STUDY ON SILTATION FOR IMPLEMENTATION OF THE NAUTICAL DEPTH CONCEPT IN THE PORT OF COCHIN, INDIA

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ABSTRACT

The port of Cochin has the largest siltation rate among Indian ports: more than 20 million m³ per year. Siltation occurs mostly during the Monsoon (June-September) when both river discharges and ocean dynamics are high. The need for continuous maintenance dredging has serious budgetary impacts for the Cochin Port Trust (COPT). Therefore, COPT ordered a study to analyze the siltation processes and to assess the feasibility to implement the nautical depth concept. An extensive monitoring campaign, including measurements of waves, currents, tide, wind, salinity, bathymetry, sea bed composition, suspended sediment concentration and mud rheological properties is conducted during one year to cover the seasonal variation of hydrodynamic and morphodynamic processes. These data feed a numerical 2D/3D model to simulate hydrodynamics, wave transformation, tidal circulation, salinity, sediment transport and siltation processes in the harbor, the navigation channel and the surrounding areas. The Telemac platform is applied, including the Tomawac (waves) and Delwaq (sediment transport) modules. Understanding the physical processes of siltation will allow to suggest methods for arresting it. In order to investigate the nautical implications of a new nautical depth criterion in the Port of Cochin simulations are performed using a ship maneuvering simulator especially equipped for maneuvering in mud conditions in shallow ports (Flanders Hydraulics Research). This 3D nautical model contains visualization of the port infrastructure, signalization and the most important landmarks. A range of mud layer characteristics (density, viscosity and layer thickness) is selected based on the results of the monitoring campaign. Two pilots of the Port of Cochin operate a full mission bridge simulator to evaluate all relevant inbound and outbound maneuvers to the harbor at different bottom/mud conditions with the relevant vessel types. The simulations are analyzed based on both the assessment of the pilots and objective criteria such as application of rudder, propeller and tug boats. After assessing the feasibility for a nautical depth for the Port of Cochin, monitoring and maintenance methods are investigated as well as the implications for dredging.

Keywords: Siltation, rheology, ship maneuvering, Telemac modeling, hydrodynamic monitoring.

INTRODUCTION

The commercial Port of Cochin in the state of Kerala (South-West India) is situated in the Cochin lagoon, which has natural protection from the sea by two headlands. Between the latter, the "Cochin gut" connects the Arabian Sea with the Periyar river system and Kerala's backwaters. Cochin is located strategically close to the busiest international sea routes. The main port facilities are the Approach channel, the LNG terminal and the International Container Transhipment Terminal (ICTT) for vessels with a draft up to 14.5m and the shallower Ernakulam and Matancherry channels (Figure 1).

The nearshore area outside the Cochin Gut is relatively shallow, reaching a water depth of 5m at a distance of about 2km from the shore and gradually deepening to 10m at 6km outside the Gut. The temperature varies from 23°C to 32.5°C with limited seasonal variation and humidity is high throughout the year. The predominant wind direction

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during the Monsoon period (June-September) is west to south-west while during the rest of the year mostly northeast winds occur during morning and west winds during the evening. The annual rainfall varies between 2500 and 3500 mm and is concentrated in the Monsoon period with consequently high river discharges. Cochin experiences semi-diurnal tides with maximum amplitude around 1m. The wave climate is governed by the Monsoon when wave action can be strong with prevailing wave directions from north-west to south-west. Inside the harbor, wave action is insignificant.

While most of India's large ports have a rocky bottom, the bottom in Cochin is muddy. During the Monsoon the Suspended Sediment Concentration (SSC) is high due to increased wave action and river discharge, while a southward littoral drift brings in even more sediment. This causes more than 20 million m³ of siltation annually, which needs to be removed by maintenance dredging and gives the Cochin port the dubious distinction of having the largest siltation load in India. Over the years, the dredging expenditures meant a huge drain on the revenue of the Cochin Port Trust (COPT) and have rendered the port's finances unviable.



Figure 1. Overview of the Cochin port.

The main objectives of this study were to find ways and means to reduce and manage the high siltation in the navigation channels at Cochin port and to recommend parameters for implementation of a nautical depth concept.

According to PIANC the nautical depth can be defined as 'the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and maneuverability'. Accordingly, nautical depth can be defined as the instantaneous and local vertical distance between the nautical bottom and the undisturbed free water surface.

At present, the navigable depth of the Cochin harbor is monitored using an echo sounder of 210kHz. It is commonly accepted that at this frequency the water-mud interface is recorded. However, the determined interface is dependent on the instrument type and settings. Furthermore, a part of the fluid mud layer below this interface might be safely navigable which can be determined by investigating mud properties such as density and viscosity. The lack of a clear definition of a nautical depth could cause unnecessary depth restrictions and excessive dredging in Cochin.

The major components of the study are:

- Comprehensive field data collection of hydrodynamic parameters (wind, waves, currents, tide, discharge), sediment transport, morphology, rheology, salinity, etc.
- Conduct hydrodynamic and empirical numerical model studies to research the siltation causes and remedies.
- Set up and validate a nautical simulation model.
- Establish and apply an operational measurement practice to implement the nautical depth concept.

METHODOLOGY

Field Data Aquisition

An extensive monitoring campaign is being conducted from April 2015 until April 2016. The different activities are described below. In Figure 1 the monitoring locations (T1, T2 and C1 to C6) are shown.

Bathymetry

A monthly bathymetric survey is performed with a 33kHz (solid bottom) and 210kHz (top mud layer) echosounder.

Wave Measurements

At offshore locations C7 and C8 a bottom mount ADCP (SeaWave 600kHz, Rowe Technologies Inc.) measures wave height and direction, as well as currents velocity and direction and pressure. Wave spectrum analyses are performed to determine the wave climate characteristics.

Tide Measurements

Both at T1 and T2 a tide gauge is installed to measure the water height variation throughout the tidal cycle.

Current Measurements

During each of three seasons (pre-monsoon, monsoon and post-monsoon) currents are measured for min. one month at locations C1 to C6. In the shallow locations C1 to C5 bottom mount ADCP's (SeaWatch 1200kHz, Rowe Technologies Inc.) with a limited bin size (0.25m) are applied to derive the vertical velocity profile. At the Cochin Gut (C6) a Horizontal ADCP (RDI Channelmaster 300kHz, Teledyne) is mounted on each shore in order to measure the full velocity profile over the channel width.

Discharge Measurements

The current measurements at C1 to C6 are continuous but do not cover the full 2D profile of the different channel's cross sections. The latter is however necessary in order to map the system hydrodynamics fully and to derive the flow discharges in these channels. Therefore, during each of three seasons a 13 hours monitoring campaign, covering one full tidal cycle, is conducted at every location once during spring tide and once during neap tide. During these campaigns, currents are monitored over the full channel cross section by means of a vessel mount ADCP (SeaProfiler 600kHz, Rowe Technologies Inc.). Afterwards, correlation analyses are performed between the vessel mount ADCP data and the simultaneous bottom mount (or horizontal) ADCP data, so continuous time series of cross section averaged current velocities can be derived. These current velocities will be transformed into discharges by taking the tide-depending wet cross section area into account.

Wind Measurements

A MetPak weather station (GILL Instruments) was installed at location T2 to measure wind speed and direction continuously. Additionally, air temperature, pressure and humidity are registered. At C7, an ultrasonic wind sensor was mounted on a buoy to measure the offshore wind conditions.

Suspended Sediment And Salinity Measurements

Water samples at surface, mid-depth and close to bottom are collected by means of Niskin bottles during high tide, mid tide and low tide over one neap and one spring tide during each of three seasons at locations C1 to C8. Simultaneously, an OBS3A multiparameter probe (Campbell Scientific) measures the conductivity, turbidity and temperature of the sea water. The water samples are analyzed in a laboratory for conductivity and SSC. Salinity values will be derived from the conductivity readings.

Bed Composition

In the pre- and post-monsoon seasons, bed sediments were sampled by means of a Van Veen grab. This was done at 35 locations within the harbor area and 35 offshore locations. The samples were analyzed in a laboratory for grain size distribution (sieve and hydrometer analysis).

Longshore Sediment Transport

To analyze the evolution in beach profiles, two bathymetric beach profiles are measured each at north and south of the Cochin Gut monthly during spring high tide.

Hydrodynamic Model Studies

The key objective of a using numerical model is to develop trustworthy decision support tools to study hydrodynamics of wave transformation, tidal circulation, salinity, mixing, sediment transport of the region encompassing Cochin port, entrance channel and the Cochin backwaters. The TELEMAC-MASCARET integrated suite of solvers is the model applied in this study. It contains in particular the TELEMAC 2D module (Hervouet and Bates, 2000) for hydrodynamic calculations, the TOMAWAC module (Benoit et al., 1996) for calculating the wave propagation and the DELWAQ module (Kopmann and Goll, 2013) for sediment transport. These three modules are coupled and interact with one another during simulations. If significant vertical stratification is observed in the field data collected in the areas of interest, a 3D model will locally be developed. Wave propagation towards the coast will be modelled on a large model (200x500km), while nearshore wave dynamics, currents and sediment transport will be simulated on a smaller scale (25km radius). This is illustrated in Figure 3 and Figure 4.

The proposed software is based on the well known Finite Element Method which is very well suited for complex geometries (such as the study area) as it allows discretizing the domain using unstructured meshes (Figure 2). An additional advantage is the ability of the finite element approach to perform mesh refinement from large scales (outside the main region of influence) to fine scales in focus areas.

Field data (e.g. tide, wind) and global open source databases (e.g. ERA-INTERIM) will be used as an input for the model while other field data (e.g. waves, currents) will be applied for model calibration. The latter will be performed based on a historical and a synthetic event, with focus on the monsoon season.







Figure 3. Bathymetry (left) and unstructured mesh (right) of large wave propagation model.



Figure 4. Bathymetry (left) and unstructured mesh (right) of small current and sediment transport model.

Nautical Simulations

In order to investigate the nautical implications of a new nautical bottom criterion in the Cochin port a real-time simulation study will be performed of the relevant inbound and outbound maneuvers at different bottom/mud

conditions. For this purpose a full mission bridge simulator located in the offices of FHR in Antwerp (Belgium) will be utilized (Figure 5).

The behavior of deep-drafted vessels in muddy navigation areas has been thoroughly investigated at FHR by means of a comprehensive, unique experimental program of captive model tests. The bottom of the towing tank was covered with simulated mud layers with different characteristics: density between 1100 and 1260 kg/m³; viscosity between 0.03 and 0.46 Pa.s; layer thickness between 0.75 and 3.0 m. Based on these towing tank tests with scale model vessels, mathematical maneuvering models were derived for slender hull forms (e.g. container ships, general cargo) and full hull forms (e.g. bulk carriers, tankers). The mathematical models were implemented in the simulators of FHR and were applied to determine the operational limits for navigation in the muddy areas of ports (e.g. Zeebrugge, Belgium).



Figure 5. Full mission bridge simulator at FHR.

The presence of different mud conditions in the port of Cochin will be studied by means of real time simulations of the critical navigation maneuvers with different ship types performed by local pilots. The following design vessels are selected: container carrier with length of 335m and draft 14.5m; tanker with length of 250m and draft 12.5m; cargo vessel with length of 250m and draft 10.7m; cargo vessel with length of 180m and draft 9.1m. The full mission bridge simulator will be provided with a 3D visualization model of the Cochin harbor, containing the port infrastructure, signalization and the most important landmarks. A recent bathymetry of the solid bottom will be implemented in the simulator as well. The present bottom conditions of the port of Cochin will be implemented in order to achieve a reference condition. The mud layer characteristics (density, viscosity and layer thickness) for simulation analyses will be selected based on the results of the measurement campaign and the available maneuvering models. A maximum number of 12 combinations of layer thickness, density, viscosity and water depth (tide) will be implemented in the simulator environment. A maximum of four current vector fields resulting from numerical modeling (TELEMAC) will be implemented. The prevailing wind conditions will be taken into account by means of a uniform wind field. During the simulation runs, a ship can be assisted by maximum six tug boats which will be controlled by an operator by means of a control desk allowing push-pull operations of both ASD and Voith-Schneider tugs. The number of tugs, tug types and bollard pull will be selected in agreement with COPT.

The simulation program will consist of six simulation days divided in two sessions of three days with at least three weeks between the end of the first and the start of the second session. This period should allow FHR to define the simulation program for the second session and to make minor changes to the simulation environment if necessary. The simulations will be performed by at least two pilots with experience with the design vessels in the port of Cochin. If necessary the assistance of Belgian coastal pilots, familiar with the nautical bottom concept, can be provided. In order to assess the acceptability of the simulations, the simulations will be analyzed based on trajectory plots, application of rudder, propeller, bow thruster and tug boats and on comments of pilots during the simulation. This will finally lead to conclusions on the nautical implications of different bottom conditions in Cochin port.

Nautical Depth

The nautical depth and the fluid mud layer will be surveyed by use of high resolution seismic monitoring with the Silas system and in-situ rheology measurements with the RheoTune (Stema Systems, The Netherlands).

The Silas system consists of an echosounder, a 24 kHz transducer and a computer running the Silas software. This Silas software records the full, raw signal that is received by the echosounder, resulting in sub-bottom profiles or seismics. The 24 kHz signal typically gives a sufficient resolution and enough penetration to properly map the fluid mud. Every two months, a full survey of the Cochin harbor and its channels is conducted.

The RheoTune is a probe that gravitationally penetrates the fluid mud layer and can in-situ measure the density and yield stress (depth profiles) by means of a tuning fork. During the Silas surveys, a RheoTune profile is determined at regular intervals. The high resolution seismics will also be calibrated with use of the in-situ density measurements acquired by the RheoTune. During the calibration, a density level will be linked to seismic data, resulting in density contours that are directly measured by Silas.

Viscosity can be measured using the RheoTune after calibrating the RheoTune using a site specific relation between viscosity, density and yield stress. The dynamic viscosity (η in Pa.s) can be defined as the applied stress (τ in Pa) divided by the strain rate (γ in s⁻¹), $\eta = \tau / \gamma$. The viscosity of silt is not a constant value but is related to the strain rate and is therefore also called apparent viscosity. Silt therefore behaves as a non-Newtonian fluid. The viscosity required for calibration can be determined using a rotoviscometer (Brookfield Engineering Laboratories). During this measurement the stress required for rotation of the spindle is registered together with the spindle speed (later converted into strain rate). A roto-viscosity test program was designed for this study to derive the elastic, visco-elastic and viscous behavior of the Cochin bed material. The resulting stress–shear rate curve can be used to determine the viscosity. Mud samples were taken at different locations in the harbor and channels and different dilutions (with in-situ sampled water) were created. The roto-viscosity test program was run for each dilution and also the RheoTune readings were recorded. This finally allowed to derive site specific relations between viscosity, density and yield stress.

Assessment And Decision Support System

Based on the field data acquisition, model studies, nautical simulations and nautical depth analysis, several assessments will be made to support decision-making by the COPT in their sediment management.

Estimation Of Siltation Quantities In Cochin Port And Entrance Channel

Siltation quantities will be estimated based on an analysis of the administrated quantities of dredged sediments and difference charts of subsequent bathymetric surveys. An estimate of the presence of fluid mud in the harbor can be assessed with calibrated high resolution seismic echo-sounding techniques (Silas) recorded during bathymetric surveys.

Slope Stability Characteristics Of The Navigation Channels

Long term slope stability can best be assessed by the actual slope in the navigation channels, derived from several bathymetric surveys. Perpendicular profiles derived from the survey will be evaluated for several channel sections. The characteristics of the slopes will be catalogued and compared to environmental data. Based on these findings an estimate on the required design slope will be estimated.

Establishment Of Survey Method For Nautical Bottom

To establish a survey method to map the nautical bottom, vertical density profiles will be measured using the RheoTune. Simultaneously a high resolution seismic profile of the fluid mud column will be acquired to compare with the density profile at that location. It will be verified what frequency has sufficient penetration capability to obtain density information over the total mud column. Combined with the density profile a synthetic density profile is calculated from the acoustics. The relevant density criterion is recalculated based on the outcome of the navigation modeling. Proper frequencies, survey schemes and set-ups and calibration intensity will be determined for the Cochin port, based on Fontein & Byrd (2007).

Determining The Dredging Needs

Dredging requirements will differ depending on the bed and siltation material. The characterization of bed sediments and definition of siltation prone areas will be input for the dredging methods best adopted. The presently applied dredging methods in Cochin will be evaluated in relation to the survey practice. When working with the nautical depth criterion the focus will be in-situ treatment of muddy materials and improvement of the mud to remain fluid over longer periods and prevent consolidation. Other dredging techniques will be considered for specific locations. This evaluation will benefit by adopting nautical bottom survey method.

Origin Of Silt Material

The origin of silt material deposited in the Cochin port will be determined by using model outputs of flow direction and sediment transport, in combination with data obtained from bathymetry analysis (bedform movement, erosionsedimentation maps, contour maps, etc.), sediment transport measurements and surface bed sediment characteristics (sedimentological fingerprinting). This combination will lead to a detailed image of sediment transport and the origin of the material can be determined conclusively.

Long Shore Sediment Transport

Model output, bathymetry analysis and sediment transport analysis will be used in conjunction with analysis of beach profiles to determine the residual sediment transport along the coast. The evolution of the beach profiles gives an idea of the net longshore transport. The model output and sediment transport measurements will provide detailed information about effects of seasonal influence on sediment transport and sedimentation processes.

Dynamics Of Dredged Material At Disposal Sites

The combined numerical models (hydrodynamics, waves, sediment transport) will give a first insight on the trajectories of individual (sediment) particles during different meteorological conditions. A dredging/disposal tool within the numerical model can be used to simulate the surplus sediment extraction/input at the dredging and disposal sites. Typical maintenance dredging quantities dredged material properties (grain size, density) would be used as an input. Considering the dredged material is mainly silt, it is likely that a considerable amount of the disposed and unconsolidated material shall be entrained by the hydrodynamic forces (waves, currents, tides). A study of the sediment particle paths (particle trajectories and/or morphological bed evolution) will give a reliable estimation of the amount of sediment that returns from the disposal sites to the approach channel and harbor.

Suggestion Of Methods To Decrease Siltation

Once the main sediment sources have been distinguished using both the insights from the field data collection and the numerical model results, appropriate methods to counteract siltation will be proposed. Possible countermeasures can for example act on deflection of sediment loaded water flows, enhancing siltation in less critical zones, etc. Countermeasures can be applicable to either riverside and/or seaside of the harbor. In order to determine the most feasible solutions, all limiting conditions (flow patterns, navigational restrictions, building and maintenance costs etc.) will be taken into account and discussed with COPT.

RESULTS AND DISCUSSION

The study started with a review of existing literature about the hydrodynamics and sediment processes in the Cochin area. Furthermore, interviews were held with important stakeholders such as the COPT staff, the operational dredging company, etc. This helped in gaining a first understanding of the local dynamics and was useful in planning the field data acquisition.

At the time of writing the monitoring campaign is running for seven months. Data processing is fully ongoing and the numerical hydrodynamic and nautical models are being prepared. This implies that no study results have yet been achieved. Some findings of the field data acquisition will be discussed below. The authors expect to be able to present some answers to the research questions at the time of the conference.

Current And Discharge Measurements

Figure 6 shows the measured velocities by both horizontal ADCPs and the vessel mount (VM) average velocities at location C6 during several 13hours monitoring campaigns between 25/07/2015 and 27/11/2015. For most tidal

cycles, there is a good correlation between H-ADCP and vessel mount (VM) average velocities. But for some spring tide cycles a significant hysteresis effect can be observed. This will be further analyzed in order to rescale the continuous H-ADCP velocities into channel width averaged velocities.



Figure 6. Correlation analysis between vessel (VM) and HADCP measured current velocities at C6: left-Vypeen, right-Fort Kochi.



Figure 7 shows the current speed at location C2 for different water layers.

Figure 7. Vertical stratification of current at location C2 (depth = 10m).

Figure 8 shows the measured discharge by a bottom (BM) and vessel mount (VM) ADCP at location C5 during the 13hours monitoring campaigns of 19/11/2015 (neap tide) and 25/11/2015 (spring tide). A high correlation was found between the BM and VM data and the same regression appears to be applicable for both campaigns. This relation allows to transform the continuous BM time series measured at C5 to channel profile averaged flows. Similar





Figure 8. Correlation analysis between vessel (VM) and bottom mount (BM) measured discharges at C5.

Wind Measurements

Figure 9 shows a wind rose measured at T2 during August until November, a period mostly covering the monsoon season. As expected, this season is dominated with west and north-west winds. During night time, short periods of north-east to east winds occur, which grow longer after the monsoon (November). Unfortunately, a technical problem occurred on the wind sensor at C7, causing its dataset to be inapplicable.



Figure 9. Wind rose measured at T2 from August to November 2015.

Large wave model

The large wave model (200x500km) was simulated with ERA-INTERIM wave data as boundary inputs, using an interpolation of the closest ERA-INTERIM data points to each boundary mesh cell (Figure 10). This wave model was calibrated using the ERA-INTERIM data points closest to the coastline. Bed roughness and white capping parameters were adjusted in order to reproduce the calibration data. The final dataset was applied for another time period as model validation. These results were satisfactory (Figure 11 and Figure 12). Waves were predominantly directed to the East and the significant wave height ranged from 2m offshore to 1-1.5m nearshore, which is in line with field observations. The smaller model will use the results of the large model as boundary conditions. For this model, an additional wave model validation will be performed, using the measured wave data at C7 and C8.



Figure 10. ERA-INTERIM data points (blue dots) and calibration point (yellow dot) (left) and example of wave simulation result (right).



Figure 11. Results calibration large wave model.



Figure 12. Results validation large wave model.

Bed Composition

Figure 13 depicts grain size profiles from bed samples collected before and after the Monsoon on four typical locations: upstream the Cochin port in the Ernakulam channel (02), in the center of the port near the ICTT (14), in the nearshore area 2km from the coastline (46) and in the outer channel 7km offshore (70). Figure 14 summarizes both campaigns in a pre- and post-monsoon map.

Before the Monsoon, fine sediments were dominant within the harbor with clayey silt in the Ernakulam channel and silty sand near the ICTT. Further downstream, the sediments become coarser and in the nearshore area sand is found. However, the bed of the outer channel, even at 7km offshore) consists of fine sediments (clayey silt).

After the Monsoon, the variability in bed material between the sampled locations has been significantly reduced. At all locations the bed material is coarser than before the Monsoon and can be classified as sand. Especially in the outer channel (location 70) and within the harbor this shift can clearly be observed. This suggests that during Monsoon, sandy material is imported from the Arabian Sea (given the dominant landwards wind and current direction) and fills up the navigation channel and the Cochin harbor. This is confirmed by the observation of significant siltation by means of sequential bathymetry charts. This will be further analyzed in detail.



Figure 13. Grain size curve of four typical locations before (left) and after (right) Monsoon: Ernakulam channel (02), ICTT (14), nearshore 2km from coastline (46) and outer channel 7km offshore (70).



Figure 14. Grain size distribution before (top) and after (bottom) monsoon.

Quantitative analysis of siltation

Figure 15 depicts the cumulative dredged volumes from April 2015 to March 2016. This shows that dredging mainly focusses on the nearshore zones of the outer channel and the LNG and ICTT basins. In total, around 21 million m³ were dredged.



Figure 15. Cumulative dredged volumes per harbor zone.

In Figure 16 the cumulative siltation volumes were derived from monthly bathymetry surveys and dredging volumes. Siltation mainly increases during Monsoon and is high in the outer channel and the LNG and ICTT basins. The inner harbor channels are subject to a relatively small and gradual siltation.

Figure 17 shows the same data but normalized to area and dynamic instead of cumulative. Siltation depths are peaking in Monsoon and largest in the LNG and ICTT basins, which probably act as a sediment trap. After the Monsoon, negative siltation values are found for some areas, indicating compaction and/or erosion.

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Figure 16. Cumulative siltation volumes per harbor area.

Figure 17. Siltation depths per harbor area.

Rheology Measurements

Mud samples taken at various locations in the Cochin port were found to have a density between 1.17 and 1.19 ton/m³. The roto-viscosity analysis revealed dynamic viscosities ranging from 0.01 to 0.6 Pa.s with an extreme value of 1.4 at Matancherry channel (Figure 18).





Sub-Bottom Profiling

A Silas survey was performed early August 2015 in combination with Rheotune profiling. This allowed a powerful visualization of the sub-bottom of the Cochin harbor as well as a quantitative characterization (density contours). This is illustrated for the outer harbor channel and the Ernakulam channel in Figure 19 resp. Figure 20.

In the inner and outer harbor channel, the ICTT and LNG terminal a fluid mud layer with a thickness of several meters was observed. Along the channels, this thickness decreased moving further in- and offshore. Figure 19 illustrates for the depicted zone of the outer harbor channel that the top of the fluid mud layer has a depth of around 11m. The seismic reflections are low until a depth of around 15m. The 1150g/L contour is situated around 1m below the top of the fluid mud layer.

The bed of the Matancherry and Ernakulam (Figure 20) channels appears to be more consolidated. The seismic reflections are high immediately below the top of the fluid mud contour. The 1150g/L contour is only slightly below the latter contour which has a depth of around 12m.

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Figure 19. Silas profile in outer harbor channel (August 2015) with density contours of 1150 g/L (green) and 1200 g/L (red) and the top fluid mud contour (blue).



Figure 20. Silas profile in Ernakulam channel (August 2015) with density contour of 1150 g/L (orange) and the top fluid mud contour (blue).

The fluid mud layer will be further determined and its evolution and behavior analyzed by means of Rheotune density measurements and 210kHz and 33kHz surveys conducted at different times.

CONCLUSIONS

The port of Cochin suffers from high annual siltation rates with consequently high maintenance dredging costs. A methodology was developed to study these siltation processes and assess the implementation of the nautical depth concept. An extensive monitoring campaign is conducted during one year to collect field data on hydrodynamics, sediment rheology and transport processes, weather and bathymetry. These data feed a numerical 2D/3D TELEMAC model to simulate hydrodynamics, wave transformation, tidal circulation, salinity, sediment transport and siltation processes in the harbor, the navigation channel and the surrounding areas. Understanding the physical processes of siltation will allow suggesting methods for arresting it. In order to investigate the nautical implications of a new nautical depth criterion in the Port of Cochin simulations are performed using a ship maneuvering simulator especially equipped for maneuvering in mud conditions in shallow ports. After assessing the feasibility for a nautical depth for the Port of Cochin, monitoring and maintenance methods are investigated as well as the implications for dredging. The study is ongoing and no major results are available at the time of writing.

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