Silt mitigation measures for a navigational channel in a complex estuary

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Planning of port development projects in a deltaic estuary is a tricky job and it becomes highly complex in the case of determining potential sedimentation and erosion rates in dredged channels. But accurate dredging projections are crucial for economic feasibility analysis in addition to assessing the impact of new structures interfering with the natural processes on the adjacent shoreline and the morphology of the system. Silt mitigation measures are necessary to reduce the siltation in the navigational channels. In this study we consider a range of approaches for evaluating sediment transport for evolving a new navigation channel and necessary silt mitigation measures for harbour planning, and present detailed case from West coast of India. A depth-averaged numerical model for the erosion, sedimentation and transport of cohesive sediment is applied to the estuary. This study is based on the numerical simulation of the mean river discharge and the tidal forcing. The hydrodynamic models were calibrated against field measurements corresponding to the period in which the experimental data were registered. The site described is representative of a very complex coastal environment. The Tapi Estuary in Hazira is a unique dynamic estuary in Gulf of Khambhat on the West coast of India with large tidal range, non-perennial river discharge and high sediment loads of sand, silt and clay presenting challenges for navigation and dredging. The approaches include preliminary site investigations and data collection, basic sediment transport theory, and a range of numerical modeling techniques that can be applied to determine sediment erosion, transport and deposition.

[Keywords: Tide, Wave, Dredging, Silt mitigation, Deposition]

Introduction

Human interference in hydraulic systems is often necessary to maintain and extend economic activities related ports and associated navigation channels. In many situations engineering structures are required to stabilize the shoreline, shoals and inlets, to reduce sedimentation, to prevent or reduce erosion, or to increase the channel depth to allow larger vessels to enter the harbour basins. Protection against floods and navigability are the most basic problems in many estuaries around the world.

Sedimentation problems generally occur at locations where the sediment transporting capacity of the hydraulic system is reduced due to the decrease of the steady (currents) and oscillatory (waves) flow velocities and related turbulent motions. Examples are: the expansion of the flow depth and width due to natural variations or artificial measures (dredging), the presence of vortex or eddy zones, flow separation zones, dead water zones and lee zones of structures. Expansions of the navigational depth will reduce velocities inducing shoaling. Similarly, the expansion of the width of turning and mooring basins inside a harbour area will reduce velocities stimulating shoaling conditions. Piers or piling structures create eddies resulting in increased shoaling. Sedimentation problems are most often associated with human interference in the physical system such as the construction of artificial structures or the dredging of sediment from the bed to increase the flow depth or width. However, sedimentation (as well as erosion) also is a basic phenomenon of nature dealing with loose sediments within the transporting cycle from source to sink locations. Natural sedimentation areas are known as shoals, flats, banks, sheets, bars, etc. Human interference in these natural sedimentation areas will always lead to relatively large maintenance cost and should therefore be avoided as much as possible.

Estuaries are unique and complex environments located between oceans and river mouths. As freshwater flows into the sea from land, it dilutes the salty water in a small area around the shore. This relatively small space is the site of sediment build-up resulting from fluvial (stream or river) erosion along the riverbanks. It is well known that rivers often carry large amounts of sediment which, when emptied into the oceans, construct distinctive patterns in the
underlying sediments often leading to formation of delta. In an estuary, the deposition of sediments is greatly influenced by tidal currents and ocean waves. Even climate is a factor in how the sand and mud settle into distinct patterns. The pulse events like river floods and meteorological tides introduce large amounts of fluvial material to estuarine environments\(^1\). During seasonal storms, erosion is increased and the waters become heavily laden with a wide variety of sediments. Unlike deltas, in which the finer sediments are often carried far out to sea, the estuary is bordered on the deeper ocean side by heavy sand while clays and mud are dropped at river mouths. As tidal forces work the sediments by tumbling and rolling them, the lighter and finer particles are left near the river mouth. The build-up of coarse-grained (larger particle size) sand at the estuary edge often makes a barrier at the outer edge of the estuary that contains the bulk of the fine sediment and diluted water. The sediment structures in these ridges are described as longitudinal or oblique bars. The structures in the upper reaches of the estuary are described as asymmetric and longitudinal bars become point bars similar to those observed in rivers. A dendritic (tree-shaped) pattern of channels occurs in these finer, flat lying sediments.

Cohesive sediments are composed primarily of clay, which have strong interparticle forces due to their surface ionic charges. As particle size decreases, its surface area per unit volume (i.e. specific surface area) increases, and the interparticle forces, not the gravitational force, dominate the behaviour of sediment. There is no clear boundary between cohesive sediment and non-cohesive sediment. The definition is usually site-specific. In general, finer sized grains are more cohesive. Sediment sizes smaller than 2 \(\mu\)m (clay) are generally considered cohesive sediment. Sediment of size greater than 60 \(\mu\)m is coarse non-cohesive sediment. Silt (2 \(\mu\)m -60 \(\mu\)m) is considered to be between cohesive and non-cohesive sediment. Indeed, the cohesive properties of silt are primarily due to the existence of clay. Thus in engineering practice, silt and clay are both considered to be cohesive sediment. Cohesive sediments consist of inorganic minerals and organic material\(^2\). Inorganic minerals consist of clay minerals (e.g. silica, alumina, montmorillonite, illite, and kaolinite) and non-clay minerals (e.g. quartz, carbonates, feldspar, and mica, among others). The organic materials may exist as plant and animal detritus and bacteria.

Within an estuary the processes of erosion or accretion are likely to have feedback effects on the hydrodynamics within the system. Large amounts of deposition may cause the tidal flow in that area to considerably increase or shifted into different channels. For this reason sediment transport models should only be used to compute sediment transport rates over relatively short time scales, (one to two tidal cycles.) If sediment transport rates in an estuary are particularly small the model could be used to predict transport over longer periods\(^3\). In very dynamic estuarine systems it is important that morphological bed-updating models are used, as these take into account feedback affects by updating the estuary bed.

Materials and Methods

Background and Characteristics of Tapi Estuary

Tapi estuary is located at the northern part of the west coast of India and is part of the Gulf of Kambhat in the state of Gujarat as shown in Fig.1. Over a period of time, the Tapi estuary is flanked by wide mudflats and has silted up at many places with depth being only 0–1 m (with respect to Chart Datum) near the berth at Essar Jetty. Until 2006 an existing natural channel was being used as the approach channel by the Industrial establishment operating in Tapi estuary. Thus the navigation in the channel is possible only during high water for duration of about two hours per tide. Further the course of the river itself has changed over a period of time. It is observed that landward end of the channel is shifting as well as getting silted up. The depths at the seaward end of the channel are of the order of 2.5 m, whereas the depths

Fig. 1—Location of Tapi Estuary (Courtesy Google 2012)
at the landward end of the channel are less than 2 m. The ships, in the past, would approach the jetty taking advantage of high water. However, operation of ships is greatly restricted due to heavy siltation in the channel. Hence one of the industries (Essar steel) operating in southern part of Tapi estuary desired to create a new channel from the existing berth located approximately south of Tapi estuary to connect the sea, which will reduce the transit time and also provide deeper depths allowing almost round the clock operations. A comprehensive study of development of navigational channel was taken up at the Central Water and Power Research Station.

Tapi estuary is influenced by strong semidiurnal tides with the spring tidal amplitude >5 m at the entrance to the estuary. Tidal influence is strongest near the mouth and gradually reduces upstream. The flood period decreases from mouth to inner estuary, and the ebb extends over a period of 7-10 h. Thus flood period close to the mouth are shorter than ebb period with slack period of nearly an hour. The river experiences pronounced freshwater discharge only during monsoon period i.e. from July - August. Flow diminishes considerably during the post-monsoon and is minimum during May – June. Thus seawater intrusion and the tidal influence in the estuary are affected by river flow during monsoon.

High tidal influence generates strong currents. Currents are strong in the Tapi estuary both during flood & ebb. During spring tides the peak flood current magnitude in the mouth region is about 1 m/s and 0.6 m/s during neap tide. The peak current observed in Tapi is 1.6 m/s during spring flood. High seawater influx, strong tidal currents and the small low-tide volume results in good mixing & flushing characteristics in the estuary. The flushing time (t in tidal periods) is given by t = (V+P)/P; where V is the low water volume of the estuary & P is the volume of the tidal prism. The flushing time for Tapi estuary is 16–19.4 tidal cycles. Tapi estuary has extensive sand banks and stretches about 60 km in dry season. Suspended load in rivers is generally low during dry season.

Field data and analysis

Field studies were collected in the year 2005. The data required for model studies like bathymetry, tide, wave, wind, currents and sediment loads were collected and analyzed. The existing bathymetry is digitized from the Admiralty Chart No. 2101 and is used for the present study and the latest hydrographic survey chart supplied by ESSAR was superimposed on the digitized bathymetry to get the updated bathymetry. The depth contours show that there is wide stretch of tidal flats and also shoals in the vicinity of proposed project site. As the tidal range is more than 6 m, large area is subjected to flooding and drying. The hydrographic chart shows that the 6 m to 20 m depth contours converge at an offshore distance of 1.5 km from Essar Jetty indicating sudden steep bed beyond 5 m depth contour. The contours towards south are spread apart indicating wide tidal flats. This depth information was used for setting up the computational model.

The tide data shows that the tidal range is of the order of 6.55 m during spring tide and 4.6 m during neap tide. Fig. 2 shows the generated water levels considered as boundary condition for model simulation.

The bed sediments reported in the Tapi estuary is fine sand with low amounts of silt and clay. The bed sediments in the harbour area are silty clay. From the field survey reported it is seen that the water in the proposed site is highly turbid and muddy. The concentration of suspended solids is very high. The analysis of suspended solids observed from the year 1985 to 2002 was considered.

The average sediment concentration recorded in the month of May 1998 is of the order of 1260 mg/l. The survey conducted during May and December, 2002 indicates that the maximum suspended sediment (SS) is 260 mg/l at the southern side and the minimum SS is 116 mg/l on the northern side of the harbour. Further field studies were conducted during September, 2005 and it was observed that the SS concentration near ESSAR Jetty is of the order of 565 mg/l. For the model studies an average value of 300 mg/l is considered.

![Fig. 2—Tide used for model boundary](image_url)
It is also reported that the wind has significant effects on the tidal currents at Hazira. The analysis of data has shown that from March to September, during the SW monsoon, a clockwise circulation persists in the Arabian Sea, south of the gulf of Khambhat for which the average wind speed is of the order of 30 Km/hr and peak speed is of the order of 40 Km/hr. From November to January, during the NE monsoon, the circulation is reversed and usually the speed is less than 20 Km/hr. In the hydrodynamic model studies the average wind speed of 30 Km/hr is considered in the SE direction during March to September and NW from October to February. Further updating of the field data on bathymetry and currents was taken up in 2011 and accordingly a series of studies were undertaken with updated data.

Modeling Approach

The selection of the most appropriate model approach for the problem at hand often is a difficult decision and depends on many things such as - spatial and temporal scales involved, available buoy data on bathymetry and boundary conditions, accuracy and capability of existing models, available budget, etc. The model results should always be validated with respect to the natural variability of the physical system for the relevant time and space scales involved. For example, the long term erosion of the coast may be relatively small, but the short term variability of the sand volume in the nearshore zone may be relatively large due to storm sequential effects. Model predictions of this parameter (sand volume in nearshore zone) are only meaningful if the model variability (due to variation of model settings) is smaller than the natural variability. Considering all the above factors and the prevailing sediment properties at site, which are predominantly cohesive sediments (as it comprises of fine sand, silt and clay), the MIKE 21 MT model was used which is suitable for modeling cohesive sediments.

Model description

Due to considerable morphological variations in the lateral direction of the estuary (see Fig. 1) and the fact that the estuary is well mixed, two-dimensional depth-averaged models have been used - MIKE21 hydrodynamic model (HD) and coupled surface wave model with mud transport (MT) model. For any developments in coastal areas it is necessary to know dynamics of the water body in terms of velocity and water level fluctuations beforehand. The appropriate governing equations for studying water movement in coastal areas are the two dimensional shallow water equations. These are obtained by vertically integrating the three-dimensional Navier Stokes equations of motion making the following simplified assumptions:

- the flow is incompressible,
- the flow is well mixed (no variation in density),
- vertical accelerations are negligible,
- bed stress can be modelled.

Simulation of hydrodynamics is based on these shallow water equations given below,

Equations

Continuity Equation

\[ \frac{\partial z}{\partial t} + \frac{\partial (zu)}{\partial x} + \frac{\partial (vz)}{\partial y} = 0 \]

(1)

Equation of Motion in X-direction

\[ \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{\partial z}{\partial x} + C_f \cdot v \cdot E \cdot \nabla^2 u = 0 \]

(2)

Equation of Motion in Y-Direction

\[ \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{\partial z}{\partial y} + C_f \cdot u \cdot E \cdot \nabla^2 v = 0 \]

(3)

where,

- \( z \) : water surface elevation
- \( h \) : total water depth \((z+d)\)
- \( u, v \) : Velocity components in x & y direction
- \( C_f \) : Coriolis force
- \( E_c \) : Eddy viscosity coefficient
- \( d \) : Depth w. r. t Chart Datum

The governing equations are solved using Alternating Directions Implicit (ADI) finite difference technique based on Crank-Nicholson scheme. This entails covering the estuary with a mesh or grid and discretising elevations and velocities in space and time to fit on this grid. Having discretised the variables, derivatives are approximated by simple differences divided by the distance between consecutive grid points. The space differences involve variables at the unknown time level calculated, thus a system of equations involving the boundary conditions has to be solved before the value of the variables at the next time step can be obtained by Alternating Directions Implicit scheme (ADI). It implies that in one time step, there are two half time
steps. In one half time step, the scheme is implicit in the east-west direction and explicit in the north-south direction. In the next time step, computations are implicit in the model north-south direction and explicit in the model east-west directions. ADI scheme is computationally efficient and widely used in solving shallow water equations. The solution of equation at every grid point results in simulation of flow conditions over a period of time.

Further for simulating sediment transport MIKE 21 (HD) Flow Model, Mud Transport Module (MT) was used which describes erosion, transport and deposition of mud or sand/mud mixtures under the action of currents and waves. The two dimensional depth averaged sediment transport model (MIKE-21-MT) takes into account conservation of mass of sediment, depth averaged velocities, longitudinal dispersion coefficient, lateral diffusivity, settling velocity, critical deposition stress, and critical erosion stress for the given sediment. A simple explicit, upstream finite difference technique is used to solve this advection diffusion equation. The model takes into account the littoral currents due to waves along the littoral zone. The rates of deposition and erosion are computed based on the critical shear stress condition. In case of significant bed load movement the model takes into account the additional sediment source in the transport equation. Thus the model considers the total load while predicting the morphological changes.

The calibration of sediment transport model is difficult because morphological changes are too slow and temporal bed changes are too variable to measure anything significant for comparison. The sediment fluxes at various locations may differ and the following factors contribute for these variations:
- unsteadiness of flow,
- mixtures of sediment in suspension,
- variability of supply of mobile sediment on the bed,
- presence of sandy (non-cohesive) sediment,
- omission of depth variation,
- Effect of wave stirring.

In the present case data pertaining to silt concentration and sediment characteristics were available from field studies and was considered for model studies and typical zone of siltation and zone of erosion were predicted. This prediction was further analysed to arrive at a suitable silt mitigation measure for the maintenance of the Essar approach channel.

**Results and Discussion**

**Model studies conducted**

Series of model experiments were conducted for the evaluation of Essar channel in Tapi estuary with baseline conditions of 2005. Initially a comprehensive study was conducted for the new alignment of the channel, the studies comprised of Hydrodynamics and sediment transport studies, wave tranquillity studies, ship navigation studies, shoreline evolution studies (2006). Further studies were conducted to assess the impact of Reclamation-A which is a low lying area along the north of the navigational channel (2008) where the capital dredge material is intended to be used for reclamation. Subsequently studies were conducted to assess the impact of Reclamation - B south of the navigational channel along with the impact on the existing mangroves in the development area (2009). Subsequently studies were also conducted for the Phase II development of the Essar port, which has significant developments with three turning circles along the navigational channel and further deepening of the channel to (-) 16 m below Chart Datum (2011). During the implementation of Phase II development the navigational channel near north turning circle encountered severe siltation due to huge discharge from Tapi river during monsoon. Further studies are in progress to suggest silt mitigation measures to overcome the problem of siltation in the navigational channel as well as to divert the river flow into the natural course so that the other upstream industrial users may be facilitated for navigation. This lecture notes highlights the several options studied for the silt mitigation measures.

**Model studies for silt mitigation**

Studies with proposed developments

The computational model considered for tidal flow simulation covered an area of 30000 m by 22500 m. The model limit extends up to 35 m depth contour in the offshore in the west direction and up to 25 m depth in the south direction. The model area covers the entire proposed channel along the reclamation is shown in Fig. 3.

The complete model area has been discretised into computational mesh of 50 m grid. The model was calibrated with the observed currents in Tapi estuary and the computed results matched satisfactorily are shown in Fig. 4.

Further the model studies were simulated with proposed developments without any silt mitigation measures for one month monsoon and non-monsoon
seasons. The results indicated that the zone of probable deposition would be mainly in the turning circles and northern portion of the channel between the north turning circle and the centre turning circle. Also there was a trend of sedimentation in patches along the navigational channel. In the worst scenario of monsoon season the depth of sediment deposition in the approach channel is predicted to be in the range 80 – 150 cm. A typical flow field is shown in Fig. 5 and siltation pattern is shown in Fig. 6.

Studies with alternative silt mitigation measures
Initially the studies were conducted with a submerged diversion bund of about 2300 m length and a depth of 3.5 m from the sea bed level along the alignment shown in Fig. 7. The height of the bund is based on the tidal range which reaches about 6.5 m during spring tide, also the natural flow in the estuary is not obstructed completely and the objective of diverting the flow along with the silt carried by the river flow into the natural river course. The study results indicated that the flow is diverted into the natural river course as desired. The siltation in the navigational channel is reduced to some extent but not completely as part of the suspended sediments pass over the submerged bund and get deposited in the turning circles of the navigational channel even though the silt deposition along the channel section has reduced considerably as shown in Fig. 7. Further studies were
conducted with diversion bund and encapsulating the channel with submerged bund all along shown in Fig. 8, with an objective to divert the flow and avoid siltation in the channel. As the studies did not yield the desired results and appears to be uneconomical, it was discarded. One more option was studied with encapsulating the entire navigational bund with submerged diversion bund right from the north turning circle covering the entire length of the channel as shown in Fig. 9.

As the studies did not yield the desired results and appears to be uneconomical, it was discarded. One more option was studied with encapsulating the entire navigational bund with submerged diversion bund right from the north turning circle covering the entire length of the channel as shown in Fig. 9.

The studies yielded good results from siltation point of view in the channel, but the practical implementation was difficult as we had suggested layered geo tube bags as diversion bunds, field engineers expressed apprehension about the stability of the diversion bund and cost effectiveness. Hence this alternative was also discarded. Finally an innovative and environment friendly silt mitigation measures which is also considered as soft measures were tried as other alternative. This option comprises of sediment trap north of the northern turning circle with a channel connecting the turning circle to the sand trap having a depth of -7 m to facilitate for the dredgers to reach the sand trap. Along with this sand trap two more innovative sand traps were incorporated concentrically along the exposed perimeter of the two southern turning circles and are shown in Fig. 10.

The study results were encouraging and the siltation in the navigational channel would be reduced considerably in the channel and the silt deposited in the sand trap and two southern turning circles can be dredged occasionally as it would not interfere with the operation and maintenance dredging of the port as well as no obstruction to the natural river flow.

Conclusion

Extensive model studies were conducted in Tapi estuary for evolution of a navigational channel and necessary silt mitigation measures to maintain the navigational channel economically. Numerical models were used to investigate the current pattern and siltation in the navigational channel. The findings emerging from these studies are as follows:
Several alternative measures were studied to arrive at a suitable economical and effective silt mitigation measures for a navigational channel in Tapi estuary.

The study with diversion bund on the north of the north turning circle was effective in diverting the flow to the natural river course but was not found to be very effective in silt mitigation in the channel.

Next alternative of additional encapsulation of the navigational channel in addition to the diversion bund worked quite effectively but it was not cost effective.

The other alternative with encapsulation of the navigational channel with geo tubes was effective in reducing the siltation in the channel to some extent but the stability of the structure was in doubt.

An innovative soft and environment friendly measure with sand traps yielded the desired results in arresting the silt and making suitable provision for dredger operation at site for effective maintenance dredging of the navigational channel.

It is also to be noted that the suggested silt mitigation measure is the most economical as far as execution and maintenance dredging of the navigational channel is concerned.

The recommended silt mitigation measure also fall in line with the present concept of minimum interference with the hydraulic regime of the estuary.

There are several numerical models that can be used to predict cohesive sediment transport movement, but they are subject to great uncertainty unless detailed measurements of important parameters can be made. In particular, it is necessary to measure the critical shear stresses for deposition and erosion.

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