

INTRODUCTION

1.1 GENERAL

It is believed that Oceans constitute about 70% of the surface of the Earth and about 97% of the water content of the Earth belongs to the oceans. It is believed that about 1% is fresh water, and 2–3% is in the form of glaciers and ice caps. The ocean is rich in natural living and non-living resources. In order to explore and exploit the vast non-living resources like oil, gas and minerals from beneath the ocean floor, a variety of structures are needed to be designed and installed. The perennial instability of shorelines leading to coastal erosion along certain stretches of the coast and the natural coastal hazards like storm surge, tsunami, etc., necessitate protection measures mostly in the form of structures like seawalls, groins, offshore detached breakwaters, etc. constructed along or near the coast. One major developmental activity along the coast is the development of harbors by constructing breakwaters. The major environmental parameters that need to be considered in the design of all the aforementioned different types of structures are the wind, waves, tides and currents. Among these, although the loads due to waves dominate and dictate the design of structures in the marine environment, the characteristics of other parameters are also essential.

Further, the continuous depletion of the conventional energy resources and rapid research towards **alternative or renewable energy** (a term used for an energy source that is an alternative to using fossil fuels) are in progress. Alternative energy resources are the renewable energy resources that are naturally available and can be naturally replenished. This energy cannot be exhausted and is constantly renewed unlike energy generated from fossil fuels. Apart from the solar and wind energy, the energy from the Ocean comes from a number of sources like waves, tides and currents. In addition, the gradient between salient, temperature and density apart from tides and waves generates ocean currents that can be effectively utilized for extraction of energy. For designing efficient energy extraction devices from these natural resources, a critical knowledge on the characteristics and the basic physics of waves, tides and currents is absolutely essential. Hence, this chapter would discuss the important basic aspects of these parameters.

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1.2 STRUCTURES IN THE MARINE ENVIRONMENT

The structures in the marine environment can broadly be classified as coastal structures, port and harbor structures and offshore structures which are briefly discussed in this section.

1.2.1 Coastal Structures

The types of coastal structures are (a) Breakwaters (b) Seawalls and bulkheads (c) Revetments and (d) Groins. In addition, we have intake structures for drawing seawater continuously for power plants, aquaculture, etc. and outfalls for discharging effluents into the marine environment.

Seawalls

Seawalls and bulkheads are structures placed parallel or nearly parallel to the shoreline to separate the land area from water area. The primary purpose of a bulkhead is to retain or prevent sliding of the land, with a secondary purpose of affording protection to the back shore against damage by wave action. Seawalls are used primarily to protect areas in the rear of the beach against severe attack of waves and storms. They are necessarily massive and expensive and should be constructed only where the adjoining shore is highly developed and storm attack is severe. Seawall is, in essence, a retaining wall which, in addition to earth pressure from landside, is acted upon by the impact force of the waves. A typical cross section of a seawall is shown in Fig. 1.1.

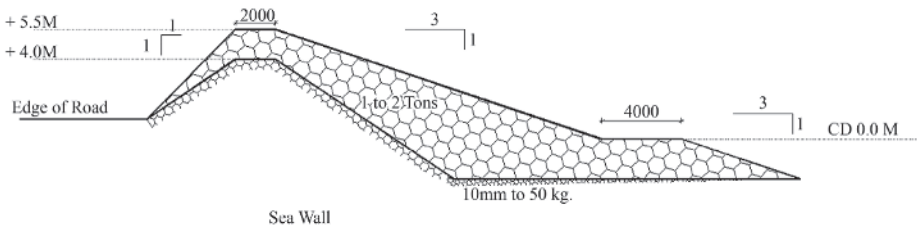


Fig. 1.1: Typical cross section of a seawall groins

Groins

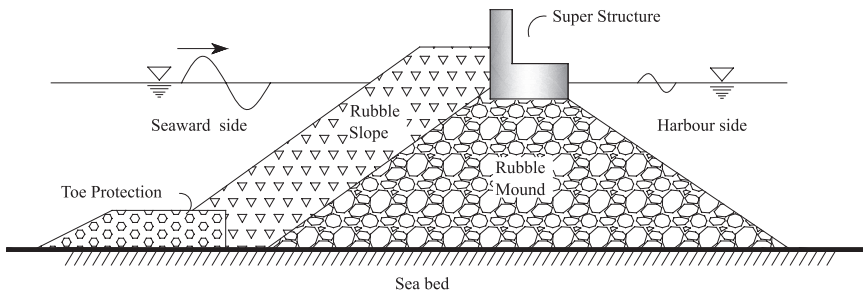
A groin is usually perpendicular to the shore, extending from a point landward of a possible shoreline recession into the water; it is at a sufficient distance to stabilize the shoreline at a desirable location. Groins may be classified as permeable or impermeable, high or low and fixed or adjustable. They may be constructed of timber, steel, stone, concrete or other materials or combinations thereof. Groins are built in order to halt or reduce shoreline erosion by means of controlling the rate of along-shore or littoral drift of beach material. They are designed to trap the maximum volume of material. Functional design is the determination of length, spacing, height, alignment and type of groin which will halt or reduce beach erosion to an acceptable degree. The groins should extend beyond the zone of breaking of waves and the distance between them should be 1.5 to 3 times its length. An aerial view of a groin field protecting Paravoor ((8° 49' 52.7"N; 76° 38' 9.9"E) along the Kerala coast is shown in Fig. 1.2.



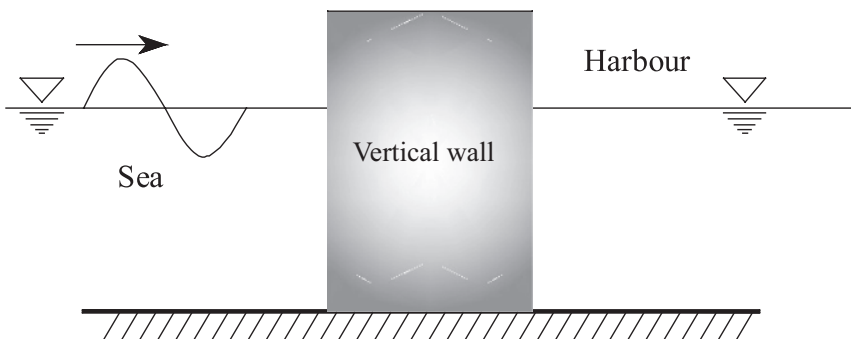
Fig. 1.2: A view of the coast of Paravoor, Kerala, showing the effect of groin field.

Breakwaters

Harbors are classified broadly as natural and artificial harbors. Artificial harbors are formed by constructing usually a pair of breakwaters. They protect the coast or a harbor from waves, thereby preventing their destructive influence on the coast or within the area of the harbor. Isolated offshore breakwaters, usually of mound type, are aligned parallel to the shoreline to serve as a shore protection measure. Offshore breakwaters are expensive and should be used after good model tests since they sometimes bring in precisely the opposite effects as against what is desired. From the shape of the breakwaters, they are classified as vertical wall type, sloping mound and composite type consisting of a vertical wall type kept over sloping mound type (Fig. 1.3).

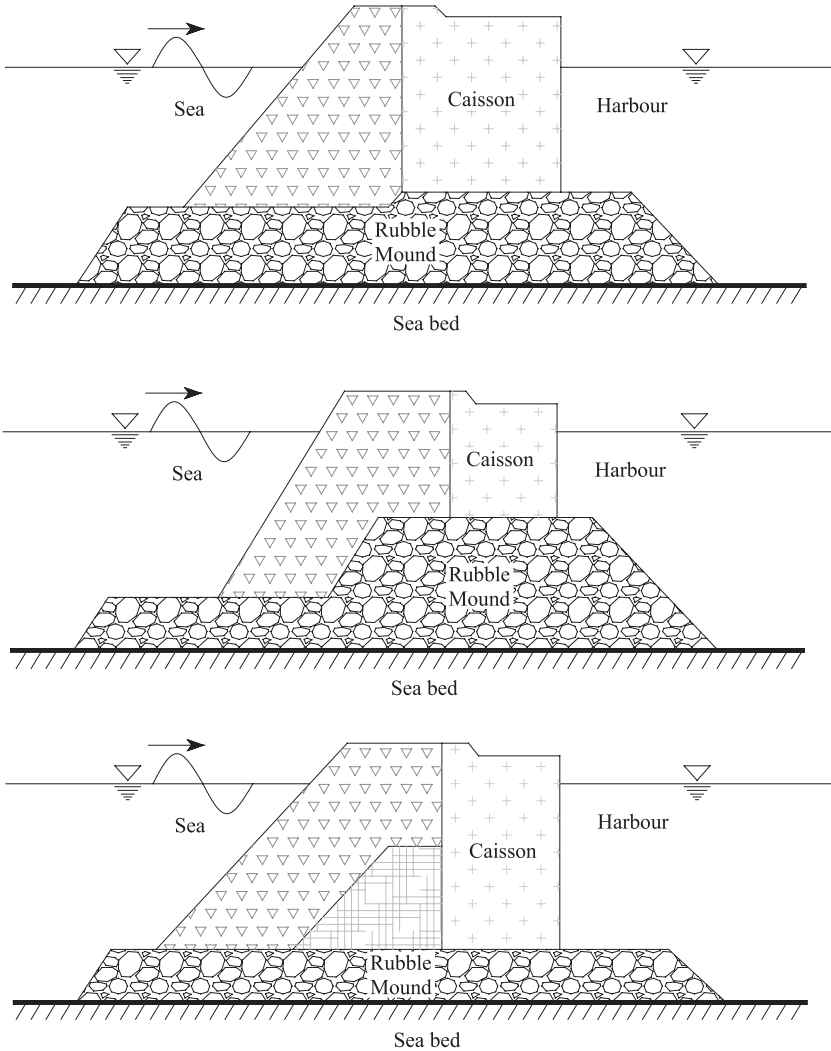


a. Rubble mound breakwater



b. Vertical breakwater

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c. Typical cross section of horizontal composite breakwaters

Fig. 1.3: Types of breakwaters

Revetment

To improve the stability of the slope of the shorelines, riprap revetment provides another method of shore protection measure. A typical cross section of a riprap revetment is shown in Fig. 1.4. For additional details on coastal structures, the reader is recommended to refer to *Coastal Engineering Manual* (2006), Horikawa (1978) and Sorenson (1978).

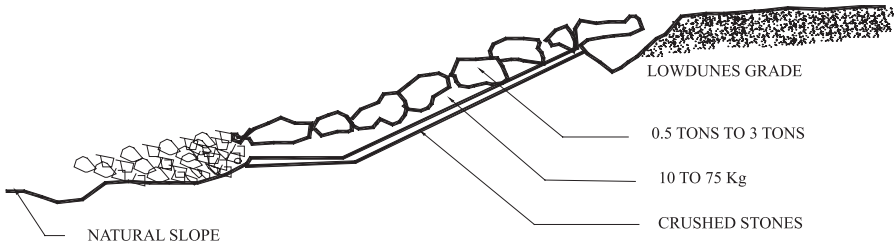


Fig. 1.4: Typical cross section of a revetment

1.2.2 Port Structures

The most important structure to form a harbor which also is the main component of a port falls under the category of coastal structures that has been briefly discussed earlier. A port or a marine terminal is intended to provide facilities for trans-shipment of cargo and movement of passengers. The structures constructed as facilities for ports or harbors are quays or wharves, jetties, piers, dolphins are denoted by a general name **docks**.

A **Wharf** is a structure supported on piles and constructed along a river or a sea that facilitates safe berthing of vessels.

A **Quay** is generally erected along the river bank or shoreline where it is ideal for the purpose of docking. Quays are very much similar in function to a wharf, except that its platforms are long enough and fairly above the water surface, which can sustain loading and unloading of vessels, and its supporting component is made up of a solid vertical wall touching the sea/river bed.

A docking platform handling cargo is constructed for handling a specific type of cargo like cement, oil or grains, etc. Hence the type of docking platform depends on the type of cargo to be handled. The main factors that need to be considered in their design are direction of wind and waves, size of ships to be berthed and soil conditions. The total number of wharves for a particular location is determined based on the mooring population and its capacity. The quays are constructed as sheet pile wall, open piles structure or as gravity structure.

A **Pier** projects/overhangs from the shore to the sea above the water level such as to enable disembarkation of passengers at deeper waters further away from the shore. Also along the length of the pier, smaller boats can be berthed. Piers are of three types (a) piers consisting mainly of reclaimed land and bordered by quays (b) piled piers (c) floating piers. The first type is similar to quays already discussed. Piled piers consist of a deck supported on piles. The deck is of concrete and the piles may of steel or reinforced concrete. To effectively take horizontal loads, a few piles may be kept inclined, and these are called battered piles. Floating pile is a structure used in places where soil conditions are too poor for a fixed structure or where water depths are excessive to make (i.e., where a fixed structure becomes uneconomical). It consists of a floating pontoon, an anchoring system and an access bridge connected to an abutment at the shore. Piles are usually widely spaced and wharves are narrowly spaced, the former carters loading and unloading of vessels or pleasure boats.

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A schematic plan view of a marina formed by a pair of breakwaters, a berthing structure as well as finger piers for berthing small boats is shown in Fig. 1.5.

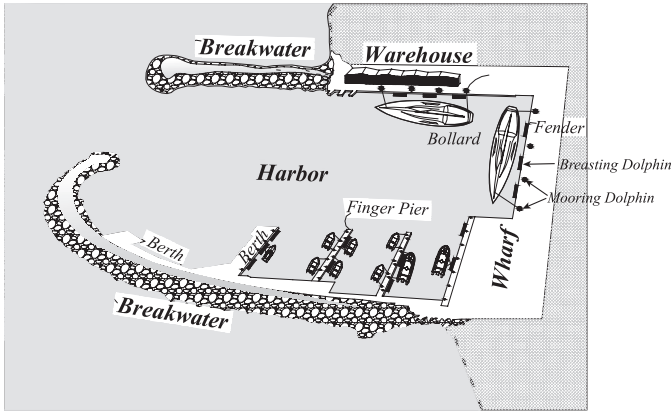


Fig. 1.5: A schematic plan view of a marina

Jetties are structures projecting into the water. Jetties may have berths on two sides and abut land over their full width. A closed jetty consists of solid wall up to the water bed, thereby obstructing the flow of currents. Jetties can also be supported on piles (open jetty). The characteristic feature of a jetty is that it consists of a number of individual structures, each of which supports special types of loads.

A **mole** is a large jetty constructed in view of forming an artificial harbor. **Groins** are aimed to increase/advance sand build-up in a beach. In order to prevent siltation at the mouth, jetties in pairs commonly flank either sides of the river as it enters a sea or lake.

A **sheet pile wall** consists of a vertical wall to retain earth. The wall is laterally supported by rods at the level near the top. In the sheet pile with relieving platform, the weight of the backfill or part thereof, immediately behind the wall is carried by piles directly to a firm stratum, whereby, the active earth pressure on the sheet pile will be reduced and the wall relieved.

Dolphins are structures at the entrance of a locked basin or alongside a pier or a wharf. Their main purpose is to absorb the impact force of the ships and also to provide mooring facility. Dolphins are broadly classified into two types, viz., breasting type and mooring type. Breasting dolphins are provided in front of the sea-face of the berth. The bollards or the mooring posts are housed on them. Since, sometimes, the mooring dolphins are insufficient to hold the vessel in position against currents acting away from the berth, they are provided as counter measures. The mooring dolphins pick up the pull from hawsers, the breasting dolphins support fenders which absorb berthing impacts and onshore wind loads on the moored vessel and loading platforms support special loading or unloading equipment.

A **trestle** is a structure connecting the main berthing pier to the shore or shore connected facilities. They are supported on piles which need to be designed for forces due to waves and currents. For additional details on ports and harbor structures, it is suggested to refer Brunn (1981).

1.2.3 Offshore Structures

The diversity of factors involved makes it difficult to have a classification of offshore platforms. The number of parameters includes functional aspects, construction and installation methods, geometric forms, etc. However, they can be broadly classified as bottom-supported units and floating units. Jacket structure, gravity-based, compliant structures and guyed towers are a few bottom-supported units. Semi-submersibles, tension leg platforms, SPAR and FPSO are a few floating units.

Based on their application, platforms in general are categorized into exploration and exploitation/production platforms. Exploration platforms are employed for searching for oil reserves in the Ocean and these are the drill ships, semi-submersibles, and jack-up platforms. The exploratory rigs can move from one location to another in search of oil.

Exploration Platforms

The **drill ships** are ship-shaped and self-propelled. The ship motions and thruster or anchor capacity limit the weather conditions. The **semi-submersibles** may be 4-, 6- or 8-legged. Legs are connected by buoyancy chambers. The primary buoyant members are positioned below the SWL and hence unaffected by waves. They are difficult to tow and expensive particularly beyond 450 m. The **Jack up rigs** are towed to any desired location in the sea. They float on their hull. The platforms are initially lowered to the seafloor using pneumatic jacks, hydraulic jacks or electric rack and pinion drives. To achieve the required clearance, the hull is lifted above the sea surface. It can operate up to about 200 m. Once rigged, they are stable and continue operations in high seas.

Production Platforms

The production of oil and gas from these platforms can last for usually 20–30 years. The seabed-based structure usually operates in less than 500 m and may operate even up to 800 m. The floating structures can operate in water depths greater than 800 m.

The **jacket platform** of steel on a pile foundation is the most common kind of offshore structure which exists worldwide as the oldest type. It is constituted by framed open trusses which are driven into the seabed through piles. The jacket platform can support 2 to 3 decks. All the platforms in Bombay High, India, are of the jacket type. The use of these platforms is generally limited to a water depth of about 150–180 m in the North Sea environment. The horizontal and vertical loads effected due to the action of wind-waves and the weight of the deck, machinery for drilling or production operation are transmitted to the ocean floor / seabed through the piles by lateral thrust and skin friction. When four main piles are insufficient to transmit the horizontal and vertical loads, additional piles called the skirt piles are sometimes driven. These supplementary skirt piles are connected to the jacket tower, with skirt sleeves extending to one- or two-panel lengths in the tower.

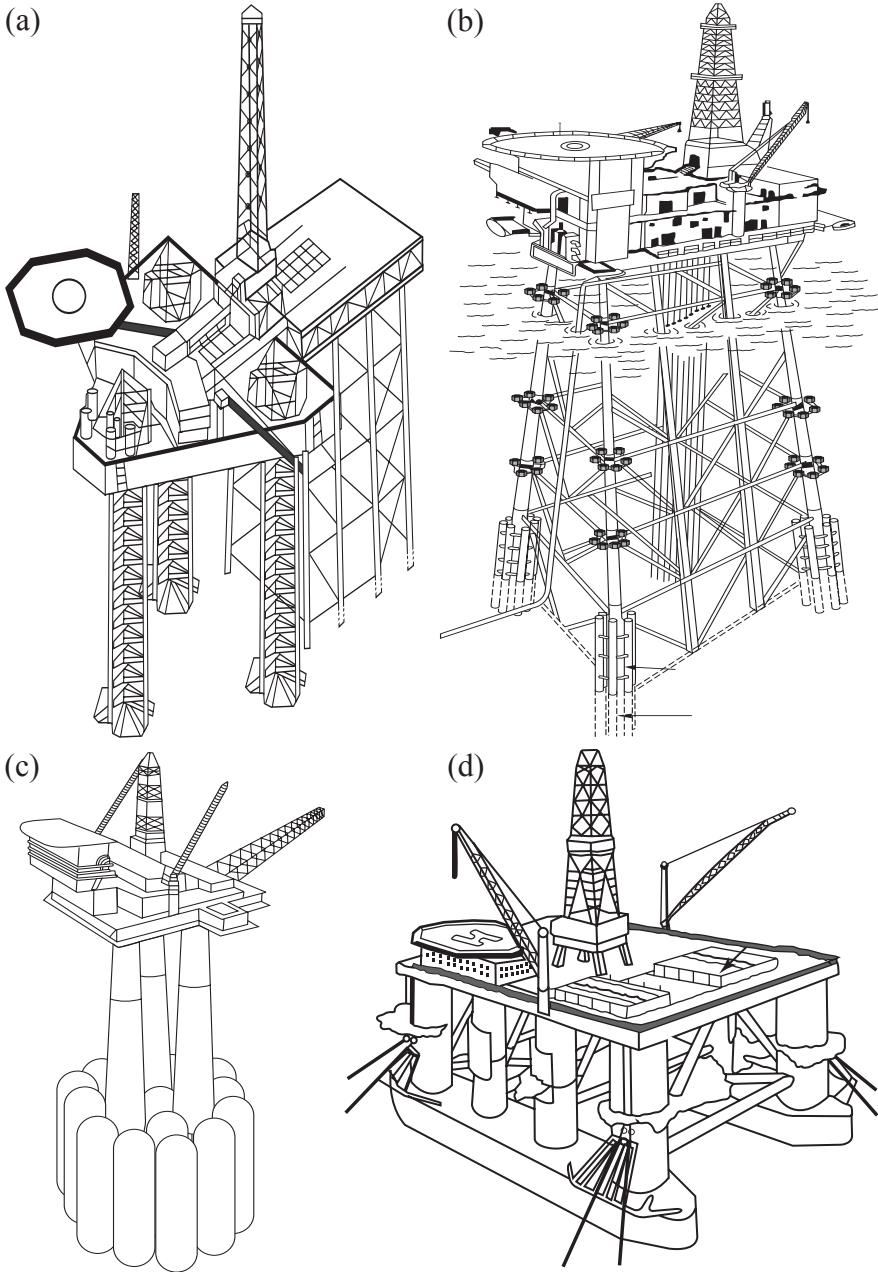


Fig. 1.6: Typical views of (a) Jack-up rig, (b) Jacket platform, (c) Gravity platform and (d) semi-submersible

The **gravity platform** structures are offshore structures that are placed on the seafloor and held in place by their weight. These structures do not require piles or anchors. Moreover, the huge bottom section is quite suited for production and storage of oil. Since gravity-based structures require large volume and high weight, concrete has been the most common material for gravity structures. The type of foundation is the pivotal parameter to decide the type of platform.

Considerable horizontal load and moments are experienced by the offshore structures at the mud level due to the action of wave loads. The gravity platform resists moment and horizontal load by non-uniform distribution of the soil up thrust and shear resistance of the soil respectively. Gravity type structures are preferred when the soil surface condition at the site can withstand heavy loads. Construction of these structures can be done either on shore or in sheltered waters. They are then towed to an offshore location and positioned by controlled flooding with water in a short span of time. Typical views of a jack-up rig, jacket platform, gravity platform and semi-submersible are projected in Fig. 1.6.

An **articulated platform** is a column attached with buoyancy tanks at one or two locations along its depth. It is fixed through a universal swivel joint to a plate resting on the seabed. The columns with buoyancy tanks are usually of truss type. Buoyancy tanks can be attached at convenient levels to the truss-type columns. The advantages of articulated platforms include lowered cost of construction and lesser siting problems, and also that it is an eco-friendly loading method.

A **guyed tower** consists of a slender steel space frame, and the vertical forces on the platform are taken by a foundation base. The base can partially penetrate the seabed. The support structure is held upright by several guy lines that run to clump weights on the ocean floor. The horizontal loads caused by waves and currents transferred to the clump weights through guy lines, cause them to be lifted off the seafloor, under normal operating loads. The weight and the foundation constraints of conventional offshore structures make them scarcely sought-after forms for deep waters usually more than 300 m depth. Guyed towers and the tension leg platforms are preferable forms of design for such high water depths.

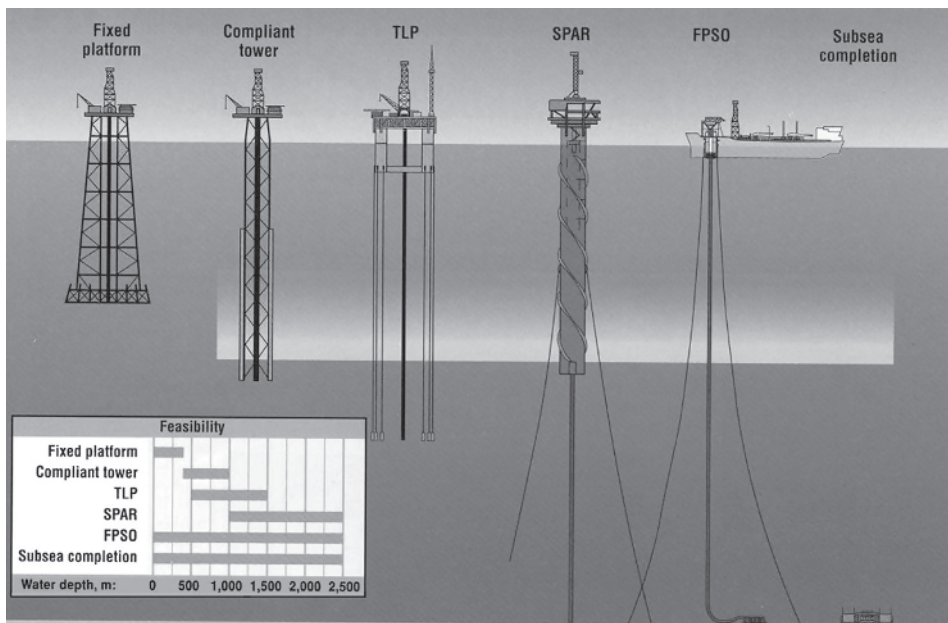


Fig. 1.7: Development of platforms from fixed to compliant and floating systems with increasing water depths

The **tension leg platform** (TLP) is one which is buoyant and fixed to the seafloor through vertical cables under tension. The mode of operation is such that loading or unloading would not cause any heave, as vertical loads are taken by anchor cables. The key advantage of TLP is that there is no considerable increase in cost with rise in water depth.

The **spar** which is usually a cylindrical caisson moored to the seabed and is adopted for drilling, production as well as for storage. The operations are performed above the water level. It is usually anchored to the seafloor with multiple taut mooring lines.

An overview of the development of different kinds of offshore platforms with increasing water depths is projected in Fig. 1.7. For further details on offshore structures, refer to Chakrabarti (1987) and Reddy (2013).

1.3 ENVIRONMENTAL PARAMETERS

1.3.1 General

Environmental parameters are the most important parameters to be considered in the design of marine structures or in the conservation and management of coastal developmental activities and for this, a knowledge on the tides, waves and current is essential. Depending on the site conditions, one process may augment another or may act against another. Nevertheless, it is convenient to separate the three components—astronomically generated tidal movements, winds and wind-generated wave action and various forms of current flow—for the purpose of discussion.

1.3.2 Wind

One of the important factors in the design of marine structures is the characteristics of the wind blowing over the ocean surface. Extreme water levels and wave climate may simultaneously occur with wind loading which need to be considered for the survival of the structures. The probability of marine structures being exposed to extreme winds compared to land-based structures is quite high, as in the former, there is no sheltering effect of terrain or vegetation. The important parameters that dictate the wind characteristics are its direction, frequency and intensity. The wind velocity usually referred by Beaufort scale that ranges between 0 and 12 can be expressed as

$$V = 2.99\sqrt{B^3} \quad (1.1)$$

where V is wind velocity in kmph and B is the Beaufort number.

Wind speed is measured 10 m above the earth. V_s , the wind speed at any elevation, s m is given by

$$V_s = V_{10} \times (s/10)^{1/7} \quad (1.2)$$

The pressure intensity due to wind (p) in kg/m^2 with C defined as a coefficient = 0.00481 is given by

$$p = CV^2 \quad (1.3)$$

The total force due to wind F_w , is given by

$$F_w = K_{sf} pA. \quad (1.4)$$

Here, A is the area of the exposed surface and K_{sf} is a shape factor varying between 1.3 and 1.6. The wind data is usually presented in terms of percentage of occurrence of wind intensity in a particular direction either monthly, seasonally or annually. A typical wind rose diagram is shown in Fig. 1.8.

1.3.3 Waves

General

Waves are undulations of the ocean water surface about a reference level, which may be the mean sea level, high tide line or low tide line, the details of which will be discussed later. The undulations are due to the wind blowing over the ocean's surface. The characteristics of waves are defined by its height which is the distance between its crest and trough, the distance between successive crests termed as its length, while the time taken for the wave to travel one wavelength is its period. The ultimate state of wave growth depends primarily on three parameters of wind fetch (F) or the distance over which it blows on the water surface, its velocity (v) and the duration (t) of time for which the wind blows. Although the theoretical and simplistic waveform is a sinusoidal curve, that form is not common in nature. Wave shape depends on the conditions of the wind, water depth, and the progression of the wave itself. Waves are basically surface phenomena characterized by their oscillatory motion, the magnitude of which reduces rapidly towards the seabed. This would mean that a body floating on the surface of the ocean will undergo an oscillatory motion and when structures are exposed to such motions, they will experience cyclic loading.

Wave Generation

Waves propagating in an area under the influence of the winds, i.e., within the fetch region are called wind waves, or a sea. These have relatively peaked crests and broad troughs. After the waves leave the generating area of the fetch, principally they are smoother and lose their rough appearance. These waves are called swell waves. Swell waves commonly have a long wavelength and small wave height, thus having a very low steepness value, much lower than sea waves. For a given steady wind speed, the development of waves may be limited by the fetch or the duration. However, if the wind blows over a sufficient distance for a sufficient length of time, in a more or less steady state of conditions, any additional transfer of energy from the wind to the ocean surface does not result in the growth of waves; in other words, the steady state has been reached. This condition is called a fully developed sea (FDS). Fig. 1.9 shows the development of ocean waves within generating area. Hence the three parameters that dictate the growth of waves are fetch F , wind velocity V and its duration t_d .

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A few empirical relationships for estimating the maximum wave height and period are as follows:

$$H_{\max} = 0.026V^2 \tag{1.5}$$

$$H_{\max} = 0.0555\sqrt{V^2 F} \tag{1.6}$$

$$T_{\max} = 0.5(V^2 F)^{1/4} \tag{1.7}$$

Here, H_{\max} is maximum wave height in feet, F is the fetch in nautical miles, V is the wind speed in knots and T_{\max} is the maximum wave period in seconds. These relations are particularly useful for short fetches and high wind speeds such as those found in hurricanes and other intense storms.

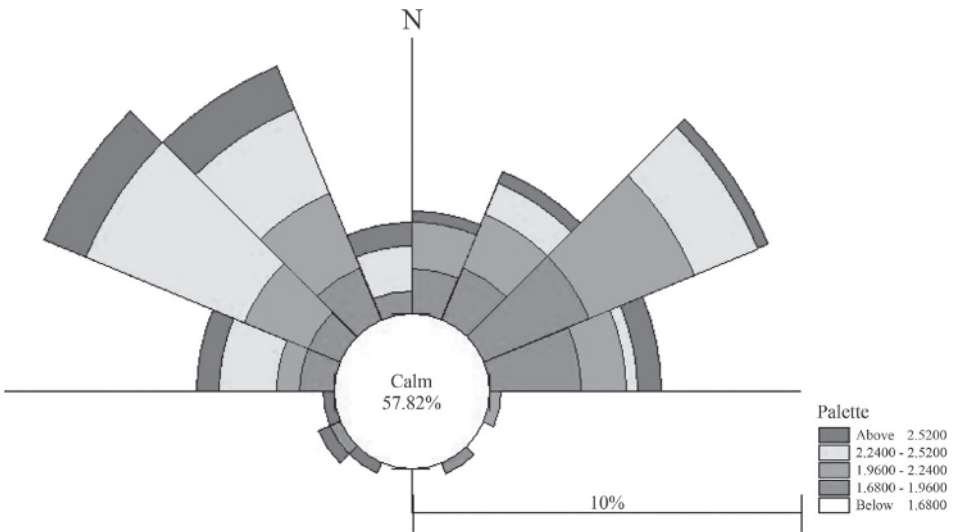


Fig. 1.8: Typical wind rose diagram

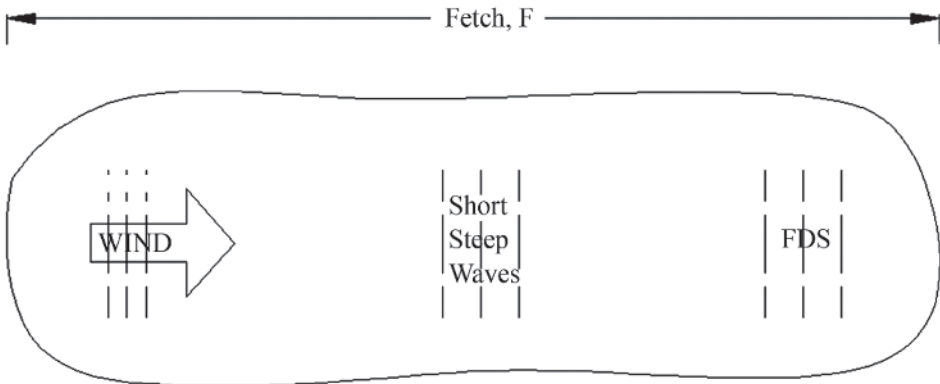


Fig. 1.9: Development of waves within generating area

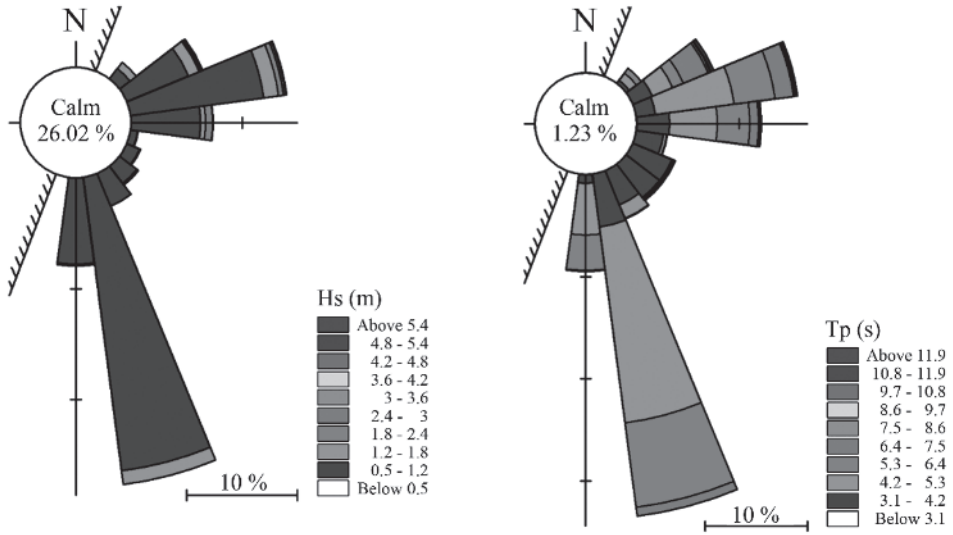


Fig. 1.10: Typical wave rose diagram

Wind force and direction are of importance in the study of establishing weather window, design, construction and maintenance of structures in the marine environment. The relationship between wind and wave characteristics has been brought as a scale that was devised in 1805 by Rear Admiral, Francis Beaufort, an Irish Navy officer, which is called Beaufort scale and is given in Table 1.1. The average wave height along the Indian coast was reported by Narasimha Rao and Sundar (1982) to range between 1 and 2.8 m, whereas, the wave period was found to vary between 5 and 8 sec. The wave data is usually presented in terms of percentage of occurrence of its height and period in a particular direction either monthly, seasonally or annually. A typical wave rose diagram is shown in Fig. 1.10.

Importance of wave characteristics

The information on wave characteristics is essential and has a wide application in studies related to oceanography and ocean engineering. A few of them are listed below.

- Establishment of weather window needed for the planning of marine operations
- Design of structures and ships
- Design and stability of floating structures
- Coastal process studies
- Coastal protection measures
- Development of fishing and commercial harbors
- Verification of wave forecasting and hindcasting models
- Wave energy potential and performance evaluation of wave energy converters

Major applications of wave data include offshore platform design, breakwater jetty design, site selection criteria, operation planning, military operations, transportation studies, environmental impact assessment, real time input to wave forecasting, search and rescue pollution and clean-up. Wave data also find important applications in the specification of ship responses, ship design and ship operation and planning. In coastal processes studies, measured wave data are needed for studies and applications involving sediment structure interaction, shore line erosion, design of navigation channels, beach nourishment, coastal hydrodynamics, coastal zone planning, coastal operations, harbor surging, dredging, recreation and marine facilities designs. Wave data are also important in testing newly developed wave forecasting models and in verifying existing hindcasting and forecasting models. Wave data analysis forms the most important component in studies relating to estimation of wave energy potential for different offshore and coastal regions.

1.3.4 Tides

General

A tide is the gradual oscillation of the water surface in the ocean, which is caused by the gravitational attraction between the sun, moon and the earth, which in turn is modified by the rotation of the earth, friction forces, and the ocean boundaries. The moon being closer to the earth exerts more force and is believed that the sun exerts only 46% of the force of the moon. Hence, tides are generally influenced by the moon more than the sun. The net effect is that the acceleration due to gravity at the earth's surface directly below the moon is effectively reduced because of the moon's attractive force, and water is then heaped up towards the moon. They are essentially long waves with its dynamic component having almost negligible effect on the loading of structures. The tidal levels at a site dictate the fixing of the top levels of fixed and floating structures. In order to avoid overtopping and to prevent coastal flooding during extreme events, when the highest high-tide level (HHTL) is considered, an additional buffer accommodating the wave run-up that will be over the HHTL and a free board will be considered. Further, the scope of mooring lines of floating structures and the minimum water level may affect the stability of bulk heads. The tidal range affects the vertical extent to which the structure is affected by corrosion and deterioration. The construction of any structure necessitates the establishment of some vertical reference plane and it is very important for the engineer to understand the chart and survey datum in use in the site of interest and the relation of changes in water level to that datum. The various tidal levels as per (NOAA) *National Oceanic and Atmospheric Administration* are shown in Table 1.2.

Types of Tides

The time taken for the moon to make a complete revolution around the earth is about 24 hours 50 minutes. This period is called a lunar tidal day. The highest tide for a location does not occur during the new moon and the full moon, but

occurs after a constant interval. This interval may be as much as two and a half days and is known as the age of the tide.

The tides which occur twice during each lunar day are called semi-diurnal tides in which case there will be two high tides and two low tides during a tidal day. If there is only one high tide during a tidal day, it is called a diurnal tide, e.g., at Pensacola, Florida. If one of the two daily high tides does not reach the height of the previous tide, it is called a mixed diurnal tide, e.g., at San Francisco, U.S.A. The representation of these different types of tides is shown in Fig. 1.11. Mean Sea Level (M.S.L.) can be defined as that average sea level about which the tides oscillate. Even though M.S.L. is important in establishing fundamental benchmarks for land surveys, it is not generally used as a reference plane for marine structures. Different datum levels are used in different parts of the world. However, it has been determined by international agreement that the chart datum shall be some level below which the tides will not fall frequently. The chart datum used in India is the Indian Spring Low water. The Mean Low Water is the average of the low water over a 19-year period. The Mean High Water is the average of the high water over a 19-year period. The Highest High water and Lowest Low water are the highest and lowest respectively of the spring tides record.

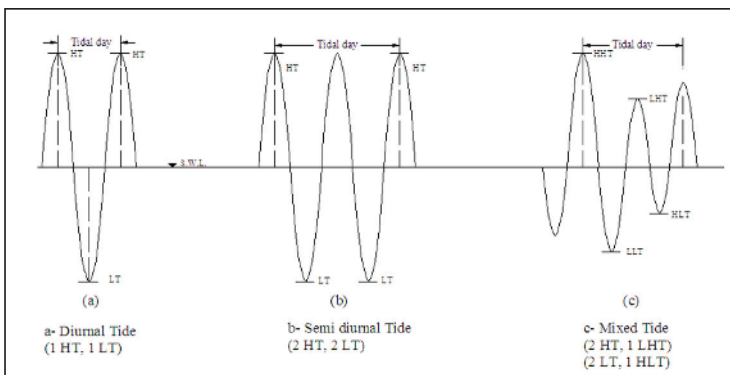


Fig. 1.11: Classification of tides

Tide Tables

Present-day tide predictions are done by performing harmonic analysis, in which the movements of the sun and the moon are broken into various periods during which some cycles of motion are repeated. Tidal tables are prepared which give the times and levels of high and low water at the standard ports in the world. Tidal computations for a comprehensive harmonic analysis based on hourly tide reading used to be a most laborious occupation when carried out manually. The tidal levels at various locations along the Indian coastline are found using national hydrographic charts.

Tides along the Indian coast

The vertical difference in height between the high water and low water at a place is called the tidal range. If it is the mean high water and mean low water, the

difference between them will be the mean tidal range. The highest tidal range in India occurs at Bhavanagar, exceeding 11 m. At the Bay of Fundy in Canada, the highest tides in the world occur; a rise of 30 m has been recorded. A high tide of 18 m has been observed in the Bristol Channel.

Along the Indian coast, the maximum tidal range is observed in the Gulf of Kutch and Gulf of Kambhat region along the west coast with a range of 10 to 11 m. The next higher tidal range observed along the Sundarbans area along the east coast is about 5.5 m a magnitude of which is experienced in several other locations. Apart from this, the regions south of Gujarat and West Bengal also experience moderate tidal range of 3 to 5 m. The tidal range is less than 1.5 m along the coast of the southern maritime states of India.

1.3.5 Currents

Current is defined as the movement of mass of water due to the existence of a gradient. The gradient could be due to changes in salinity, density, temperature, pressure, wave height and tidal levels. Coastal currents often accelerate deposition of sediments or lead to erosion depending on the coastal features, and wave and sediment characteristics. Currents are also responsible for the development of a variety of coastal features like formation of inter-tidal spits and sand bars, tombolos, salients, various kinds of ripple patterns on foreshores and tidal flats, on the floors or lagoons and seabed as schematically presented in Fig. 1.12. Currents inside harbour basins can lead to shoaling of approach channels, seafloor scour, increased corrosion rates, and also lead to modification of wave characteristics. Hence, it is important to consider the flow characteristics particularly in the coastal zone. They are also sources of significant loads on marine structures, especially upon moored vessels and when additive to wave loads on offshore structures.

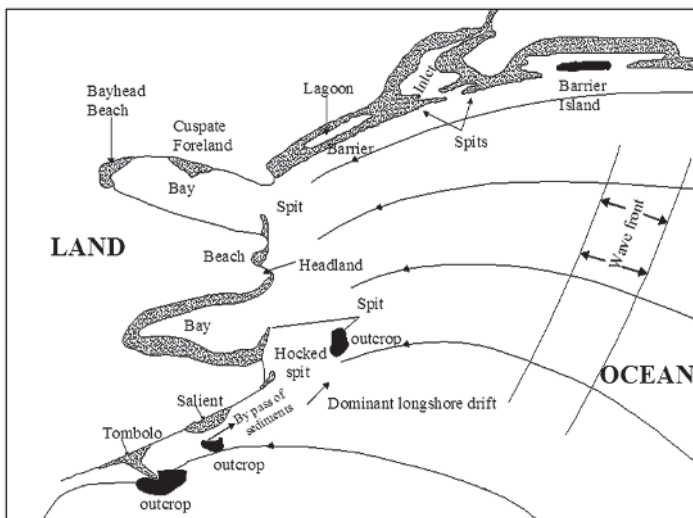


Fig. 1.12: General coastal features

Ocean currents can broadly be classified according to (i) the forces by which they are created, (ii) the time of appearance, (iii) the locality and (iv) the region in which they are situated. The details of these classifications are projected in Figs. 1.13–1.15.

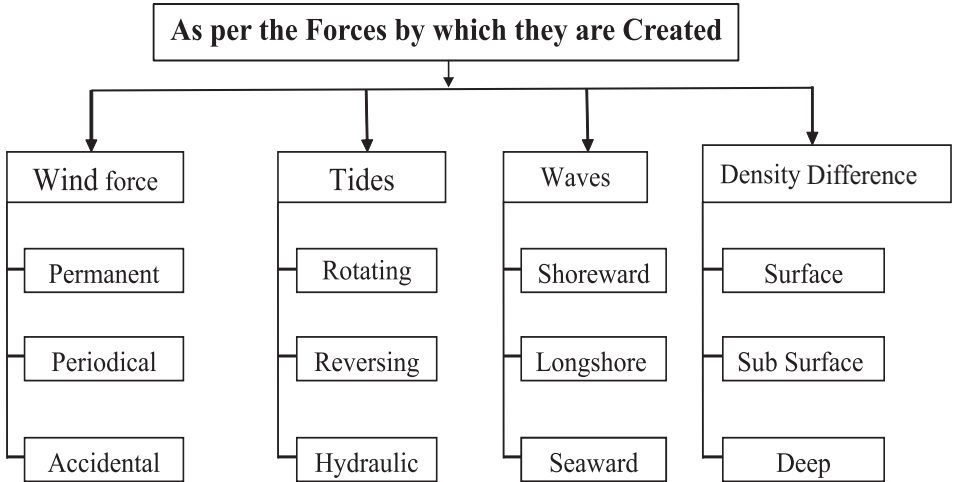


Fig. 1.13: Classification of currents as per forces by which they are created

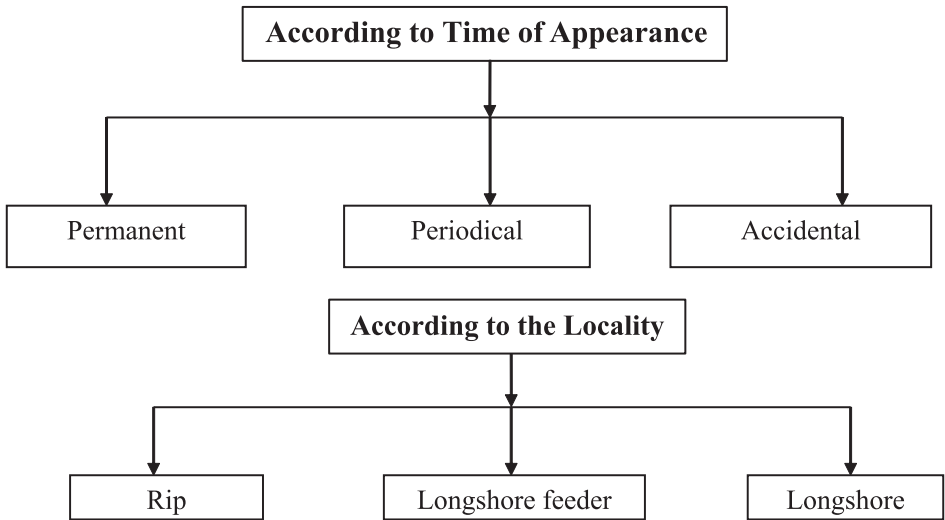


Fig. 1.14: Classification of currents as per time of appearance and locality

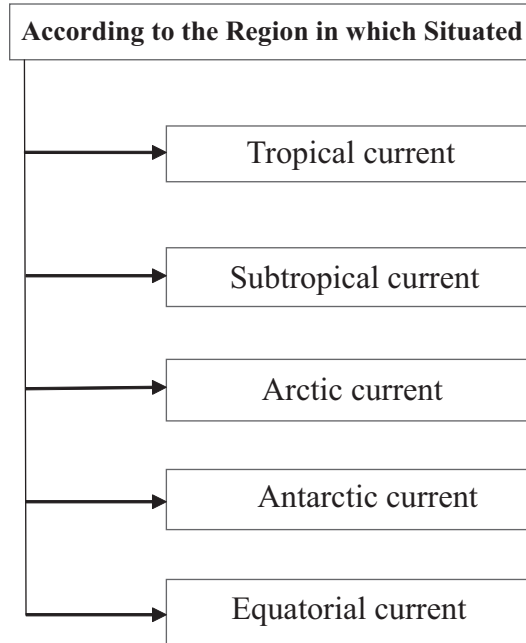


Fig. 1.15: Classification of currents as per regions

1.3.6 Nearshore currents

Consider the action of waves on any beach in plan, the wave crests reaching the shore are seldom parallel to the shoreline or the underwater depth contours. The effect of this oblique attack of the waves in the break zone is to generate two components of the fluid velocity, of which, one along the direction parallel to the shore is called longshore current and is responsible for the transport of sediment along the shore and the other termed as cross shore current sets the sediments on the coast in the offshore–onshore direction, i.e., normal to the shoreline. These currents may be even of the order of 0.5 m/s. The magnitude and direction of the longshore currents depends mainly on the angle between the wave crest and the shoreline.

The longshore sediment transport or “littoral drift”, however, is more dominant and mainly responsible for the shoreline instabilities. As the sea waves approach the shoaling water (i.e., lesser depth of water), they become waves of translation and pile up water against the coast. A hydraulic grade line is thus established and hence, somewhere along the beach, there must be a return flow to the sea. This water is met by the next oncoming wave. The oncoming wave flows over the returning water, building up a hydraulic head at the beach line. This hydraulic head forces the returning water downward and outward, thus setting up what is called the “undertow”. The undertow in some instances becomes a longshore current of considerable importance. As waves propagate towards the coast, there is considerable mass transfer.

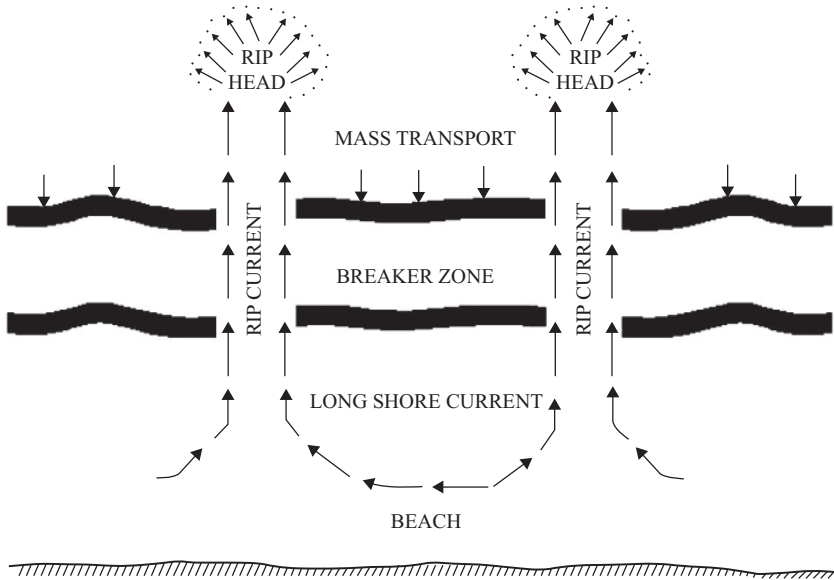


Fig.1.16 Schematic representation of nearshore currents

Along certain stretches of the coast, in particular, along a barred coast or along some of the steeper coasts, there could be a large gradient in the height along the wave crest and this in addition to the set-up produces seaward flowing currents that are rather narrow and that create circulation cells within the surf zone as shown in Fig. 1.17. These narrow currents, with a magnitude of even up to few tens of centimeters per second, can transport sediment and are called rip currents. Rip currents can be a danger to swimmers. In actuality, they should not be a problem to swimmers because they are narrow and the swimmer simply needs to move a short distance along the shore to escape their seaward path.

1.4 STORM TIDES, TIDAL BORES, TSUNAMIS AND SEICHES

1.4.1. Storm surge

Coastlines may be subject to higher-(and lower)-than-normal water levels associated with meteorological conditions such as strong winds and low atmospheric pressures occurring during periods of intense storm activity, and these are referred to as storm tides or surges. A storm surge is an abnormal rise of seawater due to tropical cyclone and is greatly amplified where the coastal water is shallow, in the estuarine region and where the shape of the coast is like a funnel. Thus a storm surge is one with peculiar characteristics and having a very high damage potential.

The major factors include, (i) A fall in the atmospheric pressure over the sea surface, (ii) The effect of the wind, (iii) The influence of the seabed, (iv) A funneling effect, (v) The angle and speed at which the storm approaches the coast and (vi) The tides.

The low-pressure area or **eye** of the cyclone allows the sea level to rise. The high-speed winds surrounding the **eye** drive more water over this rise. The sloping bed of the sea and contours off the shoreline add further to the height. A further contribution to the height of the storm surge is added if the cyclone arrives at high-tide. Storm surges are not waves though they may look like them. A storm surge is a mass of water, which will submerge everything in its path, till it recedes back into the sea. It moves at the same speed as that of the cyclone. It travels up to the point where the ground height is equal to the height of the surge.

The coastal areas of North Bay of Bengal satisfy most of the above-mentioned criteria and the storm surge gets enormously amplified there. Due to several favorable factors in these areas, the world's highest storm surge of over 13 m was reported from the area in 1876 near Bakerganj. Cyclonic storms are sometimes accompanied by tidal waves with heights of 5 m and sometimes hit 20 km inland with wind speed of 150 kmph.

The Indian National Centre For Ocean Information Services (INCOIS) has categorized the entire Indian coast into 4 zones.

1. Very high risk zones, VHRZ (surge height > 5 m)
2. High risk Zone, HRZ (surge height between 3 and 5 m)
3. Moderate risk zone, MRZ (surge height between 1.5 and 3 m)
4. Minimal risk zone (Surge height < 1.5 m)

The coastal areas and off-shore islands of Bengal and adjoining Bangladesh are the most storm-surge-prone (~10–13 m), the east coast of India between Paradip and Balasore in Orissa (~5–7 m) and the Andhra coast between Bapatla and Kakinada holding estuaries of two major rivers, Krishna and Godavari (~ 5–7 m), are classified as VHRZ. The Tamil Nadu coast between Pamban and Nagapattinam (~ 3–5 m) is considered as HRZ, whereas, Gujarat along the west coast of India (~ 2–3 m) falls under MRZ.

1.4.2 Tidal bores

Tidal bores occur when waves propagate in channels particularly with converging sides. Under such conditions, the tidal energy of the waves act on a decreasing width and their height is set to keep on increasing. In exceptional cases, a tidal wave may form a steep wall of water and rush up in the channel or river estuary. This phenomenon is usually referred to as a tidal bore.

1.4.3 Tsunamis

A tsunami is basically a long wave in deep offshore waters, which has the characteristics of waves in shallow waters. Ordinary wind-generated waves possess a period varying between 5 and 30 seconds and a wavelength of few hundred metres, whereas a tsunami possesses a prolonged time period in the range of 10 minutes – 2 hours and a wavelength exceeding 500 km. Tsunami

waves' relative behavior to shallow water waves is due to their longer wavelengths. **Tsunami** is a Japanese word which translates as **harbor wave**.

The major reasons for a tsunami outbreak are volcanoes, earthquakes and landslides occurring above or below the sea surface, although these activities produce tsunamis with comparatively much lesser impact than those produced by submarine faulting (earthquake). During such an instance, huge water mass in the ocean in the vicinity of the disturbance is displaced from its equilibrium position and travels in concentric circles. It can propagate uninterrupted over several km. The speed of the tsunami is a function of only the water depth and when the water depth is about 4 km, its speed will be 713 kmph. Moving with such tremendous speeds, they pile up along shores causing great destruction.

Among about 100 tsunamis around the globe which have occurred in the past, the great Indian Ocean tsunami of 26 December 2004 caused by an underwater earthquake of strength 9.3 on the Richter scale off the coast of Banda Aceh, Indonesia, led to the worst disaster in history. Its effect was felt in Bangladesh, India, Malaysia, Myanmar, Singapore, Thailand and the Maldives. The two maritime states that were severely affected were Tamil Nadu and Kerala. The height of water that propagates along the beach or a structure from mean sea level termed as **run-up** is referred to as inundation height. Similarly, the distance up to which the seawater rushes into the land is the inundation distance. For Tamil Nadu, the Tsunami run up was up to a maximum of about 5 m and inundation distance into the land was about 1.5 km (Sundar et al., 2007), whereas, for Kerala, the maximum run-up and inundation distance as per Kurian and Praveen (2010) were reported to be about 4.5 m and 2.5 km respectively. To understand the clear difference between the hydrodynamic behavior of a tsunami and a wave close to the seabed, example 3.6 in Chapter 3 may be referred.

1.4.4 Seiche

A seiche is a surge generated within an enclosed or partially enclosed body of water which has a resonance similar to that of the disturbing force. The wave in seiche is non-progressive in nature and remains stationary in the horizontal plane. Unlike the wind waves' forward motion in the sea, the waves in a seiche move up and down. Hence they are called standing waves instead of/as opposed to progressive waves.

The characteristics of progressive waves and standing waves are discussed in chapters 3 and 4. Seiches tend to be triggered in a still body of water by strong winds, variation in atmospheric pressure, earthquakes, etc. This is most frequently encountered in an enclosed or semi-enclosed basin such as lakes, bays, harbors and bathtubs.

During the tsunami of 2004, a number of boats within the harbors along the affected coast experienced this phenomenon which resulted in their damages.

Table 1.1: Beaufort wind and wave scale

Beaufort number	Description	Wind speed (kmph)	Wave height (m)	Sea conditions	Land conditions
0	Calm	<1	0	Flat.	Calm. Smoke rises vertically.
1	Light air	1.1–5.5	0–0.2	Ripples without crests.	Smoke drift indicates wind direction; still wind vanes.
2	Light breeze	5.6–11	0.2–0.5	Small wavelets. Crests of glassy appearance, not breaking	Wind felt on exposed skin. Leaves rustle, vanes begin to move.
3	Gentle breeze	12–19	0.5–1	Large wavelets. Crests begin to break; scattered whitecaps.	Leaves and small twigs constantly moving; light flags extended.
4	Moderate breeze	20–28	1–2	Small waves with breaking crests. Fairly frequent white horses.	Dust and loose paper will rise. Small branches begin to move.
5	Fresh breeze	29–38	2–3	Moderate waves of some length. Many white horses. Small amounts of spray.	Branches of a moderate size move. Small trees in leaf begin to sway.
6	Strong breeze	39–49	3–4	Long waves begin to form. White foam crests are very frequent. Some airborne spray is present.	Large branches in motion. Whistling heard in overhead wires. Umbrella use becomes difficult. Empty plastic garbage can strip over.
7	High wind, moderate Gale Near gale	50–61	4–5.5	Sea heaps up. Some foam from breaking waves is blown into streaks along wind direction. Moderate amounts of airborne spray.	Whole trees in motion. Effort needed to walk against the wind.
8	Gale fresh gale	62–74	5.5–7.5	Moderately high waves with breaking crests forming spindrift. Well-marked streaks of foam are blown along wind direction. Considerable airborne spray.	Some twigs broken from trees. Cars veer on road. Progress on foot is seriously impeded.

Beaufort number	Description	Wind speed (kmph)	Wave height (m)	Sea conditions	Land conditions
9	Strong gale	75–88	7–10	High waves whose crests sometimes roll over. Dense foam is blown along wind direction. Large amounts of airborne spray may begin to reduce visibility.	Some branches break off from trees, and some small trees blow over. Construction/temporary signs and barricades blow over.
10	Storm whole gale	89–102	9–12.5	Very high waves with overhanging crests. Large patches of foam from wave crests give the sea a white appearance. Considerable tumbling of waves with heavy impact. Large amounts of airborne spray reduce visibility.	Trees are broken off or uprooted, saplings bent and deformed. Poorly attached asphalt shingles and shingles in poor condition peel off roofs.
11	Violent storm	103–117	11.5–16 m	Exceptionally high waves. Very large patches of foam, driven before the wind, cover much of the sea surface. Very large amounts of airborne spray severely reduce visibility.	Widespread damage to vegetation. Many roofing surfaces are damaged; asphalt tiles that have curried up and/or fractured due to age may break away completely.
12	Hurricane-force	≥ 118	≥ 14 m	Huge waves. Sea is completely white with foam and spray. Air is filled with driving spray, greatly reducing visibility	Very widespread damage to vegetation. Some windows may break; mobile homes and poorly constructed sheds and barns are damaged. Debris may be hurled about.

Table 1.2 Definitions of tidal datum

HAT (Highest Astronomical Tide)	The elevation of the highest predicted astronomical tide expected to occur at a specific tide station over the national tidal datum epoch.
MHHW (Mean Higher High Water)	The average of the higher high water height of each tidal day observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch.
MHW (Mean High Water)	The average of all the high water heights observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch.
MTL (Mean Tide Level)	The arithmetic mean of mean high water and mean low water.
MSL (Mean Sea Level)	The arithmetic mean of hourly heights observed over the national tidal datum epoch. Shorter series are specified in the name; e.g., monthly mean sea level and yearly mean sea level.
MLW (Mean Low Water)	The average of all the low water heights observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch.
MLLW (Mean Lower Low Water)	The average of the lower low water height of each tidal day observed over the national tidal datum epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the national tidal datum epoch.
LAT (Lowest Astronomical Tide)	The elevation of the lowest astronomical predicted tide expected to occur at a specific tide station over the national tidal datum epoch. (Co-ops.nos.noaa.gov)
Storm surge	A temporary water level increase (surge) due to persistent action of wind over water, as during cyclones. They may last for up to a couple of hours.