LITTORAL DRIFT AND SHORELINE EVOLUTION

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1. INTRODUCTION

Large amount of energy from winds is transferred to sea in the offshore region. This energy is transported to the coast in the form of waves, which constantly agitate the coastal region. The coastline is the interface between the land and sea where the winds, waves, tides and currents attack the land. The land responds to this attack by dissipating the sea’s energy and changing the shape and position of the coastline continuously. Beaches and the nearshore zones are the most directly affected areas by the forces of the sea. The action of waves is the principal cause of most the shoreline changes.

The breaking waves in the surf zone provide the turbulent energy to bring the sediment in suspension and the longshore current produced by obliquely incident waves provide the mechanism to transport the sediment along the shore. This longshore transport taking place between the threshold depth of sediment movement and the height of wave run-up, i.e., the nearshore zone (Fig.1) is known as littoral drift. The schematic presentation of generation of longshore transport due to obliquely incident waves is shown in Fig.2.

In many cases, longshore transport of sand in thousands of cubic meters is prevailing along the coastlines. Man’s interventions into such natural processes taking place in the coastal zone also has an impact on the beaches and shorelines. These are construction of ports and coastal structures, dredging, mining etc. The longshore transport is interrupted (Fig.3) by construction of ports and coastal structures such as breakwaters, jetties, sea walls, etc. Due to this built-up of a beach along the updrift side of a structure together with erosion in its downdrift direction causes problems to adjacent communities and often threatens the usefulness of the harbour etc. In order to anticipate such impacts and suggest remedial measures to minimize adverse effects of the impacts, it is desirable to estimate quantities of the longshore sediment transport and predict shoreline changes due to such constructions beforehand.

It is often difficult to simulate littoral drift and shoreline changes in physical models. Mathematical modeling is a useful tool for estimation of littoral drift and for predicting shoreline changes due to construction of ports and coastal structures. In this lecture mathematical modelling techniques for computing littoral drift and shoreline changes are discussed.

2. WAVES – ENERGY TRANSFER AGENTS

Wind generated waves are important as energy-transfer agents; first obtaining their energy from the winds, transferring it across the oceans and then delivering it
to the coastal zones where it can generate variety of nearshore currents and sand transport patterns. The waves are generated due to the transfer of energy from wind to initially calm water surface of sea (seas). After leaving the generation area they propagate towards the coastline without major change in their characteristics (swells). As they enter into shallow waters and travel towards coastline they undergo shoaling, refraction, diffraction and backward reflections. These are non-dissipative processes in which redistribution of wave energy takes place. The dissipative processes such as wave breaking and bottom friction are also important in the coastal area. Thus the energy obtained from the storm winds is carried to the nearshore zone and expended over a relatively narrow area. The wave energy is related directly to the wave height by

\[ E = \frac{\rho g H^2}{8} \]  

(1)

where, \( \rho \) is the water density. The flux of energy carried by the moving waves is then

\[ P = ECn \]  

(2)
here, $C_n$ together is the group velocity of the waves, the rate of energy transfer, $n$ being a function of the water depth ($n = \frac{1}{2}$ in deep water, $n = 1$ in shallow water). The energy flux $P$ can also be viewed as the power of the waves per unit crest length. This is the power delivered to coastal zone when the waves reach the nearshore and break. Without significant bottom frictional drag on the waves, and for the moment neglecting refraction, $P$ remains constant as the waves move across the ocean. Even when the waves reach shallow water it is $P$ of equation (2) that remains relatively constant, not the energy $E$ of equation (1). As a consequence, when waves reach deep water and begin to shoal, $C_n$ in general decreases so that $E$ and hence the wave height must increase in order to $P$ to remain constant. Therefore, in general, the wave heights increase as they approach shore which is known as shoaling. In shallow water near the shore, the phase velocity $C$ of waves is governed by the water depth. Therefore part of the wave crest in deeper water will move faster than the part of the wave crest in shallower water causing bending of waves so as to become more nearly parallel to shoreline. This bending of the waves in response to the change in water depth is known as refraction. Due to refraction the wave height may increase or decrease depending on configuration of sea bed topography. If the sea bed is characterised by the presence of submerged features such as shoals, channels, islands etc. redistribution of wave energy takes place in lateral direction, which is known as the mechanism of internal diffraction. Due to coastal structures such as breakwaters wave energy spreads laterally perpendicular to the dominant direction of wave propagation and is transmitted in the geometric shadow zone. This is diffraction of waves due to long structures.

As waves approach shore, the wave length $L$ and wave celerity $C$ decrease and wave height $H$ increases and hence the wave steepness $H/L$ progressively increases. The wave crests also become narrower and peaked, the troughs becoming wide and flat. Eventually, the waves oversteepen, become unstable, and break. It is found that the ratio of the breaker height, $H_b$, to depth is given by

$$\gamma = \frac{H_b}{h_b} = 0.78$$

In general, waves with a range of heights are arriving at the coast, and larger of these will break in somewhat greater water depths than the smaller waves. This gives rise to breaker zone whose width depends on the wave-size range and on the beach slope. The longshore component of the wave energy flux in the breaker zone given by

$$P_l = (E C_n)_b \sin \alpha_b \cos \alpha_b$$

is the driving force of the longshore sediment transport. Here $\alpha_b$ is the breaking angle between the wave crest and the shoreline.

3. MECHANISM OF NEARSHORE SEDIMENT TRANSPORT

The currents are generated by the momentum carried by waves. Due to wave breaking the orbital motion is disrupted and translatory motion is generated. The wave breaking in the surf zone provides the turbulent energy to dislodge the
sediments and bring them into suspension. The combined action of waves and currents generated by waves provide the mechanism to transport the sediment onshore-offshore or along the shore.

Considering the action of waves on any beach in plan the wave crests reaching the shore are seldom parallel to the shoreline or depth contours. The effect of this oblique attack of the waves on the shore is to generate two components of wave energy. The longshore component of energy generates longshore currents which are responsible for longshore transport. The component normal to shore generates the onshore-offshore sediment transport. The longshore sediment transport however, is more dominant and is responsible for the shoreline instabilities.

Longshore sediment transport figures prominent in situations involving loss of sediment supply such as damming of rivers, and in impoundment at structures such as breakwaters, jetties and groins. In these cases longshore transport is the major process governing nearshore topography change and can not be neglected.

4. **LONGSHORE CURRENTS**

When waves break at an angle to shoreline longshore currents are generated by the momentum (radiation stress) carried by the waves. When the wave motion approaches the shore the angle of approach of the waves changes due to refraction, the wave length decreases causing increase in wave height and the oscillatory motion of waves which in deep water is the form of circular orbits become more elliptical as the wave approaches shallow water. Finally when the wave approaches a depth equal to approximately 1.3 times the wave height, the wave begins to break. Breaking is a process in which the normal orbital motion attributed to waves is disrupted owing to higher friction at the wave trough, and a translatory motion is generated within the breaker zone. This translatory motion results in an longshore current between line of breakers and the shore.

Longshore currents typically have velocities with mean value of 0.3 m/sec or less. Although longshore currents generally have low speeds, they are important in littoral processes because they flow along the shore for extended period of time, transporting sediment set in motion by the breaking waves. The following is the modified Longuet-Higgins formula for longshore current at mid-surf position based on radiation stress (momentum flux) concept.

\[ v = 1.19 \left( gH_b \right)^{1/2} \sin \alpha_b \cos \alpha_b \]  

5. **LONGSHORE TRANSPORT**

The transport of material in the longshore direction by waves and currents near the shore is known as littoral drift. Depending on the direction of transport with respect to the observer standing on the shoreline facing the sea, the gross and net transport rates are given by \( Q_g = Q_{rt+} + Q_{lt} \) and \( Q_n = Q_{rt} - Q_{lt} \) where, \( Q_{rt} \) is transport rate from left to right of observer and \( Q_{lt} \) is transport rate from right to left of observer.
When wave approach the shore obliquely, the longshore component of energy flux (Fig. 4) is responsible for longshore transport. The wave energy flux method of Coastal Engineering Research Centre, Vickberg, USA (SPM, 1984) is the commonly used method for estimation of the longshore sediment transport. This method is based on the assumption that the longshore transport \( Q \) depends on the longshore component of energy flux \( P_l \) in the surf zone given by equation (4) and the longshore sediment transport rate is given by

\[
Q = K P_l
\]  

(6)

Based on the field measurements for sand sizes between 0.2 mm and 0.6 mm the value of \( K \) was estimated to be 1290 taking the units of \( Q \) and \( P_l \) cum/year and \((N\cdot m)/(m/s)\) respectively. The breaking wave parameters and the corresponding wave frequencies obtained from the wave data analysis are used to estimate the littoral drift prevailing in the coastal region. An important application of the littoral drift formula (6) is the numerical model of the shoreline evolution described in para 6.

Based on available field data and laboratory data researchers have related the energy flux to the quantity of longshore transport by choosing different values of the empirical factor \( K \). Some of the relations are shown in Fig. 5 Typical values of \( Q \) range from \(10^5\) to \(10^6\).

The distribution of sand transport across the surf zone is obtained using the method suggested by Komar (1977) which gives the local sand transport produced by waves and longshore currents as

\[
I_l = K_2 [ C_r \rho v^2 + 0.5 f \rho (0.25 \rho g d) ] v
\]  

(7)

Where, \( f \) is the drag coefficient for oscillatory wave motions, \( d \) and \( v \) are local water depth and longshore current which are functions of the distance from the surf zone and \( K_2 \) is proportionality coefficient between the available wave power and resulting transport.

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The most important parameters for computation of longshore transport are the breaker wave height \( H_b \) and the breaking wave angle \( \alpha_b \) which can be obtained from the following equations.

\[
d_b = 1.3 \ H_b, \quad d_b = \text{water depth at breaking point, } H_b = \text{breaker wave height.}
\]

\[
L_b = L_0 \tanh \left( 2 \pi \frac{d_b}{L_b} \right), \quad L_0 = 1.56 \ T^2 = \text{deepwater wave length, } T = \text{wave period}
\]

\[
\sin \alpha_0 / \sin \alpha_b = C_0 / C_b \quad (\text{Snell's law}), \quad \alpha_b = \sin^{-1}(C_0 \sin \alpha_0 / C_b), \quad C_0 = 1.56 \ T
\]

Here, \( C_0 \) and \( C_b \) are celerities in deep water and at breaking point respectively.

6. **SHORELINE EVOLUTION**

The general approach of mathematical modelling of shoreline changes is closely analogous to that of fluid flow. The continuity equation is replaced by the following continuity equation for the beach sand.

Similar to the fluid flow model, the environment is divided into a number of cells and the shoreline model consists of following the shift of sand from one cell to another. A stretch of shoreline is divided into a series of cells [Fig. 6(A)], the end of each cell terminating in a schematic beach profile [Fig. 6(B)]. As shown, all the cells have a uniform width \( \Delta x \), though this need not necessarily be the case, and

\[
\frac{\partial y_i}{\partial t} = - \frac{1}{d} \frac{\partial Q_i}{\partial x} + \frac{Q_i}{d \Delta x} \quad \quad \quad (8)
\]

have individual lengths \( y_1, y_2, ...y_i, ...y_n \) beyond some base line. The series of cells is seen to approximate the smoothly curving shoreline, the greater the number of cells and the smaller their widths, the more nearly they represent the smooth shoreline.

The basis of any shoreline model is the evaluation of the quantities of sand entering and leaving each cell, and the resulting changes in the shoreline position due to the balance of input vs. exit. The littoral drift is usually the main cause of sand moving from one cell to another. If \( Q_i \) is the rate of littoral drift from cell \( i \) into cell \( i+1 \) and \( Q_{i-1} \) is the drift into cell \( i \) from cell \( i-1 \) [Fig. 6(B)], then the net volume of sand \( \Delta V_i \) gained or lost from cell \( i \) is

\[
\Delta V_i = (Q_{i-1} - Q_i \pm Q_s) \ \Delta t \quad \quad \quad (9)
\]

where \( \Delta t \) is the elapsed time, the increment of time over when the model is run. Note that \( \Delta V_i \) can be positive or negative signifying erosion or net deposition. It is desirable to express \( \Delta V_i \) as an actual change in the shoreline position, that is as a change in the length \( y_i \) of the cell. If \( \Delta y_i \) is the corresponding change in \( y_i \) in time \( \Delta t \), then from the geometry of the cell shown in Fig. 6(B).

\[
\Delta V_i = d \Delta y_i \Delta x \quad \quad \quad (10)
\]
The linear dimension $d$ must be chosen to yield the correct correspondence between $\Delta V_i$ and $\Delta y_i$ and will depend on the nature of the beach profile. It can be seen that $d y_i$ is cross-sectional area of the wedge of sand deposited or eroded – multiplication by $\Delta x$ yields the volume. The linear dimension $d$ tends to be of the order of water depth at the breaker position. Combining equations (9) and (10) gives
for the change in shoreline position of cell I as a function of the sand inputs and exists. Since in the model parameters $\Delta t$, $d$, $\Delta x$ are generally fixed, the $\Delta y_i$ shoreline changes are produced simply by the balance of Q-terms. Positive and negative $\Delta y_i$ represents shoreline advance and shoreline retreat (erosion). As the finite elements are decreased to their limits, the equation becomes the continuity equation (8).

The littoral drift terms $Q_i$, $Q_{i-1}$ are evaluated with a littoral drift formula such as equation (6). This evaluation requires knowledge of breaking wave parameters $H_b$, $(Cn)_b$ and $\alpha_b$.

The breaker angle will generally change from cell to cell due to changing orientation of the shoreline. As shown in Fig. 6(C) the angle which the shoreline makes with a parallel to x-axis, between cells $i$ and $i+1$ is given by

$$\tan \alpha_i = (y_i - y_{i+1}) / \Delta x$$

If the incoming waves make an angle $\alpha_0$ with the x-axis then the angle at the shoreline is $\alpha_b = \alpha_i + \alpha_0$, the subtraction occurring when $\alpha_0$ opens in the negative x-direction. This breaker angle can be obtained from the following equation.

$$\tan \alpha_b = \tan(\alpha_i + \alpha_0) = (\tan \alpha_i + \tan \alpha_0)/(1 + \tan \alpha_i \tan \alpha_0)$$

Fig. 7 provides a simple example of simulation of shoreline changes where a jetty is blocking littoral drift.

7. CHARACTERISTICS OF INDIAN COASTLINE

At this stage, it is appropriate to look at the characteristics of the Indian coastline. The east coast of India is about 2650 km long whereas the west coast is 2900 km long. Important features of the Indian coastline are given below –
**West Coast**
- Flat sea bed slopes (1:100 to 1:500)
- Wide continental shelf (about 250 km)
- Tidal range: 1 to 6 m
- Strong tidal currents (especially in the Gulfs)
- Wave climate less severe
- About 2 storms per year
- Southwest monsoon (May to Sept)
- Littoral drift negligible
- Only two major rivers meet the Arabian Sea
- Bed material: Clay, Silty-Clay

**East Coast**
- Steep sea bed slopes (1:30 to 1:100)
- Narrow continental shelf (about 20 km)
- Tidal range: 1 to 1.5 m
- Weak tidal currents
- Severe wave climate
- Frequent storms (about 5 per year)
- Two monsoons: Southwest (May to Sept) and Northwest (Oct to Jan)
- Large littoral drift: 0.5 million cum at Chennai to 1.5 million cum at Paradip
- Almost all rivers meet the Bay of Bengal: High source of sediment
- Bed material: fine sand

8. **LITTORAL DRIFT ALONG INDIAN COASTLINE**

Distribution of longshore sediment transport along the Indian coast was computed by Chandramohan et al (1990). An sediment transport model was developed by them which was based on an empirical equation relating the longshore energy flux in the breaker zone to the longshore transport rate. Their study indicated that along the east coast, the longshore transport is northerly during April-September, southerly during November-February and variable in March and October. Along the west coast, the longshore transport is generally southerly during January-May and in October. It is variable during other months showing northerly drift along the Maharashtra and south Gujarat coasts and southerly along the Karnataka and Kerala coasts during June-September. This phenomenon gets reversed in November and December. The general distribution of annual net transport rates is shown in Fig. 8.

9. **CASE STUDIES**

9.1 **Simulation of Shoreline Changes at Kudankulam**

A power station of 2000 MW capacity is proposed at Kudankulam, Tamilnadu (Fig. 9), for which cooling water would be drawn from sea through an intake channel of 1100 m length protected by embankments on both sides. It was desired to estimate littoral drift and assess the effect of the construction on the coastline around Kudankulam by carrying out numerical modelling. Based on the site inspection, littoral drift at Kudankulam site was estimated to be of the order of 0.05-0.1 million cu m per year, with general direction towards east. Numerical model studies indicated [Kanetkar et al, 2001] that the littoral drift was confined within 800 m from the shoreline. Due to obstruction by the intake channel, the shoreline on the west would advance and that on the east would recede by about 70-80 m.

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9.2 Simulation of Shoreline Changes at Ennore

The layout of Ennore port is shown Fig. 11. It is located on the east coast of India about 20 km north of Chennai port. It was constructed in 1999 to meet the increasing demand of cargo. It is in operation since 2001 with coal as major cargo. The port is sheltered by northern breakwaters of 3.2 km length and southern breakwaters of 1.1 km length with entrance from southeast direction. Since the region is located in highly sensitive zone of littoral drift, the development of the port was expected to cause significant impact on the coastline. After the construction of the port, the southern shoreline has witnessed accretion due to the southern breakwater and also due to presence of Ennore creek while the northern coastline has experienced severe erosion. Shoreline changes adjacent to Ennore port due to development of the port were simulated by mathematical model (LITPACK, 2000) and compared with the shoreline changes derived from remote sensing/image processing technique. The study indicated that the cross-shore and longshore impacts predicted by mathematical model and satellite information

(Fig. 10) in the course of 50 years duration and the effect would be felt up to a distance of about 3000 m on either side.
match satisfactorily (Fig. 12). Thus the satellite information is useful for calibrating the mathematical model which can be further used for predictive purposes.

FIG.11(A): LOCATION OF ENNORE PORT

FIG.11(B): ENNORE PORT

FIG.12 : COMPARISON OF SHORELINE CHANGES OBTAINED BY MATHEMATICAL MODEL & IMAGE PROCESSING AND IMAGE PROCESSING

9.3 Simulation of Shoreline Changes due to Proposed port at Kakinada

It is proposed to develop Kakinada SEZ Port at about 20 km north of Kakinada Port. It consists of an offshore breakwater of about 1750 m in length aligned parallel to the coast in a depth of about 12 m and a shore connected north breakwater of about 2500 m. The littoral drift was estimated by site inspection and assessment of the impact of the port on the adjacent coastline was carried out using a mathematical model (LITPACK, 2000). The site inspection indicated that the general direction of drift is towards south in local coastal reach of about 30-40 km from Kakinada port and the net littoral drift was estimated to be of the order of 0.03 million cu m per year. Due to obstruction by the port, the shoreline on the
north would advance and that on the south would recede. Also the coastline in the shadow zone of the offshore breakwater would advance. Mathematical model studies indicated that the littoral drift was confined within 400 m from the shoreline. After 10 years, the cross-shore changes in shoreline would be within 20-100 m with longshore effect limited to coastline adjacent to port of length 1-2 km. As the longshore transport is not significant at the site of development, the impact of the proposed SEZ port would not be much significant. For avoiding the adverse impact of the port, regular bypassing of the deposited sand to the southern coastline would be desirable. In addition it would be desirable to protect the southern reach of about 2 km, by providing suitable coastal protection works such as sea wall.

REFERENCES


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