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Modelling Coastal Sediment Transport for Harbour Planning

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Present study provides a detailed account on the performance and limitations of Cuddalore port breakwaters based on an analysis made on the sediment pattern in breakwaters area of Cuddalore port using MIKE21 modelling software. Possible solutions for the problem are also demonstrated.

[**Key Words**: Port Planning, Breakwaters, Sediment Transport, Sand Bars, Port Structures, Coastal Modelling, MIKE21]

Introduction

The main drawback of the Cuddalore port is sediment deposition. Sandbars are formed due to the deposition of sediments which is visible from the breakwaters. Opening of the break water is at east and the waves directly enter into the entrance channel & hence the sediments transportation is taking place. From discussion with fishermen and the users of Cuddalore port, it was found that, several difficulties were being faced in every day operations.

Due to very low depth at one end, the launchers enter and leave on the same side. Also, in the entrance channel of the breakwater, there is a heavy sediment deposit on the southern side compared with the northern. Small boats can enter the port even with the sediment deposition, whereas launchers have to change their route periodically depending upon the tidal range. During high tide, water from the sea enter into the channel and during low tide the water goes back to sea and the fisherman can use the port only during high tide period.

Due to spring tides, the water depth is higher during full moon and new moon period. The concrete breakwater which was built during the 20th century in on Northern side got eroded due to wave action. In the recent years, armour stones are placed next to the concrete structure and also in the Southern side. An analysis has been made on the sediment pattern in breakwaters area using MIKE21 Modelling software. This case study is to understand the mechanism of failures in Cuddalore Port area. This research gives an idea about the pattern of wave direction, long-term sediment transport and potential areas of improvement in port operations.

Materials and Methods

Engineering studies in natural environments have site specific conditions that require a unique approach to each problem. Therefore some or all of the following methods may need to be applied in order to determine the impacts of harbour structures on the sedimentological environment. Some adverse impacts may include interruption of the net wave-induced long shore transport causing down drift erosion, scour at the base of breakwaters or jetties, silting-up of harbour basins requiring repeated dredging, increased agitation due to reflected waves, or increased currents through harbour openings. After the construction of new structures, sediment flows will adjust to a newequilibrium, typically over a timescale of years. Thus the effects of human-intervention on the coastal environment are not immediately obvious and coastal developments require careful planning.

Fig.1. ArisaigHarbor[1]

Every harbour has a unique combination of structures, environmental forcing conditions, sediment sources and supply. Site investigations should include:

1) Acquisition of bathymetry, water level, wind, wave and sediment properties information.
2) Observation of shoreline features to identify erosional/ depositional landforms.
3) Examination of aerial photographs, which gives a larger scale view of the area and may allow other landforms to be identified. Analysing a sequence of historical aerial photography is the first (and oftentimes the most accurate) method to assess sediment processes and determine rates of change. As a brief example, sediment flux at Arisaig Harbour (Fig.1), on Nova Scotia's North shore is dominated by wave-driven long shore transport supplied by sandy cliffs.

The original harbour facing the direction of longshore transport became a natural sand trap. A new breakwater and extension of existing rock structures were recently considered. Some important aspects considered in the design process included impacts of episodic major storms, seasonal and annual climate variability, changes in water levels, and changes in up-drift shoreline use that affect the sediment supply from beaches, rivers or cliffs.

Shoreline contour models simulate the evolution of one bathymetric contour (generally the shoreline at mean water level). They typically assume uniform grain size, beach profile shape and depth of closure (the seaward depth at which repeatedly surveyed profiles intersect). These models, developed for straight sandy coastlines, predate the full morphological models discussed next. However, within limitations, these models are very effective for long-term predictions of shoreline change when coastal structures are introduced or modified.

As an example, consider the one-dimensional diffusion equation: $\frac{\partial y}{\partial x} - D\frac{\partial^2 y}{\partial x^2} = 0$ (1)

Where, y is the cross-shore coordinate, x is the alongshore coordinate, t is time and D (long shore diffusivity) is related to the sediment transport rate, beach profile shape and wave conditions. The equation can be solved analytically[2,3].and used to model the progressive shoreline evolution from an initially straight shoreline, assuming steady-state wave and sediment conditions and one structure perpendicular to the coast. As shown in Fig. 2,

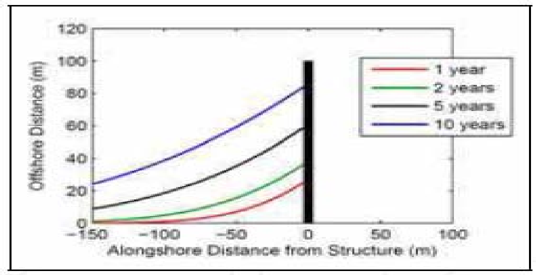

Fig. 2. Example sediment accretion along a groin estimated by a 1-D shoreline change model [1]

accretion against the up-drift side of the structure increases with time until the contour intersects the end of the structure, at which time bypassing begins.More sophisticated 1D model have been developed with the capability of simulating thebeach response to the introduction of different coastal structures such as groins, detachedbreakwaters or seawalls. The shoreline models LITPACK (DHI 2008) and GENESIS (Generalized Model for Simulating Shoreline Change[4], simulate long term averaged shoreline change produced by spatial and temporal differences in wave parameters and longshore sediment transport. The NLINE model[5] simulates beach evolution for multiple contour lines.

Morphodynamic models rely on numerical routines that explicitly predict the wave and hydrodynamic forcing, and sediment transport in two or three dimensions. The hydrodynamic models numerically solve the fluid momentum and continuity equations in order to predict water level changes, circulation and transport driven by winds, waves, tides, river discharge or density forcing. Some examples include Delft3D6, the Regional Ocean Modelling System (ROMS[7]), Coupled MIKE21[8]and Finite-Volume, primitive equation Community Ocean Model (FVCOM)[9].

The ample sediment supply combined with the hydrodynamic regime cause extensive sedimentation in dredging areas. These areas tend to decelerate sediment-bearing flows, and represent a departure from a natural equilibrium state where sedimentation is balanced by erosion. An extensive review of harbour sedimentation (or 'siltation') mechanisms is provided in[10].Sediment transport modelling must resolve the following three major site-specific processes:

a)Density currents- The density difference between tidally-driven salt water inflow and freshwater river out flow causes an estuarine circulation pattern characterized by a mean seaward surface flow and a mean up-harbour bottom flow. The residual dense bottom flows carry silt that is deposited in the more stagnant areas. Sedimentation in dredging areas is due in most part to marine silt carried into the Harbour by the bottom density current[11]. Notably, yearly variations in river outflow and suspended concentrations in the river do not correspond to variations in the measured dredged quantities.

b)Tidal exchange -Water within a harbour basin is replaced by freshwater from the river water on the ebb tide, and then by saline water on the flood tide (with the exception of the near-surface where a layer of freshwater persists). This efficient and continuous exchange mechanism is caused both by the very large tidal range and by the large river discharge. Settling then occurs wherever weaker currents allow. The sedimentation rate depends on a complex array of variables including tidal prism (volume entering the harbour), trapping efficiency, suspended sediment concentrations, dry bed density and settling rates vs. local currents. Of these variables, settling rate probably has the highest variability and influence.

c) Horizontal eddy exchange- During peak flows, suspended sediments are transported inthe lee of protruding wharf structures due to energetic residual eddies shed from the structures. Deposition occurs where weak currents and high settling rates allow.

Results and Discussions

Climate Parameters for Cuddalore Port[12]

Wind

Cuddalore experiences the change in wind direction throughout the year and wind speed varies from 1 and 19 Km/hour. During South-West monsoon between March and September, the wind blows predominantly from the South. In June, July and August, strong wind is experienced from South-West direction in morning, South during afternoons and South-East during nights. The North-East monsoon starts in October during which wind first blows from the coast then changes to Northerly direction in December and gradually decreases in force during January and February. The direction also changes from North-East to East. North-East monsoon winds are usually stronger than the South-East monsoon winds.

Cuddalore, being a part of Indian subcontinent, experiences tropical cyclones which originate from the depression generated in the Bay of Bengal during the North-East monsoon season (October to December). The occurrence of storms in this region is about once in three years. Cuddalore is also affected by cyclone generated waves during this period. One important issue in the design of any works along the East Coast of India is the littoral drift. The prevailing wave direction for nine months of the year is an oblique wave from the South-West. The energy in such waves breaking at and near the shore tends to cause sand particles on the beaches to be carried Northwards, in quite large quantities. Estimates[13] made by the National Institute of Ocean Technology at Chennai suggest that the total volume of sand moved is at the rate of about 1,500 cubic meters a day for nine months of the year, which works out as about 400,000 cubic meters a year. Any form of breakwater or other device which results in calm water being made for part of the coast breaks this cycle and prevents the sand moving northwards. This results in accretion of the land to the South of the obstruction and erosion of beaches to North. Waves predominantly from NE, ENE and E during NE monsoon and S, SSE, SE, SW and SSW during SW monsoon approach the site.

From the monthly distribution of wave frequency, it is observed that for four months of the year, waves are from the NE quadrant and the other eight months waves are from Southern quadrant. Tides in these areas are semi diurnal with two highs and two lows during the day. Tidal levels are referred to Datum of sounding. The simulated storm surge along the Cuddalore coast is 1.35m waves. The tide levels during spring and neap tides of Cuddalore coast are given below: (Chart Datum - 0.00m)

Highest High Water Spring (HHWS)
+ 1.18m CD
Mean High Water Spring (MHWS)
+ 1.00m CD
Mean High Water Neap (MHWN)
+ 0.80m CD
Mean Sea Level (MSL)
+ 0.69m CD

Mean Low Water Neap (MLWN)
+ 0.60m CD
Mean Low Water Spring (MLWS)
+ 0.40m CD

Bathymetry is very much essential and important to know about the depth variation and also to analyze the beach profile.From Fig.3 it is seen that, the depth at the entrance is -2.00m to 0m. Hence, the vessels navigate the entrance channel with difficulties. Using Google Earthsoftware, the shoreline is plotted for about 2km on both sides from the entrance of the port.

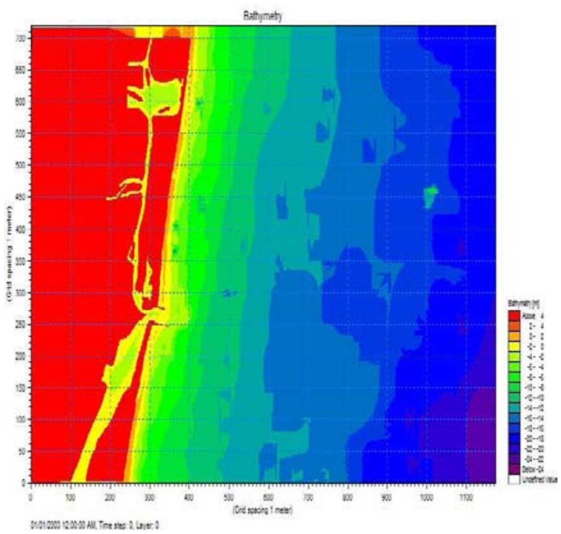

Fig.3. Digitized form of Hydrographic survey chart (2010) using MIKE 21.

There are a number of numerical models available today ranging from open source (Delft3D by Deltares) to commercial (MIKE21 by DHI). The choice of selection of MIKE21 is based on different factors. The advantage of using the MIKE21 modelling suite is the provision of flexible mesh which enables much more accurate representation of the actual area. 2D application has been considered as sufficient to arrive at a reasonably accurate model of the area. The flexible mesh approach allows a reduction of grid size locally at areas of special interest. The bathymetry data have been extracted from Naval Hydrographic Chart. Simulation of hydrodynamics has been carried out by solving 2D shallow water equations of mass and momentum thanks to the HD model of MIKE 21FM. To solve these equations using finite volume numerical methods, unstructured grids were used to define the topography of the study area[14]. Simulations generate unsteady two-dimensional flows in one layer fluids (vertically homogeneous). Flow and water level variations are described by the Saint-Venant equations[15] (the conservation of mass and momentum integrated over the vertical) which are the following:

$$\frac{\partial h}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=w \quad (2)$$

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+gh\frac{\partial z}{\partial x}+gp\frac{\sqrt{p^2+q^2}}{C2h2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx})+\frac{\partial}{\partial y}(h\tau_{xy})\right]$$
$$+\frac{h}{\rho_w}\frac{\partial p_a}{\partial x}=0 \quad (3)$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+gh\frac{\partial z}{\partial y}+gq\frac{\sqrt{p^2+q^2}}{C2h2}-\frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy})+\frac{\partial}{\partial x}(h\tau_{xy})\right]$$
$$+\frac{h}{\rho_w}\frac{\partial p_a}{\partial y}=0 \quad (4)$$

Where, *h* is the water depth [m], w=R-I is the net incoming flow rate [m/s], z is the surface elevation[m], (*p*,*q*)=(*hu*,*hv*) are the flux densities in directions x and y respectively [m²/s], C is the Chezy resistant [$m^{1/2}$/s], g is the acceleration due to gravity(m^2/s), p_a is the atmospheric pressure [kg/m/s^2], $\rho_w$is the density of water[kg/m^3], τ_{xx}, τ_{yy}, τ_{xy} are the components of effective shear stress. Wave breaking in the surf zone near the coast mobilizes the sediments around the breaker line and current generated by waves transport sediment along and across the coast. The sediment transported along the coast is referred to as the long-shore sediment transport or also known as littoral drift and that transported across the coast is known as cross-shore sediment transport. When there is a variation in the supply of sediments or obstruction to sediment movement along the coast imposed by coastal structures, the long-shore sediment transport is the major process governing the long-term changes in the shoreline. In beaches located far from the coastal structures and sediment sources as river mouths, the gradient of the long-shore transport rate will be generally small and cross-shore sediment transport will control the short-term changes in the beach profile. While dealing with long term coastline changes and planning mitigation measures to prevent adverse impacts due to human interference, particularly along the coasts with high littoral transport, the prediction of along shore sediment rate becomes important. There are a few empirical methods to calculate the long-shore sediment transport rate. Existing empirical formulae relate long-shore sediment transport rate with wave parameters at the breaker point, sediment characteristics and the sea bed slope, and they are based on data measured in the field. Frequently used empirical formulae for long-shore sand transport computation are those of [16]and [17].

CERC Formula

This formula, as per [17] is based on dimensional analysis, and it relates the immersed weight, Q_{imw} ,of the long-shore sediment transport to long-shore wave power(wave energy flux), P, per unit length of the beach as,

$$Q_{im\,w} = K\,P \qquad (5)$$

where, $Q_{im\ w}$ includes both the bed load and the suspended load transports, K is a non-dimensional calibration coefficient, and P is given by,

$$P = E\,C_{gbr}\,\mathrm{Sin}\theta_{br}\,\mathrm{Cos}\theta_{br} \qquad (6)$$

Table 1.1 The monthly observations of wave climate at Cuddalore Port

Month	T_p(s)	H_{sbr}(m)	Θ (degrees)	Θ_{br}(degrees)
January	12	0.8	60	45
February	12	0.8	70	35
March	10	1.2	90	15
April	10	1.2	90	15
May	10	1.2	110	5
June	8	1.6	110	5
July	10	1.2	130	25
August	10	1.2	135	30
September	10	1.2	130	25
October	8	1.6	65	40
November	8	1.6	45	60
December	8	1.6	45	60

in which,

$E = \frac{1}{8}\,\rho\,g\,H^2_{rms,br}$ = Average wave energy at breaker line

$H_{rms,br}$ = Root mean square (rms) wave height at breaker line;

$C_{gbr}= n_{br}C_{br}$= wave group velocity at breaker line, the coefficient

$n_{br} \approx 1$ at the breaker line;

C_{br} = Wave phase speed at breaker line; Θ_{br}= Wave angle (in degrees) at the breaker line (between wave c crest line and coastline or between wave propagation direction and shore normal direction).

CERC transport formula does not take into account the particle size of the beach sand and the beach slope. Kamphuis studied the influence of beach sediment size and the beach slope on littoral transport. His formula for volume transport rate can be written as,

$$Q_{tim} = 2.33\,(T_p)^{1.5}(\tan\beta)^{0.75}(d_{50})^{-0.25}(H_{s,br})^{2}[\sin(2\,\theta_{br}) \qquad (7)$$

With :$Q_{t,im}$ = long shore sediment (immersed mass) transport (kg/s); the dry mass is related to the immersed mass by $Q_{t,mass}= \rho_s/(\rho_s - \rho)\,Q_{timmersed\ mass}$; the conversion factor is about 1.64; $H_{s,br}$= significant wave height at breaker line (m); θ_{br} = wave angle at breaker line (°); d_{50}= median particle size in surf zone (m); $\tan\beta$ = beach slope defined as the ratio of the water depth at the breaker line and the distance from the still water beach line to the breaker line;

Table 1.2 Estimated long-shore sediment transport rate in Mm^3/year

Month	Northernly transport in Mm^3/year	Southernly transport in Mm^3/year
January	--	0.055
February	--	0.053
March	--	0.062
April	--	0.062
May	0.033	--
June	0.042	--
July	0.080	--
August	0.086	--
September	0.080	--
October	--	0.118
November	--	0.109
December	--	0.109
Net transport	0.321	0.568
Total transport		0.889

T_p = peak wave period. The value 2.23 is a dimensional coefficient related to the SI system assuming saltwater (1030 kg/m^3).Table 1.1 shows the monthly observations of wave climate at Cuddalore Port. The Table.1.2 shows that the sedimentation transported in the North to South direction is much larger than that of south to north direction. Hence the materials are largely deposited near the Southern breakwaters and one can observe sediment deposition near the breakwater at the entrance channel. As such, the users are found it very difficult to navigate boats, barges in the entrance channel. The depth at the entrance channel of the port is less than -2.00m; hence the port cannot accommodate even small ships.
Transportation takes place from the anchored ship to the port via barges. Those barges, launchersand boats are entering the port along Northern breakwaters as shown in the Fig.4.

Fig.4 Google Map of Cuddalore Port Breakwaters

It is observed that the barges are taken into the port during the period of high tide; because of the low depth at the entrance channel.

Comparison of satellite images

The comparison of satellite images of Google earth before and after the construction of the Southern breakwater is shown in Fig.5 and Fig.6. It has been noticed that there is a considerable accretion in the southern side. The 2003 image indicates, there was a deeper depth available at the entrance channel (from the colour of the image). Also the satellite image of 2008 shows that after the construction of breakwater, the sediments were deposited near the southern side and by 2011 the deposition was kept on increasing. The shoreline of southern side of the Cuddalore Port is plotted in Fig.7, for 2003 and 2011 for the distance of 1750m. It is found that the shoreline is drifted towards the East for a distance of about 56m. Hence it is seen that construction of breakwater without proper study could increase the sediment transport as in the case of Cuddalore Port.

Fig.5 Google Map of Cuddalore Port Breakwaters (2003)

Conclusions

Breakwaters play a major role in creating calm water basin in harbour area for safe loading and unloading of passengers and cargo. Proper planning and design of breakwater geometry and alignment with respect to shoreline makes it efficient in maintain the harbour tranquillity for berthing of ships. This in turn influence the planning the number of berth, its geometry and alignment of berths, in port planning.

An analysis has been made on the sediment pattern in breakwaters area using MIKE21 Modelling From this case study, it is known that, the failure of Cuddalore Port is mainly because of the deposition of sediments at the entrance channel. This may be solved by, (a) Deepening the entrance channel by capital dredging, (b) Re-alignment of breakwater structures. In case (a) after carrying out the capital dredging, there is a need for proper maintenance dredging; as large quantity of sedimentations will be deposited in the dredged area. These will not only increase the operation cost but also in long run there will be considerable erosion at Northern side. Hence, the shore has to be protected by groins and also all the dredged materials should be dumped near the Northern shore. As such, it seems the case (b) be the better solution.

If the above solutions are followed, it will be beneficial to the local fishermen as their catchers can be brought immediately to the shore and it will be economical to them as they consume less fuel. Deep water trawlers can also be accommodated in the harbour and then in future the companies using the port for export and import will also be benefited. It may create job opportunities for the local people and in turn the port can develop in the forthcoming years.

Fig.6 Google Map of Cuddalore Port Breakwaters (2005)

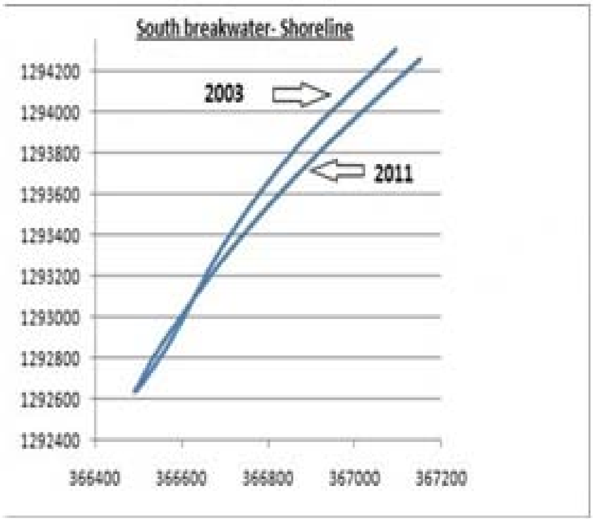

Fig.7 Comparision of shoreline of South Side of Cuddalore Port [X and Y axis are coordinates of UTM 44 zone]

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Nomenclature

Symbol	Definition
Q_{imw}	Immersed Weight of Stone, kg
P	Wave Energy Flux
K	Calibration Coefficient
E	Average Wave Energy
H_{rm}	Root mean square (rms) wave height at
$_{s,br}$	breaker line
C_g	wave group velocity at breaker line
C_{br}	Wave Phase Speed at Breaker Line
T_p	Peak wave period ,(s)
$tan\beta$	Beach slope
d_{50}	Angle of wave incidence at breaker line in deg.
Greek	
Symbols	
Θ_{br}	Angle of wave incidence at breaker line in deg.
ρ_s	Sediment Density, kg/m³

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