

DYNAMICS OF SILT IN ESTUARY, RESIDUAL CURRENT

OR FLOCCULATION WHICH PREVAILS ?

by
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ABSTRACT

The transport of fine suspended sediment in a partly-mixed estuary has been simulated on a physical model of a schematic estuary reproducing the main geometrical and hydrodynamical characteristics of the Gironde Estuary (France). The natural sediment consisting of silt and clay is simulated using a light and fine material, gilsonite, and the flocculation processes in salt water and under turbulence induced by tidal currents have been reproduced by adding in salt water a flocculating salt solution (sodium pyrophosphate). Then the formation of the turbidity maximum surveyed in the field and its upstream-downstream migration in response to varying river discharge have been successfully simulated and the results of different series of tests lead to the following conclusions :

- flocculation processes - which are responsible of the variation of the settling velocity with salinity and turbulence-have to be reproduced to explain the formation of the turbidity maximum ;
- after high river discharges the convergence of bottom residual currents (null point) due to the salinity intrusion creates a trap for suspended sediments supplied by the river flood which accumulate in the form of the turbidity maximum. Without salinity intrusion, a large amount of sediment would escape out of the estuary to the sea ;
- during low river flows, a part of the suspended sediment migrates upstream but the amplitude of this migration is small compared with the displacement of the upstream limit of the salinity intrusion ;
- the upstream migration of the turbidity maximum is increased when a transverse bottom morphology (existence of a deeper navigation channel) is represented.

1. INTRODUCTION

Transport of fine suspended sediment in partly-mixed estuaries is generally characterised by the existence of an accumulation zone with high turbidities migrating with the season ; this maximum of concentrations occurs in the lower part of the estuary after high river flows and part of it progressively migrates upstream during low river flows. This mechanism has been attributed to various processes,

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e.g. flocculation, tidal resuspension of bottom sediment, convergence of bottom residual currents depending on the salt intrusion, river flow and estuary geometry. The contrasting results from different estuaries indicate that the question of defining the process controlling the transport has no general solution at the present stage of progress.

In order to study these phenomena in laboratory, a fixed-bed small scale model of a schematic estuary has been developed. The beginning of the study consisted in reproducing salinity intrusion for different tidal amplitudes and river flows, and extracting residual currents from flow velocity measurements with an optic fiber laser anemometer.

Then the simulation of suspended sediment transport has been undertaken ; the extreme complexity of the factors involved in suspended transport and their simulation on a very small scale model raised many difficulties but interesting results have been obtained which are presented in this report.

2. DESCRIPTION OF THE SCHEMATIC ESTUARY MOEEL

The geometrical and hydrodynamical characteristics of the schematic estuary are those of the Gironde estuary, France. This estuary has been chosen because of the smooth and monotonic longitudinal variation rate of both its width and cross sections and also because of the availability of numerous field measurements although most of them are located in the navigation deep channel.

The Gironde estuary (cf fig. 1) is formed by the junction of the Garonne and Oordogne rivers. The navigation channel is about 7 m deep (below LWL) upstream PK 80 (distance in kilometers from Bordeaux) where a break in slope occurs. Downstream the depths increase and reach 30 m at the mouth. The north channel is wider and shallower (3-5 m) and is also marked by a slope break at PK 80 with increasing depths downstream ; the two channels merge in the mouth. The upper estuary, extending from the Bec d'Ambès to about PK 50, is characterized by numerous banks, shoals and islands. The lower estuary exhibits a simpler morphology consisting of two channel systems separated by a succession of sandy banks.

The monthly averaged river discharge varies from 200 m³/s in summer to 1 500 m³/s in winter with a mean of 800 m³/s. During river floods the instantaneous discharge can often exceed 3 000 m³/s. The tidal amplitudes in the inlet vary from 2 m during neap tides to 5 m during spring tides. In spring tides, the tidally averaged ebb or flood discharges vary from 12 000 m³/s (15 times larger than the annual averaged river discharge) at the Bec d'Ambès to 100 000 m³/s (125 times larger than the mean river discharge) at the mouth. These figures show that the velocities of the tidal currents are not significantly influenced by the river discharge in the lower part of the estuary.

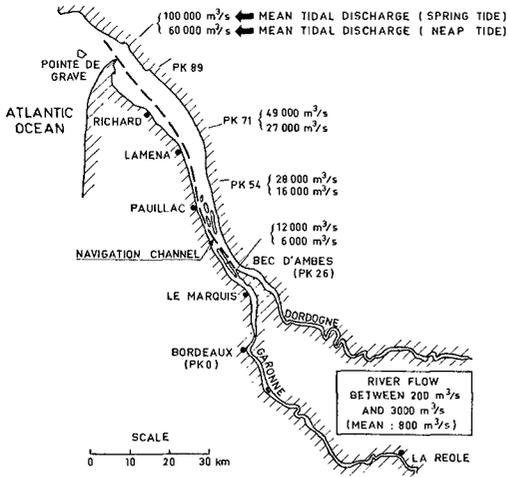


Fig. 1 : THE GIRONDE ESTUARY (France)

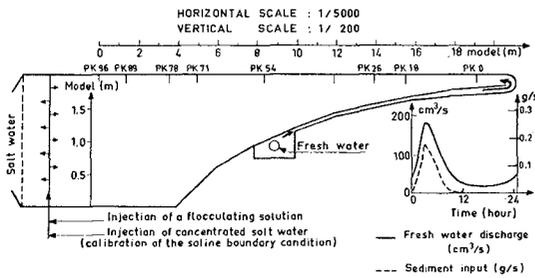


Fig. 2 : DESCRIPTION OF THE SCHEMATIC ESTUARY MOEEL

The silt and clay presently accumulating in the estuary are mainly supplied by the rivers. This influx of suspended sediment has been evaluated at about 2×10^6 tons/year.

The schematic estuary model presented in figure 2 reproduces the entire tidal part of the Gironde estuary.

It is a fixed-bed, distorted scale model with length scales of 1/200 vertically and 1/5000 horizontally with rectangular cross sections ; the longitudinal rate of variation of cross sections of the Gironde estuary is fitted by an exponential law.

The variation rate of its width is also exponential except near the mouth where the width is supposed to be constant between PK 76 and PK 96. The depth is constant transversely and equal to the cross sectional area divided by the width.

The experimental equipment allows to reproduce the following mechanisms :

- fortnightly variation of the tidal amplitude at the sea boundary ;
- annual variation of the river flow, as shown in figure 2 ;
- annual variation of sediment input introduced at river source with a turbidity proportional to the river flow ; in the experiments suspended sediments are supposed to be supplied only by the river ;
- variation of salinity intrusion with the tidal amplitude and river flow ;
- flocculation of sediment in salt water.

The natural sediment is simulated using a light and fine material, gilsonite, with a density of 1.035, an average grain size of 45 μm and a mean settling velocity of 0.04 mm/s in freshwater. The flocculation processes in salt water have been reproduced by adding in salt water a flocculating salt solution (sodium pyrophosphate). The flocculating solution induces formation of large flocks which entrap gilsonite particles (cf fig. 3).

This mechanism seems to be mainly linked with the value of the PH of the solution. So, the settling velocities of gilsonite flocks depend on both salinity and concentrations of pyrophosphate as shown in figure 4.

The concentrations of flocculating salt solution influence the characteristics of flocks - size and shear strength and consequently those of deposits - especially the critical shear stress of resuspension.



Fig. 3 : FLOCCULATION OF GILSONITE

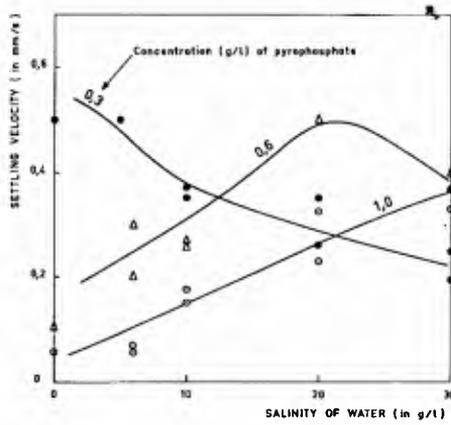


Fig. 4 : SETTLING VELOCITIES OF GILSONITE FLOCKS
IN STILL WATER
(initial concentration of gilsonite : 2 g/l)

This condition has been respected using a concentration of pyrophosphate of about 0,6 g/l for the salinity 20 ‰. If we suppose that the longitudinal gradients of salinities and pyrophosphate concentrations are identical in the model, the settling velocity of gilsonite flocks varies from about 0,3 mm/s to 0,5 mm/s (ten times more than the settling velocity of gilsonite without flocculation) when the salinity increases from 5 ‰ to 20 ‰. But in the model the size of flocks depends on turbulence ; so the settling velocity is a function of the flow velocity.

Gilsonite flocks represent the behavior of natural silt and clay much better than individual particles of constant size. Nevertheless it is doubtful that the extreme complexity of depositional and erosional behavior of cohesive sediments is reproduced in detail. For example the rates of deposition, which probably depend on the distributions of flocks shear strengths and the value of bed shear stress, have not precisely compared to their values in nature. So the experimental results must be considered as more qualitative than quantitative.

3. SALT INTRUSION AND RESIDUAL CURRENTS

In a first part of the study the model has been calibrated to reproduce water surface elevations, current velocities along the estuary and the mixing of salt and freshwater for different tidal ranges at the mouth of the estuary and different river discharges. Then the vertical profiles of residual currents¹ have been extracted from flow velocity measurements with an optic fiber laser anemometer. These results presented in detail in [1] lead to the following conclusions :

- salinity intrusion creates a zone of upstream bottom residual currents in the lower part of the estuary ;
- the point of convergence of the bottom residual currents (null point) depends on the tidal range (cf fig. 5) ;
- the migration of the null point with the river discharge is small in the range 500-2 500 m³/s for a fixed mean tidal amplitude, as shown in figure 6. So the zone of convergence of bottom residual flow does not follow the migration of the upstream limit of the salinity intrusion.

In nature the bottom residual flow field measured in the navigation channel is more complicated due to the influence of bottom topography, which creates successive zones of convergence and divergence (fig. 9). Nevertheless the measurements show the same influence of the tidal elevation as is pointed out by the results of the physical model : the residual velocities in spring tides are directed seaward for any river flow except at PK 89 near the bottom.

¹ It is the Eulerian residual velocity equal to the time average of the flow velocity within a tidal period calculated at a fixed point.

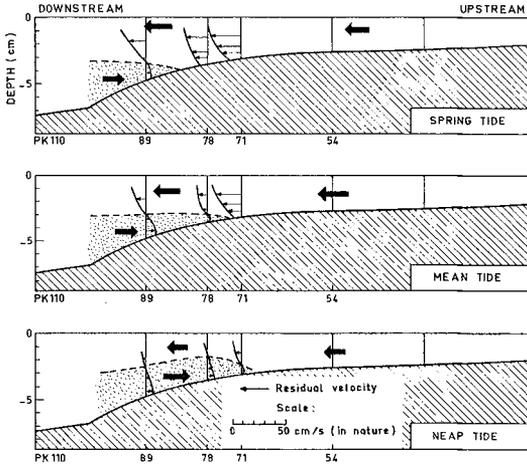


Fig. 5 : RESIDUAL VELOCITIES MEASURED IN THE MDEL (results for a mean river flow)

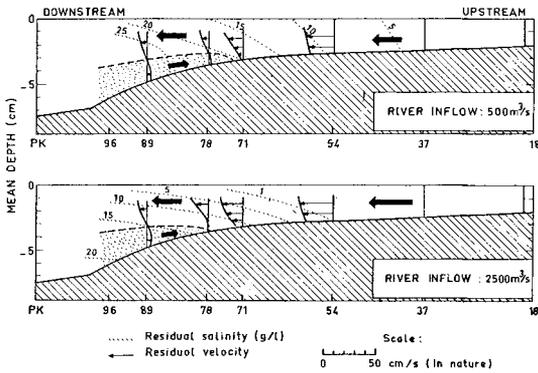


Fig. 6 : RESIDUAL VELOCITIES AND SALINITIES MEASURED IN THE MDEL (results for a mean tidal amplitude)

4. SUSPENDED TRANSPORT TESTS

4.1. Description of tests

At the beginning of a test, the model is operated with low river discharge until salinity concentrations throughout the model has become stabilized. Once stability has been obtained without sediment injection, the river discharge and suspended sediment influx cycles, as shown in figure 2, are initiated. The annual cycle is about one day long on the model. Salinity and suspended sediment concentration measurements are made continuously during the following cycle using an electro-optical system based on colorimetry method (colorimeter) and recorded on a magnetic tape.

Three series of experiments have been conducted : the first without reproducing flocculation processes. In this case the settling velocity of gilsonite particles is equal to 0,04 mm/s in fresh water and diminishes a little when moving from the fresh water to the salt water areas (for a salinity of 20 ‰ the settling velocity is about 0,02 mm/s). The following tests have been made with reproduction of flocculation. In that case the settling velocity increases from 0,04 mm/s to a maximum of about 0,5 mm/s when moving from the fresh water to the salt water areas. Other tests have been made in the same conditions but without upstream bottom residual currents (no salt but the flocculating zone is reproduced).

4.2. Principal results of tests

4.2.1. Without flocculation

The results show that the tidally-averaged concentration of suspended sediment diminishes seaward by dilution and settling out and there is no formation of a turbidity maximum. In the lower part of the estuary, a large amount of suspended material escapes out of the estuary by downstream advection. In the upper part of the estuary there are deposits of coarser gilsonite which are badly resuspended during spring tides.

4.2.2. With flocculation

The results obtained through the experiments taking into account flocculation processes can be summarized as follows :

- the tidal amplitude has a very important influence on the gilsonite flocks transport : after neap tides, the flocks deposit on the bottom and the turbidity decreases whereas after spring tides the deposits are resuspended and the turbidity increases ;

- the tidally averaged concentrations measured in spring tides depend on the river flow according to the following sequence described in figure 8 : at the maximum of flood the sediment input is large and the turbidity is high in the whole estuary ; when the river flow decreases, the development of a turbidity maximum is observed in the lower part of the estuary and the maximum is located near PK 85 at the end of the flood. During low river flows, the maximum diminishes and shifts upstream but the amplitude of this migration is small, the maximum being located near PK 71 at the end of low river flows ;
- different deposits can be observed : in the upper part of the estuary there are deposits of coarse non flocculated gilsonite which are badly resuspended during spring tides ; in the same way in the lower part of the estuary near the sea boundary there is an accumulation of flocculated gilsonite on the bottom ; except these two particular zones, the formation of deposits, only after neap tides, is linked to the turbidity maximum ; the upstream limit of the flocculated deposits is located near PK 75 after flood and near PK 54 after low river flow but several small deposits can be observed up to PK 30 ;
- the location of turbidity maximum seems to be linked to the convergence of bottom residual currents and not to the upstream limit of flocculating zone.

4.2.3. Without residual currents

The preceding conclusion has been confirmed by other tests carried out without residual circulation ; the results of these tests have shown no formation of turbidity maximum in spite of the reproduction of flocculation.

5. EFFECT OF TRANSVERSE BOTTOM MORPHOLOGY

In a last serie of experiments, the rectangular cross sections of the schematic estuary have been modified in order to study the influence of a deep navigation channel ; this channel was reproduced with the same depths as in nature without changing the cross sectional areas ; of course the lateral curvatures of the Gironde estuary are not still simulated. The measurements of tidally-averaged suspended sediment concentrations in spring tides and in the deep channel (fig. 8) show that the turbidities are higher in the channel than in the preceding tests with rectangular cross sections and that the upstream migration of the turbidity maximum is more important during low river flows.

So the transverse topography plays an important complementary role ; this influence is probably due to an enhanced density generated flow in the deeper channel but the results of velocities measurements are not yet available to confirm this hypothesis.

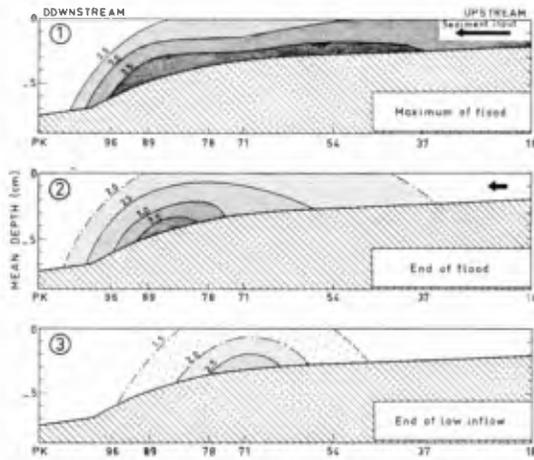


Fig. 7 : RESIDUAL SUSPENDED SEDIMENT CONCENTRATION (IN g/L) MEASURED IN SPRING TIDE (MODEL WITH RECTANGULAR CRDSS SECTIONS)

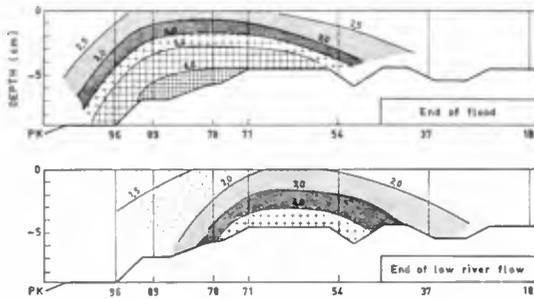


Fig. 8 : RESIDUAL SUSPENDED SEDIMENT CONCENTRATION (IN g/L) MEASURED IN THE CHANNEL (SPRING TIDE) (MODEL WITH TRANSVERSE GEDMETRY)

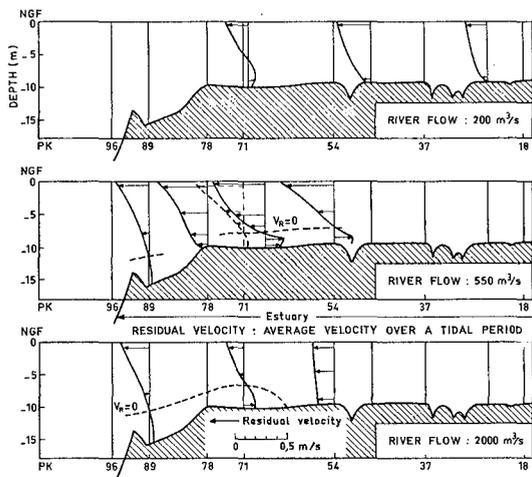


Fig. 9 : RESIDUAL VELOCITIES MEASURED IN THE MAIN CHANNEL OF THE GIRDNE ESTUARY (MEAN TIDAL RANGE)

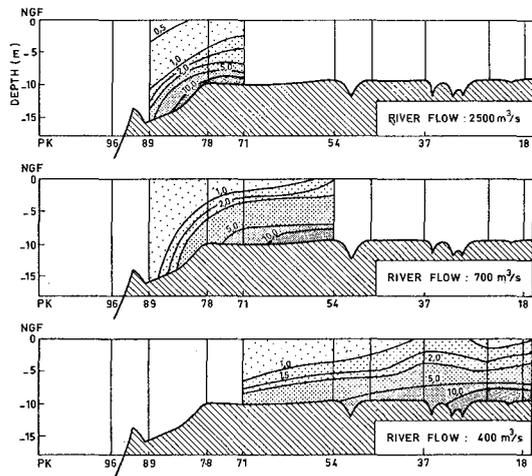


Fig. 10 : SUSPENDED SEDIMENT RESIDUAL CONCENTRATIONS MEASURED IN THE MAIN CHANNEL OF THE GIRDNE ESTUARY (SPRING TIDE)

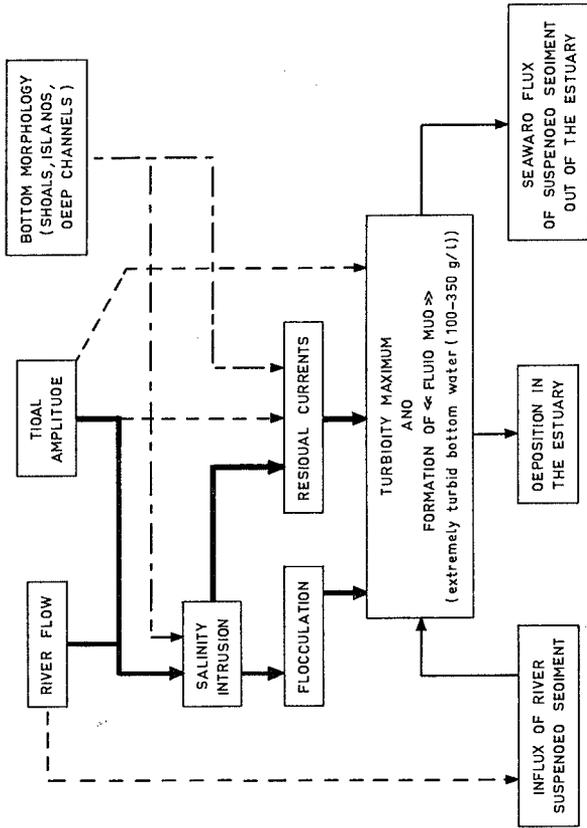


Fig. 11 : PRINCIPAL PHENOMENAE INVOLVED IN SUSPENDED SEDIMENT TRANSPORT IN ESTUARIES

6. CONCLUSION

The figure 11 summarizes the principal mechanisms involved in transport of fine sediments in estuaries. All these mechanisms or part of them have been simulated on a schematic physical model of the Gironde estuary. The formation of the turbidity maximum surveyed in the field has been successfully simulated by reproducing both the density generated residual currents and the flocculation processes when fresh water mixes with salt water. Gilsonite (density : 1.035, mean grain diameter : 45 μm) has been used for simulating natural sediment consisting of silt and clay and the addition of sodium pyrophosphate in salt water allows the reproduction of flocculation processes. The concentrations of sodium pyrophosphate have been adjusted to have a satisfactory reproduction of the fortnightly erosion-deposition cycle of the sediment in response to varying tidal amplitudes at the mouth of the estuary. With these concentrations the gilsonite flocks have a settling velocity of about 0,4 mm/s in still water (ten times more than the settling velocity of gilsonite without flocculation) but the observation of gilsonite flocks behavior in the model shows clearly that the settling velocity depends on the tidal current velocities.

In spite of some scale effects and the fact that the experimental approach is more qualitative than quantitative the results obtained on the schematic estuary show a sufficient likeness to field measurements (cf fig. 10) to let us suppose that the mechanisms reproduced in the model (flocculation and residual currents) are those which play an important role in the Gironde estuary. So we may conclude that residual velocities and flocculation are both responsible for the development of high turbidity zones in a partly-mixed estuary with hydrodynamical characteristics near those of the Gironde estuary.

The lateral geometry (effect of a deep channel) plays also an important role in the behavior of the turbidity maximum.

REFERENCE

- [1] M. DAVESNE. Intrusion saline et vitesses résiduelles dans un estuaire. Proceedings AIRH 1977 Vol. 3, pp 15-22.