Estuarine and Coastal Fine Sediments Dynamics
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A preliminary study on the hindered settling of kaolinite flocs

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This paper describes hindered settling experiments carried out with kaolinite suspensions in settling columns. In these columns, the settling velocity of the interface and the concentration in time at three or four specific heights were determined. From these measurements the gelling concentration and the settling velocity of the suspension could be determined. A mean gelling concentration of $C_{gel} = 81$ g/l was found and the settling velocities of the suspensions ranged from $w_s = 0.019$ mm/s for a suspension of 108 g/l to $w_s = 0.17$ mm/s for a suspension of 27 g/l. The settling behaviour was analysed with Kynch's theory which was found to be applicable to the measurements. In accordance with this theory, the experimental data could be divided into two groups. When the initial concentration was around a concentration of 35-46 g/l the settling behaviour changed from settling with two interfaces to settling with one interface. The experimental data was also compared with a theoretical model. The occurrence of both types of settling behaviour implied that the return flow depicts non-linear effects.

1. INTRODUCTION

High concentrations of mud flocs are present in natural environments such as estuaries, but also around dredging locations. The dispersion and the residence time of the fine fraction in the water column is an important factor in environmental studies. Especially, as high concentrations of fine sediment may influence primary production, the growth of plants and the forage possibilities of animal species. The dispersion and residence time is determined by the settling velocity of the mud flocs. At high sediment concentrations the mud flocs interfere with each other and their settling velocity is determined by the hindered settling effect. Information, data and literature on consolidation of mud flocs is available, but data on the hindered settling of mud flocs is scarce, probably because hindered settling of mud flocs is difficult to measure.

A detailed review on hindered settling of sand was given by Scott (1984). Part of these review results were presented elsewhere (Mandersloot *et al.*, 1986). The results showed that hindered settling is often described with models which are based on the well known formula by Richardson and Zaki (1954). For hindered settling of mud flocs, Mehta (1986) suggested a modified form of the Richardson and Zaki formula:

$$w_s = w_{s,0}(1 - k\phi_p)^n \tag{1}$$

where w_s is the effective settling velocity, $w_{s,0}$ the settling velocity of a single particle in still water, k is an empirical parameter, ϕ_p is the volumetric concentration of primary particles, $\phi_p = c/\rho_s$ in which c is the mass concentration and ρ_s the density of the sediment, and n is a function of the particle Reynolds number. Although Mandersloot *et al.* (1986) and Scott (1984) focused mainly on massive, Euclidean particles (sand), Winterwerp (2002) reasoned that their rationale can be applied to cohesive sediments as well. He suggests that, as each individual floc within a suspension is considered to settle in the rest of the suspension, this would result in three hindering effects:

- Return flow and wake formation. A settling particle generates a return flow and a wake. Other neighbouring particles will be influenced by this and their effective settling velocity will be decreased by a factor (1-ϕ), where ϕ is the volumetric concentration of flocs.
- Viscosity. Each individual particle within a suspension is considered to fall in the remainder of that suspension which has an increased viscosity.
- Buoyancy or reduced gravity. For the same argument, an individual particle settles in a suspension with an increased bulk density. The effective settling velocity is decreased by a factor (1-ϕ_p).

This led to a new theoretically derived formula for the hindered settling of mud flocs:

$$w_s = w_{s,0}\frac{(1-\phi)^m(1-\phi_p)}{1+2.5\phi} \tag{2}$$

Here the factor (1-ϕ) accounts for the return-flow effect, (1-ϕ_p) accounts for the buoyancy effect and (1+2.5ϕ) accounts for augmented viscosity. The exponent m is an empirical parameter to account for possible nonlinear effects. When the return flow effect is linear, (*i.e.*, m = 1), only the volume effect of a suspension settling in a liquid is taken into account. The downward flux of sediment is thus expected to create an equal upward flux of water with sediment. When nonlinearity is taken into account, all the effects generated by a settling particle in a suspension (*e.g.*, acceleration, deceleration of flow and the curvature of streamlines) are incorporated.

The volumetric concentration is herein related to the gelling concentration ($\phi \equiv c/c_{gel}$), in which $c_{gel}$is the concentration at which flocs become space-filling and form a network structure, called a gel, and a measurable strength builds up. The volumetric concentration, ϕ can thus become larger than unity when consolidation takes place. The volumetric concentration of primary particles is also related to the gelling concentration, $\phi_p = c/\rho_s = c_{gel}\phi/\rho_s$. Winterwerp (2002) compared Eq. 2 to data by fitting the model parameters and not actually using parameter values derived from data. A reasonable fit was obtained. The objective of this study is to test this theoretical formula against data from which the necessary parameter values for the model can be obtained. Experiments were carried out in the Laboratory of Environmental Fluid Mechanics at the TU Delft, The Netherlands, to obtain a data set from which gelling concentrations and settling velocities of the different suspensions could be determined. These parameters were determined by visual observations of the interface and conductivity measurements at several heights in the suspension in the settling column. First the hindered settling theory and tools for data analysis are given, whereafter this theory is applied to the experimental data.

2. KYNCH'S THEORY

The theory of sedimentation of highly concentrated suspensions was first studied by Kynch (1952). He introduced an empirical relationship between settling velocity and local sediment concentration as he assumed that at any point in a suspension the fall velocity of particles depends only on the local concentration of particles. This implies that the settling process can be determined from a continuity equation. In this section Kynch's theory with some further elaborations by Kranenburg (1992) is described.

First the particle transport flux is introduced:

$$S = w_s\phi \tag{3}$$

in which w_s the settling velocity. The effect of hindered settling is introduced by assuming that the settling velocity is a decreasing function of the local concentration,

$$w_s = w_{s,0} f(\phi) \tag{4}$$

where $w_{s,0}$ is the settling velocity of a single particle in still water and $f(\phi)$ is a function that describes the effect of the concentration on the fall velocity, thus $f(0)$=1 and $f(1)$=0. The one-dimensional volume balance for a settling suspension can then be written as:

$$\frac{\partial \phi}{\partial t} + \frac{\partial S}{\partial z} = 0 \tag{5}$$

where t is time and z is height, positive upwards. When Eqs. 3, 4 and 5 are combined, this leads to the following equation:

$$\frac{\partial \phi}{\partial t} + w_{s,0} F(\phi) \frac{\partial \phi}{\partial z} = 0 \tag{6}$$

where

$$F(\phi) = \frac{\mathrm{d}}{\mathrm{d}\phi}[\phi f(\phi)] \tag{7}$$

Equation 6 comprises the 1-D simple wave equation. It describes the settling process of a cohesive sediment suspension in still water. It can be solved by integrating along characteristic lines in the (z, t) plane. These characteristic lines are given by

$$\frac{\mathrm{d}z}{\mathrm{d}t} = w_{s,o} F(\phi) = C_c \tag{8}$$

they present lines of equal concentration and C_c is the celerity (wave speed). Because the characteristic lines present lines of equal concentration (ϕ), the characteristics are straight lines in the physical plane and their height in time is given by:

$$z = z_0(\phi) + w_{s,0} F(\phi) t \tag{9}$$

where $z_0(\phi)$ represents the concentration distribution at $t = 0$.

Figure 1 shows two possible characteristics and settling curves for a settling suspension. If the initial concentration is low (Fig. 1a) there will be a distinct point of contraction (A). At the point of contraction the gelling point is reached. This is the volumetric concentration at which a space filling network appears, in other words, a bed starts to form. This

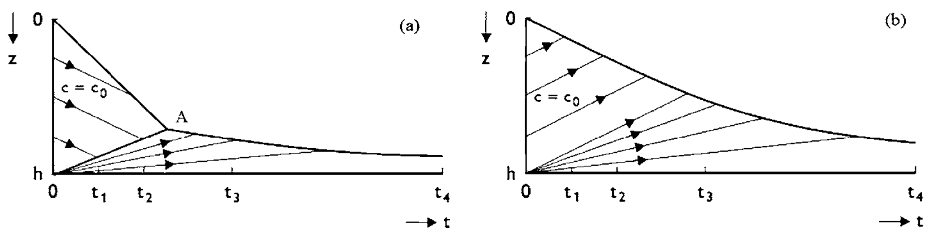

Fig. 1. Types of hindered settling: (a) low initial concentration, two interfaces develop; (b) high initial concentration, one interface develops (After Kranenburg, 1992).

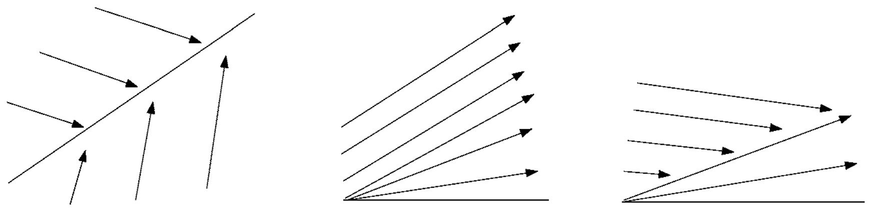

Fig. 2. Three possible types of characteristic wave paths. (a) Regular type; (b) Rarefaction type; and (c) Compound type (After Bartholomeeusen *et al.*, 2003).

point separates the hindered settling regime (steeper curve) from the consolidation regime (flat curve). In this research we only deal with the hindered settling regime; the right part of the settling curve is thus not taken into account. The second possible settling curve (Fig. 1b) is a concave, smooth line, when the initial volumetric concentration is larger than a specific concentration ($\phi > \phi_{cr}$), and indicates a different settling behaviour, or consolidation. The hindered settling phase is very short or absent in these cases.

The characteristics for both settling curves in Fig. 1 have a different appearance. When the lines converge and intersect, as in Figs. 1a, 2a and 2c, an interface develops. If such an interface develops it can be visualised by drawing a line from the origin to the gelling point. This line represents the interface of the rising bed. When the characteristic paths do not intersect, as in Figs. 1b and 2b, a rarefaction type occurs. The local wave speed in this case diverges away from the original characteristic towards the upper and lower side (Bartholomeeusen *et al.*, 2003).

The condition for convergence is that along a characteristic path the derivative of the height between two characteristics over the original height of these characteristics decreases as time elapses, $\mathrm{d}z/\mathrm{d}z_0 < 1$. In other words, the distance between two characteristic lines becomes smaller with time and the concentration increases with depth $\mathrm{d}\phi/\mathrm{d}z_0 > 1$:

$$\frac{\mathrm{d}z}{\mathrm{d}z_0} = 1 + w_{s,0}\frac{\mathrm{d}F}{\mathrm{d}\phi}\frac{\mathrm{d}\phi}{\mathrm{d}z_0}t \tag{10}$$

As an interface develops when characteristic paths converge, Eq. 10 implies that an interface will therefore develop when $\frac{\mathrm{d}F}{\mathrm{d}\phi} < 0$. In settling columns this always occurs between the water above the suspension and the settling suspension (Fig. 1b). As the upper interface is always present (in a mono-dispersed suspension) it can be stated that when:

$$\frac{\mathrm{d}F}{\mathrm{d}\phi} < 0 \tag{11}$$

two interfaces develop (Fig. 1a) and when

$$\frac{\mathrm{d}F}{\mathrm{d}\phi} > 0 \tag{12}$$

one interface develops (Fig. 1b).

For both Eqs. 1 and 2, f decreases monotonically with ϕ (Fig. 3. The function F, however, behaves differently for both equations. In the case of Eq. 1, F has a minimum at a volumetric concentration ϕ_{cr}. This concentration indicates the change from Eq. 11 to Eq. 12, and thus, the change from the occurrence of two interfaces in a settling suspension to the occurrence of one interface. The function F of Eq. 2 shows different profiles depending on the choice of value for parameter m, an empirical parameter that cannot be quantified analytically. For $m = 1$, F decreases monotonically with ϕ, but for $m > 1$, F depicts a minimum. When $m = 1$ the return flow effect is linear, while when $m > 1$ there are nonlinear effects in the return flow. These nonlinear effects will lead to the occurrence of two or one interfaces, depending on the initial conditions, while a linear return flow will always give two interfaces. From the type of settling curves and the type of characteristics, one thus should be able to determine whether $m > 1$.

3. EXPERIMENTAL SET-UP AND METHODS

3.1. Experiments

The experiments were carried out in the Laboratory of Environmental Fluid Mechanics at Delft University of Technology. Small settling columns of 40 cm high with a diameter of 7 cm were used. The clay mineral kaolinite was used to make the suspensions.

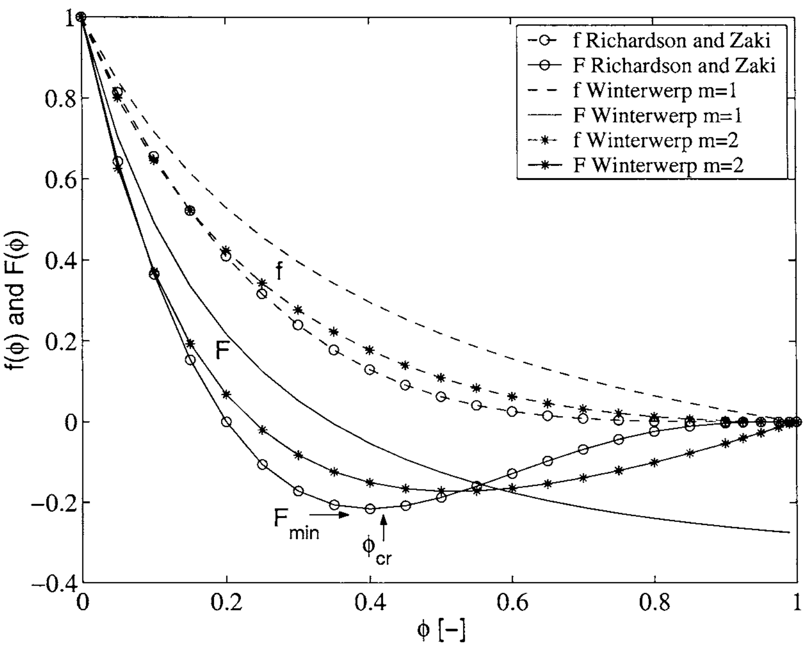

Fig. 3. Variation of hindered settling functions f and F with ϕ for Eq. 1(k = 1, n = 4) and Eq. 2 (m = 1 and m = 2). Based on Kranenburg (1992) and Winterwerp (2002).

The mineral was prepared and diluted with salt water (5 promille) to a suspension of about 100-120 g/l. A 12 litre tank was filled with this mixture which was mixed thoroughly for at least 2 hours every day during at least two weeks, in order for the kaolinite suspension to reach a steady chemical state.

A total of 16 experiments was carried out in two series. The second series of experiments was performed two months later than the first series, but with the same mixture. For every experiment, a sample was taken from the tank and diluted with salt water to the desired initial concentration.

3.2. Settling of the interface

The lowering of the interface of the kaolinite suspensions was measured for various initial sediment concentrations in the settling columns. Before every experiment, the column was shaken gently, but thoroughly, in order to create a homogeneous mixture, but not disturbing the flocs. Thereafter the experiment started immediately. During the experiments the settling of the interface was observed visually. The height of the interface was recorded at an interval of one minute. When the settling slowed down strongly, *i.e.*, beyond the gelling point, the recording was done every 5 minutes. These measurements led to settling curves for the different suspensions. The bed interfaces could not be detected visually. Their settling curves are thus not available.

3.3. Concentration profiles

Sediment concentrations were measured using a conductivity probe developed by Delft Hydraulics. The principle of a conductivity concentration meter is based on the fact that the conductivity of a sediment mixture decreases when the concentration increases. The probe has four electrodes and is supplied with an alternating current to eliminate polarisation effects.

The aim was to measure the concentration at several heights during the settling and consolidation phase. Measuring concentrations in the vertical is a destructive process as the probe damages the structure of the bed. Therefore it was decided that every experiment should be repeated several times with the concentration measured at different heights. For the experiments in Series 1 three different levels were selected for every experiment, depending on the initial concentration and the expected level at which a bed structure would be formed. For the experiments in Series 2 four different levels were selected. In general one measurement was done in the top layer, one or two in the middle part and one 5-10 cm above the bottom of the column.

Before every measurement the probe was calibrated. To calibrate the probe the suspension had to settle first. Then, two samples were taken from the bed layer and one from the clear water layer with a pipette. The samples were placed in a small jar. The conductivity was measured and the density of the suspensions was determined with an Anton Paar density meter. Thereafter, the settled suspension in the settling column was mixed thoroughly and another sample was drawn from the suspension. From this sample, the density and conductivity were determined as well. With these four measurements calibration curves could be drawn for each experiment. Calibration before every experiment is necessary as the probe is sensitive to temperature changes and different amounts of solutes in the water. Nonetheless, during the experiments, which had a duration of approximately one hour, the temperature in the settling column always rose. This increased the conductivity which led to an under-estimation of the concentration. The maximum under-estimation of the data used in this analysis is around 5 g/l. Furthermore, due to the settings of the software of the conductivity probe, the measured concentrations has a resolution of ± 2 g/l. The data is not compensated for temperature change, because it is not known exactly when and how much the temperature changed in every experiment.

4. RESULTS

4.1. Settling curves and characteristic lines

The results of the visual observations of the settling interface are shown in Fig. 4. The height of the lines is normalised by the initial height and multiplied by 100. A majority of the lines have a similar appearance as the idealised settling curves in Fig. 1a. The curves for the lower concentrations show a kink with a clear inflection, *i.e.*, the point of contraction. The line from this point to the origin of the graph depicts the second interface of the settling suspension, the rising of the bed. For those lines with a high initial concentration in Fig. 4, this point of contraction is not clear or not present. These experiments showed a gradual transition from suspension to bed and a second interface does not exist (Fig. 1b).

The settling velocity of the suspensions and other experimentally derived parameters are given in Table 1. Only the velocities of the part above the point of contraction are elaborated as this research focuses on the hindered settling regime.

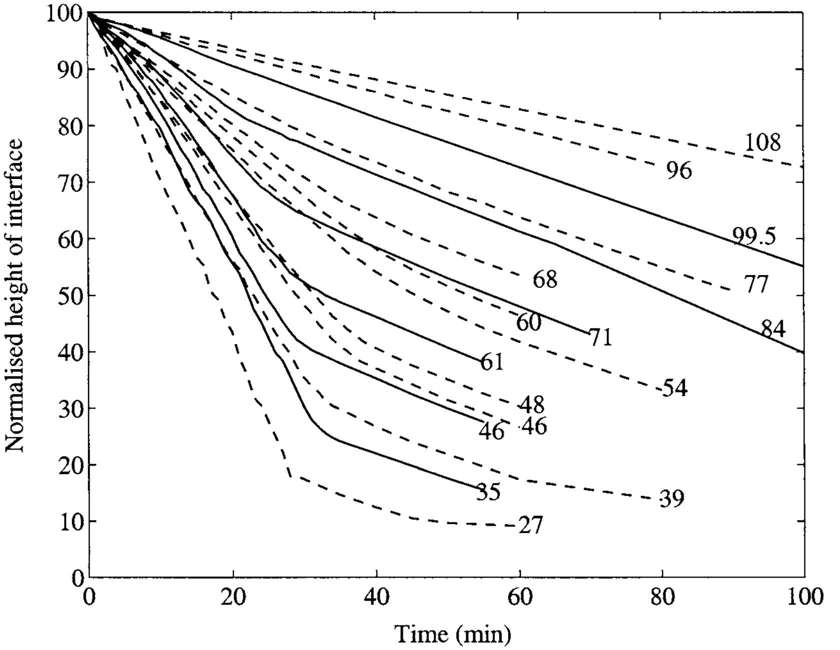

Fig. 4. The normalised settling curves of different kaolinite concentrations. Solid lines represent Series 1, dashed lines represent Series 2. Numbers indicate the initial concentration (g/l). The initial height varied between 34 and 37 cm.

Table 1. All experiments with their initial concentration, effective settling velocity and gelling concentration.

Id	Initial concentration (g/l)	w_s (mm/s)	c_{gel} (g/l)
30kol	35	0.134	66
40kol	46	0.111	83
50kol	61	0.071	87
60kol	71	0.058	90
70kol	84	0.052	-
80kol	100	0.028	-
10tt	27	0.170	-
20tt	39	0.133	80
30tt	46	0.101	67
40tt	48	0.096	77
50tt	68	0.067	88
55tt	54	0.075	85
60tt	77	0.059	-
70tt	60	0.044	83
80tt	96	0.022	-
90tt	108	0.019	-

In the settling curves lines of equal concentration, so called characteristic lines, were drawn for a further analysis of the occurrence of interfaces. Four examples of such settling curves with characteristic lines are shown in Figs. 5 and 6. Note however that many characteristic lines can be drawn only approximately, especially in the area around the second interface. Figure 5a clearly shows two interfaces. The first is the top interface, presented by the dot-dashed line, and the second interface where the characteristic lines converge. Figure 5b has a rather different appearance. It has only one interface, the top water-sediment interface, and the characteristic lines are diverging more, which implies:

- hindered settling with one interface ($\phi > \phi_{cr}$) or
- consolidation ($\phi > 1$, $c_0 > c_{gel}$)

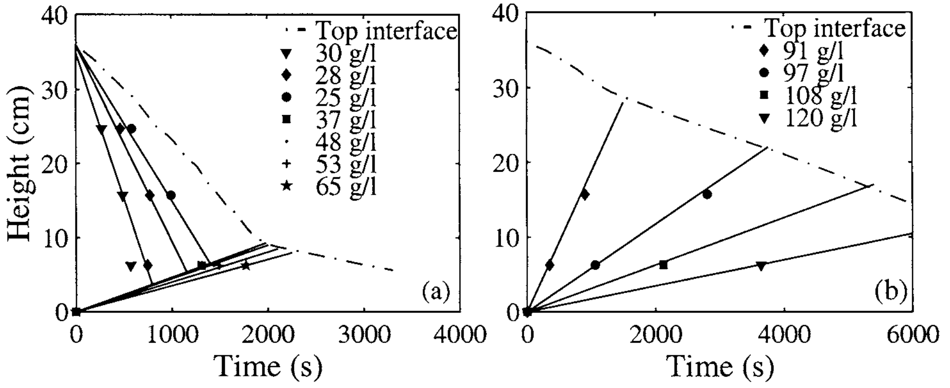

Fig. 5. Settling curves of experiment 30kol (c_0 = 35 g/l) and 70kol (c_0 = 84 g/l) with characteristic lines.

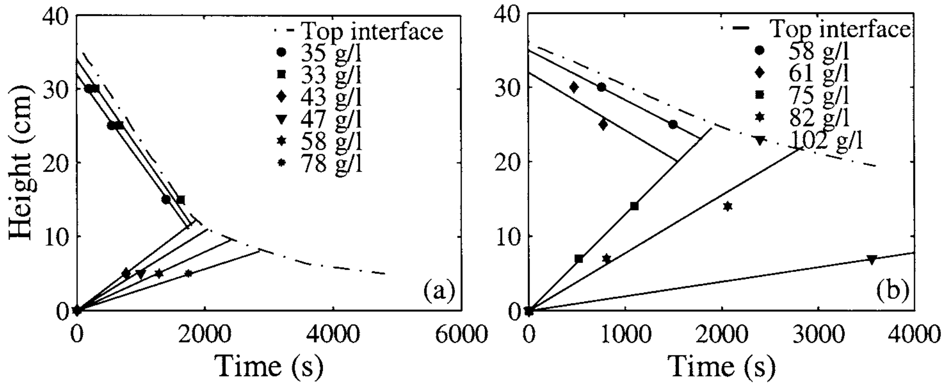

Fig. 6. Settling curves of experiment 20tt (c_0 = 39 g/l) and 5tt (c_0 = 68 g/l) with characteristic lines.

As c_0 = 84 g/l and c_{gel} = 81 g/l, the solid line drawn in this graph represents consolidation of the material. Figure 6a show a somewhat similar behaviour as that in Fig. 5a. It shows two interfaces, a point of contraction and converging characteristic lines. The point of contraction in this plot, as well as in Fig. 5a, is the gelling point or the structural density. It is however difficult to determine the point of contraction precisely. The change of slope can be abrupt, but also more gradual. Around the point of contraction, the concentration changes gradually from the initial concentration to the gelling concentration. Although this change is gradual, it still reveals the features of an interface. This in contrast to the settling type at which no interface between the suspension and the bed develops. Because of the gradual change, some of the characteristic lines may not start from the origin.

However, our data are not sufficient and accurate enough to draw such lines.

The characteristics in Fig. 6b are more ambiguous than the ones in Fig. 5b. At first sight, characteristic lines can be drawn and they reveal the occurrence of two interfaces. The occurrence of two interfaces is remarkable as at this concentration only one interface is to be expected. This will be explained in section 4.2. Note that characteristics can be drawn but their direction is not always unambiguous.

4.2. Concentration profiles

A typical result of the measurements with the conductivity probe is shown in Fig. 7. In Fig. 7a the passage of the top interface is very obvious at the three highest positions. When the interface passes, a rapid decrease in concentration occurs. The time series of the lowest position in Fig. 7 show the concentration at a position 5 cm and 6 cm above the bottom of the column respectively. This position was chosen to measure the rise of the sediment bed. This rise can be seen in the first part of the curve. After about half an hour this bed building stops and the concentration does not increase with time anymore. This implies that the suspension has attained the gelling concentration at this point. When consolidation is ignored, the flocs settling on the bed at that moment do not increase the density at that specific height anymore but cause a rise of the bed level and an increase in density in the layers above the measured layer.

The gelling concentration thus can be obtained from the bed level measurements of the conductivity meter. This has been done for most of the experiments, except for the ones in which the initial concentration was already higher than the gelling concentration, or when the conductivity probe was placed too high. Table 1 shows the gelling concentrations which are obtained with this method. From these values a mean value of c_{gel} = 81 ± 8 g/l is obtained.

Another parameter that can (partly) be obtained from the concentration time series is the parameter m that accounts for nonlinearity in the return flow effect in Eq. 2. The change in concentration in the curve at the lowest position in Fig. 7a is not as abrupt as with the passage of the top interface (the lines of the three highest positions) or as the rising profile in Fig. 7b. It was explained in Section 2 that a second interface, the one of the rising bed, increases rapid and strongly in concentration. In Fig. 7a we see a more gradual change in concentration, which implies that a second interface is not present. Furthermore, Fig. 5 also indicates that at higher concentrations only a top interface exists. This would mean that for the present experiments one or two interfaces may develop, depending on the initial concentration. In Eq. 2 this implies $m > 1$, thus nonlinear return flow effects do occur. We found, from observations in the settling column and by comparing the rising bed in the concentration time series, that the settling behaviour

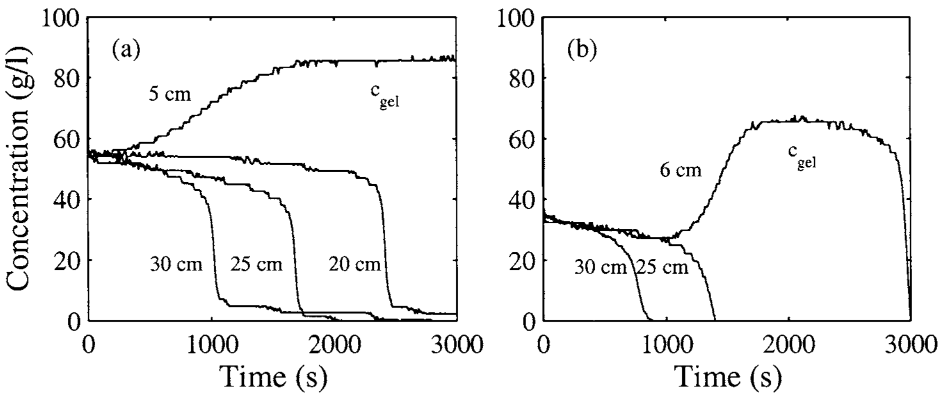

Fig. 7. Concentration time series at selected heights above the bottom. (a) For experiment 55tt with initial concentration c_0 = 54 g/l, and (b) for experiment 30kol with initial concentration c_0 = 35 g/l.

changed when $35 < c < 46$ g/l, or $0.53 < \phi_{cr} < 0.55$ for the current experiments with kaolinite. To calculate ϕ_{cr} we used the specific gelling concentration per experiment (see Table 1) and not the mean gelling concentration. Considering $\mathrm{d}F/\mathrm{d}\phi = 0$ at $\phi = \phi_{cr}$, m is obtained as follows:

$$m = \frac{1}{2}\frac{5\phi_m^2 - 2\phi_m + 4 + \sqrt{25\phi_m^4 + 60\phi_m^3 - 116\phi_m^2 + 64\phi_m + 16}}{\phi_m(2 + 5\phi_m)} \tag{13}$$

from which we find $m \approx 2.0$.

5. DISCUSSION

In this paper experiments on the hindered settling of mud flocs are described. Firstly, the settling behaviour of highly concentrated cohesive material suspensions is described and compared to Kynch's theory. Secondly, from the experiments the values of typical hindered settling parameters were determined. A method was developed to determine these values. The parameter values are used to validate the hindered settling formula (Eq. 2) for mud flocs. The relevant parameters that needed to be determined were the gelling concentration (c_{gel}), the coefficient that accounts for nonlinearity in return flow (m) and the settling velocity of single flocs in still water ($w_{s,0}$). The gelling concentration could be derived from the conductivity measurements. The conductivity time series at a height of 5-10 cm in a 40 cm settling column gave a good indication of the gelling concentration.

The measured gelling concentration differed for every settling experiment, but always was within the range of 66 and 90 g/l, with a mean of c_{gel} = 81 ± 8 g/l. It was expected that the gelling concentration would decrease with increasing concentration due to the more possible collisions, the longer settling time and therefore larger flocs. This, however, did not seem to be the case for the present experiments.

The parameter m, which accounts for nonlinearity in the return flow, could be determined when ϕ_{cr} was known. The latter parameter could be derived from visual observations of the settling suspension and from the shape and especially the steepness of the conductivity time series close to the bed. This led to a value of $m = 2$. It is difficult, however, to determine the value of ϕ_{cr} and thus m accurately. The parameter m may therefore vary around 2. Most likely these parameters change in value when different clay minerals are used and when in experiments with one material the samples have a different stress history or when a different sample preparation procedure is applied.

Another method to determine the m parameter is to analyse characteristic paths from the settling suspension. When the characteristic paths converge and intersect a second interface will develop, while this will not happen with non-intersecting characteristics. From the occurrence of intersecting and non-intersecting paths in different experiments one will be able to determine the concentrations at which the settling behaviour changes. This method shall be used at a later stage of our research.

The value of $w_{s,0}$ could not be determined from the experimental data directly; it needs to be determined from model fitting.

6. CONCLUSIONS

This paper describes measurements of hindered settling velocities for highly concentrated mud suspensions. Simple techniques as visual observations of the settling interface and concentration measurements with a conductivity probe were found to perform well and produce good data. The settling behaviour was analysed with Kynch's theory. This theory was found to be applicable. The suspensions were found to develop one or two interfaces while settling, depending on the initial concentration. Beyond a critical initial volumetric concentration the settling behaviour changes from two interfaces to one interface. The fact that both settling behaviours do exist means that in the proposed formula, $m > 1$, thus that the return flow effect needs to be nonlinear.

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