Deposition and erosion of fine sediments from the Port of Lisbon
Study in annular flume

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Abstract

The purpose of this work is to study the effect of flow velocity on the erosion and deposition of fine-grained sediments in suspensions with different salinity values. The study was performed in the annular flume available at LNEC. In the tests that were carried out, the effect of salinity on sediment deposition is not expressive, which may in part be explained by the importance of the turbulent stresses.

1. Introduction

The study of erosion and deposition of fine sediments in estuaries is essential for a better knowledge and forecasting of the behavior of the bed, becoming even more important in the event that the estuaries are navigable as is the Tagus estuary.

The existing sediments in estuaries are predominantly of silt-clay nature and may constitute very relevant problems in environmental and economic terms due to their ability to be transported and settle in harbour basins.

The Port of Lisbon is one of the main national and European ports, having excellent geographical and morphological conditions that make it a point of passage of world trade. However, due to fine sediment transport, a large annual investment in dredging is necessary to ensure good operational levels.

The objective of the proposed study is to analyze experimentally, in an annular flume, the effect of flow velocity and the effect of salinity on the processes of erosion, transport and deposition of a sample of sediment from the Tagus estuary. In particular, it aims to analyze the effect of salinity on the process of deposition of sediment in a situation when velocity is not zero.

2. Literature review

2.1. Sediment properties

The sediments found in most estuaries are cohesive, *i.e.* a mixture of fine sediment fractions (clays and silts), organic matter of a diverse nature, salt or brackish water and, in some cases, coarser sediments such as fine sands. Cohesive sediments display a specific area large enough to ensure that the effect of the physical-chemical forces between them is as important as the effect of gravity (Costa, 1995). That is, interparticle forces can dominate the behavior of sediment. In general, the finer the grain, the more cohesive the sediment.

Cohesive sediments may be in four states: suspension in the water column, high concentrations near the bed, partially consolidated or consolidated in the bed. One of the properties of cohesive particles in suspension is the ability to aggregate, producing larger flocs or aggregates. This phenomenon is called flocculation. Salinity is one of the factors that contribute to flocculation (Ramos, 2013).

2.2. Deposition

Mehta and Partheniades (1973) performed studies in a laboratory and concluded that the deposition of cohesive sediment in suspension depends on the bed shear stress, turbulence processes in the area near the bed, sedimentation velocity, type of sediment, depth of flow, suspended sediment concentration and ionic constitution of the fluid (Mehta and Partheniades,1973 *in* Huang et al., 2006). These sediments when suspended with a given initial concentration (C_0) and in motion for a certain velocity (high), will deposit for lower velocities at the rate C_f/C_0, where C_f is the residual concentration that corresponds to a given strength and independent of C_0 (Krone, 1962 in Costa, 1995):

$$C_f/C_0 = e^{-\frac{w_s\,p\,t}{h}} \tag{2.1}$$

with h - height of flow; w_s - sedimentation velocity; p - likelihood of deposition.

Part of the sediments deposited in the bed may not withstand the bed shear strength, suffering a process of disaggregation and becoming resuspended.

The probability of deposition is given by:

$$p = 1 - \frac{\tau}{\tau_{d,full}} \qquad \tau \leq \tau_{d,full} \tag{2.2}$$

Deposition occurs when the bed shear strength is lower than a certain critical shear stress of deposition. However, only the aggregates with sufficient shear stress to withstand the disturbing shear strength in the region of the bed will deposit and adhere to the bed (Huang et al., 2006).

When the bed shear stress (τ_d) is lower than the critical shear stress of total deposition ($\tau_{d,full}$), all the particles of sediment and flocs will deposit. Krone (1962) formulated the equation (2.3) that describes the deposition rate (D):

$$D = p\, w_s\, c \qquad \tau \leq \tau_{d,full} \tag{2.3}$$

The critical shear stress for the total deposition of cohesive sediments was found through various tests performed by Krone (1962). The values range between 0.06 and 1.1 N/m^2, depending on the type of sediment and concentration (Huang et al., 2006).

On the other hand, there is partial deposition when the bed shear stress is higher than the critical shear stress for total deposition, but lower than the critical shear stress for partial deposition ($\tau_{d,parcial}$).

In this range of bed shear stress, the strong flocs are deposited and the weak flocs remain in suspension or are resuspensed.

There is no deposition when the bed shear stress is higher than the critical shear stress for partial deposition. In this case, the deposition rate is equal to zero:

$$D = 0 \qquad \tau \geq \tau_{d,parcial} \tag{2.4}$$

However, given that the critical shear stresses of total and partial deposition are not well understood, they are frequently used as calibration parameters for determining the deposition rate (Huang et al., 2006).

For non uniform sediments (sediments of various sizes and consequently different sedimentation velocities) the deposition depends on the bed shear stress and the initial properties of each class of sediment.

The deposition rate is calculated as the result of the sum of the deposition fluxes of all classes (Mehta et al., 1989 *in* Costa, 1995):

$$D = \sum_{i=1}^{n} p_i\, w_{s_i}\, c_i \tag{2.5}$$

where p_i is the probability of deposition of class i, w_{s_i} the sedimentation velocity of class i and c_i the concentration of sediments in suspension of class i.

Complete deposition occurs when the bed shear stress is lower than the critical shear stress for total deposition ($\tau_{d,full}$).

In previous studies in a settling column (Ramos, 2013), a strong influence of salinity on the sedimentation velocity was observed. Thus, it was considered interesting to analyze in the present study if this effect of salinity has repercussions in the deposition of sediment in a situation where flow velocities are not zero, as would be expected, in particular, of equation (2.3).

3. Methodology

The sediment was collected in the Parque das Nações Marina, in the waiting quay area, in the outer basin, at the time of low tide. The sample weighed about 3 kg. After collection, the sediment was transported to the laboratory of the Estuaries and Coastal Zones Division of LNEC.

In the preparation of the suspension, the sediment was previously passed through a 1 mm sieve in order to remove the coarser material.

3.1. Description of the channel

The channel where this experience was performed is called an annular flume. It has 4 m of external diameter and 3.4 m internal diameter, a section 0,30 m wide and 0,40 m high, its net volume being equal to 1395 dm^3. The circular form allows it to avoid the singularities of flow entry and exit of rectangular channels, being suitable for the study of the processes of fine sediment transport. The channel is composed of a base-channel of transparent walls and an upper ring that contacts the fluid.

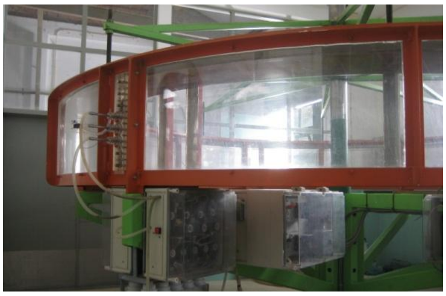

Figure 1 – Annular flume of LNEC

In this study, tests were carried out while maintaining the basis immobile, the flow being set in motion just by the rotation of the upper ring. This means that a relation between the angular velocities of the ring (w_t) and the basis (w_b) to minimize secondary circulations has not been adopted. The angular velocity to impose on the upper ring to obtain a particular average flow velocity referred to the base of the channel ($u_{av,b}$) was estimated by the analytical expression (Portela and Brito, 2010):

$$u_{av,b} = \left(w_t \frac{r}{1+\sqrt{\frac{b+2h}{b}}} + w_b \frac{r\sqrt{\frac{b+2h}{b}}}{1+\sqrt{\frac{b+2h}{b}}} \right) - w_b r \quad (3.1)$$

in which r is the average radius of the channel and b and h are, respectively, the width and height of the section of the channel.

3.2. Description of tests

Tidal and deposition tests were carried out. Five tests of each type, each with different values of salinity in order to analyze its influence on the processes under study.

The tidal tests are intended to analyze the processes of erosion, transport and deposition. In these tests the flow velocity is variable and seeks to represent part of the tidal cycle, composed of maximum velocities in the beginning (half flood or half ebb tide), decreasing until zero (high tide or low tide) and increasing until a new maximum velocity at the end (half flood or half ebb tide). The duration of these tests is 6 hours and 30 minutes, half of a normal tidal cycle.

The deposition tests are specifically aimed at the study of the process of deposition. These tests are performed starting with a sudden reduction of the initial velocity, which is followed by a period of 8 hours of low and constant flow velocity so as to favor the deposition of sediment.

The purpose of the tests is to analyze the evolution of the concentration and granulometry of sediments in suspension over time.

The tests involved the collection of samples in duplicate, 150 ml to determine the concentration and 200 ml for analysis of the grain-size by laser diffraction. Together with each collection the velocity of the upper ring of the channel was changed and the level of water was reset after sample collection.

In the tidal tests the collection of samples and the change of velocity of the upper ring of the channel were performed at half-hourly intervals.

In each period of zero velocity, the salinity and water temperature were always measured using the YSI Multi-Probe System 556 MPS (Multi-Probe System).

3.2.1. Variation of salinity

Five sets of tests were carried out whose single variant was the salinity of the water. The objective was to assess the effect of salinity on the deposition of sediments. The first test was done with salinity approximately equal to zero, i.e. without the addition of salt to the suspension.

In the following tests, sea salt was added, so as to obtain salinity equal to 2.5‰, 5 ‰, 10 ‰ and 15‰.

3.2.2. Analysis of the concentration

The determination of suspended sediment concentration involves collecting samples, the measurement of volume, filtering, drying in an oven and weighing the filters with the sediment.

The concentration of each sample is obtained by dividing the weight of the sediment by the volume of the sample solution.

3.2.3. Granulometry analysis

For the grain-size analysis of the cohesive sediments by laser diffraction, a Malvern Mastersizer Micro diffractometer was used.

The solution used in the analysis is constituted by the sample and a dispersant. The dispersant used is distilled water due to it not dissolving nor changing the granulometric characteristics of the material to be analyzed. The concentration of the solution must be such that the diffractometer measures an appropriate value for the obscuration of the optical beam (between 10 and 15%).

4. Presentation and discussion of results

4.1. Concentration and velocity as a function of time

4.1.1. Tidal tests

The results for the five tidal tests are presented (Figure 2).

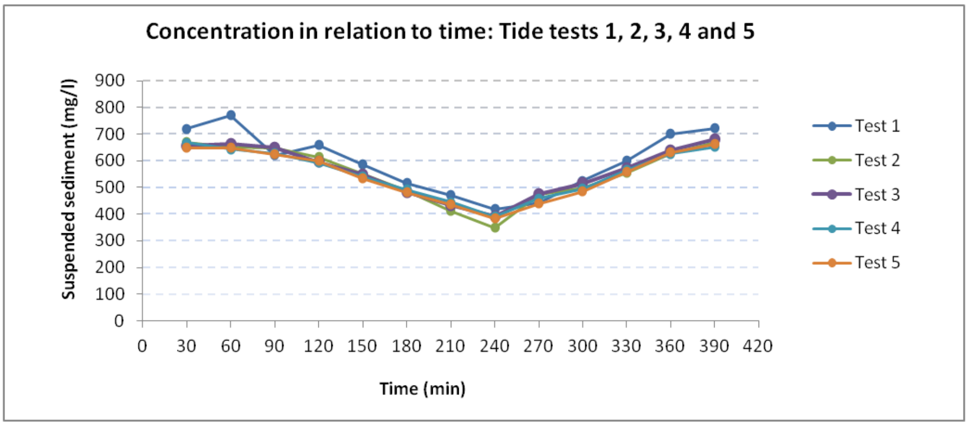

Figure 2 - Concentration in relation to time for tidal tests 1, 2, 3, 4 and 5

The results of the five tests show a similar pattern, with the minimum concentrations occurring in the same moment of time (at the end of 4 hours), with a time lag in relation to the period of zero velocities (situated between 3 and 3.5 hours). This behavior is physically explained by the fact that the deposition of fine sediments is a slow process, and coincides with what has been obtained in other tests (Portela and Brito, 2010).

The percentage of sediment that remains continuously in suspension is above 50% in the 5 tests. The low sedimentation velocities and the short period of time in which the velocity of the flow is low and/or zero are two plausible reasons for this to happen.

As for a possible salinity effect, such effect is not observable.

4.1.2. Deposition tests

The results obtained for the five deposition tests are presented (Figure 3).

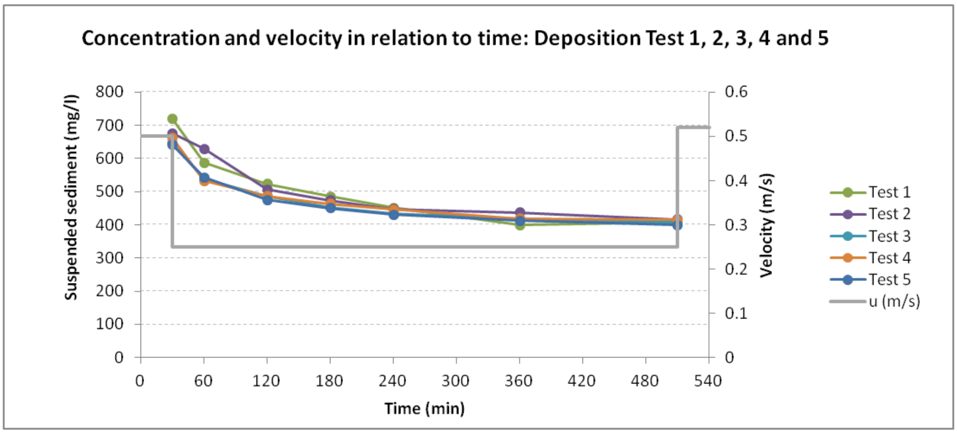

Figure 3 - Concentration and velocity in relation to time for deposition tests 1, 2, 3, 4 and 5

As with the tidal tests, the results of the five deposition tests can also be considered consistent, although the initial results of the first test are higher than the remaining tests and the second test results have some dispersion.

The deposition show a very similar pattern throughout the five tests, with concentrations at the end of 8 hours practically coincident. The range of variation between the five tests is less than 5% of the average value.

The percentage of sediment that remains in continuous suspension is around 60% and the salinity effect, even in the first few hours, is not expressive.

4.2. Granulometry and velocity in relation to time

Results were collected in regard to the D10, D50 and D90 diameter for each of the 5 tests, for both the tidal conditions as well as the deposition conditions. D10, D50 and D90 correspond to 10%, 50% and 90% of the distribution of the sample particles with a lower diameter.

4.2.1. Tidal tests

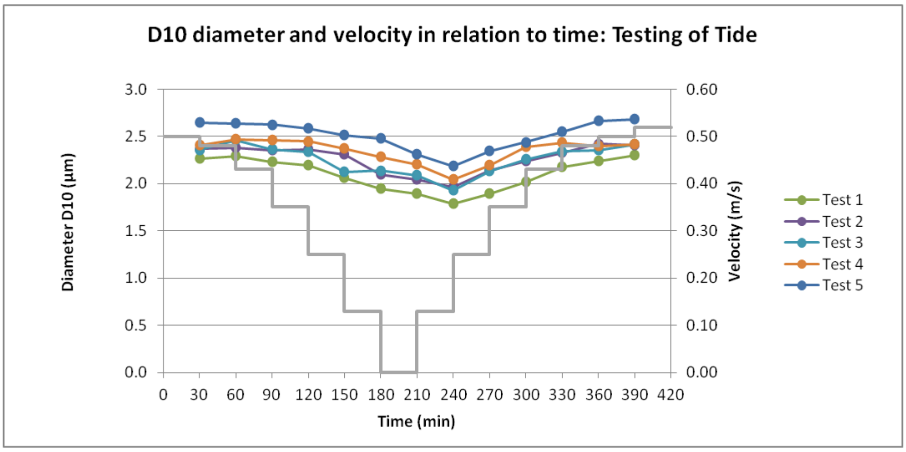

Figure 4 - D10 Diameter and velocity in relation to time: Tidal tests

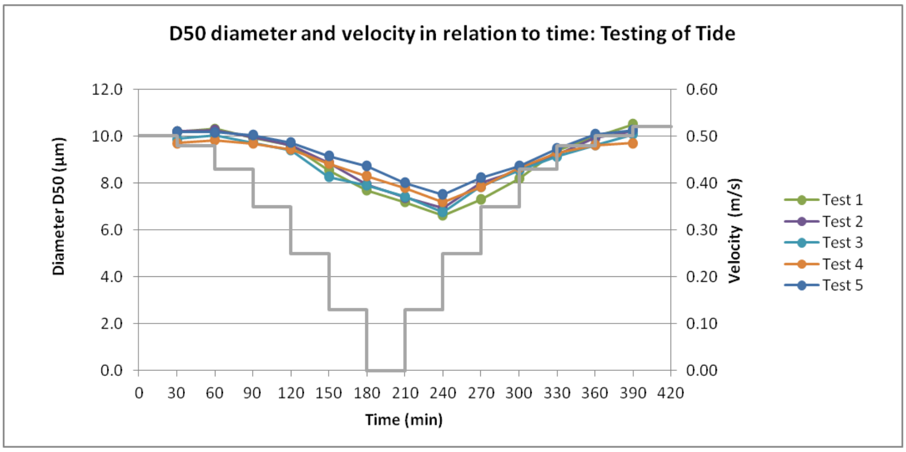

Figure 5 - D50 Diameter and velocity in relation to time: Tidal tests

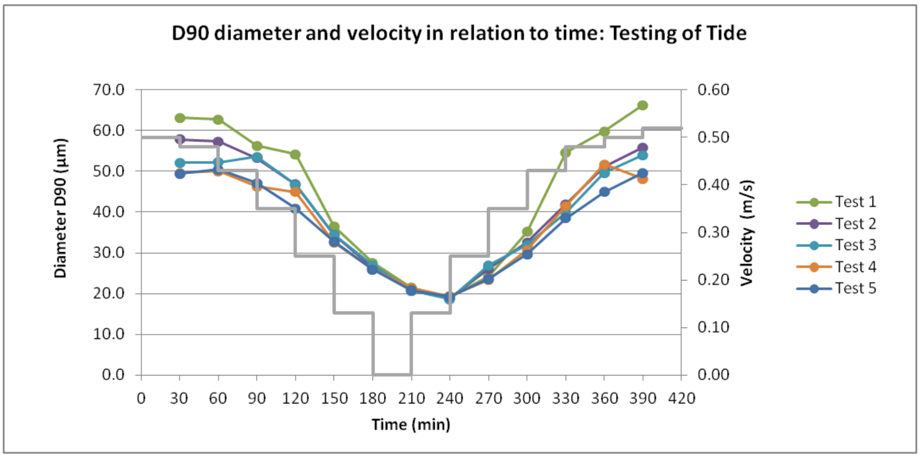

Figure 6 - D90 Diameter and velocity in relation to time: Tidal tests

As is seen in Figures 4 to 6, the results of the 5 tidal tests are very similar amongst them. As can be observed, the D10, D50 and D90 diameters decrease with decreasing speeds and increase for increasing speeds. As one would expect, the larger particles are probably the first to be deposited.

4.2.2. Deposition tests

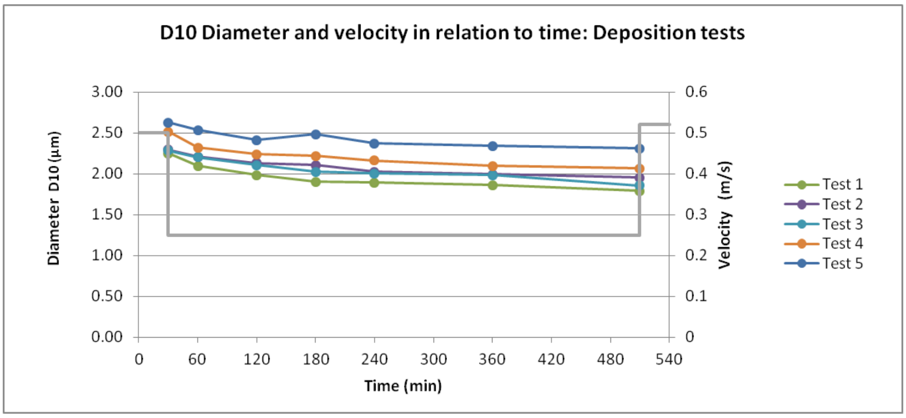

Figure 7 - D10 Diameter and velocity in relation to time: Deposition tests

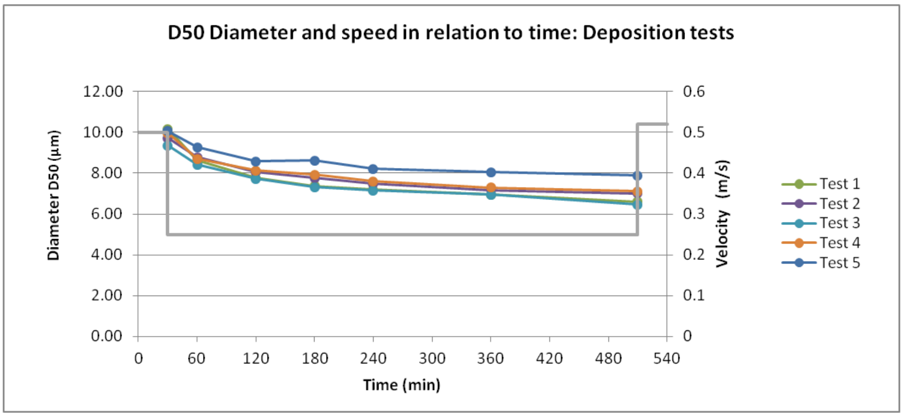

Figure 8 - D50 Diameter and velocity in relation to time: Deposition tests

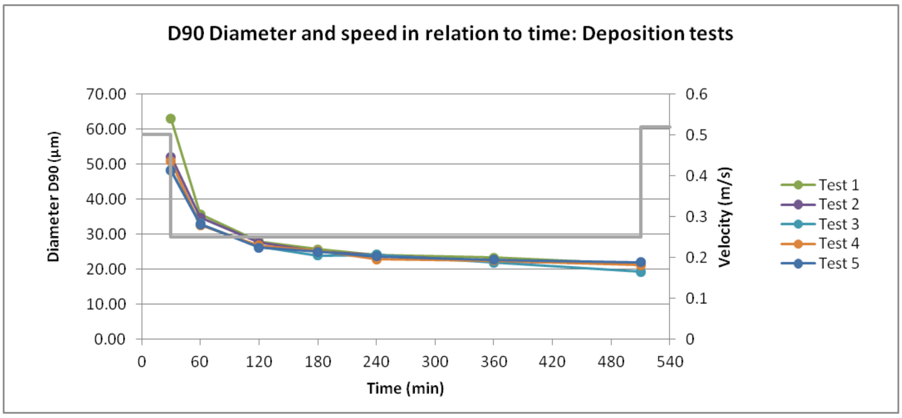

Figure 9 - D90 Diameter and velocity in relation to time: Deposition tests

It is noted that in the case of D10 the values increase with the salinity. This effect is due to the influence of salinity on the aggregation of finer particles. In the case of D50, the values also increase with salinity, but in a less pronounced way. In the case of D90, the influence of salinity was not observed (Figure 7 to 9).

5. Conclusions

The ability to predict the movement of fine sediments in estuaries is crucial to minimizing economic and environmental impacts. In the case of the Port of Lisbon, frequent dredging is required due to the deposition of fine sediments.

Laboratory flume tests can provide a useful contribution to the understanding of the processes of fine sediment transport. However, the processes that involve fine sediments are of complex and difficult analysis.

This experimental study in annular flume investigated the relation of erosion and deposition of fine sediments with the temporal evolution of velocity. It was verified that the deposition rate is greater when the flow velocity is low and/or zero (Portela and Brito, 2010).

The tests conducted also have the aim to analyze the effect of salinity on the deposition of fine sediments. The results referring to this point were inconclusive, as opposed to those observed in still water (Ramos, 2013), which may in part be explained by the importance of the turbulent stresses, that cause disaggregation of flocs and remove effectiveness to deposition (van Rijn, 1993).

As a recommendation for the continuation of the study, it is considered that, in order to better clarify the effect of salinity on the deposition of fine sediments, it would be interesting to investigate what would happen by repeating the deposition tests, but applying instead a velocity lower than 0,25 m/s, since it would be an intermediate situation between the one that was tested in this study and the situation in still water

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