

Fluid Mud and Nautical Bottom – Concept and Application in Itajaí Port Complex (Brazil)

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ABSTRACT: Considering the demand for mooring larger ships at Brazilian port terminals, both private and public, in a scenario of growing exports, engineering interventions that can provide improvements in the vessel's maximum allowed dimensions can represent significant profits. Hence, this work presents an approach of Nautical Bottom, defined as the minimum depth in which ships can navigate without significant adverse effects in ship control and maneuverability without physical damage, with the goal of raising the maximum ship draft allowed in nautical spaces with fluid mud beds. Due to its rheological properties, fluid mud, in general, allows for vessels navigate with low or negative under keel clearance, respecting the established Nautical Bottom concepts. In addition, fluid mud layer thickness at port areas can possibly vary according to hydrodynamics and sedimentologic variations. This article presents an analysis of fluid mud thickness variations within the Itajaí Port Complex (Santa Catarina, Brazil) turning basin, where fluid mud layers are up to 2.5 meters thick, by means of analyses of bathymetric surveys and numerical modeling. The Itajaí Port Complex is located at the Itajaí-açu river estuary, which presents high variability of river discharge and suspended sediments. From bathymetric surveys, it is possible to observe fluid mud thickness from 0.5 to 2.5 meters. Numerical simulation results indicate suspended sediment load as a main environmental aspect for fluid mud thickness variations in the study area.

1 INTRODUCTION

Estuarine areas are usually amenable to port activity development due to the favorable location, sheltered from wave action in most cases. Moreover, natural great depths are commonly found in estuaries, which are also important for port terminal activities, as there is less need for dredging to allow the entrance and mooring of larger cargo ships.

In estuaries, interaction of fresh and salt water causes fine sediments to deposit. Physical and chemical properties of brackish water allow for fine particle attraction, due to the presence of sodium cations. These particles form heavier flocs that tend to

get easily deposited on the bed. This process occurs at different stages, depending on the strength of chemical bonds formed between particles. One of these stages is called Fluid Mud, in which chemical bonds are yet not strong enough to form large flocs with low mobility (McAnally et al, 2007).

Fluid mud is an aqueous solution with rheological properties that allow for safe navigation with low or negative under-keel clearance. Thus, it can be associated with the Nautical Bottom Concept. According to PIANC (2014), Nautical Bottom is the minimum depth in which there can be safe navigation, without adverse effects in ship control

and maneuverability and without significant physical damage on vessels.

In Brazil, several port terminal locations could apply the Nautical Bottom concept due to fluid mud layers near the bottom, such as the Santos, Paranaguá and Antonina ports, the Alumar terminal (Estreito dos Coqueiros, Maranhão, Brazil) and Itajaí Port Complex, which is the object of this study.

At the turning basin of the Itajaí Port Complex, double frequency bathymetries were compared with specific density measurements, in order to define which specific density better corresponds to a 33 kHz bathymetric survey, concluding that low frequency bathymetry surveys, in that area, correspond to specific densities between 1,150 and 1,200 kg/m³ (Pion and Alfredini, 2014).

The Itajaí Port Complex is composed of the public port of Itajaí and several private terminals installed at the Itajaí-açu river margins, near its outfall (Figure 1). The Itajaí Port Complex logistics is based on the cities of Itajaí and Navegantes. This port complex was responsible for approximately 900,000 TEUs transport in 2015, being the second port in Brazil in container transportation, after the Santos Port Complex.



Figure 1. Itajaí Port Complex Localization

The nautical areas of the Itajaí port complex are divided in external access channel, internal access channel and turning basin. At access channels, the minimum under keel clearance is 15% of ship draft. At the turning basin, under keel clearance of 0.6 meters is allowed, independently of ship draft. Maximum ships LOA allowed to enter Itajaí Port Complex is about 285 meters.

1.1 Itajaí-açu river

The Itajaí-açu estuary is approximately 70 km long, considering its upper limit next to Blumenau (Santa Catarina, Brazil), where water level variations due to tidal effects are still observed, and covers a 15,500 km² drainage basin.

The average Itajaí-açu river discharge was estimated in 228 m³/s with standard deviation of 282 m³/s by Schettini (2002), considering data measurements collected between 1934 and 1998 at Indaial (Santa Catarina, Brazil), a city located 90 km far from the river outfall. The minimum discharge observed was 17 m³/s and the maximum discharge measured was 5,390 m³/s. According to the same author, this location represents approximately 70% of

the Itajaí-açu river drainage basin. The measured discharges of the Itajaí-açu river could not be associated with seasonality, as the monthly maximum discharge was measured on February and October and the monthly minimum discharge was measured on April and December (Schettini, 2002).

At the Itajaí-açu river outfall, the tidal amplitude varies from 0.3 meters on quadrature to 1.2 meters on syzygies, with an average tidal amplitude of 0.8 meters. The mean sea level is approximately 0.57 meters. Meteorological effects can amplify tidal amplitudes by 25% (Truccolo, 2009). Water level measurements can be also significantly modified by high discharges occurrence (Schettini and Truccolo, 2009)

Salt intrusion in the Itajaí-açu river estuary is related to river discharge magnitude. When river discharges reach about 300 m³/s, salt intrusion occurs up to 18 km from the river outfall. High discharges (1,000 m³/s or higher) expel salt intrusion from the estuary (Schettini, 2002). However, the Itajaí-açu river discharges are lower than its average value most of time, thus salt intrusion can be considered practically permanent, reaching up to 30 km in low-discharge periods (Schettini and Truccolo, 2009). When the Itajaí-açu river discharges reach approximately 500 m³/s there is an evident salt wedge (Schettini, 2002). At the turning basin area, salinity varies from 30 ppt (bottom) to 10 ppt (surface) (Medeiros, 2003)

The Itajaí-açu river estuary bed is predominantly composed of clay deposits, in which the clay fraction is higher than 70% (Schettini, 2002). River discharges higher than 700 m³/s increase bed sand fraction, due to higher flow sediment transport capacity. The suspended solid concentration varies from 7 mg/L to 500 mg/L when measured at Indaial station, depending on river discharge (Schettini, 2002).

1.2 Goal of the research

The goal hereby is to describe fluid mud layer thickness at the turning basin of the Itajaí Port Complex and its variation through bathymetrical surveys and analysis of river discharges and suspended solids. We also aim, by using hydrodynamic and fine sediment transport numerical modeling, specifically software Delft3D®, to analyze environmental conditions that may cause variation in fluid mud layer thickness at this location.

2 MATERIAL AND METHODS

The analysis of fluid mud layer thickness at the Itajaí Port Complex was developed from double frequency bathymetric surveys, river discharge and suspended sediment data and hydrodynamic and sedimentologic numerical modeling.

2.1 Bathymetric surveys

The analysis of the turning basin of the Itajaí Port Complex was based on four different double frequency bathymetrical surveys (33 – 200 kHz).

These data were collected on 30/03/2007, 15/05/2007, 12/07/2007 and 15/11/2007.

2.2 River discharge and suspended solids data

In addition to bathymetric surveys, the analysis was based on river discharge and suspended solids data, collected at Indaial (Santa Catarina, Brazil), located approximately 90 km from the Itajaí-açu river outfall. These data were collected over the course of 2007. River discharge and suspended solid data were used as boundary conditions for the numerical model, considering the goal of justifying fluid mud thickness variations.

2.3 Delft3D® Hydrodynamic Module

Delft3D hydrodynamic module simulates non-uniform flows and transport phenomena using water level variation, river discharges or meteorological forcing variables, including density gradient effects, calculated from salinity and temperature distribution. This model can be used to predict flow patterns on shallow regions, coastal, estuarine or lake areas (Deltares, 2014). In this case, numerical modeling is based on the continuity equation, the momentum conservation equation (Navier-Stokes) and the transport equations solution.

The model solves Navier-Stokes equations for an incompressible fluid, considering the Boussinesq approximation, in which fluid density is considered to be constant, except for the baroclinic term, which represents flow variations due to vertical density gradients (Deltares, 2014). Moreover, the Boussinesq approximation does not account for vertical flow acceleration, considering hydrostatic pressure. This hypothesis is valid when the horizontal extension is much larger than flow depths (Deltares, 2014).

The numerical simulations are performed through the finite difference method, and the space is divided in cells from a computational grid. Delft3D® cohesive sediment transport model

The Delft3D fine sediment transport model is based on continuity principle. Considering a certain control volume, increase of fine sediment

concentration is equal to incoming fine sediment added to particle generation inside this control volume (McLaughlin, 1961).

The model considers eddy diffusivity to be independent of sediment concentration, which is a valid hypothesis considering usual sediment concentrations found at rivers and estuaries (Partheniades, 2009). Settling speed is calculated based on sediment concentration, considering that high concentrations hinder sediment settling.

Cohesive sediment reference settling speed is a function of salinity. The presence of salt causes a reduction in the repulsion force of electrical forces between clay minerals, inducing flocculation (Alfredini and Arasaki, 2014). These flocs are bigger and heavier, so they tend to settle faster than smaller particles. Delft3D calculates fine sediment settling speed based on water salinity.

3 RESULTS AND DISCUSSION

Results obtained are presented separately, first from field data analysis and then numerical model calibration and simulation results. These results are further integrated in the discussion section.

3.1 Comparative surveys

Comparative surfaces presented high variability of fluid mud layer thickness at the turning basin of the Itajaí Port Complex (Figure 3 and Figure 4). As it can be observed, on 15/05/2007 (Figure 3 (b)) and 05/11/2007 (Figure 4 (b)), the fluid mud layer is thicker than what was observed in other bathymetric surveys. In 15/05/2007, the fluid mud layer is up to 2.5 meters thick in some regions within the interest area and most of the turning basin of the Itajaí Port Complex presents fluid mud layer thickness of between 1 and 1.5 meter. Instead, bathymetric surveys from 30/03/2007 (Figure 3 (a)) and 12/07/2007 (Figure 4 (a)) present a layer of fluid mud near the bed that does not surpass 0.5-meter thickness in most of the turning basin area.

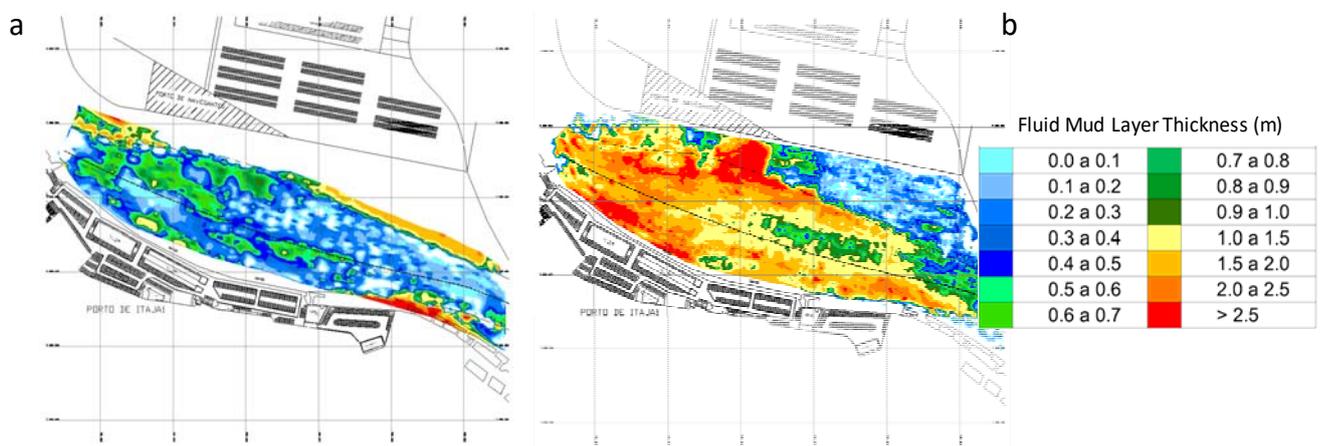


Figure 3. Comparative surfaces - (a) 30/03/2007 (b) 15/05/2007

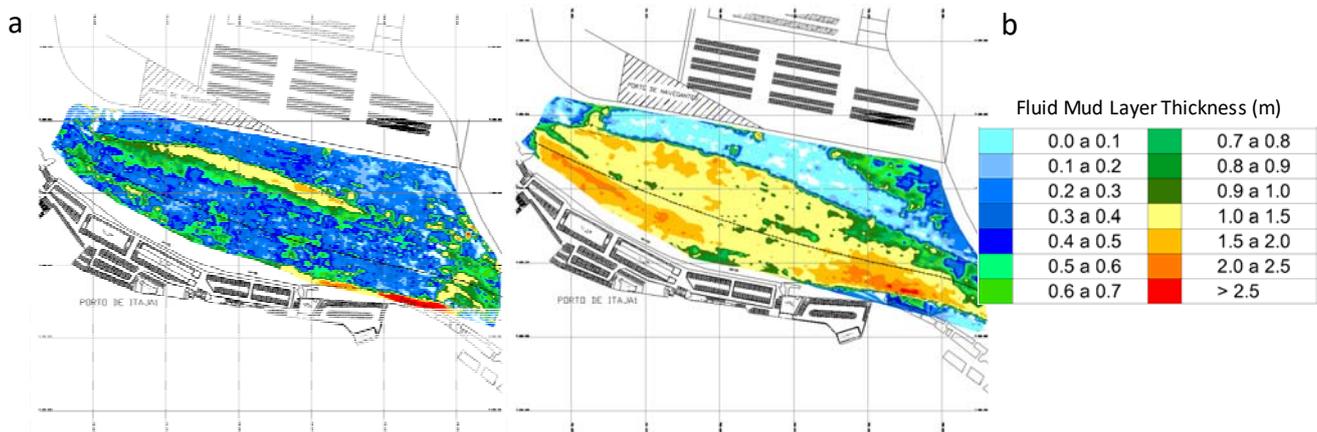


Figure 4. Comparative surfaces - (a) 12/07/2007 (b) 05/11/2007

3.2 Model conception and calibration

The modeled area was defined considering the land boundaries conceived using the Google Earth® software. Oceanic boundaries were determined in order to adequately represent tide wave propagation over the entire model domain. Fluvial boundary was defined considering the extension of salt intrusion and the border was located at approximately 20 km from the river outfall, where salinity is approximately zero (Schettini, 2002).

The computational grid (Figure 5) employed has 14,011 cells, with variable resolution. At the turning basin of the Itajaí Port Complex, the resolution employed was of approximately 40 x 20 meters. In order to precisely represent estuarine stratification, the model was conceived with 12 vertical layers, with better resolution near bottom. Layers were divided in 2-2-3-4-5-6-7-9-11-14-17-20% from bottom to surface.



Figure 5. Computational grid

The Model bathymetry (Figure 6) was based on bathymetrical data collected in 2007, which were also used for variation analyses of fluid mud thickness. For areas which are not covered by bathymetric surveys, information contained in nautical charts of the Itajaí Port Complex were used to fulfill model bathymetry.

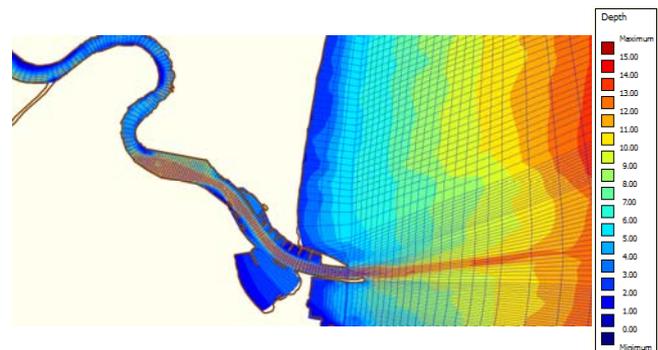


Figure 6. Model bathymetry

Oceanic open boundary was forced with astronomic constants extracted from the TPXO global tide model (Egbert and Erofeeva, 2002) for the Itajaí-açu river outfall area. River boundary was forced with river discharge data measured at Indaial multiplied by 1.43, considering that discharges measured at Indaial represent approximately 70% of all drainage basin (Schettini, 2002)

Bed roughness was set according to the bed material characteristics. Wave and wind effects are not representative for sediment transport at the interest area (Schettini, 2002), so they were not considered. Salinity was set to zero at river boundary and 35 ppt at oceanic boundary.

Only one cohesive sediment fraction was simulated, in order to evaluate sediment concentrations near the bed. The sediment properties were chosen with the aim of hindering it from settling, in order to represent a fluid mud layer in the most accurate way possible. At the river boundary, suspended sediment measured in 2007 at Indaial was forced. Considering that this sediment is originated from the drainage basin, fine sediment concentration at the oceanic boundary was considered null.

Water level was calibrated using a time-series for the Itajaí Port Complex generated by the TPXO global tide model. Current speeds were evaluated comparing model results with monthly average speeds measured by CTTMar (Univali, Itajaí, SC) between 2006 and 2012. Salinity model results were calibrated with longitudinal salinity profile based on measurements at the Itajaí river estuary by Schettini (2002). Suspended sediment was based on 11 points inside the turning basin of the Itajaí Port Complex.

Model results were compared with suspended material measurements performed by Schettini (2002), analogously to salinity measurements.

3.3 Dredging volumes estimate

Aiming to analyze variations of fluid mud layer thickness as precisely as possible, dredged volumes from the Itajaí Port Complex were calculated. This estimate was based on total sediment contribution to the interest area extracted from model results. The model estimate was compared to the 2007 annual total dredged volume estimated by the Itajaí Port Complex administration (2,000,000 m³). In this case, the estimated volume pertains to all nautical spaces. Dredged volume at the Itajaí Port Complex area cannot be precisely determined because water injection dredging is performed in this region.

The model estimated that approximately 1,500,000 m³ of sediment contributed to the Itajaí Port Complex in 2007 (Figure 7), presenting the same magnitude order of dredging volumes informed by the port administration in 2007. It is important to highlight that approximately 60% of sediment contribution occurred between 15/05/2007 and 12/07/2007 (Table 1). Thus, it is possible to infer that dredging was intensified in this period.

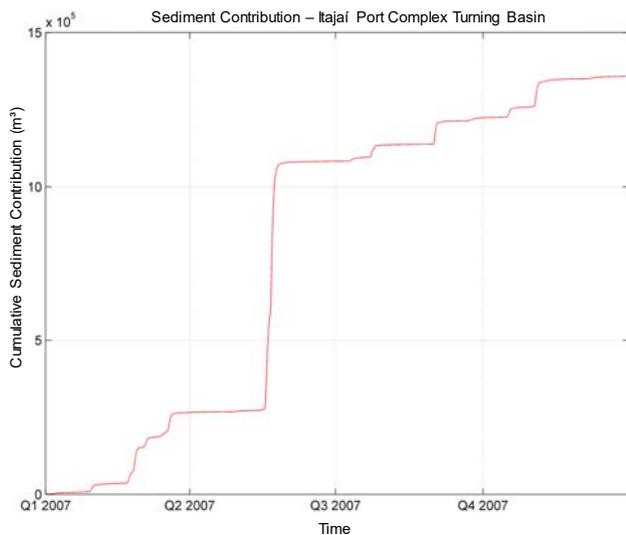


Figure 7. Modeled sediment contribution to the turning basing of the Itajaí Port Complex in 2007

Table 1. Sediment contribution to the turning basin of the Itajaí Port Complex

Modeled Sediment Contribution Between Bathymetric Survweys (m ³)		
Period	Sediment Contribution (m ³)	% from Annual Volume
30/03/2007-15/05/2007	8,159	1 %
15/05/2007-12/07/2007	816,378	60 %
12/07/2007-08/11/2007	242,320	18 %

3.4 Numerical simulations results

From model results (Figure 8), it was possible to conclude that suspended fine sediment concentration is not related to tidal cycles. Variations of surface and

bed fine sediment concentration are not correlated to syzygies or quadrature standards.

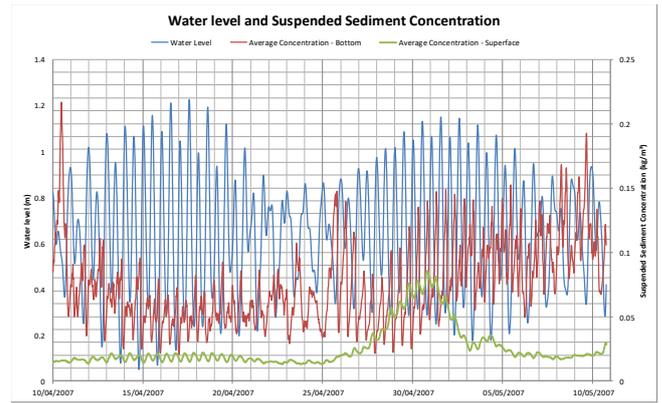


Figure 8. Water level and Suspended Sediment Concentration

Comparison between river discharges and sediment concentrations showed that surface layer sediment concentrations slightly raise when river discharges are over 400 m³/s (Figure 9). However, sediment bed concentrations seem not to be directly related to river discharges.

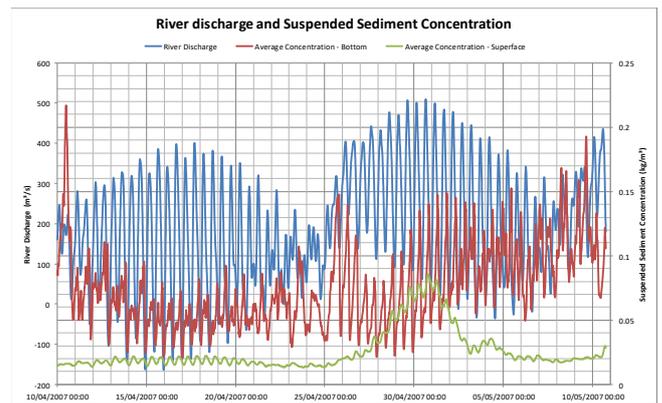


Figure 9. River discharges and Suspended Sediment Concentration

Thus, suspended sediment concentration was compared to suspended sediment load at the turning basin of the Itajaí Port Complex (Figure 10). From these results, it can be stated that suspended sediment concentration is directly related to suspended sediment load. Suspended sediment load peaks generally cause an immediate increase in surface sediment concentrations, followed by a delayed increase of bottom sediment concentrations. This delay is justified by the necessary interval for the suspended sediment to settle. Hence, the variation of fluid mud layer thickness was analyzed using the suspended sediment load parameter, in addition to sediment concentration.

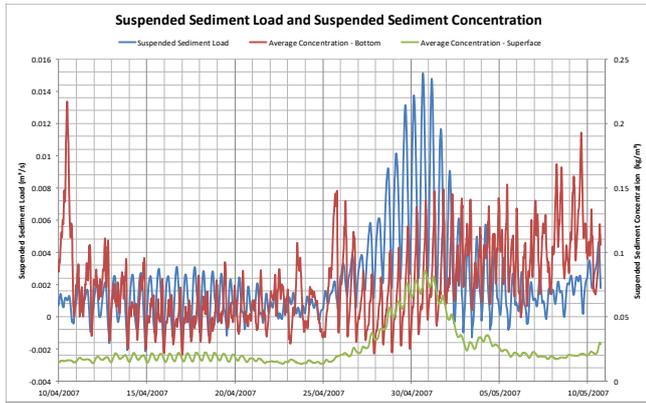


Figure 10. Suspended suspended sediment load and concentration

Fluid mud layer thickness analysis was based on the following simulated periods: between 15/03/2007 and 15/04/2007, 01/05/2007 and 01/06/2007, 28/06/2007 and 20/10/2007 and 20/11/2007. The results are expressed in Figure 11.

Before 30/03/2007 (Figure 11 (a)), there were low suspended sediment loads and, consequently, low sediment concentrations at the surface and bottom. Instead, in the period close to 15/05/2007 (Figure 11 (b)), simulation results indicate an increase of sediment concentration near the bed, according to suspended sediment load variations for the same period.

In July 2007 (Figure 11 (c)), immediately before 12/07/2007, the model results indicate a suspended sediment load and, consequently, a sediment concentration peak, mainly near bed layers.

In November 2007 (Figure 11(d)), the highest Itajaí-açu river discharges were measured, causing peaks of suspended sediment load and, consequently,

high suspended sediment concentrations at surface and bed layers.

3.5 Discussion

Comparative surfaces conceived from bathymetric survey data indicated that the field data measurements on 15/05/2007 and 05/11/2007 showed a thicker fluid mud layer than others surveys, with thickness up to 2.5 meters in some areas within the turning basin of the Itajaí Port Complex. Instead, on 30/03/2007 and 12/07/2007, fluid mud layer thickness did not present thickness higher than 0.5 meters in most of the interest area.

From model results, it was possible to identify suspended sediment load as the main environmental conditioner to the concentration of suspended sediment in the interest area, both at the surface and bottom layers. Suspended sediment load is a function of river discharges and suspended sediment concomitantly, so an increase in one of these variables does not necessarily entail an increase in suspended sediment load, if there is a decrease in the other one. However, it is possible that high flow speed may cause bed material remobilization, raising suspended sediment concentrations independently of suspended sediment load contribution to the interest area.

Considering a bathymetric survey conducted on 30/03/2007, in which fluid mud layer thickness did not reach 0.5 meter, low suspended sediment load values were observed, justifying low fluid mud layer thickness. Yet, simulation results for a period immediately before 15/05/2007 indicated higher suspended sediment concentrations near bottom layers, justifying an increase on fluid mud layer thickness.

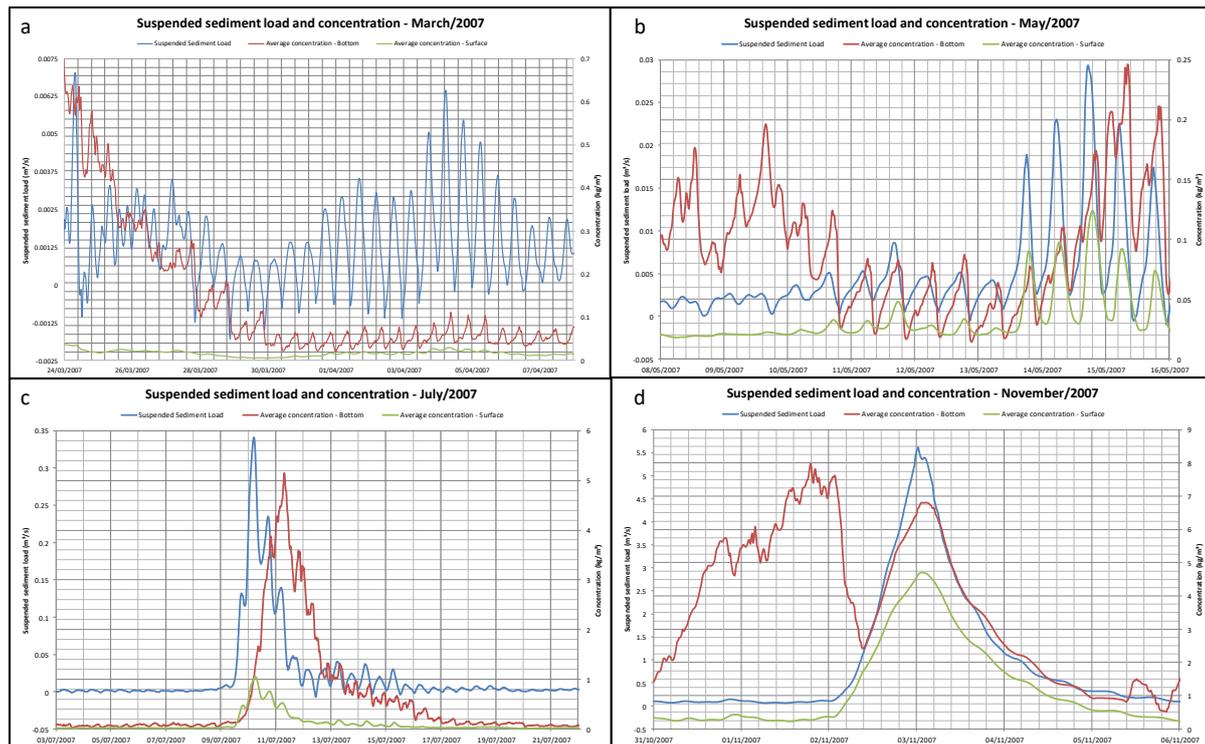


Figure 11. Suspended suspended sediment load and concentration - (a) March 2007 (b) May 2007 (c) July 2007 (d) November 2007

In July 2007, model results indicated peaks of suspended sediment load and, consequently, high suspended sediment concentrations near the bed in the period just before the 12/07/2007 bathymetric survey. This result is not consistent with field data, in which the fluid mud layer observed did not exceed 0.5 meter in most of interest area. However, between May and June 2007, an 815,000 m³ sediment contribution was estimated, representing 60% of all 2007 contribution. Thus, it is possible that a significant part of all 2007 dredging estimations (2,000,000 m³) was performed in this period. As this dredging is not represented in the model, it may be the cause of this incongruence.

Furthermore, it is significant to emphasize that dredging procedures are also limitations for other periods analysis. The dredging at the Itajaí Port Complex is performed through water injection, aiming at the remobilization of bed material, so it cannot be represented simply as bed material removal, once dredging procedures in this case can also increase suspended sediment concentration near the bed.

The model presented hereby, besides yielding results consistent with field data, was conceived and calibrated based mostly on bibliographic references and global models. For a more comprehensive analysis, further data would be necessary, such as current speeds and water level time-series and suspended sediment measurements within the interest area. Moreover, it is important to monitor occasional meteorological effects, such as water level increases, which can change flow pattern and influence sediment transport. Plus, fluid mud specific density variations should be analyzed, in addition to rheological properties measurements.

4 CONCLUSIONS

Considering a scenario in which ship drafts tend to increase in order to meet the demands for exports of Brazilian products, fluid mud navigation represents a profitable possibility. Due to low efficiency of the dredging procedures in muddy bottoms, these procedures can be significantly expensive without bringing the expected results in enhancing nautical space depths.

The application of the concept of Nautical Bottom depends, also, mandatorily, on an approval by the maritime authority, so that it could be possible that a homologated maximum ships draft will come to consider fluid mud layers, evidently always prioritizing navigation safety.

Fluid mud layers at the turning basin of the Itajaí Port Complex presented high variability along 2007, with thickness measurements varying between 0.5 and 2.5 meters according to bathymetric double frequency surveys. Previous results allow for the determination of the most influential hydrodynamic and sedimentological processes upon fluid mud thickness variation at the turning basin of the Itajaí Port Complex. Modeled results showed that this thickness varies according to suspended sediment load variations, which are function of river discharges

and suspended sediment. As the Itajaí-açu river discharges present high variability, with no seasonal patterns, it is not possible to establish fluid mud thickness predictions such as a monthly estimate.

An aspect that must be highlighted concerns dredging activities. As there is no information about a dredging schedule over the analyzed period, these procedures, hence, can cause undetectable effects. Further analysis should evaluate the consequences of dredging procedures over fluid mud layers, such as the reduction of fluid mud layers and bed fluidization due to water injection.

Also, model results were based basically on bibliographic references and global models' data. In this case, it must be emphasized that further data should be collected in order to check and, mainly, improve hydrodynamic and sediment transport model accuracy.

Furthermore, it is important to highlight that, in addition to verifying the causes of formation of and variations in fluid mud layers, further work is necessary in order to apply the Nautical Bottom concept. An interdisciplinary study should be developed, covering fast-time and real-time maneuvering simulations and physical scaled models, to verify the effects of local fluid mud layers upon vessels, which have to be coupled to numerical maneuvering models in order to obtain the desirable accuracy

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