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Thiébot, Jérôme; Guillou, Sylvain

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Simulation of processes acting on water-sediment mixtures in estuaries

Jérôme Thiébot and Sylvain Guillou

This study deals with the different steps that take place when, under gravitational effects, suspended cohesive sediment particles deposit on estuarine beds. We will focus on the evolutions of the deposit's characteristics that lead to the formation of a cohesive bed. The Gibson's theory which constitutes a reference framework in the field of consolidation is presented. We have developed a numerical model based on the resolution of the Gibson's equation that simulates the settling and the consolidation of mud. The numerical results are compared with the experimental data obtained with settling columns.

Diese Studie beschäftigt sich mit den verschiedenen Phasen die stattfinden, wenn unter Gravitationseinfluss, suspendierte kohäsive Sedimentpartikel sich an Sohlen von Ästuaren ablagern. Wir konzentrieren uns auf die Entwicklung der Ablagerungscharakteristiken, die zur Bildung von kohäsiven Sohlen führt. Die Theorie von Gibson, die für das Verfestigungsgebiet einen Bezugsrahmen festlegt, wird präsentiert. Ein numerisches Modell das auf einer Lösung der Gibson Gleichung beruht, wurde entwickelt, um die Schwebstoffe und die Verfestigung von Schlamm zu simulieren. Numerische Ergebnisse werden mit Versuchsergebnissen aus einer Setzungssäule verglichen.

1 Introduction

European estuaries are subjected to an increasing siltation. Due to the combined effects of river flow and tide, very turbid zones called « turbidity maximum » appear in the downstream part of some estuaries. When the cohesive sediment contained in these zones settles rapidly on the bottom, mainly during slack periods, a layer called « fluid mud » is formed. It is a very concentrated suspended matter that can move due to the effects of slope or water current. But when laid on the bottom for a long time, it consolidates and becomes a part of the estuary's bed. Numerical simulations are a useful tool to predict the evolution of the topographical profiles, the determination of the intense deposition areas and the dredging operation's optimization. When settling and consolidation are introduced in sediment transport numerical models, they are not always treated correctly. Empirical methods are sometimes employed: despite their interesting simplicity and low calculation cost, they suffer from a lack of adaptability. In some models, settling and consolidation are treated separately although the two processes are closely linked. There are also several models which describe the evolution of the mud deposits with a high degree of accuracy but the number of parameters introduced is important and the required calculation time does not permit their use in an already costly sediment transport simulation.

2 The settling – consolidation model

2.1 Definitions

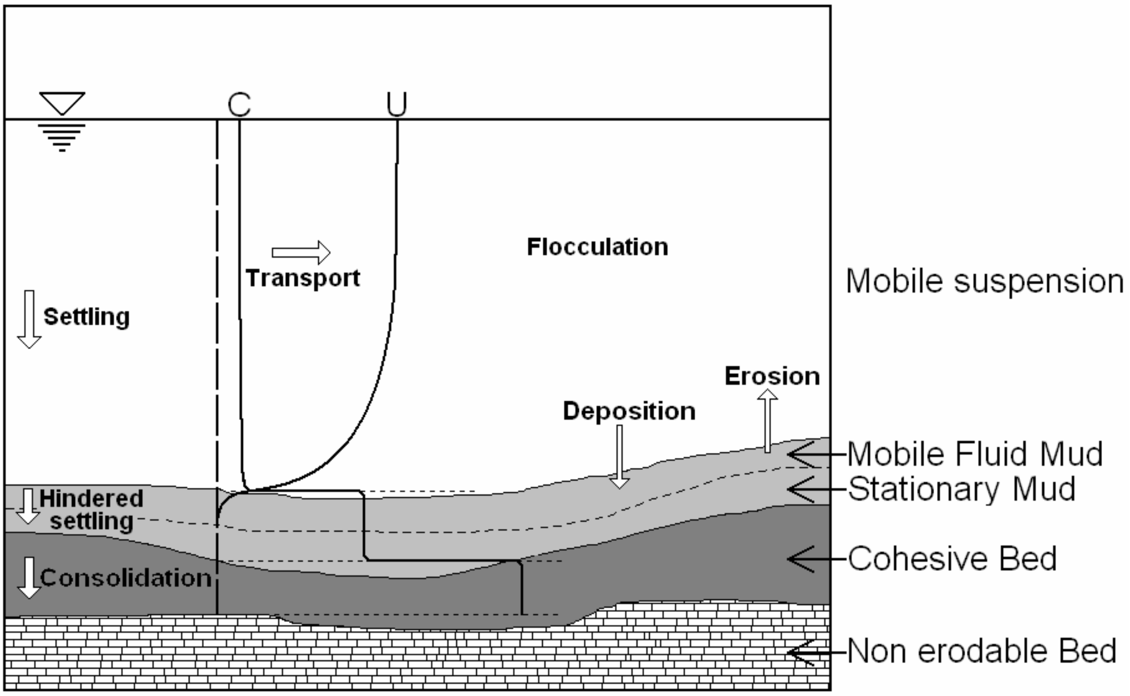

Figure 1 Processes acting in estuaries

Various types of water-sediment mixtures are encountered in estuaries, as it is represented on Figure 1. From the free surface to the bottom, one can encounter, by increasing concentration: the mobile suspension, the fluid mud, the cohesive bed and the “non erodable bed”. In the mobile suspension, according to physical, chemical and biological effects, cohesive particles of sediment agglomerate to form flocs whose fall velocity is grater than the fall velocity of isolated particles. When, by gravitational settling, flocs accumulate on the bottom, the space between them decreases; they collide and hinder each other in their settling. As a consequence, the vertical velocity of sediment slows with increasing concentration. When the flocs reach the bottom (very slowly), they form a dense layer called fluid mud. Beyond a certain concentration, flocs are crushed under their own weight and the water they contain is expulsed, a skeleton appears and the mud can no more be considered as a fluid but as a saturated soil. Finally, under the cohesive bed, there is a consolidated soil which does not evolve much: the “non erodable bed”.

2.2 Mathematical background

Settling and consolidation of cohesive sediment has been widely investigated. The Gibson’s theory (1967) always constitutes a reference on the subject. The Gibson’s equation which characterizes the evolution of the void ratio (or concentration) as a function of time and space is obtained by considering the mechanisms involved in the formation of mud: as long as the flocs collapse under their own weight, the induced pore water flow creates excess pore pressure which reduces the load carried by the structure (skeleton) which is called effective stress. The hypotheses made in the Gibson’s theory are the following:

- Mud is saturated: voids are filled by water
- Grains and fluid are incompressible
- Darcy law is applicable to describe the interstitial water expulsion
- Effective stress and permeability depend on the concentration only
- Settlement is a vertical process only

In the Gibson’s theory, the interstitial water’s flow within the mud is taken into account thanks to the Darcy law. The appearance and collapse of the structure is described by mean of stresses which satisfy the Terzaghi’s principle (the total stress due to the weight of mud and water is supported both by effective stress (skeleton) and by water pressure). The water pressure includes a hydrostatic term and a term called “excess pore pressure”. When adding the continuity equation, the following expression of the vertical solid velocity comes:

$$V_s = k(C).\left(1 + \frac{1}{g.\rho_w}.\left(\frac{\partial \sigma}{\partial z} - \frac{\partial \sigma'}{\partial z}\right)\right) \qquad \text{Eq. 1}$$

Introducing the mass conservation in Eq. 1, an equation equivalent to the Gibson’s one is obtained:

$$\frac{\partial C}{\partial t} - \frac{\rho_s - \rho_w}{\rho_w.\rho_s}.\frac{\partial}{\partial z}\left(C^2.k(C)\right) - \frac{1}{\rho_w.g}.\frac{\partial}{\partial z}\left(C.k(C).\frac{d\sigma'(C)}{dz}\right) = 0 \qquad \text{Eq. 2}$$

The Gibson’s equation can be resolved thanks to iterative procedures like Toorman’s (1999) finite element method or Le Normant’s (2000) finite difference with implicit scheme technique which has been implemented in the

Telemac modeling system. The latter methods are time consuming and consequently can be employed with difficulties in estuaries simulations. That is why we propose the use of an explicit resolution of the Gibson's equation.

2.3 Explicit resolution of the Gibson equation

In the presented model, the settling and consolidating mud is considered to be distributed in a stacking of layers of specified concentrations. At each time step, the solid fluxes between layers are calculated thanks to Eq. 3 which is deriving from Eq. 1. Then, the corresponding quantities of sediment are transferred to more concentrated layers. As a consequence, the thicknesses evolve.

$$\mathrm{Flux(i)} = \mathrm{C(i).k(C(i))}\left(1+\frac{1}{\mathrm{g}.\rho_{\mathrm{w}}}.\left(\frac{\mathrm{C(i)}-\rho_{\mathrm{s}}}{\rho_{\mathrm{s}}}.\mathrm{g}.\rho_{\mathrm{w}}-\mathrm{C(i).g}-2.\frac{\sigma'(\mathrm{C(i+1)})-\sigma'(\mathrm{C(i)})}{\mathrm{Epai(i+1)}+\mathrm{Epai(i)}}\right)\right) \quad \text{Eq. 3}$$

2.4 Determination of the constitutive relations

In order to fit the parameter to introduce in our model, that is to say, the constitutive relations k(C) and σ'(C), we have used a settling column. It consists in putting initially a homogeneous sediment-water mixture of known concentration in a transparent tube. After a few minutes, a distinct interface appears between seemingly clear water and the underneath suspension. The graphical representation of the height of the interface as a function of the time gives the settling curve. Constitutive relations can be calculated, with an instrumented column, from pressure measurements and concentration's profiles (Masutti(2001)) but the measurements are not very accurate especially regarding the pressure. The presented method permits the calculation of the constitutive relations from the settling curve only. On the latter, three phases can be distinguished as it is represented on Figures 2 and 3. During the first phase (t < 40 min), the interface slowly sinks down at a nearly constant speed. Below this interface, the suspension's concentration is close to the initial value; on the bottom of the column, a more concentrated matter appears as a consequence of hindered settling. During the second phase (40min < t < 1350 min), the hindered settling is the preponderant phenomenon. A second interface appears near the bottom of the column revealing that the mud is acquiring saturated soil characteristics. In the third phase (t > 1350min), the solid structure has developed in all the height of mud and the consolidation acts.

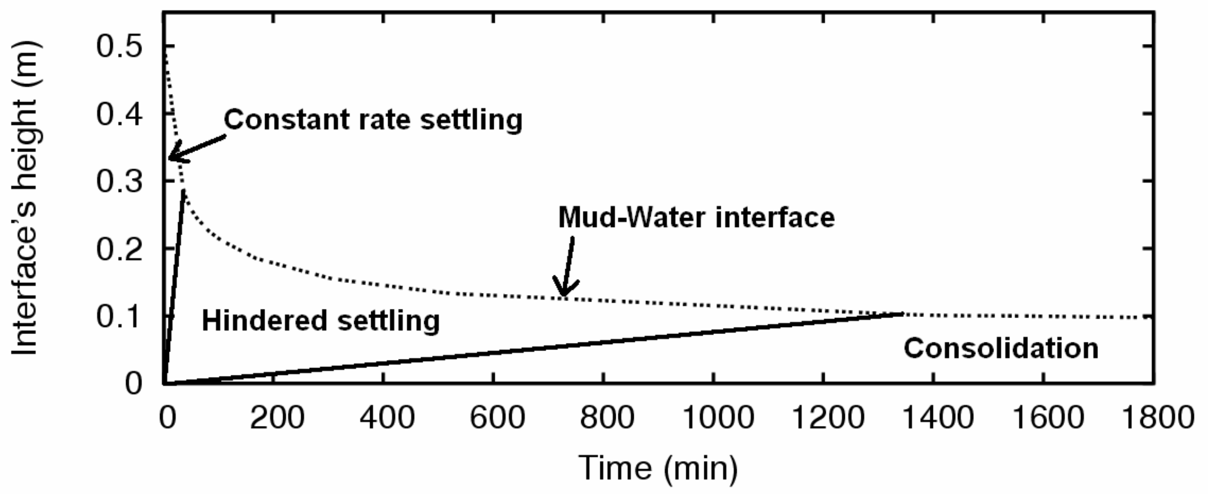

Figure 2 Settling curve obtained with mud of the river Rance

For the calculation of the constitutive relations, we make the assumption that k(C) and σ'(C) can be expressed with the following functions:

$$k(C) = A.\left(\frac{\rho_s - C}{\rho_s}\right)^B , \qquad \text{Eq. 4}$$

$$\sigma'(C) = F \qquad \text{If } C < C_p$$

$$\sigma'(C) = D.C^E + G \qquad \text{Otherwise} \qquad \text{Eq. 5}$$

F and G are unspecified constants. It is not worthy to determinate their value since, in our model, the calculation of the fluxes implies the subtraction of effective stresses of two different layers.

Some authors, like Pane and Schiffman (1985), have shown that hindered settling can be described with a consolidation equation by considering the effective stress null. Applying this principle on our model, hindered settling can be described by:

$$\mathrm{Flux}(i) = C(i).\left(k(C(i)) + \frac{k(C(i))}{g.\rho_w}.\left(\frac{C(i) - \rho_s}{\rho_s}.g.\rho_w - C(i).g\right)\right) \qquad \text{Eq. 6}$$

In the second phase of the settling curve, the permeability plays an important role and the effective stress contribution to the evolution of the mud's height can be neglected, thus, Eq. 6 is applicable. By combining Eq. 4 and Eq. 6, we can find the couple (A,B) which minimize the difference between calculated and measured interface's heights. With this technique, we find:

$$k(C) = 0{,}073.\left(\frac{\rho_s - C}{\rho_s}\right)^{121{,}6}$$

Concerning effective stress, we have introduced the latter expression of the permeability and Eq.5 in Eq. 3 and we have fitted D and E so that numerical results were close to the experimental measurements concerning the third phase of the settling curve. We have found:

$\sigma'(C) = F$ If $C < 180$ g/L

$\sigma'(C) = 1{,}22.10^{-6}.C^{3{,}2} + G$ Otherwise

3 Results

Introducing the constitutive relations in our model, we have simulated the settling and consolidation of fifty centimeters of mud of initial concentration 50 g/L. The results are presented on Figure 2 and 3. A good agreement is observed between the experimental and the calculated settling curve. Some samples of mud have been taken on the bottom of the mud deposit (at t = 2 days and at the end of the process of settlement) in order to measure the concentrations, they are close to the calculated values. The Figure 4 represents the general shape of the concentration's profiles. It is coherent with theory: on the first profiles, the concentration is close to the initial value in the high part of the suspension and the concentration increases progressively near the bottom as a consequence of hindered settling. The intermediate profiles (t=500 and 1000 min) are composed of two regions: on the top, the fluid mud and on the bottom the consolidating soil. On the final profile, the mud can be considered as a saturated soil.

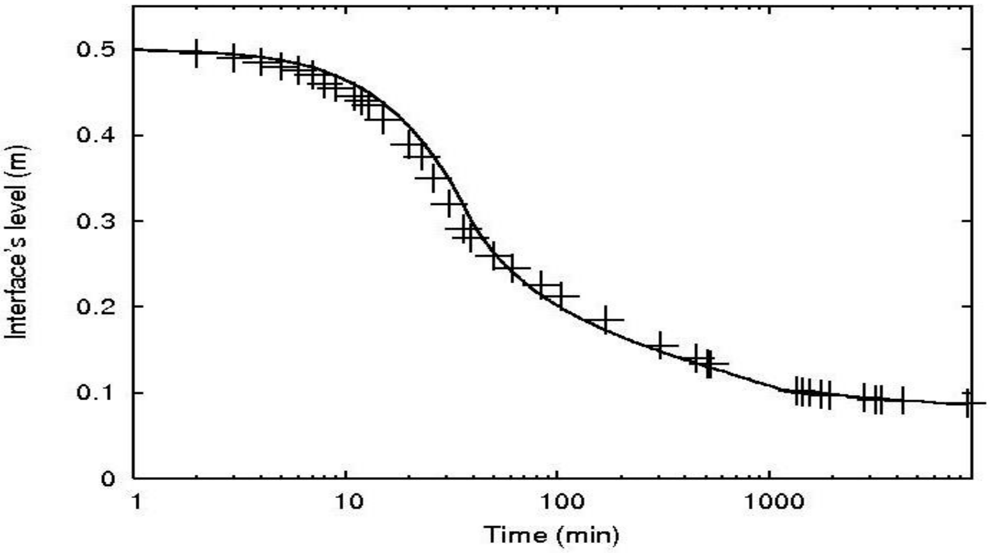

Figure 3 Settling curve (simulated: line ; experimental: points)

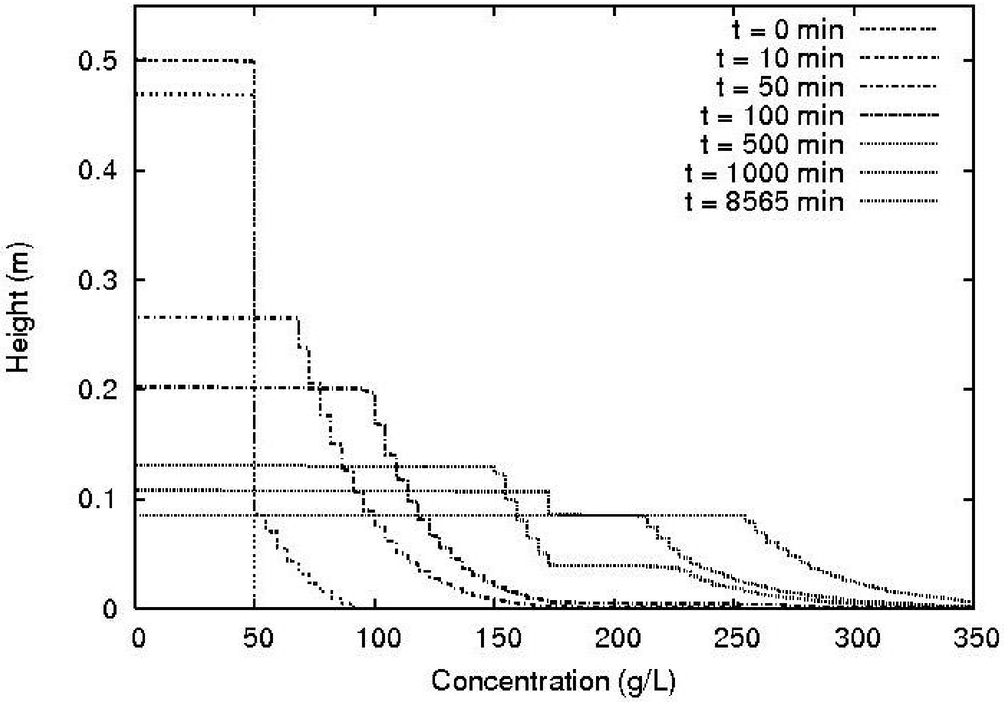

Figure 4 Concentrations profiles

4 Conclusion

A numerical model has been developed to simulate the settling and the consolidation of mud deposits in estuaries. The fact that the Gibson's consolidation equation can characterize the settling of sediment particles (by considering the effective stress null) enables to use a unique equation. An explicit resolution of the Gibson's equation has been chosen in order to avoid a costly iterative method. The constitutive relations are simply calculated from a settling curve: the permeability law is calculated from the interface's level measurements done when the hindered settling is preponderant whereas the effective stress law is obtained by focusing on the consolidation phase. Once the constitutive relations introduced in the model, a good agreement is observed between simulated and measured data. A good compromise has been found between accuracy and cost in term of CPU time.

5 Acknowledgements

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6 Notation

$C(i)$: mass concentration of solid in the i^{th} layer
C_p : concentration beyond which the mud becomes plastic
$Epai(i)$: thickness of the i^{th} layer
$k(C)$: permeability as a function of the concentration C
g : gravity constant
ρ_w, ρ_s : water and solid density
σ : total stress
$\sigma'(C)$: effective stress as a function of concentration
$V_s(i)$: vertical solid velocity in the i^{th} layer
z : vertical coordinate oriented upward

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Authors:

PhD. student Jérôme Thiébot
LUSAC
Site universitaire
50130 Cherbourg-Octeville
France
Tel.: ++33 2.33.01.41.37
Fax: ++33 2.33.01.41.35
jerome.thiebot@chbg.unicaen.fr

Dr. Sylvain Guillou
LUSAC
Site universitaire
50130 Cherbourg-Octeville
France
Tel.: ++33 2.33.01.42.13
Fax: ++33 2.33.01.41.35
sylvain.guillou@chbg.unicaen.fr