Effect of salinity on the settling velocity of fine sediments of a harbour basin

Luís Ivens Portela†, Susana Ramos‡, António Trigo Teixeira‡

†National Laboratory of Civil Engineering, LNEC, Av. do Brasil 101, 1700-066 Lisboa, Portugal
lportela@lnec.pt

‡Dept. of Civil Engineering and Architecture, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
susana.c.ramos@ist.utl.pt
trigo.teixeira@civil.ist.utl.pt

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Portela, L.I., Ramos, S. and Trigo-Teixeira, A., 2013. Effect of salinity on the settling velocity of fine sediments of a harbour basin. *In:* Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. 1188-1193, ISSN 0749-0208.

Salinity is known to increase the cohesion of clay minerals, and thus the flocculation of fine-grained sediments in suspension. However, the influence of salinity on the settling velocity of natural particles is often unclear, due to organic and biological aggregation and other controlling factors. This paper examines the effect of salinity on the settling velocity of fine sediments collected in a harbour basin in the Tagus estuary. The sediment sample consists of silt- and clay-sized particles (D_{10} = 2 μm; D_{50} = 9 μm; D_{90} = 37 μm). Quartz is the main constituent and illite the main clay mineral. The experiments were conducted in a 2.25-m high settling column, for a constant initial concentration of fine sediment (1.5 g l^{-1}) and different salinity values (0, 5, 10, 15 and 30). During each experiment, samples were collected at 10 vertical levels and at 10 time instants. Settling velocities were calculated on the basis of the time-evolution of suspended sediment concentrations. At the start of the experiments, after cessation of turbulence, settling velocities increased in direct relation with the increase in salinity, the maximum values ranging between 0.3 mm s^{-1} under freshwater conditions and 0.9 mm s^{-1} for a salinity of 30. After 5 hours, the proportion of the initial sediment remaining in suspension was 45% under freshwater conditions and only about 10% for salinities between 10 and 30. Using the mass-weighted mean settling velocity to describe the deposition fluxes, it is concluded that settling increases by a factor of 6.5 between freshwater and marine conditions.

ADDITIONAL INDEX WORDS: *Cohesive sediment, harbour siltation, settling column.*

INTRODUCTION

Fine-grained sediments commonly found in many estuaries are mixtures of fine sediment fractions (in the clay and silt grain size ranges, i.e. finer than 63 μm) and organic matter of diverse nature (Costa, 1995; Whitehouse *et al.*, 2000).

Fine-grained sediments in suspension are subject to flocculation. Therefore, settling velocities may not be directly related to grain size through Stokes' law (Berlamont *et al.*, 1993; Portela, 1997). Salinity is known to increase the cohesion of clay minerals, and thus flocculation, according to the double-layer theory (Maggi, 2005). However, in the estuarine environment, this mechanism is complicated by organic coatings on the particles and by organic and biological aggregation (Van Leussen, 1988). As a result, the influence of salinity on the settling velocity of natural particles is often unclear.

Several classic studies have examined the influence of salinity on the settling velocity (Migniot, 1968; Burt, 1986), but the topic is rarely addressed in the recent literature (Mietta *et al.*, 2009; Mikeš and Manning, 2010). In the past 20-30 years, many studies have focused instead on other controlling factors, such as suspended sediment concentration and turbulence (Shi and Zhou, 2004; Pejrup and Mikkelsen, 2010).

Due to the fragile nature of flocs (i.e. aggregates of discrete particles) it has been argued that their properties and settling velocities should be determined *in situ* (Whitehouse *et al.*, 2000; Mikkelsen *et al.*, 2004). Field studies have the advantage of minimizing changes in the size distribution of the flocculated sediment, but the natural variability of field conditions makes it difficult to study the regulating factors of settling velocity in a systematic manner. This can be better achieved through controlled laboratory experiments (Manning *et al.*, 2007).

The purpose of the present paper is to examine the effect of salinity on the settling velocity of fine sediments, through laboratory experiments. The sediments were collected from a marina basin in the Tagus estuary (Portugal).

STUDY AREA

With an area of about 320 km^2, the Tagus estuary is a large mesotidal system (Figure 1). In the middle-upper estuary, the maximum tidal range is 4.5 m, the mean spring range 3.3 m and the mean neap range 1.6 m. Due to the large tidal prism, the flow is driven mainly by the tide. Tidal currents in the middle-upper estuary reach 1 m s^{-1} during spring tides. The main source of freshwater is the Tagus river with a mean flow of 300 $m^3 s^{-1}$. Salinity at the location varies with the tide and the river flow, with typical values between 25 and 30. Fine-grained sediments are the dominant surface material in the intertidal areas of the upper estuary, where suspended sediment concentrations range between 50 and 250 mg l^{-1} (Portela, 1996).

DOI: 10.2112/SI65-201.1 received 07 December 2012; accepted 06 March 2013.

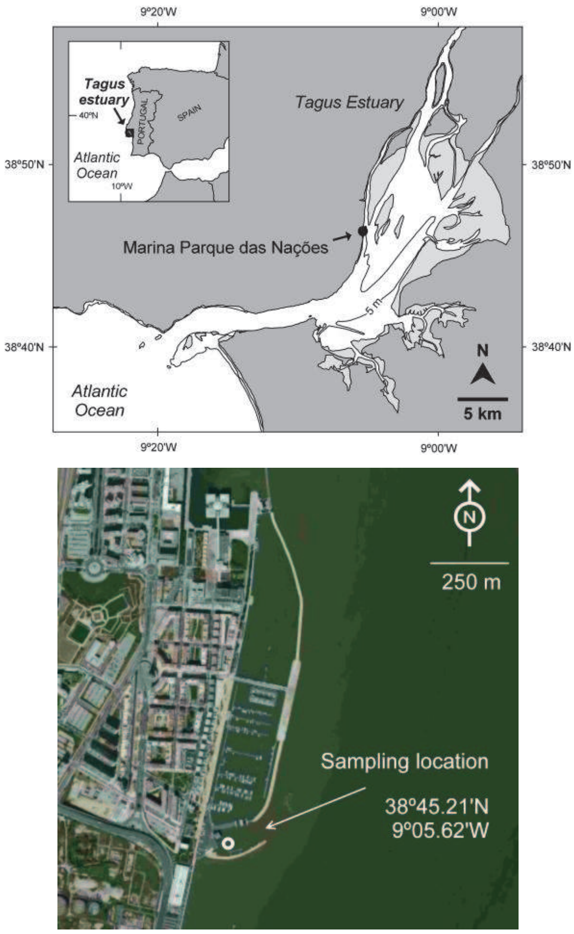

Figure 1. Top: Location map of Marina Parque das Nações in the Tagus estuary. Bottom: Sampling location (aerial photograph © 2012 Microsoft Corporation).

Sedimentation rates in dredged areas of the middle-upper estuary can reach values higher than 2.0 m yr^{-1}, depending on the dredging depth, which poses a problem to port infrastructure as it increases the expenditure in maintenance dredging.

In 1998, an international exhibition took place in the eastern part of Lisbon, EXPO´98. For that, a vast project of urban regeneration was done, including the construction of the Marina Parque das Nações. The marina was built alongshore in a place with high natural sedimentation rates. In the initial design, the basin was protected by floating breakwaters. Dredging was done in the summer 1997 to -2.0 m CD. The EXPO´98 opened six months later, in April 1998, and by that time maintenance dredging had to be performed since the basin had already lost the initial dredged depth. Sedimentation rates led to the closure of the marina to operation soon after, in 1999 (Figure 2).

The marina remained closed for a decade before a new design was produced to face the high sedimentation rates. The "new marina" is now a closed basin linked to the estuary by tidal gates. The gates are closed at night and whenever unfavourable conditions (e.g. storm) occur in the estuary. The idea is to keep to a minimum the period of time water can enter the basin. This also reduces the amount of fine-grained sediments settling in the marina. Recent experience with the new operation shows that sedimentation rates within the mooring basin were reduced by more than half (Ramos, 2013).

To have a greater insight on how salinity influences the settling velocity a sediment sample was collected in the marina and studied in the laboratory.

METHODS

Sediments

The sample was collected in the outer part of the marina, in the intertidal zone, on October 28 2010, at low tide. The sediment consists of silt- and clay-sized particles, with diameters D_{10}, D_{50} and D_{90} obtained by laser diffraction (Malvern Mastersizer Micro) of 2, 9 and 37 μm, respectively (Figure 3). The mineralogical composition examined by X-ray diffraction indicates that quartz is the main constituent and illite the main clay mineral, followed by kaolinite and smectite (Table 1). The organic content was estimated by loss on ignition at 11%.

Experimental Set-Up

The laboratory settling column available at LNEC (Figure 4) was used in this study. The settling column, with a height of 2.60 m and an internal diameter of 0.11 m, consists of an acrylic glass tube equipped with electro-valves placed at 10 different levels (0.05, 0.15, 0.30, 0.55, 0.80, 1.05, 1.30, 1.55, 1.80 and 2.05 m). Free rotation of the column around a fixed axis is provided, allowing the homogenization of the suspension at the beginning of each experiment. The column is supported by a rotating sample-container structure. Both the opening of the electro-valves and the rotation of the sample-container structure are operated by a programmable controller.

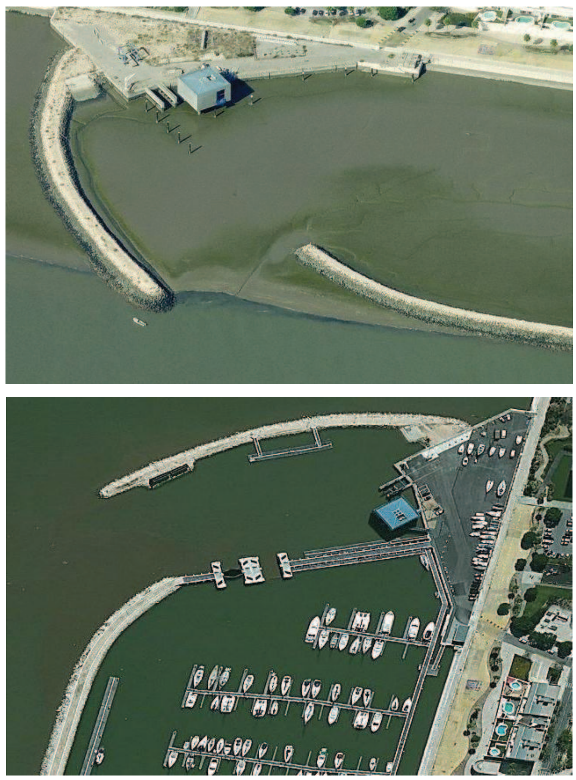

Figure 2. Top: View of the marina before rehabilitation. Bottom: View after rehabilitation (aerial photographs © 2012 Microsoft Corporation).

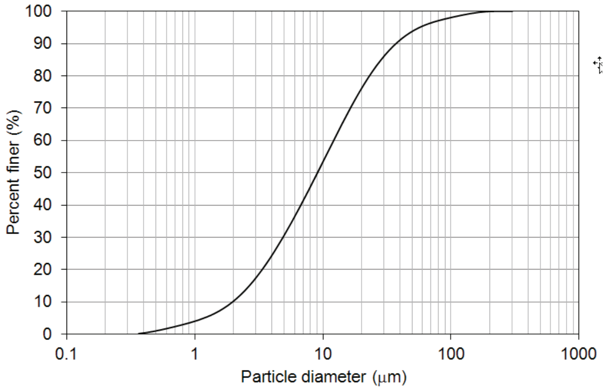

Figure 3. Grain-size distribution of the sediment sample.

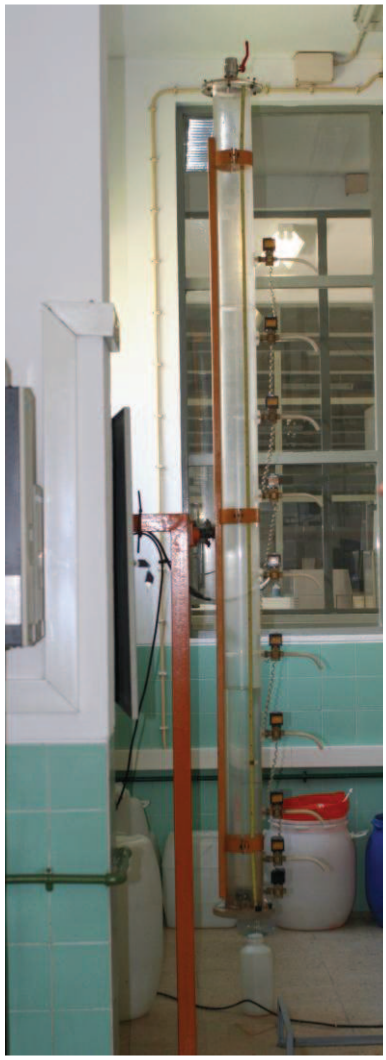

Figure 4. General view of the settling column.

The experiments were conducted for a constant initial concentration of fine sediment (1.5 g l^{-1}) and five different salinity values (0, 5, 10, 15 and 30), ranging from fresh to brackish-marine conditions, obtained using sea salt. The initial height of the water column was 2.25 m (volume of c. 21.4 l).

During each experiment, small water samples (c. 45 ±15 ml) were collected at all vertical levels simultaneously at 10 time instants (0, 1, 6, 16, 36, 66, 106, 156, 216 and 306 minutes).

Suspended sediment concentrations were determined by the gravimetric method. Samples were filtrated through pre-weighed cellulose nitrate membrane filters with 0.45 µm pore size, dried at 40°C and weighed in an analytical balance. The weight of the dry residue was divided by the original sample volume.

Settling velocities were calculated on the basis of the time-evolution of suspended sediment concentrations, according to the equation for mass conservation:

$$\frac{\partial C}{\partial t} + \frac{\partial (w_s C)}{\partial z} = 0 \quad (1)$$

where C is the concentration of suspended sediment, t is the time, w_s is the settling velocity and z is the vertical coordinate.

An approximate solution by finite differences is:

$$w_s^n = -\left(\frac{C^{n+1} - C^n}{\Delta t^n}\right)\frac{H^n}{C^n} \quad (2)$$

where w_s^n is the vertically averaged settling velocity at time n, C^{n+1} and C^n are the vertically averaged concentrations of suspended sediment at times n+1 and n, H^n is the height of the water column after sample collection at time n and Δt^n is the time interval between n+1 and n.

Table 1. Mineralogical composition of the sediment sample.

Fraction < 2 µm	(%)
% clay minerals	63
Chlorite	5
Illite	24
Kaolinite	17
Smectite	17
% non-clay minerals	37
Fraction < 63 µm	(%)
Quartz	41
Feldspar	4
Calcite	4
Phyllosilicates	51

RESULTS

Figure 5 shows the results obtained in each of the five experiments with different salinity values. Due to the reduction in water column height, samples from the higher levels (2.05 and 1.80 m) are only collected at the initial time points.

In all experiments, during the first 16 minutes, no substantial decrease in suspended sediment concentrations is observed. This is most likely caused by residual turbulence generated by the homogenization of the suspension, which takes time to dissipate and may prevent settling. The most significant decrease in concentrations occurs between minutes 16 and 36, regardless of the salinity value, after which the decrease is slower. In each experiment and at each time instant, the concentrations obtained at the different vertical levels show a relatively narrow range of variation (standard deviation σ_{n-1} = 0.08 g l^{-1}).

The same results are presented together in Figure 6, in vertically averaged form. It can be seen that settling increases in direct relation with the increase in salinity. After 5 hours, the proportion of the initial sediment remaining in suspension is 45% under freshwater conditions (S = 0) and only about 10% for salinities between 10 and 30.

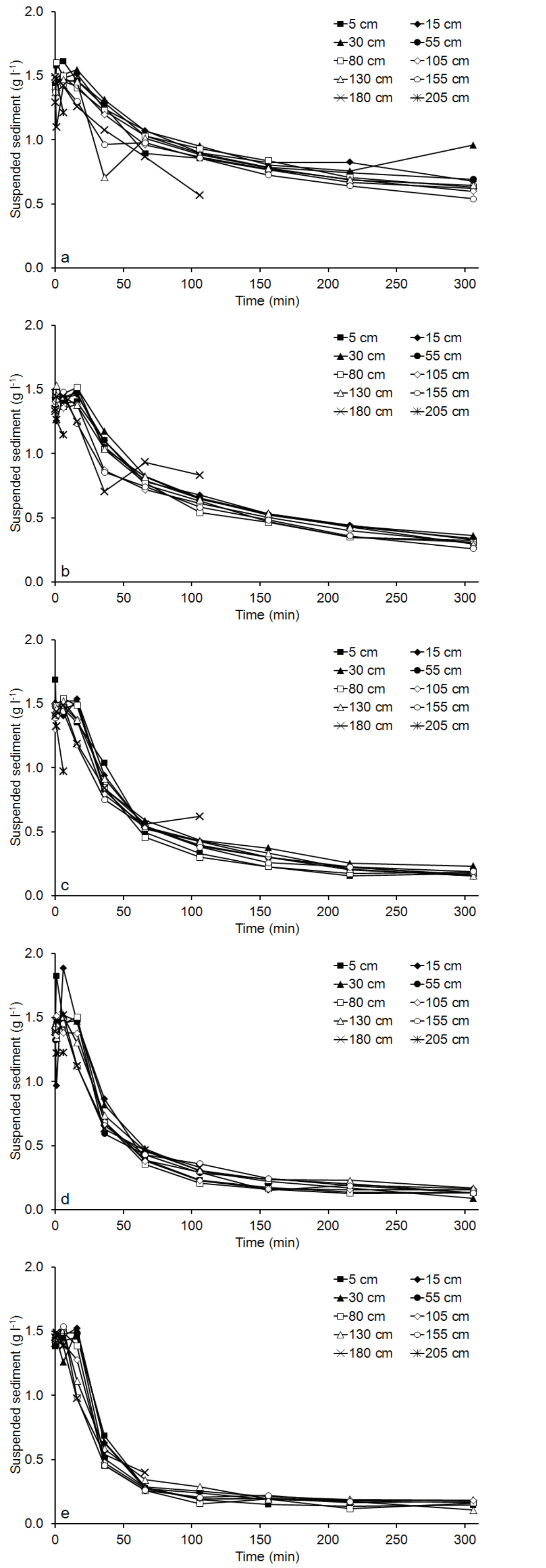

Figure 5. Evolution of suspended sediment concentration (g l^{-1}) at 10 levels in each experiment with different salinity values. **a** S = 0; **b** S = 5; **c** S = 10; **d** S = 15; **e** S = 30.

Figure 7 shows the settling velocities in each experiment and at each time interval, calculated with Eq. (2), using the results obtained between minutes 16 and 306. Settling velocities are presented as a function of suspended sediment concentration, but no cause-effect relationship is implied.

The calculated settling velocities reach maximum values in the first interval (minutes 16 to 36), ranging between 0.3 mm s^{-1} under freshwater conditions and 0.9 mm s^{-1} for a salinity of 30.

The percentage of the initial sediment remaining in suspension is shown as a function of the previously calculated settling velocities in Figure 8. Describing the range of settling velocities in each experiment by the median settling velocity, w_{s50}, leads to relatively large differences between experiments (0.03 mm s^{-1} for $S = 0$ and 0.69 mm s^{-1} for $S = 30$).

Figure 9 compares the median and the mass-weighted mean settling velocities, as a function of salinity. In the calculation of the mass-weighted mean, it is considered that the experiments start at minute 16, after cessation of turbulence, and the initial concentration is the concentration at that same time point. Because not all suspended material has settled at minute 306, minimum and maximum estimates of the mass-weighted mean settling velocity are obtained by assuming that the remaining mass in suspension consists, respectively, of unsettleable solids or solids with a settling velocity equal to the previous interval (minutes 206 to 306). With the mass-weighted mean settling velocity, it is found that settling increases by a factor of 6.5 between freshwater and brackish-marine conditions (0.10 mm s^{-1} for $S = 0$ and 0.65 mm s^{-1} for $S = 30$).

DISCUSSION

Laboratory research has shown a clear effect of salinity on the settling velocity of cohesive materials (Migniot, 1968). However, in more recent field research, it has been found that salinity has no observable effect on settling velocity (Burt, 1986). Thus, in the past 20-30 years, the role of salt flocculation has come into question (Van Leussen, 1999) and attention has been directed to other controlling factors of flocculation and settling velocity (e.g. suspended sediment concentration).

The results of the current study are consistent with previous laboratory research in suggesting that salinity is indeed a relevant factor. Significantly, changes in salinity above 2-3 had a non-negligible effect on the settling velocity (cf. Whitehouse *et al.*, 2000). Furthermore, the various correlations between settling velocities and suspended sediment concentrations did not suggest causality and could apparently be explained by the lack of uniformity of the suspension (i.e. size sorting).

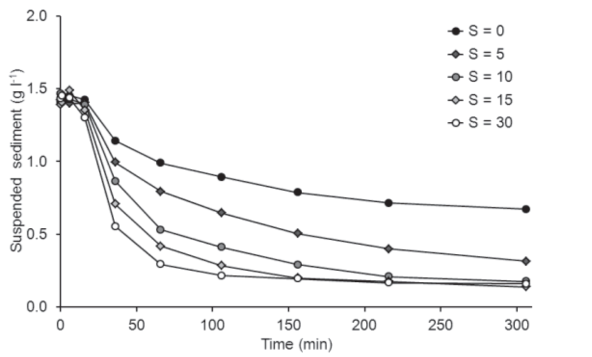

Figure 6. Evolution of vertically averaged suspended sediment concentration (g l^{-1}) in the five experiments.

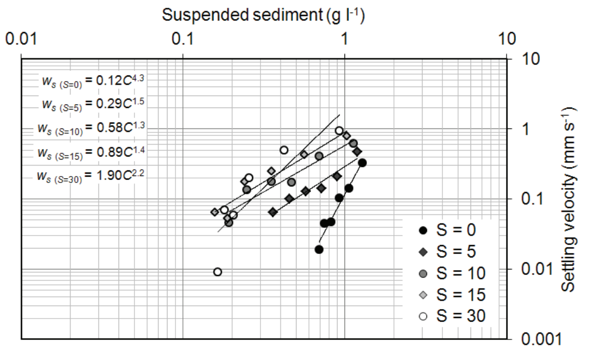

Figure 7. Evolution of settling velocities (mm s^{-1}), expressed as functions of suspended sediment concentration.

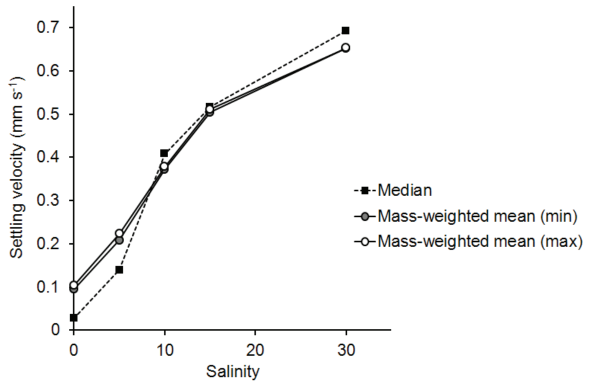

Figure 9. Comparison of the median setting velocity with mass-weighted mean settling velocities (mm s^{-1}).

Several inherent limitations of the experiments need to be considered, namely related to the nature of the suspension. For example, the initial concentration of suspended sediment was chosen an order of magnitude higher than the values observed in the field, to minimize errors due to the small volume of the water samples collected during the experiments.

Nonetheless, the study was conducted using natural sediments, not with purely inorganic material. It is also interesting to note that, while field results often show significant scatter, the results of the current study suggest that laboratory experiments are relatively precise and repeatable.

Settling velocity is often described by the median settling velocity, w_{s50}. The median settling velocity is the settling velocity for which half the sediment by weight will settle at a higher (or lower) velocity (Whitehouse *et al.*, 2000). Several reasons explain the use of the median, including practical reasons (e.g. the fact that often little more than 50% of the material studied by the settling tube method has settled at the end of the experiment; Pejrup and Mikkelsen, 2010).

However, as noted by a few authors (e.g. Graham and Manning, 2007), the mass-weighted mean settling velocity represents more accurately the sediment fluxes to the bed. The results of this study indicate that it is possible to obtain relatively narrow estimates of the mass-weighted mean settling velocity, even though not all particulate material has settled at the end of the experiments. The results of this study also seem to suggest that the mass-weighted mean may lead to a more limited range of variation in estimating sediment fluxes than the median, but further investigation is needed.

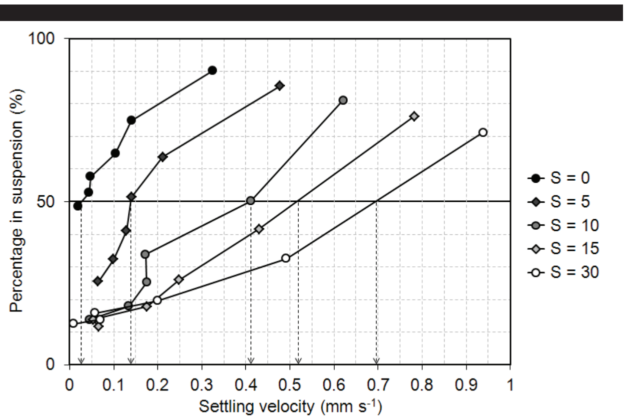

Figure 8. Determination of the median settling velocity (mm s^{-1}), defined as the settling velocity when the suspended sediment concentration has decreased to half the initial value.

Finally, it is relevant to mention that the mass-weighted mean settling velocities obtained in this study, ranging between 0.10 mm s^{-1} for S = 0 and 0.65 mm s^{-1} for S = 30, are not inconsistent with Stokes' law, for freshwater conditions, given the grain size distribution of the sediment.

CONCLUSION

The effect of salinity on the settling velocity of natural fine sediments, collected from a marina basin in the Tagus estuary, was studied using a laboratory settling column.

The following conclusions can be drawn:

(1) Settling velocities were found to increase with salinity. The maximum instantaneous values ranged between 0.3 mm s^{-1} under freshwater conditions (S = 0) and 0.9 mm s^{-1} under brackish-marine conditions (S = 30).

(2) The calculated mass-weighted mean settling velocity increased by a factor of 6.5 between freshwater conditions and brackish-marine conditions, ranging between 0.10 and 0.65 mm s^{-1}.

(3) The median settling velocity, which, while often used, appears to be a less accurate descriptor of the sediment settling fluxes, showed an even wider variation (0.03 and 0.69 mm s^{-1}).

(4) Although, during each experiment, the settling velocities decreased with the concentration of suspended sediment, this effect is likely due to the grain-size distribution of the suspension and not to concentration.

(5) The laboratory settling column provides results that are relatively precise and repeatable and allows the testing of different parameters.

(6) Salinity is a variable that should be taken into account when examining the settling of estuarine sediments.

ACKNOWLEDGEMENT

The assistance of P. Freire in the grain-size analysis and A.S. Silva in the mineralogical analysis is gratefully acknowledged. Additional lab assistance was kindly provided by A. Oliveira / IH. This work has been supported by Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) under research grant PTDC/AAC-AMB/100092/2008.

LITERATURE CITED

Berlamont, J., Ockenden, M., Toorman, E. and Winterwerp, J., 1993. The characterisation of cohesive sediment properties. *Coastal Engineering*, 21, 105-128.

Burt, T. N., 1986. Field settling velocities of estuary muds. *In*: Mehta, A. J. (ed.), *Estuarine Cohesive Sediment Dynamics. Lecture Notes on Coastal and Estuarine Studies*, 14. Berlin, Germany: Springer Verlag, pp. 126-150.

Costa, R.G., 1995. *Three-Dimensional Modelling of Cohesive Sediment Transport in Estuarine Environments*. Liverpool, United Kingdom: University of Liverpool, 320 p.

Graham, G.W. and Manning, A.J., 2007. Floc size and settling velocity within a *Spartina anglica* canopy. *Continental Shelf Research*, 27, 1060-1079.

Maggi, F., 2005. *Flocculation Dynamics of Cohesive Sediment.* Delft, The Netherlands: Delft University of Technology Ph.D. thesis, 154 p.

Manning, A.J., Friend, P.L., Prowse, N. and Amos, C.L., 2007. Estuarine mud flocculation properties determined using an annular mini-flume and the LabSFLOC system. *Continental Shelf Research*, 27, 1080-1095.

Mietta, F., Chassagne, C., Manning, A.J. and Winterwerp, J.C., 2009. Influence of shear rate, organic matter content, pH and salinity on mud flocculation. *Ocean Dynamics*, 59, 751-763.

Migniot, C., 1968. Étude des propriétés physiques de différents sédiments très fins et de leur comportement sous des actions hydrodynamiques. *La Houille Blanche*, 7, 591-620.

Mikeš, D. and Manning, A.J., 2010. Assessment of flocculation kinetics of cohesive sediments from the Seine and Gironde estuaries, France, through laboratory and field studies. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 136, 306-318.

Mikkelsen, O.A., Milligan, T.G., Hill, P.S. and Moffatt, D., 2004. INSSECT – an instrumented platform for investigating floc properties close to the seabed. *Limnology and Oceanography: Methods*, 2, 226-236.

Pejrup, M. and Mikkelsen, O.A., 2010. Factors controlling the field settling velocity of cohesive sediments in estuaries. *Estuarine, Coastal and Shelf Science*, 87, 177-185.

Portela, L.I., 1996. *Modelação Matemática de Processos Hidrodinâmicos e de Qualidade da Água no Estuário do Tejo.* Lisbon, Portugal: Technical University of Lisbon, Ph.D. thesis, 240 p.

Portela, L.I., 1997. Effect of settling velocity on the modelling of suspended sediment transport. *In*: Acinas, J.R. and Brebbia, C.A. (eds.), *Computer Modelling of Seas and Coastal Regions III*. Southampton, United Kingdom: Computational Mechanics Publications, pp. 347-403.

Ramos, S., 2013. *Efeito da Salinidade sobre a Velocidade de Queda de Sedimentos Finos de uma Bacia Portuária. Caso de estudo: Marina do Parque das Nações.* Lisbon, Portugal: Technical University of Lisbon, M.Sc. thesis, 56 p.

Shi, Z. and Zhou, H.J., 2004. Controls on effective settling velocities of mud flocs in the Changjiang Estuary, China. *Hydrological Processes*, 18, 2877-2892.

Van Leussen, W., 1988. Aggregation of particles, settling velocity of mud flocs: a review. *In*: Dronkers, J. and Van Leussen, W. (eds.), *Physical Processes in Estuaries*. Berlin, Germany: Springer Verlag, pp. 347-403.

Van Leussen, W., 1999. The variability of settling velocities of suspended fine-grained sediment in the Ems estuary. *Journal of Sea Research*, 41, 109-118.

Whitehouse, R., Soulsby, R., Roberts, W. and Mitchener, H., 2000. *Dynamics of Estuarine Muds*. London, United Kingdom: Thomas Telford, 210p.