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Mathieu Mory, Nicolas Gratiot, A. Manning, Hervé Michallet. CBS layers in a diffusive turbulence grid oscillation experiment. INTERCOH 2000, Sep 2000, Delft, Netherlands. pp.139-154, 10.1016/S1568-2692(02)80013-4 . hal-00260368

HAL Id: hal-00260368

<https://hal.science/hal-00260368>

Submitted on 6 Apr 2022

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CBS layers in a diffusive turbulence grid oscillation experiment

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The generation of a Concentrated Benthic Suspension (CBS) of a fluid mud mixture is investigated in the laboratory in a grid stirred experiment. A sediment concentration in the CBS layer in the range 3 g/l to 200 g/l was considered. The sediment concentration, the turbulence properties, and the settling velocity have been measured. The decay of turbulence with increasing distance from the grid is not found to vary with the concentration inside the CBS layer except in the vicinity of the lutocline. The settling velocity decreases rapidly with increasing sediment concentration and appears to be the most sensitive parameter in the experiment. A clear difference in the value of the flux Richardson number at the lutocline is observed depending on the sediment concentration. Ri_f is about 0.1 for the highest concentrations and increases above 0.5 for the low concentration cases.

KEYWORDS

Fluid mud, turbulence, flocculation, cohesive sediment suspensions

1. INTRODUCTION

Special attention has recently focused on the existence of Concentrated Benthic Suspensions (CBS) of cohesive sediments in numerous natural sites. The concentration is large in these suspensions which are subjected to a high level of turbulence. The concept of a saturation concentration for cohesive sediment was introduced in 1996 by Winterwerp (see Winterwerp, 1999). For a turbulent shear flow, the latter obtained a relationship between the thickness of a CBS layer, the concentration, and the hydrodynamic properties of the flow. The

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concept of saturation is based on the principle (Turner, 1973) that a turbulent shear flow collapses when the flux Richardson number Ri_f reaches a value of about 0.15.

We investigate in this paper the concept of saturation concentration in an oscillating grid experiment. Natural mud sediment was introduced in a tank where turbulence was produced by an oscillating grid. Grid tank experiments were used before to study the resuspension of cohesive sediments by turbulence (Tsai and Lick, 1986; Wolanski *et al.*, 1989). In a grid tank experiment similar to ours, E and Hopfinger (1987) observed that the layer containing non-cohesive particles resuspended by turbulence reached an equilibrium thickness, an observation which is in a qualitative agreement with the concept of saturation. Although oscillating grid experiments are far from producing flow conditions achieved in the field, they allow to study turbulence conditions with no mean flow. Turbulence is transported by turbulent diffusion. The isolated contribution of turbulence to mixing can be studied in oscillating grid devices.

A specific feature of the present study is that experiments were performed in a grid tank facility using fluid mud mixtures, implying that the settling of sediments is modified by the flocculation of particles. Because the sediment concentration is sufficiently high, it is assumed in this study that the effect of particles on turbulence is solely related to density-stratification. The focus of the paper is on the interaction between the turbulence and density-stratification. By performing settling velocity measurements, the effect of turbulence on the settling velocity is however accounted for. Turbulence properties, sediment concentration and settling velocities were all measured in the laboratory. The flux Richardson number below the interface was determined from these measurements in order to investigate a relationship between the thickness of the CBS layer and the sediment and turbulence properties. The paper is divided as follows. A review of the effect of stratification on turbulence is presented in the next section. The flux Richardson number is defined and its relation to the Rouse number and the Richardson number as usually defined in oscillating grid turbulence is given. The different measurements are presented in sections 3 to 5. The results are used in section 6 to determine the flux Richardson number at the interface.

2. THE EFFECT OF STRATIFICATION ON GRID TURBULENCE IN SEDIMENT LADEN FLOW

The evolution of the turbulent kinetic energy in a sediment laden flow is subjected to four mechanisms: the production of turbulent kinetic energy by energy exchange with the mean flow, the diffusion, the dissipation, and gravity effects. The balance equation for the turbulent kinetic energy k is often written in a symbolic form (see Winterwerp, 1999),

$$\frac{dk}{dt} = P + D - \varepsilon - B \quad , \quad (1)$$

in order to distinguish the four processes. P and D denote the production of turbulent kinetic energy by the mean flow and the diffusion of turbulent kinetic energy, respectively. They are simply expressed in the framework of the k - ε model of turbulence. ε is the dissipation rate of the turbulent kinetic energy. The buoyancy term is

$$B = \frac{\gamma}{\rho_w} g \overline{w'c'} \quad (2)$$

(Sheng and Villaret, 1989), with $\gamma = (\rho_s - \rho_w) / \rho_s$. ρ_s and ρ_w are the densities of solid particles and water, respectively. g is the acceleration of gravity. B is the rate of increase of potential energy required to maintain the sediment in suspension. Particles in a sediment laden fluid have a non-zero settling velocity W_s . Steady conditions are obtained when the turbulent flux of sediment is equal to the settling flux of sediment as deduced from the mass balance equation, i.e.

$$\overline{w'c'} = W_s C \quad . \quad (3)$$

The buoyancy term B has therefore a simple dependence with the mean concentration C :

$$B = \frac{\gamma}{\rho_w} g W_s C \quad . \quad (4)$$

Following Ivey and Imberger (1991), the flux Richardson number

$$Ri_f = \frac{B}{P + D} \quad (5)$$

quantifies the relative importance of gravity in the balance equation of the turbulent kinetic energy in steady conditions. For turbulent shear flows the diffusion term is often omitted (Villaret and Trowbridge, 1991; Winterwerp, 1999) because the production of turbulence by the mean flow gradient is usually the dominant term, except in the vicinity of the free surface. In the absence of mean flow, such as in grid turbulence, the production term vanishes and the diffusion of turbulence is the only process by which the turbulent kinetic energy is transported. For a steady turbulence with no mean shear flow, the flux Richardson is simply rewritten as

$$Ri_f = \frac{B}{B + \varepsilon} \quad . \quad (6)$$

Equation (6) is more convenient than (5) since the dissipation term is simply expressed in terms of the turbulent rms velocity u and turbulent lengthscale ℓ

$$\varepsilon \approx A \frac{u^3}{\ell} \quad , \quad (7)$$

where A is a constant of order O(1). Using equation (4), we then deduce

$$Ri_f = \frac{\frac{W_s}{u} \frac{\gamma g C \ell}{\rho_w u^2}}{A + \frac{W_s}{u} \frac{\gamma g C \ell}{\rho_w u^2}} \quad (8)$$

The flux Richardson number is a local quantity which varies over the vertical as a function of the turbulent rms velocity $u(z)$, the turbulent lengthscale $\ell(z)$ and the mean concentration $C(z)$. For the conditions considered in this paper, our experimental observations will show that the concentration in the CBS layer is uniform (see section 4). We therefore write $C(z) = \Delta C$ in the CBS layer, ΔC being the sediment concentration jump across the interface. The flux Richardson number $Ri_f(z)$ is therefore expressed as a function of the Richardson number $Ri(z)$, as usually defined for grid turbulence experiments (Hopfinger & Toly, 1976),

$$Ri(z) = \frac{\gamma g \Delta C \ell(z)}{\rho_w u^2(z)} \quad (9)$$

and the Rouse number

$$Rou(z) = \frac{W_s}{u(z)} \quad (10)$$

Considering steady conditions, the integration of equation (1) over a layer having its lower boundary h_0 below the lutocline and its upper boundary h_1 above the lutocline gives

$$F(z = h_0) = w_c \gamma g \Delta C (h_1 - h_0) + \int_{h_0}^{h_1} \varepsilon(z) dz \quad (11)$$

$F(z)$ denotes the flux of turbulent kinetic energy at the position z . The flux of turbulent kinetic energy is written

$$F(z) = A' u^3(z) \quad (12)$$

where A' is a constant of order $O(1)$. Because turbulence has vanished above the lutocline, the flux of turbulent kinetic energy at h_0 balances in eq. (11) the rate of increase of potential energy and the total dissipation within the layer. Equation (11) is of little use for determining the position of the lutocline unless the vertical variation of the dissipation rate is known. However it explains the existence of a maximum position of the lutocline for given conditions since the buoyancy term in eq. (11) increases linearly with the layer thickness.

By comparing in eq. (11) the buoyancy term to the flux of turbulent kinetic energy, we observe that the parameter driving the lutocline occurrence is the product of the Richardson

number by the Rouse number $Ri(z)Rou(z)$ as already anticipated in the expression of the flux Richardson number (eq. 8). When $Ri(z)Rou(z) \ll 1$, gravity effects are negligible and the evolution of u and ℓ with z is not modified by the presence of sediments. Gravity effects will be active when $Ri(z)Rou(z)$ reaches a value of order $O(1)$.

Different authors have considered before the significance of the flux Richardson number. Turner (1973) and Ivey and Imberger (1991) have shown that turbulence collapses when the flux Richardson number Ri_f reaches a value of the order of 0.15 to 0.25. This experimental evidence was taken by Winterwerp (1999) as a basis for establishing the concept of a saturation concentration for cohesive sediments. The critical value of Ri_f in the range 0.15 to 0.25 was obtained by Ivey and Imberger (1999) in view of experimental data for salt-stratified or temperature-stratified shear flows. The applicability of this result to fluid mud mixtures in a grid tank turbulence is questionable. On the one hand, the settling velocity of particles tends asymptotically to zero for salt stratification. In oscillating grid tank experiments, no steady state is obtained and the interface is continuously displaced upward for this type of stratification. On the other hand, diffusing turbulence and shear produced turbulence are different. To our knowledge, estimates of Ri_f in purely diffusive flows are still lacking.

Previous experiments (E & Hopfinger, 1987; Huppert *et al.*, 1995) show the existence of a saturation concentration for sediments maintained in suspension by a diffusing turbulence. The above considerations provide a physical understanding of the process, but the quantitative determination of the position of the lutocline is not available*. In our laboratory experiments, measurements of the vertical variations of the turbulent rms velocity, the integral lengthscale, the mean concentration and the settling velocity have allowed to estimate the value of Ri_f at the lutocline for various CBS experimental conditions.

3. THE EXPERIMENTAL SET-UP, PROCEDURES AND OBSERVATIONS

The experiment was performed in a square tank, 53 cm wide. For all experiments, the water depth was 40 cm. The horizontal grid, made of 1.5 cm square bars with a mesh $M = 7.5\text{cm}$, oscillated vertically. The mean position of the grid was 5 cm above the bottom of the tank. The grid oscillation conditions were determined by the stroke $S = 4.5\text{cm}$ (twice the amplitude) and the frequency F of oscillation. Three different values $F = 3\text{Hz}$, $F = 4\text{Hz}$ and $F = 6\text{Hz}$ were considered in the study. The tank and the grid geometry were similar to these used previously by Hopfinger and Toly (1976). The latter authors have shown that these experimental conditions ensure that there is no mean flow at distances from the grid larger than $2M$. The turbulence is transported away from the grid by a diffusive process. The turbulence properties are 1DV, i.e. they vary only with the distance z from the grid. The position $z=0$ is here the mean position of the grid and the Oz axis is oriented upward. Figure 1 is a sketch of the experimental set-up.

* E & Hopfinger (1987) and Huppert *et al.* (1995) have determined from an equation similar to (11) a relationship between the layer thickness, the sediment concentration and the turbulence properties, but they assume that turbulence is not modified by gravity effects.

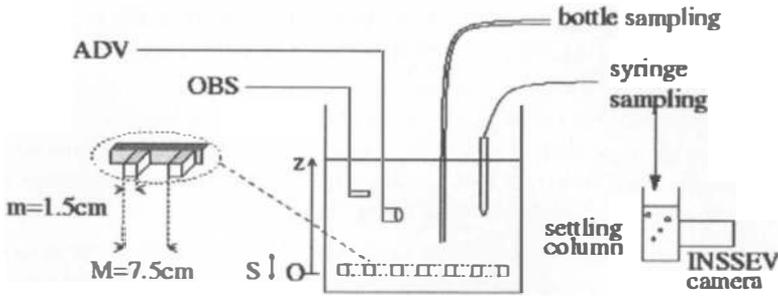


Figure 1. Experimental set-up.

An homogenous premixed fluid mud mixture was introduced in the tank while the grid oscillated. The vertical distribution of sediments was redistributed during a transient evolution in which settling of sediments and turbulent transport of sediments both occurred. Settling occurred in the upper part of the tank where the turbulence level was not sufficient to maintain the sediment in suspension. A lutocline appeared that moved downward until it became stable. Oscillations of the lutocline were observed but the mean level of the lutocline did not appear to change anymore. When the amount of sediment introduced inside the tank exceeded a certain level, the turbulence produced in the CBS layer was also not sufficient to maintain the whole amount of sediment in suspension. Sediment settled on the bottom to form a deposited bed. The equilibrium state consisted of three superposed layers: the deposited bed, the CBS layer and the clear water layer. This is called the saturated regime. When only a limited quantity of sediments was introduced in the tank a quasi-uniform suspension with no lutocline could be observed, and eventually no deposited bed was seen. This is the non-saturated regime.

Experiments were also carried out by starting the grid oscillation with the sediment initially deposited on the bottom and left to consolidate. For the same grid oscillation conditions, a smaller amount of sediment was maintained in suspension by turbulence when the sediment was initially on the bottom of the tank than when the sediment was introduced in suspension while the grid oscillated. We attribute this observation to consolidation effects in the deposited bed.

The tank was made of transparent Perplex walls which enabled the visualisation of the different sediment layers. Figure 2 shows a typical picture of the three layers stratification inside the tank taken in saturated steady conditions. Internal wave oscillations are visible at the lutocline.

Figure 3 illustrates the process that leads from non-saturated to saturated conditions. Vertical profiles of concentration, in steady conditions, are shown for four different initial concentrations \bar{C} . \bar{C} is defined as the mass of dry sediment divided by the total volume of fluid inside the tank. When \bar{C} is less than $1g/l$ the concentration is clearly uniform over the vertical. A small gradient of concentration is noticed in the upper part for $\bar{C} = 1.3g/l$ and the lutocline is clearly identified for $\bar{C} = 2.7g/l$. A further increase of \bar{C} enhances the gradient across the lutocline which is simultaneously displaced downward.

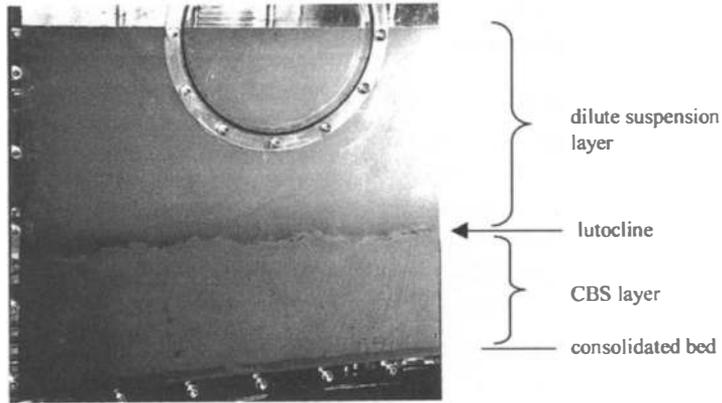


Figure 2. Photograph of the three layers observed for steady saturated conditions. The concentration in the CBS layer is $C_{CBS} \approx 80\text{g/l}$.

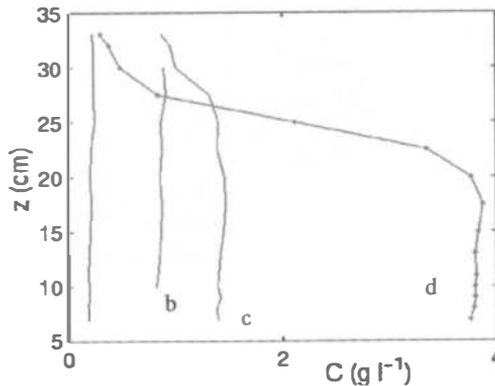


Figure 3. Vertical profiles of concentration measured for increasing values of the averaged concentration of sediments introduced in the tank. $F = 4\text{Hz}$. (a) $\bar{C} = 0.2\text{g/l}$; (b) $\bar{C} = 0.9\text{g/l}$; (c) $\bar{C} = 1.3\text{g/l}$; (d) $\bar{C} = 2.7\text{g/l}$. Inorganic mud from Gironde.

Three different natural mud have been used from the Gironde estuary (organic and inorganic) and from the Tamar estuary (organic). The inorganic mud from Gironde was chemically treated with potassium permanganate and passed through a $100\ \mu\text{m}$ sieve. Sediment analysis performed by de Croutte et al. (1996) revealed that the sediment's median diameter was about $D_{50} = 12\ \mu\text{m}$ and the sand content ($63\text{-}100\ \mu\text{m}$) was below 3%. The clay fraction was comprised of illite (35%), kaolinite (27%), smectite (24%) and chlorite (14%).

4. CONCENTRATION AND TURBULENCE MEASUREMENTS FOR SATURATED CONDITIONS

Vertical profiles of the mean sediment concentration $C(z)$ and of the rms turbulent velocity $u(z)$ were measured for different saturated conditions. The integral lengthscale $\ell(z)$ was also determined from velocity measurements for selected cases.

Saturated conditions were obtained when a sufficient amount of sediment \bar{C} was initially introduced in the tank. Table 1 summarises the different experimental conditions. Only the conditions that vary are given. Table 1 also contains the mean concentration C_{CBS} measured in the CBS layer in steady conditions and the distance z_l of the lutocline from the mean position of the grid. A wide range of concentration C_{CBS} was investigated.

Table 1
Experimental conditions of saturated concentration experiments.

mud	Sa (ppt)	F (Hz)	\bar{C} (g/l)	C_{CBS} (g/l)	z_l (cm)	symbol
Gironde I	0	3	85	202	10.5	□
Gironde I	0	3	61	149	9.8	x
Gironde I	0	6	30	51	17.0	∇
Gironde I	0	4	2.8	4.9	18.0	▷
Gironde I	0	4	7.1	11.6	17.0	◁
Tamar O	16.5	4	5.0	8.4	19.0	+
Gironde I	16.5	4	3.1	4.7	21.5	◇
Tamar O	16.5	4	5.1	8.1	20.0	△
Tamar O	16.5	4	3.6	5.1	23.5	○
Gironde I	16.4	4	2.7	3.8	23.5	•

Sa: salinity, F : frequency of grid oscillation, \bar{C} : averaged sediment concentration in the tank, C_{CBS} : mean sediment concentration in the CBS layer, z_l : distance of the lutocline from the grid. The symbols are those used in Figures 4, 5, 6 and 9.

Vertical profiles of the mean sediment concentration were measured from samples analysis and using an Optical Backscatter System (OBS) developed at the Institute of Marine Studies (Christie and Dyer, 1997). The calibration curve was determined for each mud. The voltage output of the OBS increases monotonically with increasing concentration when the concentration is below 40 g/l while it decreases with increasing concentration above 45 g/l. The OBS was therefore not used for concentrations in the range 35 – 50 g/l. Sample analysis were made to determine the appropriate part of the calibration curve.

Time series measurements of the velocity were made using an Acoustic Doppler Velocimeter (ADV) developed at Laboratoire des Ecoulements Géophysiques et Industriels. This system determines the velocity from the changes in the time shift of pulse-to-pulse back-scattered signals. The principle of operation is not new in itself, but a specific study (Gratiot *et al.*, 2000) was conducted to check its ability to measure the turbulent velocity in concentrated fluid mud mixtures. The adjustment of parameters of the ADV enabled to measure instantaneous velocities with a data rate of the order of 70 data/s for a concentration of 50 g/l. The data rate decreases to about 40 data/s for a concentration of 100 g/l. The rms

turbulent velocity u was computed from time series of about 4000 measurements. The ADV system could measure simultaneously the velocity component parallel to the beam axis at 16 positions. The distance between two successive measurement volumes was 3 mm. The integral lengthscale ℓ was deduced from the computation of the correlation function of the velocity measurements made simultaneously at the different locations.

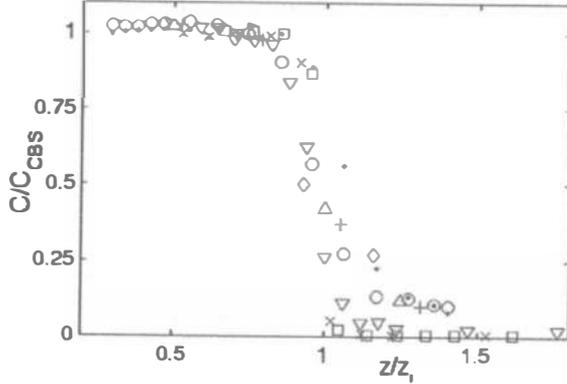


Figure 4. Vertical profiles of concentration measured in saturated steady conditions. Experimental conditions corresponding to the symbols are given in Table 1.

Figure 4 shows different vertical profiles of the mean concentration. The distance z from the grid is made dimensionless using the distance z_l of the lutocline from the grid, so that all profiles are centred around the lutocline position. We observe that the concentration is homogenous inside the CBS layer. The homogeneity of the concentration is apparently even better for the highest concentration ($C_{CBS} = 202 \text{ g/l}$); the interface thickness is smaller. This is partly because internal wave oscillations of the lutocline have a larger amplitude for smaller values of C_{CBS} , contributing to make the interface look thicker in Figure 4 when C_{CBS} is small.

The decay of the rms turbulent velocity u with increasing distance from the grid is shown in Figure 5 for different saturated experimental conditions. The concentration in the CBS layer considered for the plots in Figure 5 ranges between 3.8 g/l and 202 g/l . Also superimposed are two vertical profiles of the turbulent rms velocity made in clear water. It is observed that the decay of u is similar for all concentrations in the CBS layer considered. The uncertainty in measured data is rather large, as indicated by error bars, but no general trend indicating that u decreases for increasing values of C_{CBS} is observed. Actually the measurements made for the largest values of C_{CBS} collapse on the decay plots obtained in clear water, and the highest difference is between measurements in clear water and for $C_{CBS} = 51 \text{ g/l}$. For analysis of the data (section 6) the decay laws were interpolated by the power law function

$$\frac{u(z)}{FM} = 0.092 \left(\frac{z}{M} \right)^{-1.4} \quad (13)$$

in the range $1.2 \leq z/M \leq 3.2$ (M is the grid mesh) and for $z < z_t$. Although the exponent of the power is of the order of those obtained by different authors for oscillating grid turbulence, no particular attention should be paid to the value of the exponent, considering the narrow range of values of z/M . Because of the lutocline, turbulent velocity measurement could not be made at large distances from the grid.

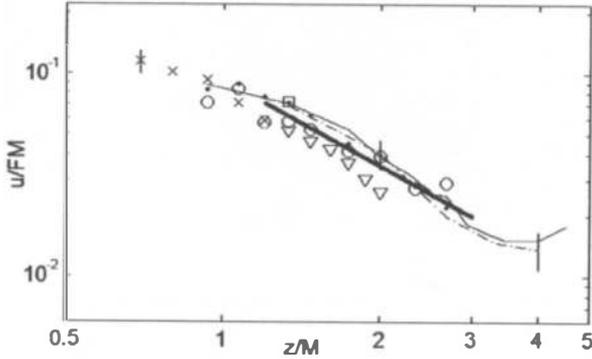


Figure 5. Vertical variations of the rms turbulent velocity in the CBS layer for saturated steady conditions. Experimental conditions corresponding to the symbols are given in Table 1. The solid light line and dashed dotted line are measurements in clear water for frequencies of grid oscillation $F = 6\text{Hz}$ and $F = 3\text{Hz}$, respectively. The heavy solid line is eq. (13).

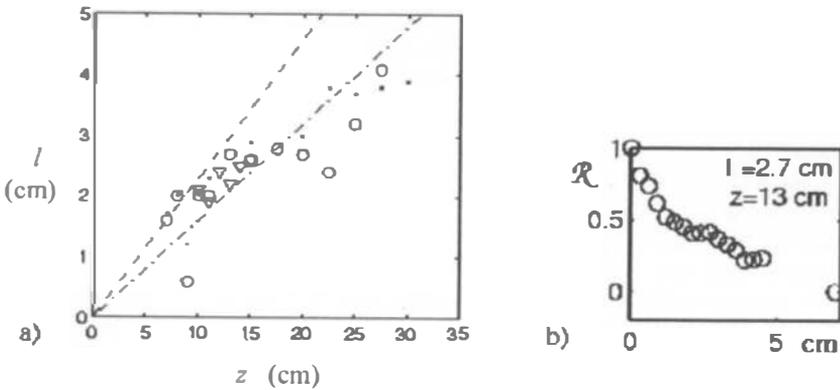


Figure 6. 6a. Integral lengthscale variations versus the distance from the grid in saturated steady conditions. Experimental conditions corresponding to the symbols are given in Table 1. The dashed line and the dashed dotted line are the results obtained by Hopfinger and Toly (1976) for $S = 4\text{cm}$ while $M = 10\text{cm}$ and $M = 5\text{cm}$, respectively. 6b. Correlation function measured at $z = 13\text{cm}$ for $C_{CBS} = 5.1g/l$.

Measurements of the integral lengthscale evolution with the distance from the grid are less common in the literature than measurements of the rms turbulent velocity, but there is a general agreement that the integral lengthscale varies linearly with the distance from the grid. This experimental result is supported by k - ϵ modelling (Sonin, 1983) in clear water, when the decay of the turbulent kinetic energy follows a power law, anyhow the value of the exponent is. Measurements of the integral lengthscale were made for selected cases. The results are shown in Figure 6a together with the results obtained by Hopfinger and Toly (1976). A correlation function R is also shown in Figure 6b. A number of correlation functions that were computed did not display such a nice and smooth behaviour as the case shown in Figure 6b. This explains the large scatter in Figure 6a. Nevertheless, the data indicate a clear increase of the integral lengthscale with increasing distance from the grid. Our measurements are not inconsistent with the results of Hopfinger and Toly. In view of this, the evolution of the integral lengthscale with the distance from the grid was taken for subsequent use of the data as

$$\ell(z) = 0.2z \quad . \quad (14)$$

5. SETTLING VELOCITY MEASUREMENTS

The settling velocity of cohesive sediments varies very much with the concentration. When the concentration in the CBS layer was below 15 g/l, the settling velocity was determined using the INSSEV system video camera (Fennessy *et al.*, 1994). This apparatus was developed at the Institute of Marine Studies for in situ measurements of the settling velocity of individual flocs. The size and the settling velocity of flocs are measured from the analysis of images of settling flocs in a column recorded by a video camera (Manning and Fennessy, 1997). Whereas the system is immersed in the water column for in situ measurements, samples were taken from the grid tank using a syringe of length 450 mm and diameter 8 mm, and introduced in the settling column for image recording. By comparing the floc properties measured in situ and measured after sampling, Manning (2001) concluded that the procedure of sampling did not modify the flocs. Figure 7 shows a typical diagram relating the floc diameter D_f , to the settling velocity W_s . The diameter D_f of the flocs measured by INSSEV is the square root of the length normal to settling direction times that measured in the settling direction. An essential feature is the dispersion in floc diameter and in settling velocity, indicating that the floc density is as well subjected to a significant variability. For further analysis, the settling velocity of each fluid mud suspension was determined by computing the mass flux of the suspension using the settling velocities measured for individual flocs. Error bars in the estimates were determined from the scatter in measurements.

For concentrations in the CBS layer larger than 15 g/l, the sedimentation of the suspension inside a column was recorded and the settling velocity was determined as a function of the concentration using the Kynch method (1952). Toorman (1999) recently reported the relevance of this method applied to highly concentrated suspensions of cohesive particles.

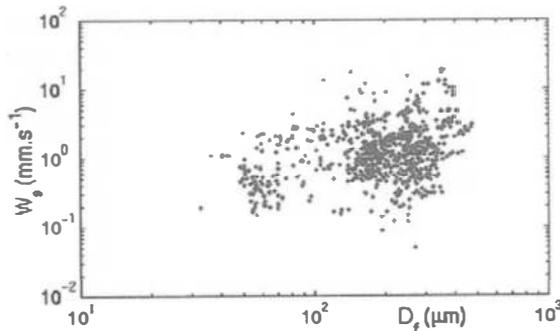


Figure 7. Variation of the settling velocity with the size of floc measured using INSSEV in a fluid mud suspension: Tamar mud, $\bar{C} = 1 \text{ g/l}$.

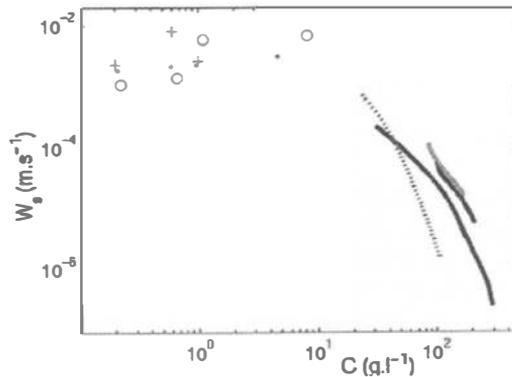


Figure 8. Variation of the settling velocity in fluid mud suspensions as a function of concentration. — Inorganic mud from Gironde ; + organic mud from Gironde; ○ and ... organic mud from Tamar.

Figure 8 shows the variation of the settling velocity with the concentration determined for the different mud considered in the study. Results obtained using INSSEV appear using symbols, whereas results obtained from sedimentation experiments are displayed as curves. Because INSSEV was available only during a limited period of the experimental study, the settling velocity has not been measured for all fluid mud suspensions concentration below 15 g/l. The variation of the settling velocity with the concentration in the CBS layer was interpolated from Figure 8. In spite of the large scatter in settling velocity estimates, Figure 8 clearly shows that the settling velocity decreases by two orders of magnitude when the concentration increases from 4 g/l to 200 g/l. The techniques used to measure the settling velocity in low concentrated suspensions (INSSEV measures the settling velocity of individual flocs) and in high concentrated suspensions (analysis of sedimentation experiments) are very different in their principles. It is however expected that the settling velocity decreases significantly when the sediment concentration is larger than 15 g/l, because of hindered settling effects.

6. THE FLUX RICHARDSON NUMBER AT THE INTERFACE

For all experiments listed in Table 1, the rms turbulent velocity u and the integral lengthscale ℓ were determined at the lutocline from eqs. (13) and (14), respectively. Their values, as well as the mud concentration C_{CBS} and the settling velocity W_s , are given in Table 2. These data were used to estimate the flux Richardson number at the lutocline (eq. 8). The variations of Ri_f with the concentration in the CBS layer are shown in Figure 9. The error bars result mainly from the uncertainties in the measurements of the settling velocity and of the rms turbulent velocity u (the dissipation rate varies as u^3). The value of $A=1$ for estimating the turbulent kinetic energy dissipation rate (eq. 7) was used for the plot in Figure 9. Similar curves were obtained for $A=0.5$ and $A=2$. They are not shown here, as the conclusions of the paper do not depend on this value.

Table 2
Turbulence properties at the lutocline and settling velocity for the CBS conditions given in Table 1

C_{CBS} g/l	202	149	51	4.9	11.6	8.4	4.7	8.1	5.1	3.8
z_l cm	10.5	9.8	17.0	18.0	17.0	19.0	21.5	20.0	23.5	23.5
u mm/s	12.9	14.2	13.1	8.1	8.8	7.5	6.3	7.0	5.6	5.6
ℓ cm	2.1	2.0	3.4	3.6	3.4	3.8	4.3	4.0	4.7	4.7
W_s mm/s	0.007	0.016	0.18	3.3	1.5	6.8	3.2	7.4	9.8	3.3
Rou	0.0005	0.0011	0.014	0.41	0.17	0.91	0.51	1.1	1.8	0.59
Ri	159	90.1	62.6	16.8	32.0	35.4	31.7	41.5	48.2	35.9

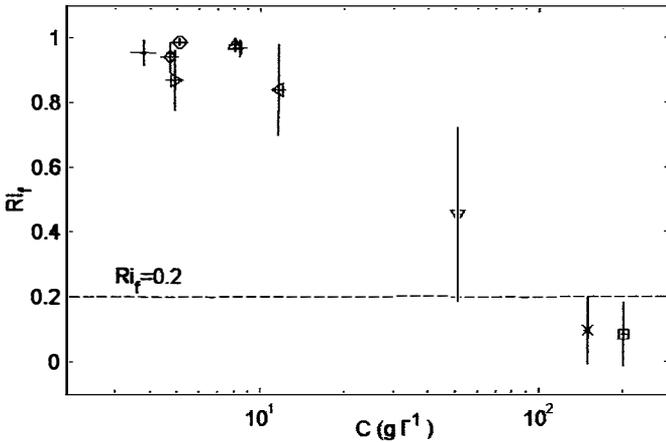


Figure 9. Variation of the flux Richardson number at the lutocline with the concentration in the CBS layer for steady conditions. Experimental conditions corresponding to the symbols are given in Table 1.

The major result of Figure 9 is that the flux Richardson number decreases from about 1 at the interface when the concentration in the CBS layer is low (a few g/l) to 0.1 when the concentration in the CBS layer increases to 200 g/l. This behaviour is due to the strong decrease in the settling velocity when the concentration in the CBS layer is larger than 50. The estimates of the Rouse and Richardson numbers at the lutocline are included in Table 2. The Rouse number is indeed very small for the large concentration cases, which correspond simultaneously to the highest values of the Richardson number (i.e. the strongest stratification).

In spite of the limited number of experiments carried out for large concentration conditions, their interpretation is less subjected to experimental uncertainty. For such conditions, the Richardson number is high (see Table 2). Because the amplitude of oscillations at the lutocline was small, velocity measurements could be performed close to the interface as shown in Figure 5. The rms turbulent velocity in the CBS layer displays no significant decrease as compared to measurements in clear water. Table 2 indicates that the turbulent Reynolds number based on u and ℓ is of the order of 200 for all conditions. The estimates of turbulence properties at the lutocline are based on measurements made close to the interface, enabling a confident estimate of the flux Richardson number at the interface. On the other hand, turbulence measurements could not be made close to the interface for the low concentration cases (less than 12 g/l) because of the oscillations of the lutocline. The estimates of u and ℓ at the lutocline given in Table 2 for the low concentration cases were extrapolated from eqs. (13) and (14). Since the product of the Rouse and the Richardson number is high, the flux Richardson number is about one at the interface. We cannot exclude that a smaller value would be obtained using measurements closer to the lutocline. Nevertheless, using measured values of turbulence, we estimate that $Rou.Ri = 1$ at a distance from the grid ranging between 11.5 cm and 13.8 cm for the low concentration range ($3.8\text{g/l} \leq C_{CBS} \leq 11.6\text{g/l}$) and at a distance of 14.5 cm for $C_{CBS} = 51\text{g/l}$. The flux Richardson number is therefore larger than 0.5 at the lutocline for the low concentration cases, a value which is clearly different from that obtained for the large concentration cases.

7. CONCLUSION

Concentrated Benthic Suspensions have been generated in a grid tank experiment using fluid mud mixtures of concentration in the range 4 g/l to 200 g/l. The concentration inside the CBS layer was nearly homogeneous. An important result of the study was that the decay of turbulence inside the CBS layer does not vary with the concentration, excepted in the vicinity of the lutocline. The decay of turbulence are quantitatively similar in a CBS layer of concentration as high as 200 g/l and in clear water.

The observation of CBS layers of thickness independent of time is not new. We have considered if the saturation effect that fixes the lutocline position can be characterised in terms of the criterion involving the flux Richardson number. The flux Richardson number at the interface (Figure 9) has been computed from measurements of turbulence and concentration inside the CBS layer and estimations of the settling velocity. Although our experiments have not been successful for determining a criterion for the lutocline position, a clear difference was found between the high concentration range ($C_{CBS} > 100\text{g/l}$) for which $Ri_f \approx 0.1$ and the low concentration cases ($C_{CBS} < 50\text{g/l}$) for which $Ri_f > 0.5$. A

numerical study is currently under investigation using a 1DV k- ϵ model in order to compute the vertical variation of Ri_f below the lutocline for the different cases considered in this study.

A significant part of the study was the measurement of the settling velocity. A very strong decrease of the settling velocity with increasing concentration was measured in our fluid mud mixtures. The theoretical analysis of the effect of stratification in a diffusing turbulence (section 2) shows that the driving parameter is the product of the Rouse number by the Richardson number, and therefore the settling velocity is indeed the most sensitive quantity when large concentration are considered.

8. ACKNOWLEDGEMENT

This work was carried as part of the COSINUS Program, which is funded by the European Commission (contract MAS3-CT97-0082). We express our gratitude to E. Hopfinger, who made the grid tank facility available, and J.M. Barnoud for his continuous technical assistance. A close collaboration was established with the Institute of Marine Studies (University of Plymouth) regarding measurements techniques. K. Dyer is thanked for his support.

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