Dynamics of Concentrated Benthic Suspension Layers

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This paper describes the dynamics of Concentrated Benthic Suspensions (CBS). CBS is defined as a suspension of cohesive sediment with a notable interaction between the sediment and the turbulent flow field through buoyancy effects, but still displaying near-Newtonian behaviour.

The mechanisms which distinguish CBS from low-concentrated suspensions are described, and the focus is on the (hindered) settling and mixing processes. Experiments were carried out in an oscillating grid tank and in an rotating annular flume, simulating entrainment and mixing associated with the turbulent CBS-layer, as occur in tide-driven flows. It is shown that CBS can be modelled as a viscous fluid, and that the entrainment rates quantitatively match relations described in the literature on salt-fresh water induced stratified systems.

Numerical simulations with one-dimensional vertical models using k-ε and Prandtl mixing length turbulence closures were carried out for hypothetical open channel flows to study the behaviour of CBS through sensitivity analyses. It is shown that high-concentrated mud suspensions may become saturated, generating a CBS-layer prior to the formation of fluid mud.

KEY-WORDS
Concentrated Benthic Suspensions, fluid mud, entrainment, mixing, buyoancy

1. INTRODUCTION

Large siltation rates of navigational channels and harbour basins are often attributed to high-concentrated mud suspensions, and a proper physical description of such suspensions is a necessary condition for a cost-effective maintenance strategy for these fairways. High-concentrated mud suspensions are also encountered in the turbidity maxima of most estuaries, in large stretches of many turbid rivers all over the world and around mud banks in coastal areas.

The COSINUS-project, executed under the framework of the European MAST3 research programme, is aimed at enhancing our understanding of the behaviour of such high-concentrated suspensions, and developing mathematical formulations to describe the relevant physical processes, together with their parameterisations, to be incorporated in mathematical models for managing authorities and engineering consultants. The present paper describes the work carried out under Task C of the project, relating to the dynamics of concentrated near-bed suspensions of cohesive sediment, referred to as Concentrated Benthic Suspensions (CBS). The interaction between sediment and turbulent flow is the characteristic feature of CBS-suspensions, and its modelling is also addressed in a companion paper (Toorman et al., 2001).

Suspensions of cohesive sediment can be classified through their concentration and the flow conditions. Increasing the amount of sediment in suspension, characterised by the overall Reynolds number and the Rouse number, a CBS is obtained upon deposition. As noted, CBS is characterised by a notable interaction between the suspension and the turbulent flow field, and an overall Richardson number is the governing parameter. At higher concentrations, a fluid mud layer occurs, which flows under laminar conditions, and its behaviour is governed by an effective Reynolds number, accounting for plastic yield effects in the mud. At still larger concentrations a stagnant consolidating bed is formed in which the yield strength exceeds the applied stresses. Figure 1 presents a diagram of these four classes, including the relevant exchange processes between the various mud phases. Note that the transfer from one class to another is gradual in general, and that a decrease in flow velocity can result in a sequence similar to the effects of increasing sediment concentration.

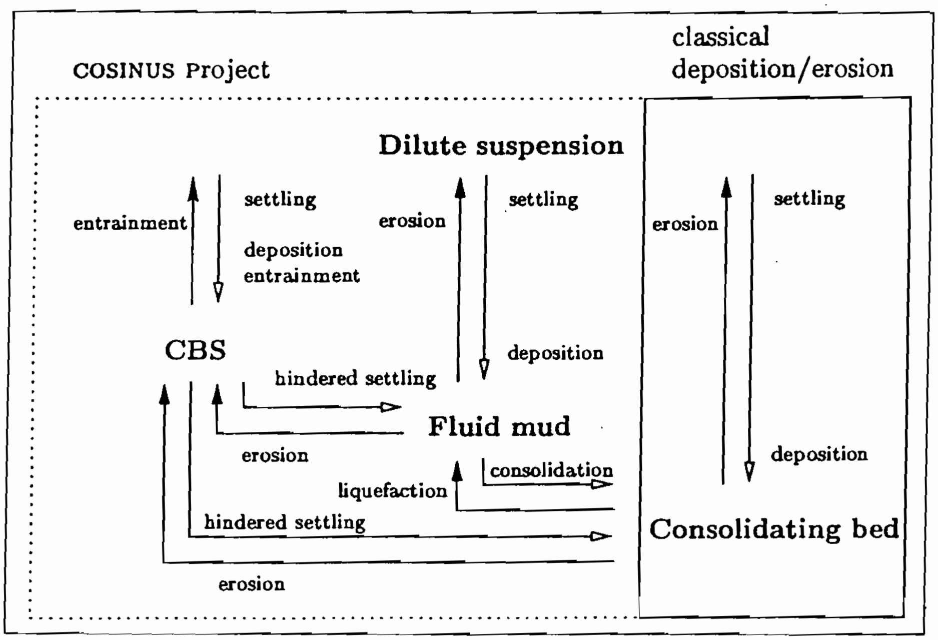

Figure 1. Four classes of suspension and exchange processes.

Whether or not these classes occur depends on the time scales of the physical processes. For instance, the time scales for settling and flocculation determine whether a fluid mud layer is formed during slack water, and the time scale for consolidation determine whether re-entrainment or erosion processes will occur during accelerating flow.

The present paper focuses on the behaviour of CBS-layers, and the processes of entrainment, (hindered) settling and vertical mixing are especially addressed. In Section 2 a phenomenological description of these layers is given, comparing CBS-dynamics with other stratified flow phenomena and with the behaviour of suspensions of non-cohesive sediment. In Section 3 measurements in an oscillating grid tank on equilibrium conditions are presented, together with a series of entrainment experiments carried out in a rotating annular flume. Theoretical and numerical analyses of the behaviour of CBS-layers around and beyond equilibrium are discussed in Section 4. Finally, discussion and an overview of the conclusions is presented in Section 5.

The work described in Section 3.1 was carried out at LEGI, Grenoble, the work presented in Section 4.2 at the Katholieke Universiteit Leuven, and the work described in the Sections 3.2 and 4.1 in Delft.

2. PHENOMENOLOGICAL DESCRIPTION OF CBS-LAYERS

A Concentrated Benthic Suspension can be considered as a turbidity current. Both can be self-sustaining provided turbulence is generated continuously to keep the particles in suspension. It is illustrative to discuss first the behaviour of two miscible fluids of different density, for instance a salt water layer below a fresh water layer. If either of the two, or both layers are sufficiently turbulent, ultimately the two layers will mix completely. The mixing process of such a stratified system is a function of a Richardson number, often characterised as a bulk Richardson number $Ri_*(\equiv B/u_*^2)$, which is the ratio of the total buoyancy $B \equiv \Delta gh$ of the stratified system and the kinetic energy available for mixing, characterised by the friction velocity u_*. Here Δ is the relative density of the sediment particles, g is gravitational acceleration and h is the total water depth.

In the case of a suspension, complete mixing does not necessarily occur, as the particles tend to restore the stratified condition by settling under the effect of gravity. Hence, an equilibrium condition, in which the sediment is not fully mixed over the entire water column, can occur as the result of a balance between the available turbulent mixing energy produced by the bed shear stress and the work to be done to keep the particles in suspension. It can be hypothesised that at equilibrium the effect of the settling velocity of the particles W_s at the interface equals the effect of the entrainment velocity w_e of the interface. The suspended sediment concentration at equilibrium C_e is therefore a function of a reference fluid density ρ, Ri_*, W_s and w_e, or, because it can be shown that $w_e = f(Ri_*)$:

$$C_e/\rho = F_1(Ri_*, \beta) \qquad (1)$$

where $\beta(\equiv \sigma_T W_s/\kappa u_*)$ is the Rouse number. Based on a more formal analysis one can show that (Winterwerp, 2001):

$$\frac{C_e}{\rho} = K_s \frac{u_*^3}{\Delta g h W_s} \tag{2}$$

where K_s is a coefficient of order one. C_e can be regarded as a measure for the total load that can be carried by a turbulent shear flow. If by some cause the flow velocity were to decrease, or the water depth were to increase, C_e would decrease, as a result of which part of the suspension would settle. During this process strong buoyancy destruction near the bed occurs, which may cause a thickening of the viscous sublayer. In case of non-cohesive sediment a rigid bed is formed rapidly at which turbulence production remains possible. Thus a new equilibrium is established at a lower load.

It is interesting to note that (2) is very similar to the so-called Knapp-Bagnold criterion (Parker et al., 1986) for the occurrence of submarine turbidity currents:

$$C < \frac{\rho}{\Delta g} \frac{U_t u_*^2}{\delta W_s} \tag{3}$$

where U_t is the mean flow velocity of the turbidity current and δ its thickness. This would be a necessary condition for a self-sustaining turbidity current; it is also known as the auto-suspension criterion.

Next, a suspension of cohesive sediment in equilibrium is considered. If the particles settle because of a decrease in flow velocity or an increase in depth no rigid bed is formed, but a layer of CBS upon which fluid mud occurs, as the large cohesive sediment flocs form a space-filling network at relative low mass concentrations. At the water - fluid mud interface little or no turbulence production is possible. Hence, as the turbulent energy for mixing decreases, C_e decreases further etc. This results in a "snowballing" effect, leading to a complete collapse of the vertical concentration profile and the turbulence field. For cohesive sediments, the equilibrium concentration C_e can therefore be regarded as a saturation concentration, denoted as C_s.

In the next sections the generation of an equilibrium condition for CBS, its mixing characteristics, and its response to changing flow conditions are discussed.

3. EXPERIMENTS ON CBS

Experiments on CBS were conducted in a rectangular tank with an oscillating grid and in an rotating annular flume. It should be noted that the turbulence properties in these two facilities are not identical. In the annular flume, turbulence is generated by shear flow over the entire water column, though the largest production is near the wall. Moreover, the near-wall turbulence is advected by the larger eddies (of the size of the water depth) throughout the water column.

In the tank, the turbulence is generated by an oscillating grid. Near the grid, the large scale eddies have the size of the grid mesh. The turbulent kinetic energy is transported away from the grid higher into the water column by diffusion, increasing more or less linearly in size away from the grid. As a result, the decay of turbulence off the grid must be included in the functional relation (1), which becomes for grid generated turbulence (e.g. Huppert et al., 1995):

$$C_e/\rho = F_2(Ri_*, u_*/W_s, z_0/\delta) \tag{4}$$

,where z_0 is a reference length scale related to the (location of the) oscillating grid, accounting for the decay of turbulence and δ is the thickness of the mixing layer (CBS-layer).

Note that similar several experiments with fresh and salt water and suspensions with non-cohesives have been reported in the literature, e.g. E and Hopfinger (1987) and Huppert et al. (1995). However, literature on experiments with cohesive sediment are rare. Tsai and Lick (1987) used an oscillating grid tank to establish the erosion rate of loosely consolidated mud, and Wolanski et al. (1989) observed steady CBS-layers in mud suspensions in a laboratory experiment in which turbulence was produced by the vertical oscillation along the vertical wall of annular rings having a regular spacing. The CBS thickness and concentration were found to be related to the grid oscillation frequency through a bulk Richardson number. As floc formation and the effects of hindered settling are important in suspensions of cohesive sediments, it was decided to carry out a new series of oscillating grid tank experiments with suspensions of cohesive sediment.

3.1. Experiments in an oscillating grid tank

Experiments were carried out in a square tank (53 cm by 53 cm, 40 cm water depth) in which turbulence was produced by an oscillating grid (see Gratiot et al., 2001, for a detailed description of the apparatus and the procedure). Sediment was led into the tank, while the grid oscillated, with an initial mean concentration C_0. An equilibrium concentration was attained after some time. By increasing C_0 step by step, the formation of a lutocline separating the CBS-layer from the upper layer was observed when C_0 exceeded 2 g/l. Experiments were carried out with organic-rich mud from the Tamar estuary and non-organic mud form the Gironde estuary.

symbol	mud	salinity S [ppt]	grid frequency F [Hz]	initial concentration C_0 [g/l]	concentration in CBS C [g/l]
'□'	Gironde	0	3	85.0	202
'x'	Gironde	0	3	61.0	149
'∇'	Gironde	0	6	30.0	51
'o'	Tamar	16.5	4	3.6	5.1
'.'	Gironde	16.5	4	2.7	3.8

Table 1. Experimental conditions and explanation of symbols.

For equilibrium conditions, vertical profiles of the sediment concentration $C(z)$, the turbulent rms-velocity $u(z)$ and the integral length-scale $\ell(z)$ were measured from the energy spectrum. Figure 2 shows a measured vertical concentration profile. For all conditions, the time-averaged sediment concentration was found to be uniform within the lower 20 cm of the CBS layer. Figure 3 shows vertical profiles of the rms-turbulent velocity (the various symbols are explained in Table 1). The turbulent velocity decreases with increasing distance from the grid, as anticipated from (4). There were no observations suggesting enhanced decay of the turbulent velocity with increasing sediment concentration.

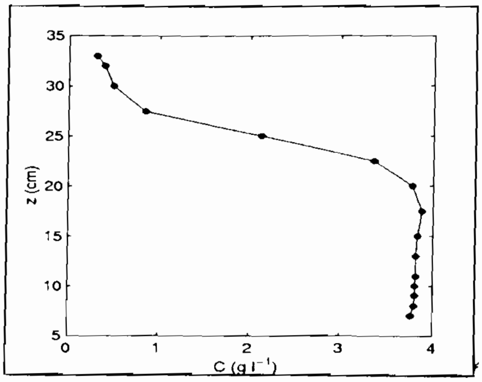

Figure 2. Vertical profile of concentration obtained with Gironde mud for C_0 = 3.6 g/l.

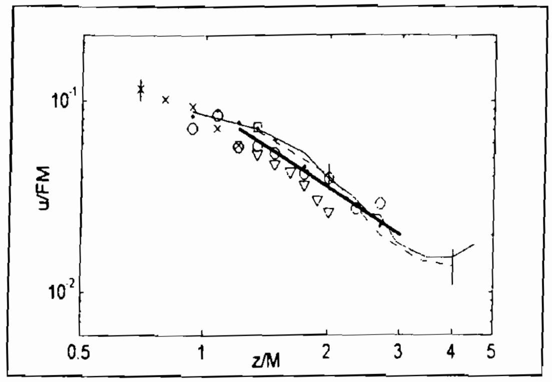

Figure 3. Variation of the turbulent velocity u with distance to the grid *z* (*F* is the frequency of grid oscillation, *M* is the grid mesh size). Full line and dot-dashed line are measurements of turbulent velocity in clear water.

Measurements of the settling velocity W_s were also carried out. Depending on the concentration, the settling velocity was found to vary by two orders of magnitude. The measured values of u, ℓ, C and W_s were used to estimate the flux Richardson number below the lutocline, expressed as (e.g. Gratiot et al., 2001):

$$Ri_f = \frac{\rho_s - \rho_w}{\rho_s}\frac{W_s}{u}\frac{gC\ell}{\rho_w u^2} \bigg/ \left(A + \frac{\rho_s - \rho_w}{\rho_s}\frac{W_s}{u}\frac{gC\ell}{\rho_w u^2} \right) \tag{5}$$

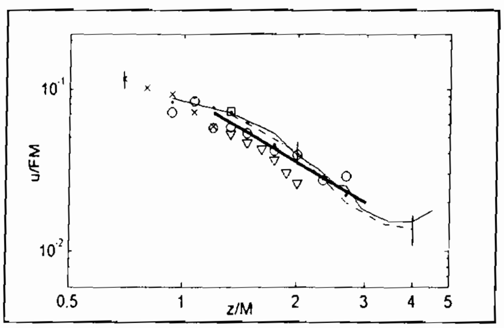

Figure 4. Variation of the flux Richardson number a the lutocline with concentration in the CBS-layer.

For a turbulent flow with no mean velocity component. A is a constant of order one which appears in the rate of dissipation of the kinetic energy $\varepsilon = A\rho_w u^3 / \ell$. Equation (5) gives a simple relationship between the flux Richardson number, the bulk Richardson number and the Rouse number. The value of the flux Richardson number at the lutocline is shown in Figure 4 as a function of the concentration inside the CBS-layer. The flux Richardson number is larger than 0.5 at the lutocline when the concentration in the CBS is less than 50 g/l, and it is of the order of 0.2 when the concentration is above 100 g/l.

3.2. Experiments in a rotating annular flume

The rotating annular flume set-up, with a rotating top lid driving the flow, was appropriately modified to study the mixing/entrainment processes of CBS. For this purpose, the top lid of the flume was replaced by a rotating base plate, supported by streamlined rods. The flume has an outer diameter of 4 m, a width of 0.3 m, and the water height was generally set at 0.25 m. The base plate floated on a bath of mercury to prevent flow around the base plate and the settling of sediment below the base plate.

Base plate and flume could be rotated in opposite directions to minimise the effect of secondary currents. An equation was derived analytically on the basis of the tangential flow momentum equation in the flume to establish the ratio of rotational speeds at which secondary current effects are minimal. This equation was verified with experiments in the flume, visualising the flow and secondary current effects, both for homogeneous and stratified flow conditions. The conditions for homogeneous flow were further substantiated with numerical analyses using the commercial software package PHOENICS. A detailed description of this set-up and the various analyses is given by Bruens et al. (2001).

The experimental procedure was as follows. After the production of a stratified flow in the flume (either salt-fresh water, or turbid-fresh water), flume and base plate were slowly accelerated in the same direction in such a way that the fluid itself was accelerated as a rigid body. Then, when the required rotational speed of the flume was obtained after a period of several tens of minutes, the base plate was accelerated fairly rapidly in the opposite direction until its required rotational speed was obtained. At that point in time the entrainment experiment (measurements) started. In this way, a shear flow in the rotating fluid was generated as long as the denser fluid accelerated through bed friction mainly. Such experiments ended when the stratified fluid was completely mixed over the water depth. Note that, because of the accelerating flow, no equilibrium CBS-height was obtained in this configuration.

During these experiments the following parameters were measured: rotational speeds of flume and base plate, height of the interface, salinity of the upper layer (only insalt-fresh water experiments), (turbulent) flow velocities in longitudinal and vertical directions at two heights and suspended sediment concentration at four heights (only for CBS-experiments).
The friction velocity u_* was not directly measured, but obtained by using the logarithmic law of the wall, a quadratic friction law, and from numerical simulations with PHOENICS. All these approaches yielded similar values.

In the first series of experiments, the mixing of a salt water layer below a fresh water layer in the flume was studied under different flow conditions (in terms of the overall Richardson numbers Ri_*). Next, experiments with China clay in mildly saline water (5 ppt) were conducted. A suspension of 40 g/l concentration was homogeneously mixed over the water column. This suspension was allowed to settle during two hours, resulting in a CBS-thickness of about 0.1 m and a concentration ranging from about 50 g/l at its top to about 200 g/l at its base. Six series of experiments were carried out at five values of Ri_* ranging from 81 to 188 by varying the rotational speeds of flume and base plate (in each case at the optimal ratio).

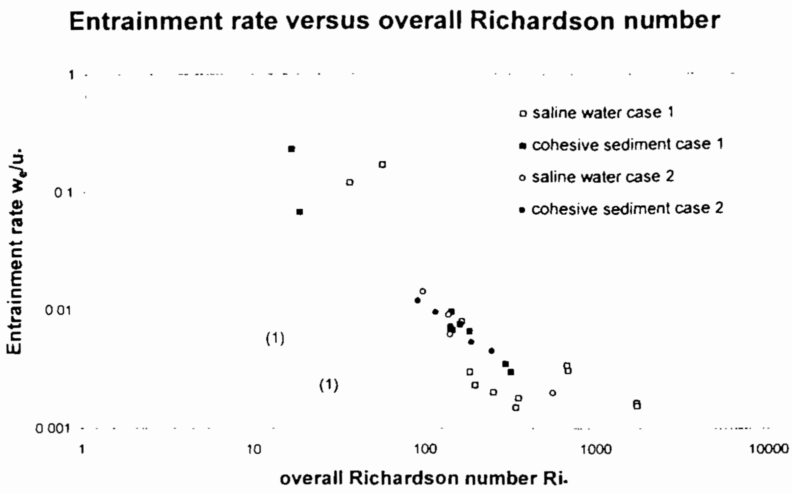

Figure 5. Entrainment diagram from experiments in the rotating annular flume (case 1: upper layer turbulent; case 2: lower layer turbulent).

The results of the entrainment experiments are summarised in Figure 5, where the initial entrainment velocity w_e on the vertical axis is made non-dimensional with the shear velocity u_*. For details the reader is referred to Bruens et al. (2001). This figure also contains data from previous experiments (e.g. Winterwerp and Kranenburg, 1997) carried out in the same rotating annular flume, but with rotating top plate, and it is shown that the results match fairly well. It can be concluded that, as long as the mud has not attained yield strength, a CBS behaves as a viscous fluid.

4. THEORETICAL ANALYSES

The interaction between cohesive sediment and the turbulent flow field may cause a significant reduction in vertical mixing and overall hydraulic resistance. Reduction in vertical mixing was measured in the field by for instance West and Oduyemi (1989) and Van der Ham (1999). A reduction in the overall hydraulic resistance was observed in a number of high-concentrated rivers in China (Dong et al., 1997, Guan et al., 1998 and Wang et al., 1998) and on the Amazon shelf (Beardsley et al., 1995). Theoretical studies on this drag reduction were reported by Zhou and Ni (1995) and Toorman (1999).

Sediment-induced overall drag reduction has a significant effect on the flow field. If the CBS-occurrences are spatially confined, as in navigational channels, at small mud banks, etc., the overall flow rate will remain constant, and the reduction in drag will cause changes in the vertical profiles of flow velocity and mixing.

If the CBS-occurrences are unconfined, as in the large rivers in China and Brazil, the overall flow rate does not necessarily remain constant, and the flow may accelerate, affecting total flow rate, velocity profile and vertical mixing.

In the next two sections distinction is made between these two situations, as this has a large effect on the flow-sediment interaction.

4.1. Confined CBS-occurrences: constant flow rate

Confined occurrence of CBS can be found in navigational channels, in the turbidity maxima in estuaries, or above small mud banks. The flow rate is governed by large scale overall processes, and is not (or only slightly) affected by local CBS-occurrences. In this case a positive feed-back, described in Section 2 of this paper, can be expected, resulting in a total collapse of the vertical concentration profile and turbulence field.

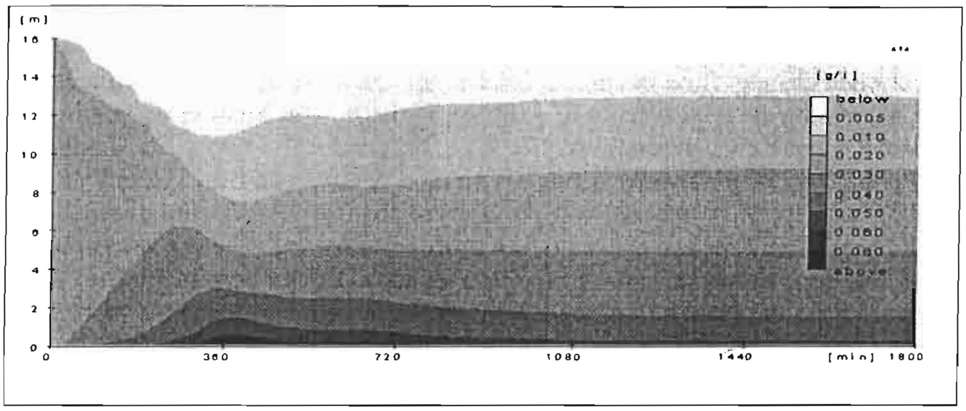

Figure 6. Isolutals for a saturated (C_0 = 0.023 g/l) suspension in open-channel flow.

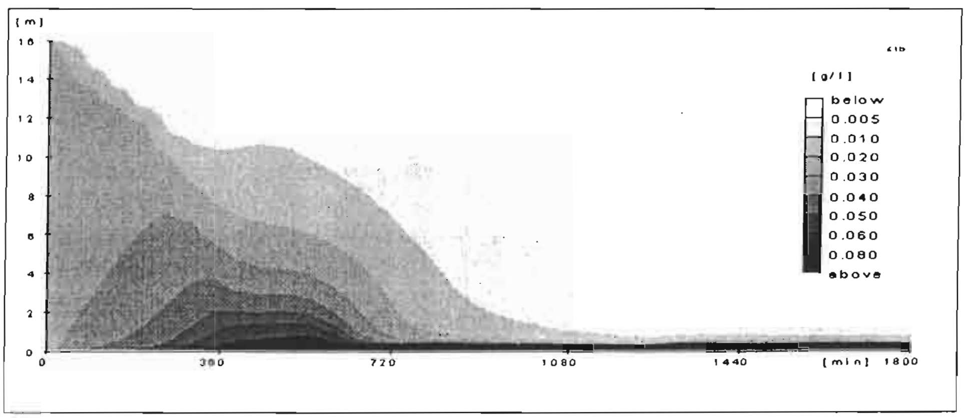

Figure 7. Isolutals for a super-saturated (C_0 = 0.024 g/l) suspension in open-channel flow.

Winterwerp (1998, 1999) analysed this feed-back process, starting from an analysis presented by Teisson et al. (1992). The basic idea behind this analysis is that experiments on stratified flow reported in the literature show that a turbulent shear flow collapses when the flux

Richardson number Ri_f exceeds a critical value. The sediment load that is transported just prior to this collapse can be regarded as the transport capacity of the turbulent flow. The related depth-mean suspended sediment concentration is referred to as the saturation concentration C_s in order to differentiate this case from the reversible condition for non-cohesive sediment, where the transport capacity is characterised by an equilibrium concentration C_e. The scaling law for C_s is presented in Section 2, e.g. equ (2).

This saturation behaviour was further studied with the numerical 1DV POINT MODEL, derived from a full three-dimensional water movement and sediment transport model in which all horizontal gradients have been stripped, except for the horizontal pressure gradient. The standard k-ε turbulence model is implemented, including a sediment-induced buoyancy destruction term. The effect of the sediment on the bed boundary condition is implicitly taken into account through the dependency of the friction velocity on the gradients in suspended sediment concentration (fluid density).

Equilibrium and saturation conditions, were studied with the 1DV POINT MODEL for a hypothetical open channel flow having various depths, flow velocities and sediment settling velocity by increasing the total amount of sediment in the flow in small steps, starting from an initially homogeneous concentration profile C_0. The results for two such simulations are shown in Figure 6 and 7 for a water depth h = 16 m, a depth-mean flow velocity U = 0.2 m/s and a settling velocity W_s = 0.5 mm/s. It is observed that for a sediment concentration C_0 = 0.023 g/l a more or less Rousean concentration profile is obtained, whereas a small increase in C_0 to C_0 = 0.024 g/l shows an almost complete collapse of the vertical profile. Above the lutocline, only little turbulence is produced by the local velocity gradients. Apparently, the 0.023 g/l case represents the sediment transport capacity of the flow, whereas the 0.024 g/l case represents super-saturated conditions.

Further simulations showed that the numerical results follow the functional relation (2) properly. These results are not presented herein, and the reader is referred to Winterwerp (1999, 2001).

Kranenburg (1998) studied the equilibrium conditions of CBS-layers with a Prandtl mixing length model, using Munk-Anderson-like damping functions:

$$\overline{u'w'} = -\ell^2 \left|\frac{\partial u}{\partial z}\right| \frac{\partial u}{\partial z} F(Ri) \;, \quad \overline{w'c'} = -\frac{\ell^2}{\sigma_T} \left|\frac{\partial u}{\partial z}\right| \frac{\partial c}{\partial z} G(Ri) \;, \quad \text{with}$$
$$F(Ri) = (1 + ARi)^{-a} \;, \quad G(Ri) = (1 + BRi)^{-b} \tag{6}$$

where $\ell(z)$ is the mixing length. Kranenburg argued that for σ_T = 0.7, A = B = 2.4, and the exponential coefficients should become a = 2 and b = 4, respectively. These damping functions were implemented in the one-dimensional vertical momentum and mass balance equation for suspended sediment, which were solved numerically. The damping function F was also explicitly applied to the shear velocity u_* to include buoyancy effects in the boundary conditions. Simulations were carried out at a constant flow rate and for various amounts of sediment, initially mixed homogeneously over the water column at a concentration C_0. It was shown that at low C_0, a more or less Rousean concentration profile was obtained, whereas for $C_0 > C_{crit}$ the concentration profile collapsed. C_{crit} can be regarded as the saturation

Time-varying isolutals similar to those described in Section 4.1 were computed, yielding qualitatively the same behaviour as described above. The results showed that lutoclines can appear temporarily, forming an interface between nearly clear water at the surface and the CBS-layer. The final steady state stratification depends on the ratio W_s/u_* and the sediment load (Toorman, 1999 & 2001).

In order to better understand the characteristics of CBS-layers, specific attention has been given to steady state calculations in which the influence of input energy (i.e. u_*), settling velocity and sediment load have been studied (Toorman, 1999 & 2001). A typical series of results, where u_* has been varied, is shown in Figure 8. The most noteworthy feature is that, starting from a well-mixed situation at high u_*, the flux Richardson number profile tends to homogenise over the entire water column when decreasing the shear velocity (Figure 8d). A further small decrease of u_* rapidly leads to an apparent total collapse of turbulence at the bottom as soon as $Ri_f = 1$, i.e. turbulence production by shear at the bottom is completely destroyed by buoyancy. What happens physically is a thickening of the viscous sublayer, accompanied by drag reduction (Toorman, 2000).

To describe this process properly, the turbulence models must be extended to include a low-Reynolds module to handle the laminarisation of the flow in the bottom layer, for which a grid refinement and a moving interface are required (Toorman et al., 2001). The value of the flux Richardson number, which corresponds to this condition, lies in the range of 0.2 to 0.25 (when no buoyancy term is used in the dissipation rate equation, and its value is slightly sensitive to the settling velocity). This value corresponds to the empirical critical value for turbulence collapse. Therefore, it seems that the condition $dRi_f/dz = 0$ determines the limiting state at which the minimal energy is provided to keep sediment in suspension. A theoretical proof for this hypothesis, however, is still missing.

Further theoretical analysis of the implementation of the condition $dRi_f/dz = 0$ reveals that the saturated concentration profile is a Rousean profile with Rouse parameter value 1, which is confirmed by the simulations (Figure 8b). These simulations show that any sediment in excess remains in the near-bottom layer where turbulence is no longer fully developed. Hence, Rouse parameter values < 1 correspond to unsaturated and > 1 to supersaturated conditions. The corresponding eddy viscosity profile is parabolic (Figure 8c) and the corresponding velocity profile is logarithmic (Figure 8a), but the value of the von Karman coefficient is reduced to $\sigma_T W_s/u_*$ (where σ_T is the turbulent Schmidt number). Consequently, the exponents of u_* and W_s in eq.(2) would become 4 and 2 respectively (Toorman, 2001).

The sensitivity study on the influence of the shear velocity also shows that the depth-averaged velocity decreases with u_* down to a minimum and then increases again due to drag reduction. This implies that for the same mean flow velocity two steady state solutions exist at a relatively low and high sediment load. This explains why simulations at constant flow rate, as described in section 4.1, performed with two different models for the same input conditions yield a saturated state in one model, but unsaturated in another (Violeau et al., 2001). Further analysis shows that the history of the bed shear stress is an important parameter, which seems to be strongly affected by the numerical scheme used and boundary conditions. Therefore, the interpretation of model results near saturation need to be done with great care.

5. DISCUSSION AND CONCLUSIONS

This paper discusses the dynamical behaviour of Concentrated Benthic Suspensions of cohesive sediment in open channel flow. It is argued that suspensions of cohesive and non-cohesive sediment can both be characterised by capacity conditions, which can be measured by an equilibrium concentration of the suspended sediment. Such capacity conditions for cohesive sediment can only occur if abundant sediment is available. The main difference between the two suspensions at post-capacity conditions is caused by the formation of a layer of fluid mud upon sedimentation of cohesive sediment flocs, whereas the sedimentation of sand results in a rigid bed at which turbulence production remains possible.

It is reasoned that CBS-layers can achieve a state of equilibrium at which the suspended sediment is mixed over only a part of the water depth. This is in contrast to stratified systems of miscible fluids, which will always be mixed completely if at least one of the layers is sufficiently turbulent. At this equilibrium, turbulence production and sediment-induced buoyancy destruction are balanced, which can be achieved only if no positive feed-back occurs between the turbulence production and the suspension (buoyancy destruction). The existence of such an equilibrium was proven experimentally in an oscillating grid tank, showing that the level of the lutocline and the mean (equilibrium) concentration beneath this lutocline are a function of the grid properties (mesh, frequency and amplitude of oscillation). This equilibrium concentration can be regarded as the transport capacity of the flow.

Starting from equilibrium conditions, an increase in turbulence intensity, e.g. by increasing the flow velocity in open channel flow, will result in vertical mixing causing a rise of the lutocline and a lowering of the suspended sediment concentration below the lutocline. Experiments in a rotating annular flume showed that this mixing can be classified as entrainment, and that this entrainment is identical to that which occurs in fresh/salt water stratified systems.

From observations reported in the literature it is known that sediment-induced buoyancy effects can cause a significant reduction in overall hydraulic resistance. This implies that distinction must be made between spatially confined and unconfined CBS-occurrences. Theoretical and numerical analyses show that in the case of confined CBS-occurrences, at which the local flow rate remains constant, post-capacity conditions result in saturation, i.e. a complete and irreversible collapse of the vertical concentration profile and turbulence field. It appears that numerical simulations with a IDV-model follow the theoretical derived scaling law for saturation properly.

However, the actual value of the saturation concentration, as computed with various numerical models (Violeau et al., 2001), appears to depend on the applied numerical schemes, the bed boundary conditions and their implementation. Furthermore the catastrophic collapse described in Section 4.1 may consist of a narrow concentration range over which the transport capacity of the flow diminishes. In addition, Section 4.2 suggests that the actual value of the saturation concentration and its functional relationship may be more complicated than described in Section 2, i.e. $C_e \propto u_*^n$ (see equ. (2)), where n = 3 or 4. It should be emphasised, however, that at present no direct empirical evidence exists for this "snowballing" effect resulting in the predicted collapse, nor on the actual functional relationship of the saturation value and the hydrodynamic parameters.

A final important observation is that in the case of unconfined CBS-occurrences, drag reduction by sediment-induced buoyancy effects will result in an acceleration of the flow, hence an increase in turbulence production. This implies that significant differences may be expected in the dynamics of confined and unconfined CBS-occurrences.

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