of Willingdon Island.
- Location of fishing harbor, location of salt water barrier at Thaneermukkam.
- Location and alignment of naval jetties, siltation and maintenance dredging for Ship Lift System for Cochin Ship Yard Ltd.
- Alignment of super Tanker oil terminal jetty, oil jetties and 10 general cargo berth, ICTT at Vellarpadam and model studies for Master Plan Outer Harbour development.
- 3 D flow simulation for inner and outer harbour to arrive at measures for prevailing siltation in the harbour.



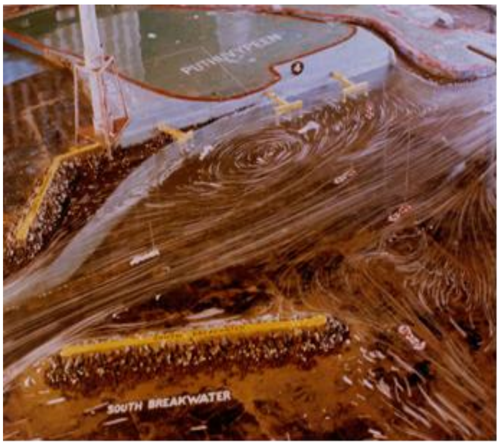
Cochin Port Layout

Outcome and Benefits

- Arresting salt water by construction of Thannermukkam salt water barrier
- Reclamation along Ernakulam shore
- Drydock facilities at Cochin Naval Base
- Berthing facilities for coastguard vessel
- Imact of ship lift system on port area
- Optimisation of outer harbour layout
- Optimization of dredging cost
- Finalising supertanker oil terminal
- Reclamation of Ship Lift System to have partly reclaimed soil and partly of RCC deck supported on piles for better flow conditions and less obstruction.



Numerical Model for Cochin



Physical Model for Cochin

V.O. CHIDAMBARNAR PORT, TAMIL NADU

Background

V.O. Chidambarnar Port (erstwhile Tuticorin Port) at Tuticorin in Tamil Nadu state is an artificial deep-sea harbour formed with rubble mound type parallel breakwaters projecting into the sea for about 4 km. The harbour basin extends to about 400 hectares of protected water area and is served by an approach channel of 2400 m length and 183 m width.

Studies Conducted

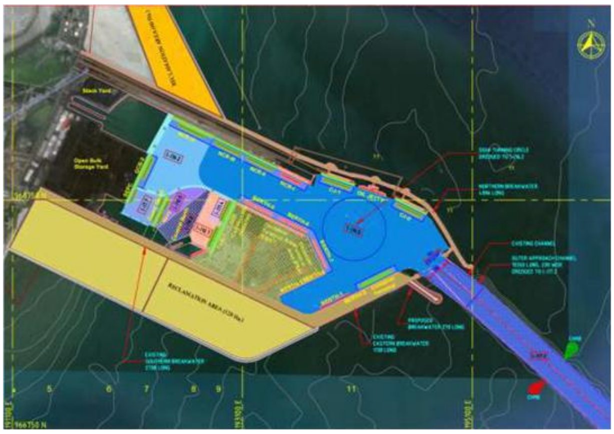
Physical model studies for wave tranquility for the development of Outer Harbour and Mathematical model studies were undertaken at CWPRS to study,

- Wave tranquility at different berths for the development of Port and also to assess the effect of reclamation
- Tidal hydrodynamics and estimation of siltation for the development of Port
- Desk studies for safe ship navigation and optimization of channel
- Desk studies for ship mooring analysis for proposed development of Port
- Desk and wave flume studies for the design of breakwaters.
- Desk studies for storm wave hindcasting.

Location of Tuticorin Port

Outcome and Benefits

- Layout of port structure for desired wave tranquility conditions
- Optimization of breakwater length and alignment
- Prediction of mooring configuration and selection of optimum fenders
- Assessment of ship motions and estimation of downtime at berth



Layout Plan of Port

Physical Model for Tuticorin

CHENNAI PORT, TAMIL NADU

Background

Chennai Port, the third oldest major port in the country, is located on east coast of India. At Chennai, maritime trade started way back in 1639. However, an artificial modern harbor was built and began operations during 1881. Located on the open coast, the port is vulnerable to the cyclones and high littoral drift prevailing along this region. The port has expanded from time to time with modern harbor facilities for handling the increasing traffic. Space restriction is a major constraint for further developments of the port; hence a satellite port was established at Ennore during 2004 to divert some traffic from this port.

Layout of Chennai Port

Physical Model of Chennai Port

The physical wave model of Chennai Port is in operation at the CWPRS from 1950. The model was upgraded from time to time to accommodate development studies. The model is constructed to a scale of 1:150(G.S.) with rigid bed with regular wave generation system for waves incident from North-East and South-East. Computerized multi-Channel data acquisition system is used for wave data acquisition in the model.

Studies Conducted on following areas (Since 1950 – till Date)

- Storms in the Bay of Bengal and their effect on Chennai (Madras) Harbour.
- Layout of berths along South Quay and layout of Oil Docks etc.
- Study of embankment for protection of Chennai (Madras) Harbour.
- Model Studies for Bharati dock.
- Problems during construction of breakwaters.
- Study of development of Outer Harbour.
- Tranquility studies for breakwater layouts.
- Tranquillity studies for all berths.
- Reclamation bund for ammonia plant.
- Harbor resonance studies in Bharati Dock
- Sand trap location and design.
- Groyne field establishment.
- Design of Breakwaters, Reclamation Bund
- Wave tranquility studies for Fisheries harbor development
- Optimization of extension of Fisheries harbor breakwaters by Random wave model studies

Chennai Port Physical Model

Wave tranquility studies with random waves

View of Chennai Port

Outcome and Benefits

- Optimization of breakwater alignment and length
- Prediction of siltation & quantum of dredging
- Location of dumping ground.
- Wave tranquillity in harbour basin.
- Alignment of breakwaters along with safe and economical design.

KAMARAJAR PORT, TAMIL NADU

Background

Kamarajar Port (erstwhile Ennore port) is located on the Coromandel Coast in Tamil Nadu state, about 24 km north of Chennai Port.. The Port was commissioned in June, 2001 with two dedicated coal berths for handling of coal for the thermal power stations of Tamil Nadu Electricity Board (TNEB). The Port has developed terminals through private sector participation to handle liquids, coal and iron ore.

Studies Conducted

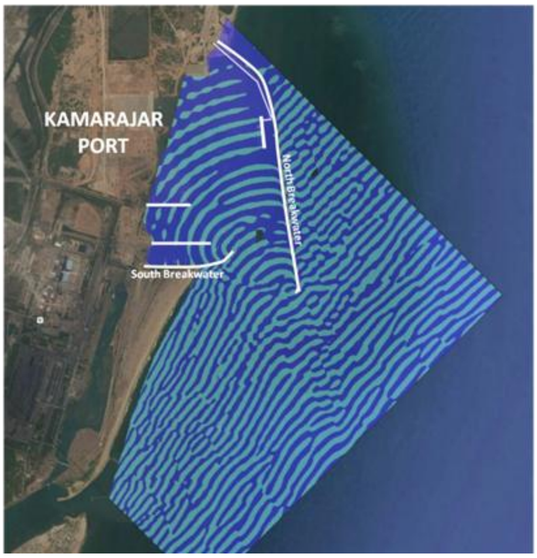
- Geometrically similar physical model on a scale of 1:120 (G.S.) to simulate random sea waves from South - East direction.
- Harbour development for LNG, VLCC berth for ships of 250,000 DWT.
- Assessment of Wave tranquility in Kamarajar Port using numerical model MIKE 21 SW and BW.
- Shoreline evolution due to development of the port.
- Ship manoeuvring studies to optimize the approach channel.
- Ship mooring studies.

Satellite Image of Kamarajar Port

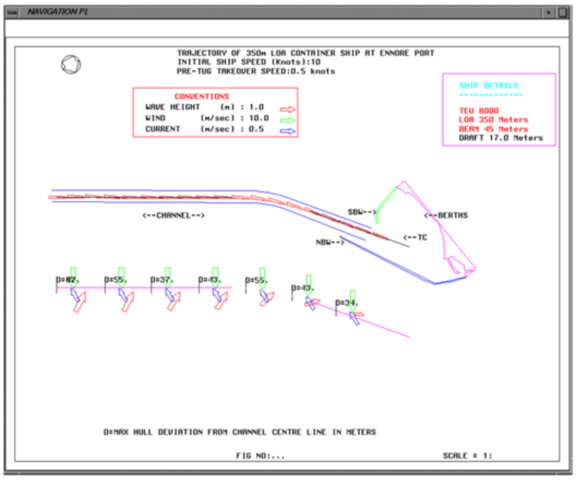
Outcome and Benefits

- Tranquility aspects at various berths and for phase wise development of port
- Navigation, Ship motions and mooring aspects of ships at berth.
- Disposal of dredged material and impact on coastal erosion
- Maintenance of breakwaters

Physical Model : Wave Propagation



Numerical Model : Wave Propagation



Numerical Model : Ship Manoeuvring

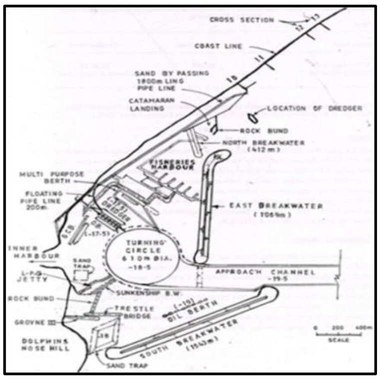
VISAKHAPATNAM PORT, ANDHRA PRADESH

Background

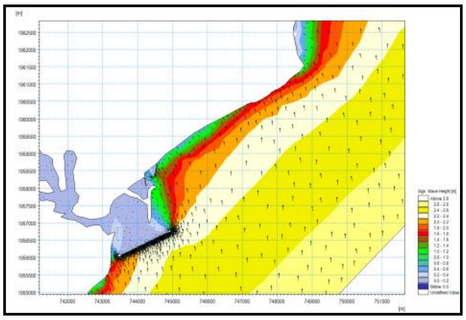
Visakhapatnam Port in Andhra Pradesh is one of the major ports on the east coast of India. Visakhapatnam port is developed in different stages as Inner Harbour and Outer harbour. River Meghadrigedda joins the harbour area on the western side at the Inner Harbour. Several Hydraulic model studies have been conducted at CWPRS right from the planning of Visakhapatnam port and for its stage-wise expansion.

Studies Conducted

- Design of optimum layout / breakwater system to achieve round-the-year tranquility at Ore Berth
- Configuration of sand trap to tackle littoral drift problem
- Sand-bypassing system evolving beach nourishment strategy to maintain dynamic equilibrium of down-drift coastline
- Design of groyne for separating Fisheries Harbour from Outer Harbour
- Studies for Off-Shore Tanker Terminal (OSTT) to achieve desired tranquility conditions with additional rubble lining to south breakwater
- Suitable extension of General Cargo Berth
- Studies for the alignment of LPG jetty
- Evolving type of structure for Multi-Purpose Berth / Container Terminal
- Reconfiguration of sand trap in view of the crude-oil pipe-line laid from Single Point Mooring system, achieving the best efficacy for trapping SW Monsoon drift
- Alignment and design of rock-bund for catamaran harbour basin
- Shifting of sand trap south of south breakwater for contemplated development by Indian Navy on southern side
- Design of suitable dredge pattern in the inner harbour to achieve suitable flow- dynamics
- Estimation of siltation in the Inner Harbour ascertaining the effect of deepening of streams debouching into the inner harbour
- Studies for the development of naval facilities evolving suitable scheme through physical and numerical models
- Radioactive tracer studies for identification of suitable dumping grounds
- Assessing impact of Hudhud Cyclone on Outer Harbour



Layout of existing outer harbour of Visakhapatnam Port



Numerical Model Study

Physical Model: Wave Propagation

Outcome and Benefits

Studies covering various aspects contributed in the optimum planning, execution and maintenance of various facilities and also helped in evolving suitable sites in connection with dredging and disposal strategies.

PARADIP PORT, ODISHA

Background

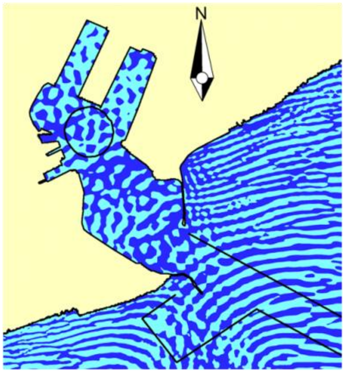
Paradip Port is situated on the East Coast in the state of Odisha, which caters to the large portion of the sea-borne trade of the eastern part of the country. This is an artificial Lagoon type protected from waves by two breakwaters viz. South breakwater with a length of 1217 m and a North breakwater with a length of 538 m commissioned in the year 1966. The wave climate during the southwest monsoon is more severe compared to the northeast monsoon season. Large wave action of about 3 to 4 m height occurs during southwest monsoon where as 2 m during northeast monsoon period, resulting in large quantum of littoral drift. The port has been developed in stages to accommodate increasingly bigger vessels of 1,25,000 DWT with 19 m draft.

Studies Conducted

More than 25 studies have been conducted on physical and mathematical models covering the following important aspects:

- Optimization of breakwater lengths and cross section for wave tranquility.
- Suitable alignment of berths
- Field studies for data collection on various coastal parameters.
- Prediction of Siltation and maintenance dredging.
- Studies for location of sand trap and nourishment of the northern shore.
- Development of fishing harbour.
- Mathematical model studies for outer harbour development, ship motion & siltation studies
- Development of Southern Dock

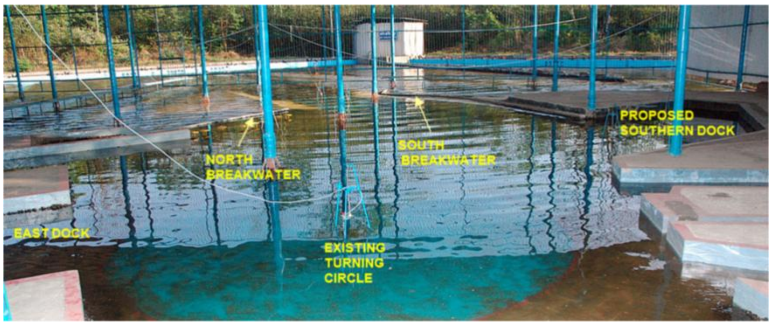
Location of Paradip Port



Numerical Model : Wave Propagation

Outcome and Benefits

- Optimizing the alignment & length of breakwater to provide necessary wave tranquility in harbour area and also evolved the location of Sand trap for minimizing the siltation in the harbour and approach channel
- Hydrodynamic studies using numerical models evolved the layout of southern dock, the rate of siltation in the harbour and approaches.
- Identification of location of sand bypassing and nourishment of northern shore
- Optimization of length of breakwaters
- Optimum alignment of berthing structures
- Alignment of southern dock



Physical Model : Wave Propagation

KOLKATA PORT, WEST BENGAL

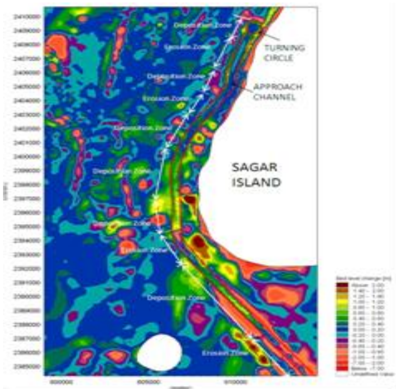
Background

The Kolkata Port (KoPT), located on the left bank of Hugli River is the first major as well as the only riverine port in India. The Haldia Dock Complex (HDC) is located on the right bank of the river at the confluence of Haldi and Hugli rivers. It has longest approach Channel of 145 km. The Bhagirathi – Hugli river system is a major distributary of River Ganga in West Bengal. The entire stretch of 280 km of river is influenced by the tides extending from Saugor downstream to Nabadwip upstream. Small rivers like Haldi, Roopnarayan, Damodar, and Churni carry large amount of sediments into Hugli River during monsoon season. This is a tidal port with severe restriction in draft and very high maintenance dredging. The dynamic nature of estuary results in frequent shifting of the navigation channels.

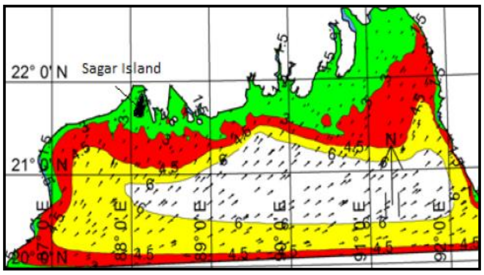
Studies Conducted

- Initially, the studies related to KoPT mainly pertained to river training and bank protection works in the upstream reaches of Hugli river and in the upstream of Kolkata.
- Subsequently, the studies were carried for development of port facilities and navigation channel from Saugor to Kolkata including few estuarine training works.
- All these studies were carried out CWPRS right from 1950's on different scale models. Afterwards the existing Hugli model (scale 1:600 H and 1: 100 V) was constructed and extensive studies were carried out. Hugli model was equipped with automatic tide generating system, and arrangement to release varying upland river discharges. Later the mathematical models were developed using MIKE 21 HD/MT for upcoming studies and all proposals were studied using mathematical models.

Hugli Estuary



Numerical Model : Bed level Change



Wind and wave field from model

Outcome and Benefits

- Improvement in river capacities in port reach by 41 MCM
- Salinity wedge pushed down from 30 km upstream of Kolkata to 30 km downstream
- Dredging requirement in Kolkata port reach reduced to nil
- Number of occurrence of bore days reduced from 150 to 20 per year
- Increase in container traffic from 30 TEU to 1,40,000 TEU
- Stabilization of low water crossings
- Reduction in turnaround time of ships
- Declaration of Inland Waterway (IW-2)
- Suitable remedial measures in the form of bank protection work etc.
- Flow diversion measures such as guide walls, spurs and orientation of jetties.
- Sedimentation and scouring phenomena and remedial measures.
- Design of navigation channels and their behavior and impact
- Suitable reclamation techniques and measures for stability of islands
- Study of impact of upland discharges
- Development of minor ports and fishing harbours

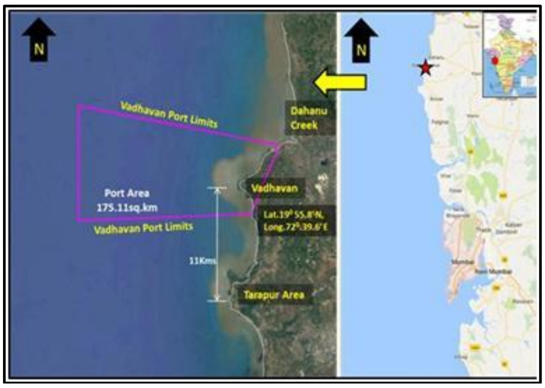
GREEN FIELD PORT AT VADHAVAN, MAHARASHTRA

Background

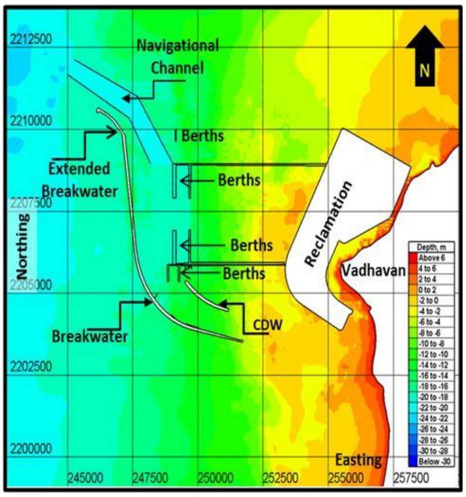
All-weather Greenfield port at Vadhavan situated in Dahanu Taluka, Palghar district of Maharashtra is proposed to be developed through a joint venture between Jawaharlal Nehru Port (JNP) and Maharashtra Maritime Board (MMB). The location of the port is about 110 km north of Mumbai and is on the open coast facing the Arabian sea. The port area is about 175 Sq km and extends up to 26 m depth in deeper part of the sea. The northern limit of the proposed Vadhavan Port is on the southern side of entrance to the Dahanu creek. The development consists of reclamation of about 1428 ha in the inter-tidal zone along with various berths for containers, coal, liquid cargo, harbour crafts, multipurpose terminals etc. The harbour area will be protected from fury of ocean waves by constructing an offshore breakwater with North-South orientation wherein macro type of semi-diurnal tides with tidal range of about 6m prevails. The studies to finalize the layout of port from tidal / wave hydrodynamics as well as design of breakwater for extreme wave climate were conducted at CWPRS.

Studies Conducted

- Mathematical model studies to finalize the layout of port from tidal/wave hydrodynamics consideration and estimation of likely siltation in harbour area.
- Desk studies for prediction of extreme wave/storm surge conditions for the design of breakwater.
- Design of breakwater structure from hydraulic stability consideration.
- Assessment of shoreline changes due to the proposed port development.



Location of Proposed Port at Vadhavan



Layout of Proposed Port at Vadhavan

Outcome and Benefits

- The optimal layout of breakwater (10.3 km long) and reclamation (1428 ha.) were evolved based on tidal hydrodynamics and wave tranquility and siltation aspects.
- The layout of breakwater evolved in association with Current Deflecting Wall (CDW)

Layout provided favourable flow conditions at berthing locations in the harbour as well as smooth movement of ships through the navigational channel at harbour entrance. It also minimizes the siltation in the harbour area along with optimum utilization of reclamation area for stacking the goods.

- The predication of extreme wave climate along with storm surge for 1 in 100-year return period provides guidance to evolve the optimal and stable cross section of breakwater for extreme storm events likely to occur during its lifetime.
- Port layout with favourable flow conditions irrespective of phase of tide along with tranquility at berth for round the year operations.
- Natural depths and reduction in maintenance dredging will ultimately increase the revenue of the port.
- The shape of the reclamation evolved provides favourable flow conditions in the harbour as well as maximal utilization as stack yard. The area being in intertidal zone there is no need to acquire the land.

HYDRAULIC MODEL STUDIES FOR KALPSAR PROJECT

The CWPRS is entrusted to undertake:

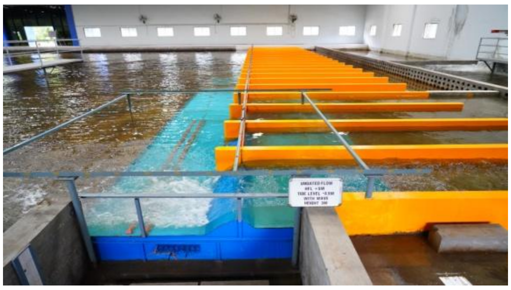
- Hydraulic physical model studies for the Kalpasar dam spillway with downstream wave basin
- Mathematical model studies for wave tranquility for the protection of spillways & allied structures from waves
- Desk and wave flume studies for the design of a breakwater/ protection bund for the main dam
- Physical model studies for breakwater alignment and assessment of wave condition near dam spillway

Kalpasar Project, in the Gulf of Khambhat, is a multipurpose development project proposed by the Government of Gujarat. After its completion about 8,000 MCM of fresh water could be stored, which is equal to 25% of average annual surface water resources of the state of Gujarat. This project also provides other benefits viz. a transportation link between Surat & Bhavnagar districts as well as to fisheries development .

The Kalpasar project consists of constructing a 60 km long dam and concrete spillway of about 2 Km length with 36 numbers of gates

Geographic Location of the Project

The hydraulic physical model to finalize the design of the spillway by simulating various discharges over the spillway along with the effects of sea waves on the downstream of the dam under different tidal levels



Physical Model of Kalpasar Project

Salient Features of this Physical Model:

- ✓ Housed in the hanger of size 60m X 40m
- ✓ Developed to the scale of 1:40 G.S. (Geometrically Similar)
- ✓ One end spillway with about 22 numbers of gates and downstream of the spillway at a distance of 32 m (about 1.3 km in prototype)
- ✓ Developed unidirectional random sea wave generator having a wave flap of length 33 m (6 units of 5.5m each)
- ✓ Equipped with Supervisory Control And Data Acquisition (SCADA)
- ✓

In this model, discharging capacity of the spillway is being ascertained with full and partial operation of gates

Outcomes and Benefits

Utilizing this physical model the performance of energy dissipater for various tidal levels with superimposition of waves, water surface profiles and pressures over spillway surface for the entire range of discharges can be ascertained.

WAVE FLUME STUDIES FOR DESIGN OF BREAKWATERS AND COASTAL PROTECTION MEASURES

Background:

Subsequent to the conceptual design of breakwater based on site-specific conditions or using Hudson/ Van der Meer formulae, the section of rubble-mound type breakwater is laid in the model as per decided model scale and structural stability of cross sections of breakwater (trunk portion) at different depths will be tested in 2-D wave flume. The round head design will be tested in 3-D hammer head of wave flume facility.

Wave flume facility - Regular Waves

Typical Section of Kalpsar Project

Wave flume facility – Random Waves

CWPRS Involvement

- Major involvement in coastal protection works in India.
- Wave flume facilities for hydraulic stability studies
- Nodal agency for Coastal Data Bank
- Member of Coastal Protection & Development Advisory Committee (CPDAC)
- Member of Technical Experts Committee for Coastal Protection works of all Maritime states
- Training programs for central/State Government Agencies

Wave Generator in Flume Facility

Breakwater round-head section

STUDIES CONDUCTED AT CWPRS FOR MAJOR PORTS

	MAJOR PORT (STATE)	Number of studies	Field data collection and analysis	Storm wave hindcasting	Wave tranquility	Stability of breakwaters, berth structures and bunds	Flow conditions and prediction of siltation	Alignment of berths and jetties\ Approach Cnannel	Ship motion and manoeuvering	Morphological aspects and evolution of shorelines	Dredging and disposal
	EAST COAST										
1.	Syamaprasad Mukherjee Port (West Bengal)	70	●			●	●	●		●	●
2.	Paradeep Port (Orissa)	35	●	●	●	●	●	●	●	●	
3.	Visakhapatnam Port (Andhra Pradesh)	90	●	●	●	●	●	●	●	●	●
4.	Chennai Port (Tamil Nadu)	65	●		●	●		●	●	●	
5.	Kamrajar Port (Tamil Nadu)	30	●		●	●	●	●	●	●	
6.	V.O. Chidambarnar Port (Tamil Nadu)	16	●	●	●	●	●	●	●	●	
	WEST COAST										
7.	Cochin Port (Kerala)	50	●	●	●	●	●	●	●	●	●
8.	New Mangalore (Karnataka)	40	●		●	●	●	●	●	●	●
9.	Mormugao Port (Goa)	65	●	●	●	●	●	●	●	●	●
10.	Mumbai Port (Maharashtra)	100	●				●	●			●
11.	JNPT (Maharashtra)	20	●			●	●	●	●		●
12.	Deendayal Port (Gujarat)	60	●				●	●	●	●	●

References

1. Abott, M.B. (1979) `Computational Hydraulics, Elements of the Theory of Free Surface Flows, Pitman, London

2. Abott, M.B., Peterson, H.M. and Skougoard O. (1978) `On the Numerical Modelling of Short Waves in Shallow Water' Journal of Hydraulic Research, 16(3)

3. Agershou, H, Lundgren, H, Sorenson, T. (1983) `Planning and Design of Marine Terminals' John Wiley and Sons

4. Bray R.N.(1979) `Dredging – A note book for Engineers' Edward Arnold

5. Bruun P. (1990) `Port Engineering', Volume – I, 4th edition, Gulf Publishing Co., Houston

6. Bruun P. (1990) `Port Engineering', Volume – II, 4th edition, Gulf Publishing Co., Houston

7. Bettjes, J.A. (1978) `Probabilistic Aspects of Ocean Waves' Delft University of Technology

8. Engelund, F. and Hansen E. (1972) A monograph on Sediment Transport in Alluvial Streams, Third Edition, Danish Technical Press

9. Hudson R.Y. et. al. (1979) `Coastal Hydraulic Models, WES Vicksburg, USA

10. Hudson, R.Y. (1959) `Laboratory Investigations of Rubble Mound Breakwaters' Journal of the Waterways and Harbour Division, ASCE, New York

11. Houmb O.U. (1981) `Latest development in Wave Statistic' Appendix B, Part-I in Port Engineering by P. Bruun, Gulf Publishing Co. Houston

12. Iribarren R., and Nagoles, C. (1954) `Other Verification of the formula for the Calculation of Breakwater Embankment' Permanent International Association of Navigation Congress, Bult. 39

13. I.S. 4651 (Port V) (1980) `Code of Practice for Planning and Design of Ports and Harbours Layout and Functional requirement'

14. I.S. 4651 (Port III) (1969) `Code of Practice for Design and Construction of Dock and Harbour structures – Loading

15. IS 4651 (Port IV) (1984) `Code of Practice for Planning and Design of Ports and Harbours – General Design Consideration

16. Longhaar, H.L. (1964) `Dimensional Analysis and Theory of Models' John Wiley and Sons, Newyork

17. Lundgren, H. (1963) ' Wave thrust and Wave energy levels', Proceedings 10th IAHR Congress Vol. I , London.

18. Quinin, A.D. (1969) `Design and Construction of Ports and Marine Structures'

19. Sand, S.E. (1982) `Wave Grouping described by Long Waves' Journal of Ocean Engineering, Pargaman Press

20. U.S. Army Coastal Engineering Research Centre (1977), Shore Protection Manual, Vol.I

21. U.S. Army Coastal Engineering Research Centre (1977), Shore Protection Manual, Vol.II

22. Vasco Costa, F. (1964) `The Berthing Ship, The Dock and Harbour Authority', published as a booklet by Foxlow Publications, London

23. Yalin, M.S. (1971) `Theory of Hydraulic Models, Macknilon, London

24. 'Major ports of India – A profile : 1999-2000' published by Indian Ports Association, New Delhi

25. PIANC (2014) Report nº 121-2014, Harbour Approach Channels design Guidelines. PIANC Brussels

26. PIANC (1997) Approach Channels A guide for design, PIANC Brussels

27. Carl A. Thoresen (2014), Port Designer's Handbook, Recommendations and guidelines, Third edition

28. OCIMF, The oil companies International Marine Forum (1997) Mooring equipment Guidelines, Second edition, London; Witherby &Co. Ltd.

29. Ministerio de Obras Pu´ blicas y Transportes (1990) ROM 0.2-90. Maritime works recommendations. Actions in the design of maritime and harbour works (ROM 0.2-90 English

30. 2004, Maritime Safety Authority, Port and Harbour Risk Assessment and Safety Management Systems in New Zealand

Central Water and Power Research Station

Khdakwasla, Pune - 411 024, INDIA

Phone No.: +91 20 2410 3240

Email: director@cwprs.gov.in

Website : https://cwprs.gov.in