Mapping and estimative of fluid mud layers thickness at Itajai-Açu river port area, seeking improvements to navigation of deep-drafted vessels

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Abstract

The aim of this study was map and estimate fluid mud layers thickness deposits at Itajai-Açu river port area, located in Santa Catarina State (southern Brazil) at Itajai city, using dual frequency bathymetry (33 and 200 kHz) and densitometry data, taking into account the “Nautical Depth” concept stated by PIANC (1997), seeking improvements to navigation of deep-drafted vessels.

Introduction

A vital element of port services is to ensure the safe passage of ships using their facilities. In ports where there is a high rate of sedimentation, this service involves high maintenance costs. These costs increase exponentially as the maintenance of deeper navigation channels are maintained. Therefore, a continuous increase in vessels carrying capacity triggers the necessity of maintenance safe waterways in an increasingly efficient way (FONTEIN & VAN DER WAL, 2006).

The manoeuvering behavior of a vessel is highly influenced by the water layer available just below ship’s keel. Changes in this behavior are intensified mainly in deep drafted vessels navigating toward port areas or through navigation channels with keel close to bottom. Enough space between ship’s keel and channel’s bed is needed for economic and safe manoeuvres can be performed (PIANC, 1997).

Particularly in deep drafted vessels, the knowledge of space between vessel’s keel and channel’s bed becomes essential for a safe navigation. Thus, it is important to have all the time reliable information about local depth available for navigation (DELEFORTRIE & VANTORRE, 2006).

The available depth for navigation can be measured through simple echo-sounding techniques, which generate accurate results when used in consolidate bottoms. However, in the presence of muddy layers the exact location of bottom becomes difficult and with low precision (KIRBY *et al*., 1980).

The use of high frequencies (*e.g.* 210 kHz) allows to locate the mud-water interface, while low frequency signals (*e.g.* 33 kHz) penetrate the mud layer. However it is uncertain if this measured level is the solid bottom or not. In addition, the monitoring of level presented by 33 kHz seems to depend on many factors and therefore, is not always entirely reliable (DELEFORTRIE *et al*, 2005).

This difference in depth reflection between the two frequencies of echo sounder above cited can reach considerable values, and is given as a function of composition variation and fluid mud layer properties with increasing depth. The upper part of mud layer is very fluid, while the material in a greater depth will be denser and more viscous. If results of high frequency echo signals are used, the bottom will be set in water-mud interface. In the case of using low frequency echo signals, the bottom will be outlined in a deeper position in the mud layer, a site that seems to be different at each measurement and therefore unreliable. These details are important once if during navigation the ship’s keel touches the denser layer of mud, the vessel’s controllability may be affected, thereby decreasing the security (DELEFORTRIE & VANTORRE, 2006).

Seeking to deal with this problem, the “*Nautical Bottom”* concept arises, which is defined by PIANC (1997) 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 manoeuverability”*. This concept has already been introduced in many ports subjected to sedimentation and fluid mud layer formation.

Until now, little was known about the behavior of ships in areas where fluid mud layer is present; an overview investigation on this subject has been presented by PIANC (1997). For this reason, the definition of “nautical bottom” so far has been based on analysis of physical characteristics of mud. The navigation depth is located at a depth below the water-mud interface, where from a rheological point of view, the transition between fluid mud and plastic mud can be defined (DELEFORTRIE *et al*, 2005).

The fluid mud is characterized by a fraction of low volume of solids and can be regarded as a lost suspension similar to water. The plastic mud, in other hand, is a deposit of sediments that, besides present a clear viscous behavior, has elastic properties as well, and in this respect is comparable to soil. The change in structural behavior is referred as a rheological passage or rheological transition. Due to difficulty of measuring other parameters (*e.g.* rheology) in a continuous way, the critical value of rheology is usually connected to critical density of the fluid mud layer (VAN CRAENENBROECK *et al*., 1998).

The accumulation of mud is a common feature in estuaries and coastal plains, where ports silting may be higher. Estuaries and their entrances are the way of transport from continental sediments toward ocean. Throughout this process of transportation, ongoing events such as erosion, transport and deposition are common phenomena on sedimentary cycle of these transitional environments (SCHETTINI *et al*, 2010). Such events are dependent on flow dynamics and particle properties (size, shape, density and composition), being differentiated according sediments nature. Cohesive sediments behave differently when compared to non-cohesive sediments due to its physical-chemical characteristics and particle interactions (NICHOLS & BIGGS, 1985).

Along Santa Catarina State coast, southern Brazil, a few studies have been conducted to determine presence and distribution of fine sediments, particularly fluid mud, as well their transport processes in estuaries and adjacent shelf (ALMEIDA, 2008). One of a few studied sites is located at Itajai-Açu river estuary, at Itajai city, where continuous monitoring over the past ten years has shown the presence of a fluid mud layer about 2 meters thick along Itajai port Turning Basin. Studies of sediment balance during high and low discharge periods in this estuary demonstrate the great influence of Itajai-Açu river discharge on the amount of sediment into estuary and adjacent continental shelf, being peaks of high discharge (even occurring only in about 10% of the time) the most responsible for this transport (SCHETTINI & CARVALHO 1998; SCHETTINI *et al* 1998 e SCHETTINI 2001).

Method

To carry out this work raw data from dual frequency bathymetry (33 and 200 kHz) and densitometry referent to November of 2007, both ceded by Itajai port administration, were used. Bathymetric charts in DWG format, containing punctual information of depth, generated using echo sounder operating in both frequencies, were extracted in X, Y and Z and then interpolated through *Natural Neighbor* method, so that two distinct Raster surfaces (one for each frequency) could be generated.

The choice of the best interpolation method depends on available dataset and how they are spatially distributed. Thereby, Natural Neighbor interpolator was adopted, once different types of interpolation methods were tested and compared. As this interpolator is not geostatiscal, a quality control was made through a correlation between depth data measured versus interpolated for each frequency (Figure 1). Relevant information about this method is that it does not extrapolate values, solving interpolation only into data domain. More information about Natural Neighbor interpolation method can be found in SIBSON (1981).

Due to high density of points containing depth information per unit area, bathymetric surfaces generated had a great resolution, allowing choose a pixel of 25m^2. Once surfaces were generated, the difference between them (33 - 200 kHz) was made for each pixel, generating a map showing the distribution of fluid mud layer thickness, as shown in Figures 2, 3 and 4 for Turning Basin, Inner and Outer Channel, respectively. The software used for such procedures and analysis was ArcGIS 9.2®. It is important to mention that in this study, Figure 4 is called by Outer Channel merely by a question of segment the study area once the Outer Channel, in fact, starts at jetties end toward continental shelf.

A total of 162 density profiles were carried out by an outsourced company contracted by Port of Itajai to characterize mud layers at port area. Possibly taking into account that there are two critical changes on density profiles, which occurs first on water - mud interface and then on unconsolidated / consolidated bottom transition, critical densities of 1070 and 1200 Kg/m^3 were therefore adopted as critical limits, probably based on studies developed in other ports subject to fluid mud layers formation (*e.g.* Rotterdam = 1.2 t.m^{-3}, Bankok = 1.2 t.m^{-3}, Surina = 1.23 t.m^{-3}, Tianjing xingang = 1.2 - 1.3 t.m^{-3}, Yangtze = 1.25 t.m^{-3}, Liang yungang = 1.25 - 1.30 t.m^{-3}, Belgium = 1.151 - 1.347 t.m^{-3} according JIANYI XU & JIANZHONG YUAN, 2003) owing a lack of rheological tests made on this site to determine nautical depth.

Locations of sampled profiles are marked and identified on fluid mud layers map. Density information acquired need to be corrected in relation to tidal elevation and then referenced to DHN (Brazilian Navy) datum (mean low water of springs). This procedure was necessary, to allow correlation between available bathymetric and densitometry data, once bathymetric data were also tide corrected and referenced to same datum.

After corrections, coordinates from density profiles were used to extract depth values from interpolated bathymetric surfaces exactly at the same location enabling correlations to be made with surfaces generated by both frequencies and density critical limits. Results can be visualized in Figure 5.

To characterize the hydrodynamic pattern of study area during bathymetric and densitometric surveys, a data series collected from November 30 to December 7 from a moored Acoustic Doppler Current Profiler (ADCP) was analyzed. The equipment was moored in estuarine channel (Inner Channel) at 8m depth nearby approximately 5 meters to port access navigation channel.

The ADCP used is manufactured by *Nortek™* model *Aquadopp Profiler®* with depth gauge, programmed to measure time series of currents in a frequency of 1MHz, with vertical profiling segmented in cells of 30 cm from near bottom to surface, performing means every 2 minutes in intervals of 10 minutes. The equipment sensors are in a 90° in relation to bottom and close to substrate, enabling the entire water column to be sampled with excellent resolution.

Removal of inconsistent data stored in the equipment during moored time was made through an application of a statistical method of disposal records that exceeded the average about one or two times the standard deviation value ($|x - x| > 2\sigma$) and from the application of a moving window (*box-car window*) containing the mean and the standard deviation of one day registration (EMERY &

THOMSOM, 1998). Gaps in the original data series, generated by removal of spurious data were filled using a linear interpolation. In the present study, the percentage of gaps filling form the hole original series through the linear interpolation ranged between 0.5 and 0.8%, that allows the data series to be considered consistent.

To decompose any vector $\vec{v}$, relative to a cartesian orthogonal referential (Oxy), according to the adopted referential, the components u and v of this vector in relation to axes Ox and Oy can be expressed by equations 1 and 2:

$$u = V cos(\theta) \quad (1)$$

$$v = V sin(\theta) \quad (2)$$

Where, V is the module of vector and θ is the angle formed between vector and the abscissa axis (Ox) measured in counter-clockwise. Thus, the decomposition will provide positive, negative or null values to components u and v, according to argument θ.

More details about this procedure can be obtained in MIRANDA *et al*. (2002), once the angle θ need to be corrected as the origin, local magnetic declination and axes coordinates rotation. Therefore, the velocity vector $\vec{v}$ was decomposed in along channel component u (aligned with the main axes of estuarine channel) and cross channel component v (normal to channel alignment), in order to observe the main physical phenomena acting in these directions.

In this work was used a temporal window filter (Fourfilt) in order to obtain the subinertial and tidal frequencies (cut frequency 1/40 h^{-1} and 1/25 h^{-1}, respectively) as initially described by WALTERS e HESTON (1982). To subinertial frequency the filter was used as a low-pass filter and for tidal frequency as a high-pass filter. It was stated that negative values of current represent flood and positive, ebb.

Results

According quality control made on bathymetric data for frequencies of 200 and 33 kHz (Figure 1), correlations showed a R^2 (correlation coefficient) equal to 0.994 using 8127 depth values and a R^2 equal to 0.9937 using 8134 depth values for each frequency, respectively. Based on this, is possible to affirm that the used interpolator had a successful application.

As can be seen in Figures 2, 3 and 4, fluid mud deposits are distributed throughout waterway. Comparing each segment of port area, it is possible to note that thickest mud layers are present at Turning Basin (Figure 2). In this place where turning manoeuvres are done, we have a gradual increasing on mud layer thickness from Port of Navegantes toward Port of Itajai, where fluid mud deposits have layers ranging from 0 to 3.0 m. At Navegantes port, berths have the lowest thick that range from 0 to 1.0 m, followed by visible transition on mud thickness evidenced by navigation channel (black lines) toward Itajai port, where channel's thalweg allows higher mud layers to get stuck, and thus, deposits thickness range from 1.0 to 3.0 m. This last and greatest thick is located close to Itajai Port´s berth.

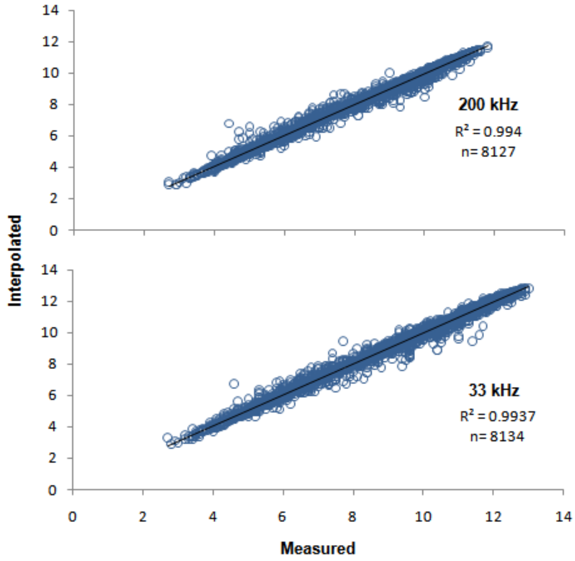

Figure 1. Correlation made between depth data measured versus interpolated for each frequency, both in meters.

In other hand, at Inner (Figure 3) and Outer (Figure 4) Channels mud deposits are smaller, where it's thickness range from 0 to 1.5 m. At first one, layers from 0.5 to 1.0 m are most representative, while at second one are from 0 to 0.5 m. A longitudinal distribution of mud along navigation channel becomes remarkable when all areas are parsed up together, enabling observe a decrease on mud layers thickness toward estuarine inlet. After Jetties, mud layers back to grow toward continental shelf.

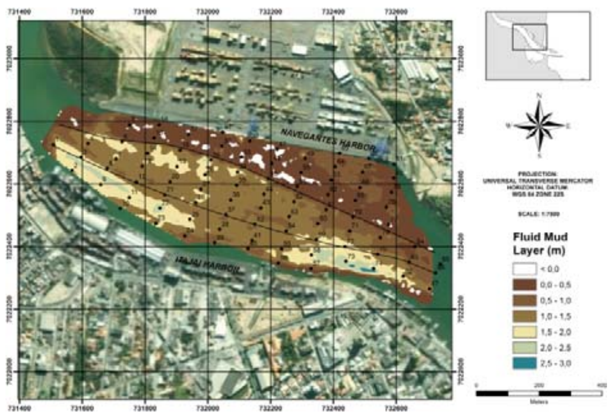

Figure 2. Fluid mud layer thickness at Turning Basin.

When punctual values of depth extracted from bathymetric surfaces are correlated to densitometry data (Figure 5), for 200 kHz versus 1070 Kg/m^3 a correlation value of R^2= 0,7984 is obtained, while for 33 kHz versus 1200 Kg/m^3 is R^2= 0.748, both using 156 data (n). Arising equations from linear trend line application are presented above R^2 values.

Higher correlation values were not reached, very probably due to errors inherent to densitometry correction in relation to tidal elevation or due to a delay between bathymetric and densitometry surveys, once bathymetry was executed on November 1th and densitometry on November 14th. Despite being a short period, is enough time to promote bottom changes that compromise correlation quality, even more if a maintenance dredging is held; a routine practice in this area. An important detail that must be considered on these obtained correlations values is that after review all density profiles, a low correlation between 1070 kg.m^3 and 200 kHz was expected, once an evident transition on water – mud interface occurs in a lower density. Regarding to 1200 kg.m^3 and 33 kHz correlation, after critical density imposed by water – mud interface density profiles do not show an evident pattern variation, making it difficult to analyze and compare.

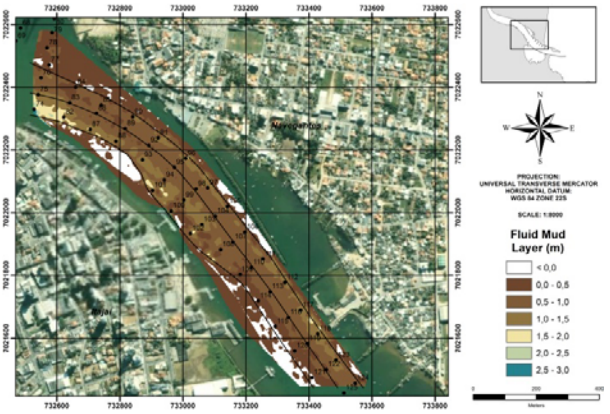

Figure 3. Fluid mud layer thickness at Inner Channel.

Only 156 of 162 density profiles were used because, as cited before, natural neighbor interpolator do not extrapolate values, so there was densitometry profiles out of interpolated area, preventing their inclusion on correlation analysis.

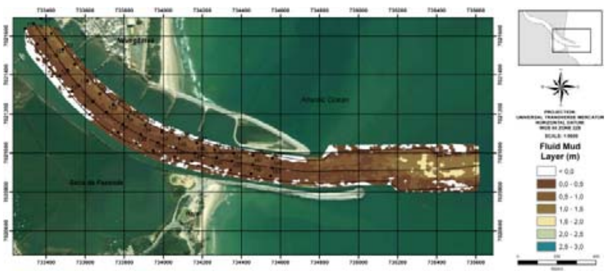

Figure 4. Fluid mud layer thickness at Outer Channel.

Concerning to currents velocities of along channel component u, surface velocities (a) were the most energetic (Figure 6), which oscillated between -0.25 and 0.24 m.s^{-1} to tidal frequencies and -0.12 to 0.28 m.s^{-1} to subinertial frequencies. The same velocity parameters to middle water column (b) ranged between -0.07 to 0.055 m.s^{-1} and -0.05 to 0.12 m.s^{-1} to tidal and subinertial frequencies, respectively. Near bottom (c), lowest velocity values are presented, as expected, which ranged between -0.045 to 0.03 m.s^{-1} to tidal frequencies and -0.035 to 0.07 m.s^{-1} to subinertial frequencies. Current velocities of cross channel component v, to subinertial and tidal frequencies, showed the same pattern, however, intensities were an order of magnitude smaller than along channel component velocities. In a general way, during study period currents intensities can be considered weak, when compared to other periods as presented in BENEVIDES *et al.* (2011).

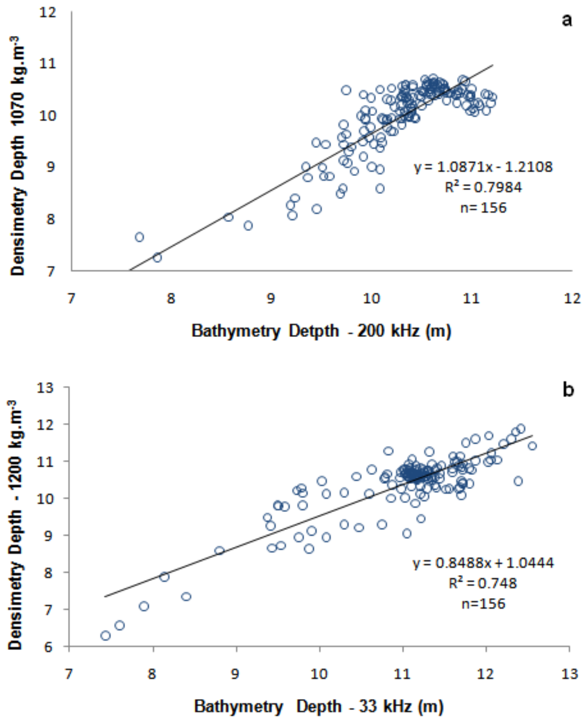

Figure 5. Correlations between bathymetry and densitometry data. Above (a) is presented 200 kHz versus 1070 Kg/m^3 while below (b) 33 kHz versus 1200 Kg/m^3.

The hydrodynamic analysis of currents pattern became important, once is known that the erosion of sedimentary particles or flakes of cohesive sediments may occur when is applied on them a bottom stress through currents or waves, above the critical shear stress needed to start erosion. This tension is related to depositional processes and consolidation that acted on sediment, also depending on variables such as pH, salinity, organic matter content and density (SCHETTINI, 2001)

According DYER (1973), density and critical shear stress needed to occur erosion increases exponentially with increasing depth. During stuff conditions, a fluid mud layer is formed over a more rigid layer. During a tidal cycle this layer is easily eroded, being sufficient to cause significant variations on suspended sediment concentration in the estuary. The more rigid layer is eroded only in extreme situations.

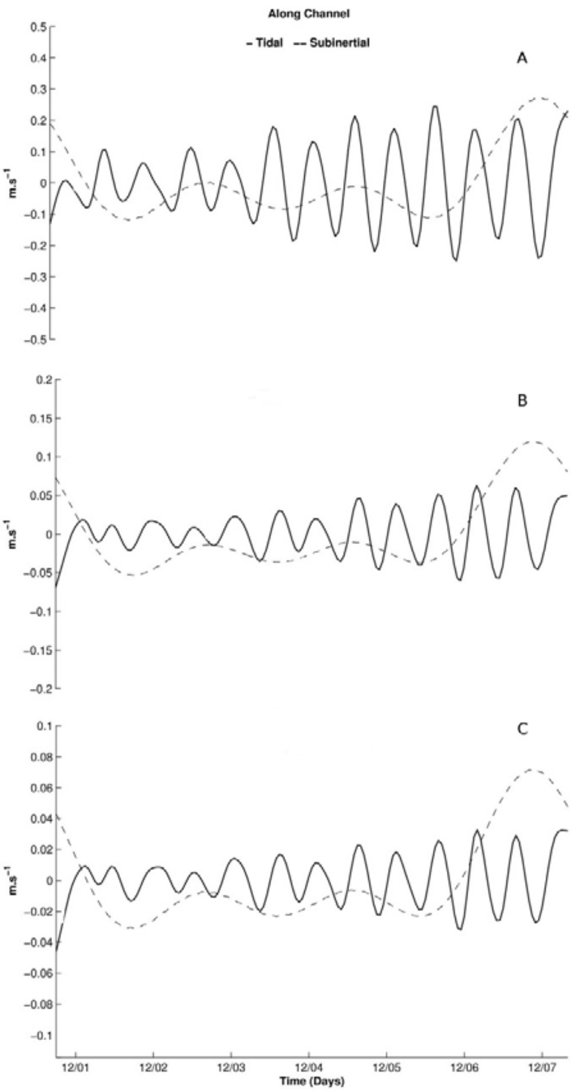

Figure 6. Tidal and subinertial along channel currents for surface (a), middle (b) and bottom (c) water column.

Conclusions

The procedure presented here on processing dual frequency bathymetric data seeking to map and estimate fluid mud layers was considered satisfactory; due to great correlations values obtained through quality control made on measured depth values and interpolated surfaces.

As regards to mud layers, it is possible conclude that fluid mud layers thickness decreases from Turning Basin toward estuarine inlet, following an expected pattern governed by jetties. Waters coming from upstream slow down at Turning Basin due to an increase on channel cross section allowing a greater sedimentation; then at Inner and Outer Channel they are confined by jetties increasing the flow and hence bottom shear stress, being deposited cohesive sediments “jetted” toward continental shelf where mud layers back to grow.

However, it is important to mention that at Itajai-Açu river port area, navigation channel’s depth is frequently maintained by a dredging method known as WID, acronym of Water Injection Dredging, where water is injected on fluid mud layers during ebb periods, putting sediments in suspension, which are then advected out of the system by tidal and density currents. Therefore, the previously mentioned deposition pattern forced by jetties may be differently presented in other periods, due to utilization of dredging method aforementioned.

Know currents pattern on estuarine ports subjected to fluid mud formation is of fundamental importance once they are responsible for transportation, dispersion and deposition of cohesive sediments on these environments. A combination of tidal forces, discharge and astronomical tides govern currents intensities at estuaries. When currents are strong, fluid mud deposits are eroded, otherwise if they are weak and not enough capable to erode fluid mud layers, siltation starts to occurs on waterway and navigation channel, compromising a safe navigation, if the concept of safe navigation is based on 200 kHz echo-soundings. During low currents period siltation occurs and then, a dredging is required. If the concept of “Nautical Bottom” is adopted, using as reference correlation between 33 kHz and 1200 kg.m^3, navigate with ship’s keel through or just above fluid mud allow a decrease on dredging operations, followed by a reducing on environmental degradation and a large financial economy on these activities demand.

However, before adopt the nautical depth concept to improve port activities several parameters must be taken into account, among which can be cited as current measurements, salt intrusion that influences on cohesive sediments particles aggregation and concentration, dual frequency bathymetry and densitometry surveys, all measured in a systematic and continuous way.

As ships were not made to navigate through or just above mud layers, manoeuvering simulations in mathematical and physical models must be done for several ship types in a joint way with local Pilots, to ensure that is possible to realize these manoeuvres in practice. Another important parameter to be considered is vessel’s refrigeration system, which uses water from external environment. The use of water with high concentration of sediments in suspension for a long period may cause damage in this system.

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