CHAPTER 239

Sediment Transport Modelling in a Macrotidal Estuary : do we need to account for Consolidation Processes ?

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Abstract

In order to investigate the role of consolidation processes on the sediment transport in a macrotidal estuary, a simple vertical model of fluid mud consolidation has been coupled to a cross-averaged sediment transport model in the Loire estuary. Simulations show that sediment patterns (turbidity maximum and fluid mud location) are few dependent on consolidation. On the other hand, the consolidation influences the residual deposition after a spring/neap tidal cycle and thus the net transport of sediment through the estuary. It is pointed out that consolidation is in competition with turbulence damping so that both processes have to be considered when predictive simulations are wanted.

Introduction

The transport of cohesive suspended sediment in a macrotidal estuary is dominated by the occurrence of a turbidity maximum, either due to tidal asymmetry or to density gradients, which partly traps material flowing through the estuary (Allen *et al.*, 1980 ; Nichols and Biggs, 1985).

Besides, many large estuaries are known for their patterns of fluid mud constituted by the deposition of suspended sediment after spring tides, where the turbidity maximum lies. This fluid mud consolidates more or less and then can either be resuspended during the increasing tidal

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amplitude or remain as consolidated mud until a larger hydrodynamical forcing occurs. Even if the process is well known, it has rarely been quantified and/or modelled.

The aim of this study is to see how consolidation processes affect the results of suspended sediment transport in order to get tracks of whether and how much one should account for it. More precisely, by means of a mathematical model, we would try to answer the following questions :

- Are the sediment patterns (turbidity maximum and fluid mud) affected by consolidation processes ?

- Is the (long term) sediment transport dependent on consolidation ?

- How accurate should be the consolidation modelling, when computing the transport of cohesive sediment in a macrotidal estuary ?

Consolidation modelling

Many factors can influence the erosive behaviour of a sediment and its consolidation. In particular, the role of biological processes as bioturbation or surficial protection by mucilage have been pointed out (Montague, 1986 ; Paterson *et al.* 1990). Also waves can induce some fluidization of the mud, and thus modify its erodibility without changing its concentration. But in the area of a turbidity maximum within an estuary, these processes are weak : waves are small if compared with the water depth and biota are poor, due to high turbidities. Thus the sediment concentration remains a good parameter to represent the degree of consolidation providing an empirical relationship with the shear strength τ_C, the usual parameter for mud erosion (see Mehta *et al*, 1989).

Brief review

Previous mathematical models for consolidation where mostly empirical when coupled with sediment transport models, for saving computing costs. In first models (Ariathurai and Krone, 1976 ; Onishi, 1982) the soil was discretized in layers of given thicknesses, with characteristic shear strengthes. The exchanges between layers were forced by the deposition rate.

For Teisson and Latteux (1986) the layers were characterized by a given residence time of sediment and naturally a specific shear strength. Hayter (1986) developed a more sophisticated model and considered the time variations of bed density and shear strength according to typical measured profiles. Le Hir *et al.* (1989) introduced a differential law for the bed density variations, allowing any empirical formulation.

All these models could not directly fit the consolidation theories because of the discretization in thick layers. But the performance of new computing facilities allows the required refinement to account for these theories.

Consolidation theories

Two types of conceptual models have been developed (see Alexis *et al.*, 1992).

- The "sedimentation" models express the mass conservation of the solid particles, with vertical exchanges represented by the settling fluxes. A common assumption of this approach is the unique dependence of the settling velocity v_S on the local suspension density (Kynch, 1952). The usual state variable of these models is the dry density or concentration c, and the equation can be written :

$$\frac{\partial c}{\partial t} + V(c)\frac{\partial c}{\partial \zeta} = 0 \qquad (1)$$

where $V(c) = v_S + c\frac{dv_s}{dc}$

ζ : vertical coordinate

t : time

- The so-called "consolidation" models account for the mass conservation of pore water and relate its expulsion between particles to the pressure vertical gradient by means of the permeability k, assuming Darcy's law. From the dynamics point of view, the stress within the soil can be split into the effective stress (σ') on the grains and the pore pressure on the fluid: only the latter forces the water movement. This concept is the basis of geotechnicians' approach for which the void ratio e is the state variable. When combined with water mass conservation, it leads to Gibson's equation (Gibson *et al.*, 1967), assuming constitutive relationships for permeability and effective stress as a function of the void ratio:

$$\frac{\partial e}{\partial t} - \frac{\gamma' s}{\gamma w}\frac{dk_r}{de}\frac{\partial e}{\partial z} + \frac{1}{\gamma w}\frac{\partial}{\partial z}\left(k_r \frac{d\sigma'}{de}\frac{\partial e}{\partial z}\right) = 0 \qquad (2)$$

where $k_r = k / (1 + e)$: relative permeability
$\gamma's$: immersed unit weight of particles
γw: unit weight of pore water
z: material coordinate, representing the thickness of solid particles.

Recently, several authors (Been, 1980, Tan *et al.*, 1990 in Alexis *et al.*, 1992; Toorman and Berlamont, 1991) have pointed out the analogy of these models and proposed unifying theories where the settling velocity can be expressed as a function of the permeability and the effective stress.

The main problem of these theories is the validation of the involved constitutive relationships (v_S (c), k(e) or σ'(e)), to which models are very sensitive (see Alexis *et al.*, 1992). Besides, in the present study, the role of effective stresses has a minor importance, as we are mainly dealing with fluid mud and fresh deposit. Thus we choose the sedimentation concept, with the formalism of consolidation models, that is material coordinate z and void ratio e. The continuity equation, which can be deduced from (2) with $\sigma' = 0$, is written :

$$\frac{\partial e}{\partial t} + \frac{dv_s}{de}\frac{\partial e}{\partial z} = 0 \qquad (3)$$

The use of discretized material coordinates prevents the exchanges of material between layers during the consolidation, which is interesting to avoid spurious numerical diffusion, especially when we look for the becoming of marked fractions of sediment.

The fundamental assumption of this simple model is the dependence of the settling velocity on the void ratio, which is equivalent to the Kynch's hypothesis. Nevertheless, such a model can fit rather well many settling tests after appropriate calibrations. In particular it can reproduce steps in density profiles (lutoclines) just by means of strong variations of the derivative dv_S/de, which are likely to correspond to changes of the soil structure.

Modelling the Loire estuary

The summer configuration of the Loire estuary, on the Atlantic coast of France has been chosen to test the effects of consolidation. This estuary is about 100 km long (fig. 1), with a tidal range of 5 m on spring tides and a fresh water flow varying from 80 to 5 000 $m^3.s^{-1}$ (average : 800 $m^3.s^{-1}$). In the case of low river flow (100-400 $m^3.s^{-1}$) a 1-D cross-averaged advection/dispersion model has proved its efficiency in simulating a realistic turbidity maximum, induced by tidal propagation only (Le Hir and Karlikow, 1991). In particular the settling of the turbidity maximum as fluid mud on neap tides and the resuspension of this fluid mud when the tidal range increases was quite well reproduced.

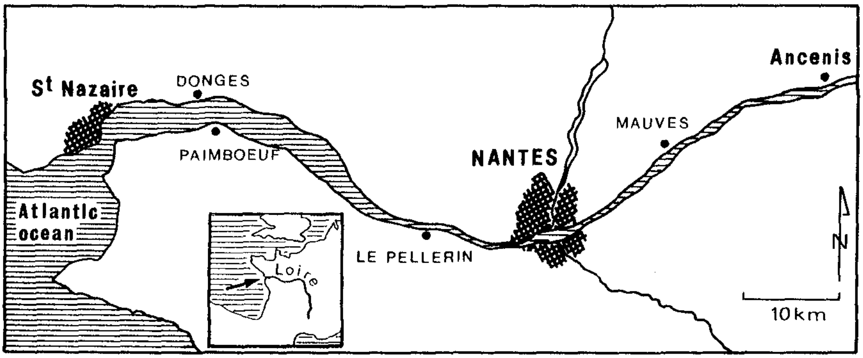

Figure 1: Location of the Loire estuary.

However, consolidation was very crudely accounted for : only two sediment classes (a little concentrated "fluid" mud and a more concentrated mud) where considered, and consolidation was represented as periodic exchangesbetween these classes.

In the present study, consolidation is computed by means of the previously described sedimentation model, coupled with the horizontal transport model through the deposition and erosion terms. The latter is empirically related to a shear strength which is deduced from the surficial mud concentration according to a power law (Owen in Mehta *et al.*, 1989) :

$$\tau_{ce} = \alpha C_s^{\beta} \tag{4}$$

τ_{ce} : critical shear stress for erosion ($N.m^{-2}$).
C_S : surficial sediment concentration, computed by the sedimentation model ($kg.m^{-3}$).
α,β : coefficients to be calibrated.

Actually the results are very sensitive to this relationship which is part of the consolidation modelling ; moreover, there can be some compensation between the uncertainty on the computed concentration (however easier to validate) and the lack of knowledge related to the shear strength, especially for fluid mud. Last but not least, the bottom shear stress itself is poorly determined, as the effects of turbulence damping by high suspensions (Teisson *et al.*, 1992) are not accounted for.

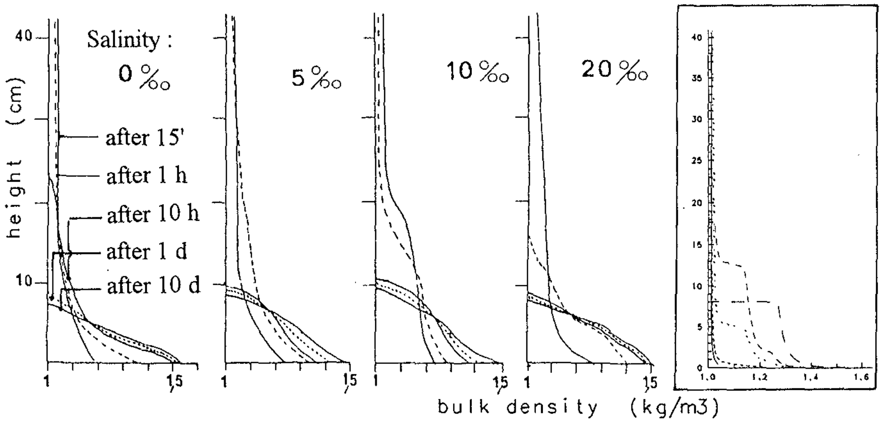

Figure 2: Evolution of sediment density profiles
(initial height : 2 m ; initial concentration : 20 g/l)
a) laboratory settling tests with sediment from Loire (after Gallenne, 1974).
b) Simulation with a sedimentation model.

Nevertheless, the sedimentation model has been briefly calibrated with laboratory settling tests made by Gallenne (1974) on the Loire sediment. Although the observations proved the dependence of the sedimentation on the salinity, which is not accounted for by the model, the simulated results are in relative agreement with the experiments (fig. 2). Settling velocities at the beginning of the settling tests have been reduced, in order to maintain low densities (very fluid mud) during the neap tide in the simulations of the Loire system. The resulting relationship v_S (e or c) is plotted on figure 3 : one can see some continuity with known values of settling velocities for flocculated suspensions (e.g. in Metha *et al.*, 1989).

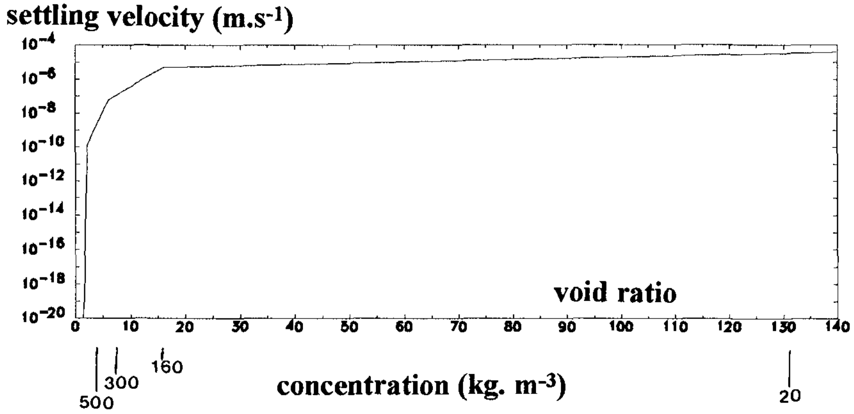

Figure 3 : relationship v_S (e) used in the sedimentation model of the Loire estuary. The relation between e and c is based on a grain density of 2,65.

In the following, four runs will be compared to show the effect of consolidation on sediment transport in the Loire estuary.

- Run 1 : no consolidation, any deposited sediment has a fixed low shear strength (0,8 $N.m^{-2}$).

- Run 2 : schematic consolidation : two sediment classes with low and high shear strengthes (respectively 0,8 and 1,6 $N.m^{-2}$).

- Run 3 and 4 : full consolidation modelling, as previously described. The difference between run 3 and run 4 is a change in the relationship τ_{ce} (C_S) : - run 3 : $\tau_{ce} = 0{,}14\ C_S^{0,4}$ for which resuspension is easy.
  - run 4 : $\tau_{ce} = 0{,}2\ C_S^{0,4}$ leading to hard resuspension .

For each run the tide conditions and river flow are identical, and presented on figure 4.

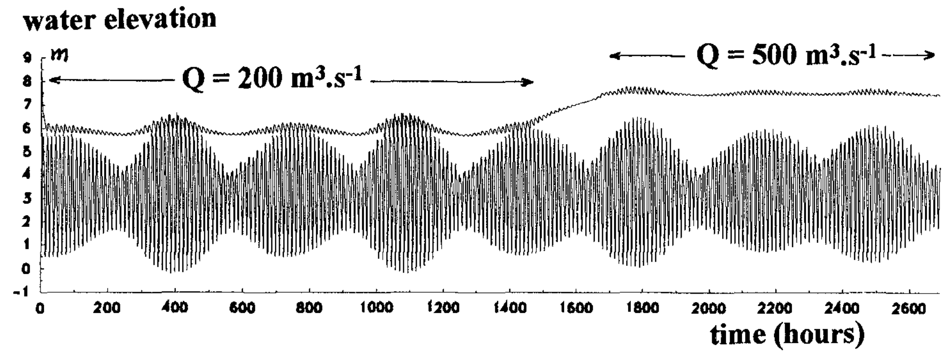

Figure 4 : Tidal forcing and riverflow regime during the simulation of sediment transport in the Loire estuary.

Note : a test with no shear strength of the (fluid !) mud has been run. In this case the turbidity patterns are completely unrealistic, with a turbidity maximum at the sea boundary and no stable mud deposit on neap tide. In fact such a result can be induced by the absence of turbulence damping in the model. In reality the latter process could maintain a fluid mud in the estuary. This comment has little impact on the following tests : in fact we are dealing with the consolidation process, that is a change in space and time of sediment characteristics, rather than the rheological behaviour of the mud. Besides, the low value of the exponent in the relation (4) partly accounts for the turbulence damping, as it reduces the large resuspension that would occur for low surficial sediment densities.

Effects of consolidation processes on the sediment transport in the Loire estuary

On figure 5, the average distribution of suspended sediment during a spring tide for a low river flow is presented for each run. The analogy between the simulated turbidity maxima is obvious. Differences only appear in the extension of the turbidity structure which is more spread when consolidation is badly accounted for, especially in the upper part of the estuary ; this is due to the fact that in such cases, just after deposition, the sediment get instantaneously some shear strength, whereas in a more realistic scenario, it should not have time to consolidate before the flow is strong enough to resuspend it. The same observation can be made for the total deposited mud (fluid mud and partially consolidated mud) on the following neap tide (fig. 6) : locations are similar but the deposition in the upper estuary is higher for run 4 (consolidation is more effective).

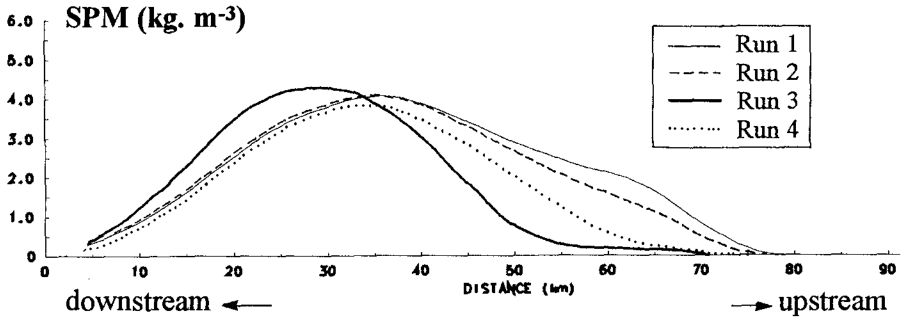

Figure 5 : Computed turbidity maximum (tidally averaged) after 46 days simulation (spring tide ; low river flow = 200 $m^3.s^{-1}$).

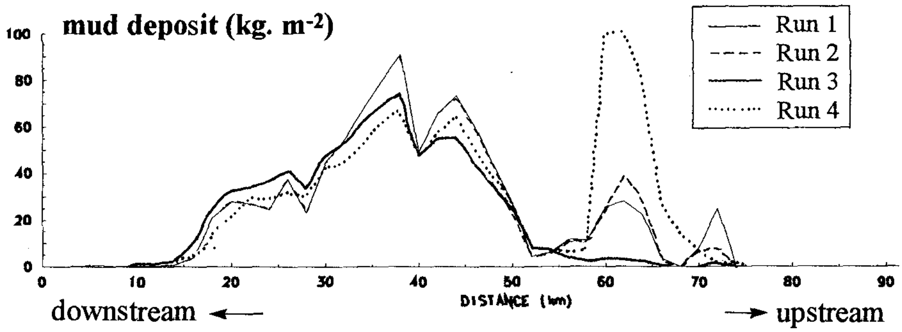

Figure 6 : Computed mud deposits (tidally averaged) after 52 days simulation (neap tide ; low river flow).

Considering the time variation of suspended particulate matter (SPM) and mud deposit in the middle of the estuary during a fortnightly tidal cycle (fig. 7), we still notice a similitude between the four runs, but the phase of resuspension is strongly dependent on the consolidation modelling. In particular, in run 4, consolidation is quick enough to prevent the total resuspension, and a net deposition after the neap/spring tidal cycle is observed. However the range of mud deposition as well as suspended particulate matter are very similar. It should be noticed that the maximum of SPM does not occur on spring tide but during the mean tides, when exchanges with bottom are maximum. The differences between the minima of SPM at high water during spring tides can be related to the variations of turbidity spreading we mentioned before, as the observation is located on the upstream edge of the turbidity maximum at high water.

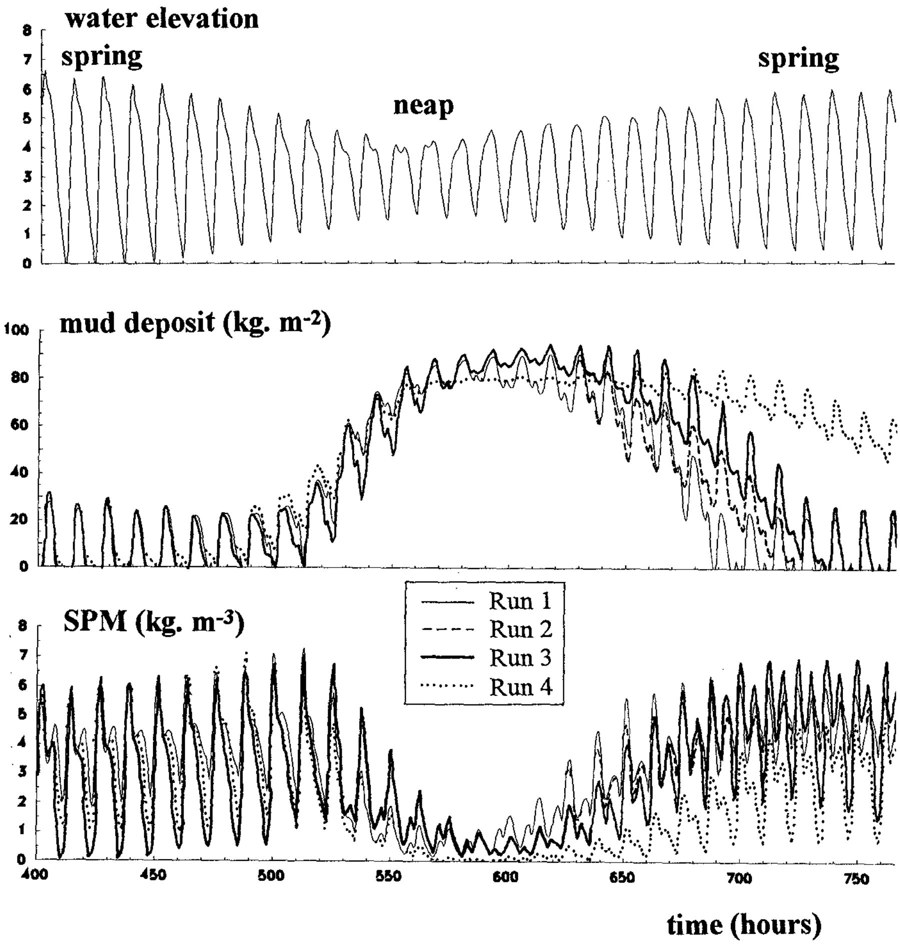

Figure 7 : Time evolution of suspended particulate matter and mud deposit, computed at station "Le Pellerin" (low river flow).

When the river flow is increased, all sediment patterns are shifted downstream (fig. 8 ; Le Hir and Karlikow, 1991). Turbidity maxima still look like each other, but the ranges can differ, due to possible previous consolidation. This is pointed out on figure 9 : when consolidation effects are more effective (run 4) some sediment previously deposited during the period of low river flow remains in the upper estuary, which notably reduces the seaward transport of material, at least for mean river flow. Thus the consolidation can affect the residual flux of sediment within the estuary during the seasonal changes.

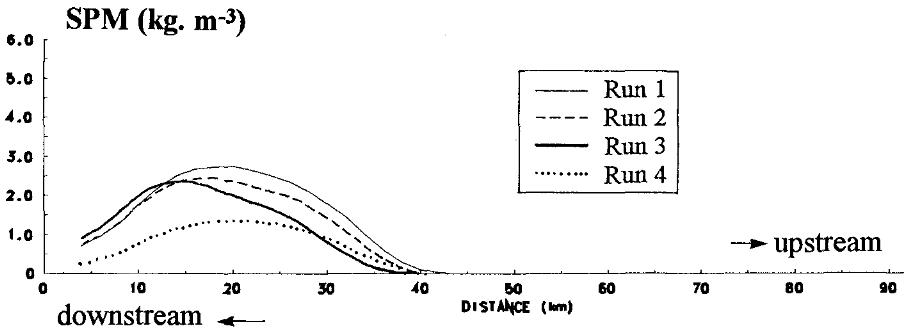

Figure 8 :

Computed turbidity maximum (tidally averaged) after 104 days simulation (spring tide ; mean river flow = 500 $m^3.s^{-1}$)

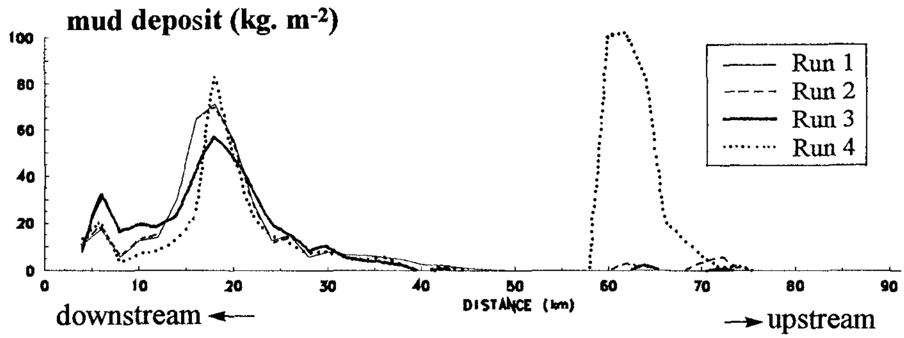

Figure 9 :

Computed mud deposits (tidally averaged) after 110 days simulation (neap tide ; mean river flow).

Discussion and conclusions

The simulation of sediment transport in the Loire estuary shows that both turbidity maximum and fluid mud patterns are few dependent on consolidation processes.

However the consolidation influences the time lags between hydrodynamical forcings and sediment processes : for instance within the fortnightly cycle, for the sediment resuspension by tidal currents, or within the seasonal cycle, for the longitudinal transport through the estuary. Thus the consolidation forces the residual deposition or erosion of mud. Naturally these results are specific to a macrotidal estuary and should not be generalized to all cohesive sediment areas.

But this study has also pointed out the sensitivity of simulations to the relationship between the sediment density and its erodibility : our knowledge on this subject is so poor that a sophisticated model for the prediction of mud density would be useless. In addition the required constitutive relationships that any consolidation model involves are still hypothetical. For theses reasons we should recommend to use simple consolidation models until the knowledge on soil behaviour progresses substantially.

Lastly, we mentioned the competition between the strengthening of sediment by consolidation and the bottom stress reduction related to the turbulence damping in highly concentrated suspensions. This means that the use of any sophisticated - and presumed realistic - consolidation model should be completed by a bottom stress computation with the same accuracy. Many field validation measurements are required to manage it.

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