Abstract

Sedimentation in a harbour basin can lead to its obstruction and its closure. Maintenance costs to reduce sedimentation are high, since it requires much regular dredging. Therefore, during the design of port basin, sedimentation is a factor that should be taken into account, implementing mitigation measures can reduce settling at the basin’s entrance and in the inner part.

The purpose of this thesis is studying the salinity effect on the settling velocity of the sediments and verifying whether should be considered as an important factor in the mitigation’s measures. Due to most of harbour basins be located in estuaries, a significant salinity gradient is generated, inducing densities, water flows and water characteristic differences.

This work begins by introducing the sediment behaviour in estuaries, explaining the reasons of deposition, describing their characteristics and how they are strongly influenced by the liquid-based conditions. Then it provides an analysis of the effects salinity on a case study, Marina do Parque das Nações. A description of the problems affecting the basin and the decisions applied to solve them are also displayed. In the end, laboratory analysis, results and conclusions on how the salinity effects the settling of velocity are presented.

Keywords: Siltation, salinity effect, flocculation, estuary.

Introduction

Most of sediments transported in estuaries has small dimensions and is in the form of suspension. The salinity effect study on settling velocity is relevant to a better understanding of its behaviour in an estuary. When flow velocity is reduced, causes siltation and periodically salinity variation. Siltation is a concern at a basin design phase, as it may conduct to harbour obstruction, which results in high maintenance costs.

The study was developed using a sample of fine sediments taken from a location near Marina do Parque das Nações, where problems due to siltation have been previously identified.

Siltation

Estuaries act as a sort of filter for sediment input to the oceans, and chemical reactions in estuarine waters can alter the character of some mineral particles, especially clays. As in
Estuaries consist of one more channels and intertidal flats, which are alternately covered and uncovered by the rise and fall of the tides, there is a progression in grain size from mud-dominated sediments at the high tide level to sand-dominated sediments at the low tide level. Intertidal flats typically have very low gradients.

The high tidal flats are mud flats submerged only at high tide when current speeds fall close to zero and are generally reached by waves of only low amplitude. Little bedload transport occurs, but during periods of slack water at the turn of the tide, muds settle out of suspension onto the mud flats. The transport of fine-grained silts, clays over the high tidal flats, and their subsequent deposition is encouraged by settling lag. As the flood tide inundates the tidal flats and the current begins to slacken, these smallest particles begin to settle from suspension. However, they do not settle vertically through the water, but are carried into shallower water by the slowly moving current as they sink, eventually to be deposited some distance shoreward of where they began to settle.

Muds are cohesive sediments which, once deposited, are difficult to erode. On tidal flats, therefore, the flow of water required to erode fine sediment on the outgoing tide is greater than that at which it can be deposited on the incoming tide. So, suspended sediment will not be moved back downstream as far as it has been moved upstream. (Brown et al., 1989).

**Sedimentation in ports**

The processes that involve sedimentation in ports could be due to tidal filling and emptying, as the density gradient caused by salinity variation, that forms density-driven flows, and also due to vortices formed in the port entrance, causing horizontal circulation. The port geometry, dimension and orientation may perform an important role in these processes. (Deltares, 2000).

It is common to describe the siltation rate $F$ in a harbor basin with a very simple formula:

$$ F_s = p \times c_a \times Q. $$

$p$ is trapping efficiency and $c_a$ is ambient sediment concentration outside the harbor basin. The rate of exchange of water $Q$ between a harbor basin and its environment may be governed by the exchange flow by horizontal entrainment, by tidal filling, by fresh and salt driven density currents, by warm and cold driven currents, and by sediment-induced density currents, $Q$. (Winterwerp, 2005).

**Fine sediment properties**

Fine sediments result from the mixture of clays and silts, from the diverse nature organic matter, salt or brackish water and, in some cases, the coarse sediment as fine sand.
Regarding the grain size of the sediments, these are divided into two groups. The particles with a diameter exceeding 63 μm are the coarse sediments, and below these, they are the fine sediments. The latter include coarse silt (20 to 63μm), silts medium (6 to 20μm), fine silt (2-6μm) and clay (<2μm). Most of these sediments are referred as cohesive because they are small particles which have a specific area large enough so that the effect of physical-chemical forces between them is as important as the effect of the gravitational force (Costa, 1995).

Cohesive sediment can be considered to exist in four states that may be described as a mobile suspended sediment, a high concentration near bed layer which is sometimes referred to as fluid mud, a newly deposited or partially consolidated bed and settled or consolidated bed.

The main difference between these fine sediment and coarse sediment is the aggregation capacity of the first one, which may produce bigger particles, nominated flocs (Whitehouse et al., 2000).

Flocculation causes

The flocculation of sediment particles arises as a direct consequence of particles sticking together as they are brought into contact with each other. Collision and cohesion are therefore the essential processes of flocculation. (Mehta, 1984)

- Collision

Collision of particles are the result of one of three mechanisms, namely, Brownian motion of the suspended particles, internal shear of the water, and differential settling velocities of the particles or flocs.

Brownian motion forms ragged structure aggregates that are week and easily crushed in a deposit. The aggregates formed by velocity gradients tend to became spherical and are stronger than those formed by other mechanisms of collisions. Differential settling mechanisms contribute to the quick clarification of water during near-slick periods in mixing zones, where the concentration is elevated. (van Leussen e Dronkers, 1988).

- Cohesion

Cohesion is governed by the electrostatic forces, which action is strong and for short distances, but falls inversely with the seventh power of distance for spheres and inversely with the square or cube of the distance for parallel plates. Particles will cohere if these short-range forces dominate over the repulsive forces generated by the clouds of cations around particles. The strength of the repulsive forces depends on the range of the mineral surface charge, which is determined by mineral composition, and by the amount and types of cations in the suspending fluid (Whitehouse et al., 2000).

The three aggregation mechanisms are biofloculation, which is organic aggregates formation; pelletization, due to filter-feeders, such as copepods and mussels, that transform suspended...
matter into pellets, whose settling velocities are many times larger than those of the constituent particles; and finally salt flocculation.

Salt flocculation is governed by physique-chemical processes. Two particles have repulsive forces from each other due to clouds of positive cations surrounding the negatively charged they have. However, they will attract each other because of the Van der Waals forces. Additionally an increase of positive ions concentrations in the water result in a compression of positive ions cloud, around sediment particles, and thus in a stronger decrease of the repulsive forces and ultimately a coagulation of colliding particles. According to Einstein and Krone, with a salinity content of more than 1‰, coagulation may persist due to collisions between fine sediment particles (van Leussen e Dronkers, 1988).

Case Study

The Marina Parque of Nações has been redesigned since then its main problems are currently solved the main problems.

It presented problems due to agitation, currents and sediment deposition. Initially it had more on sediments deposition, since it was intended to minimally maintain the current speed, to avoid a large increase in the filling rate, which was already significant locally. However, the currents remained too high within the harbor basin, and it was forced to opt for closing basin with conventional breakwaters sloping rock-fill.

That solution resulted in the increasing of siltation, conduct to marina’s obstruction in short time.

To become again operational, it was decided to close the entire perimeter. The entry consists of two gates, enclosing overnight, opening only when the tide level is the same as the basin and during periods of greatest potential unrest (winter) with large amounts of suspended sediment.

Even though it has been a very expensive solution, this became less expensive compared to what it would have been in maintaining the long-term basin. It would have been necessary to carry out dredging once a quarter while the basin kept in continuous contact with the estuary.

This fact denotes the importance that the fine sediment behaviour has in the project of a harbour basin. Due to salinity degree, the analysis of sediments deposition behaviour will be crucial in a case study like these since it is a factor contributing for deterioration or reduction of sedimentation in fine sediments.

Sample analyses

It was collected a sample near from Marina of Parque das Nações to study the sediments deposition behaviour due to salinity degree.
Before it starts, it was made prior sample sifting, keeping sediment up to 63µm in size, extracting also algae and leaves. Then, it was calculated the sample concentration: 113,3 g/l. For better information, it was also made a mineralogical, grain size and organic matter analysis.

- Mineralogical analysis

The mineralogical analysis used two samples of treated sediments, to execute qualitative and quantitative analyses by X-ray diffractometry of the Materials Department of LNEC. In the first was the global sample, containing all the sediments up to 63µm in size; the second, referred as fine fraction displays only the sediments below 2µm. Table 1 and table 2 present the semi quantitative mineralogical composition of both samples (Silva, 2011).

Table 1: quantitative mineralogical composition (%) of the global sample (Silva, 2011).

<table>
<thead>
<tr>
<th>Crystalline compounds identified</th>
<th>Fraction &lt;63µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>41</td>
</tr>
<tr>
<td>Feldspar</td>
<td>4</td>
</tr>
<tr>
<td>Calcite</td>
<td>4</td>
</tr>
<tr>
<td>Philosilicate</td>
<td>51</td>
</tr>
</tbody>
</table>

Table 2: quantitative mineralogical composition (%) of the fine fraction (Silva, 2011).

<table>
<thead>
<tr>
<th>Crystalline compounds identified</th>
<th>Fraction &lt;2µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>24</td>
</tr>
<tr>
<td>Feldspar</td>
<td>9</td>
</tr>
<tr>
<td>Calcite</td>
<td>5</td>
</tr>
<tr>
<td>Kaolinitite</td>
<td>17</td>
</tr>
<tr>
<td>Chlorite</td>
<td>5</td>
</tr>
<tr>
<td>Mica</td>
<td>24</td>
</tr>
<tr>
<td>Smectite</td>
<td>17</td>
</tr>
</tbody>
</table>

- Grain size analysis

For the grain size analysis a laser sediment diffraction was used from the experimental station of cohesive sediments of Núcleo de Estuários e Zonas Costeiras of LNEC. It was used a particles analyser by laser diffraction, Mastersizer Micro. It was considered as average median diameter 9,07 µm.

- Organic matter analyse

As the sample displayed a significant content organic matter (about 11%), the organic matter analysis employ the loss on ignition method. This method presents a limitation that may lead to overestimation of results, since it also considers water from the clay minerals. 

Salinity effect on settling
To study the sediments deposition behaviour according to salinity degree, it was used a settling column, which allows analysing the concentration of aggregates in the liquid sample along time and throughout depth.

To study the silting, five trials were made considering different salinity values: 0‰, 5‰, 10‰, 15‰ and 30‰. Each trial lasts 306 minutes.

Chart 1 shows the fine sediments average concentration evolution over time of the different trials.

![Chart 1: fine sediments average concentration evolution at different salinity levels.](image)

The chart 1 shows that the average concentration reduces more quickly with a higher salinity level, i.e., the higher the salinity on the liquid is related with the larger the settling.

- **Settling velocities**

In order to explain better the reasons about this settling behavior, laboratory settling velocities were compared with other estimated through Stokes’law.

Moreover, by using differential equation of mass conservation, laboratory settling velocities were calculated following equation 2.

\[
\frac{\partial c}{\partial t} + \frac{\partial (W_s c)}{\partial x} = 0, 
\]  

(2)

in which \( c \) (kg m\(^{-3}\)) is the suspension sediments concentration, \( t \) (s) is the time, \( W_s \) (m s\(^{-1}\)) is settling velocity and \( z \) (m) is vertical orientation (Portela, 2013).

Estimated deposition rate is determined using equation 3.
in which \( h \) is column height and \( A \) is the bottom column area and, by Krone equation, when there is no flow velocity, it can also be defined

\[
D = W_s \times C.
\]

Thus, laboratory settling velocity is defined by equation 5,

\[
W_s = \frac{(c^n - c^{n+1}) \times h}{\Delta t \times c^n}.
\]  

(5)

Chart 2 shows settling velocities of the laboratory experiment.

![Settling velocities](image)

**Chart 2: settling velocities variation through time.**

Final time intervals don’t have relevant velocity values, since sediments are already deposited.

Due to Stokes'law it is possible to calculate settling velocity by using equation 6.

\[
w_s = \frac{g \times D^2}{18 \times \nu} \times \frac{\gamma_s - \gamma}{\gamma}.
\]

in which \( D \) is the particle diameter, \( \gamma \) is the fluid specific weight, \( \nu \) is the kinematic viscosity and \( g \) is the gravity (Quintela, 1985). The diameter used to estimate velocities is the average median diameter obtained at grain size analysis.

Table 3 shows data of comparing both velocities and \( W_{s\text{Laboratorial}} \) are average velocities. At table 3 data, settling velocities following Stokes'law decrease with salinity. This happens because salinity causes a rise of the water density, thus particles fall down more slowly. As it's not considering chemical effects, these velocities are only estimating individual particles settling.
Table 3: velocities estimated following Stokes’law and estimated at the laboratory.

<table>
<thead>
<tr>
<th>Trial</th>
<th>$W_{Stokes}$ (mm/s)</th>
<th>$W_{Laboratory}$ (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0‰</td>
<td>0.079</td>
<td>0.113</td>
</tr>
<tr>
<td>5‰</td>
<td>0.076</td>
<td>0.187</td>
</tr>
<tr>
<td>10‰</td>
<td>0.073</td>
<td>0.259</td>
</tr>
<tr>
<td>15‰</td>
<td>0.069</td>
<td>0.274</td>
</tr>
<tr>
<td>30‰</td>
<td>0.068</td>
<td>0.296</td>
</tr>
</tbody>
</table>

Nevertheless, as demonstrated sample with high amount of clay and organic matter, provides cohesive properties that cause flocculation. Then, as flocs have higher weight than individual particles, the settling velocity increases.

The settling column analysis allowed the confirmation that salinity can have a great impact to settling particles.

Conclusions

Fine sediments mainly prevail in estuaries, transported across the river, currents and tidal that, due to the low current and high concentration of particles deposit on the shore, at the highest levels thereof.

In the case of harbor basins, for the same reasons, there is also a high sediment deposition, associated primarily with tidal currents and density. In these cases it is necessary to take into account the siltation problem in the basin scale, although, currently there are available several mitigation solutions to overcome these problems.

Fine sediments exhibit cohesive properties, presented in the clay minerals. They will promote flocculation of particles. Apart from other factors, the effect of salinity on flocculation is important, since the salty water has chemical features that will increase cohesion between particles due to attractive forces.

It was analyzed at laboratory a sample taken from Marina do Parque das Nações, and in that, it was found high percentage of clay minerals phyllosilicates.

The analysis at the column of sedimentation confirmed that increasing the salinity level in the liquid will increase the cohesive properties among the particles, enhancing flocculation, leading to a high rate of fall of the sediments.

Bibliography


