3 TIDAL VARIATIONS IN MUD FLOC SIZE AND SETTLING VELOCITY. THE IMPACT OF FLUID SHEAR AND THE SUSPENDED SEDIMENT CONCENTRATION ON FLOCCULATION AND BREAKUP


3.1 Introduction

Mud particles tend to clog together and form flocs that have a much larger settling velocity than the constituent particles. A downward vertical flux of sediment in the water is only possible when the settling velocity of the sediment particles is larger than the upward transport by turbulence. Flocculation therefore enables sedimentation. There would be little accumulation of fine-grained material, if the suspended fine sediment particles did not aggregate (Partheniades 1984; Van Leussen 1994). Floc sizes and settling velocities are determined by many physical factors like differential settling, fluid shear and the suspended sediment concentration (SSC). They are also determined by physico-chemical or biological factors like the presence of sticky biopolymers on the flocs, surface charge, salinity, etc. The presented research focuses on the relative contributions of especially fluid shear and SSC to floc size and settling velocity in the Dollard estuary within a tidal cycle. Floc size and settling velocity variations in two environments, the tidal channel and the tidal flat, were studied to obtain more insight in the contribution of fluid shear and SSC to the flocculation/breakup process.

3.2 Theory

Flocculation is determined by the number of floc collisions (collision frequency) and the efficiency of these collisions in aggregation (collision efficiency). The collision frequency is determined by:

1. Differential settling, that is falling flocs scavenging smaller flocs on their way down. This is especially important in deeper water.
2. Fluid shear or turbulence intensity. Increased turbulence causes an increased collision frequency and thereby flocculation. However, it is also considered to be the most important limiting factor of floc size (Dyer 1989; Eisma 1986; Luettich et al. 1993; Van Leussen 1994). Larger flocs are more fragile and will break easier due to turbulent shear (Dyer 1989).
3. The number of flocs in suspension or the SSC. The more flocs there are in suspension the higher the collision frequency. Several field studies in estuaries have shown that the median floc settling velocity increases with SSC raised to a power (Burt 1984; Dyer 1989; Pejrup 1988; Van Leussen & Cornelisse 1993a).
Both turbulence and SSC show the largest variation on the time scale of a tidal cycle. This paper focuses on the floc size and settling velocity variations within the tidal cycle as a function of both mentioned parameters. The collision efficiency is determined by physico-chemical or biological factors (biopolymers, surface charge, salinity) that mainly vary on larger time scales than the tidal cycle (e.g., seasonal variation in biopolymer concentrations). The collision efficiency is therefore assumed to be constant throughout the tidal cycle.

Dyer (1989) described the effects of fluid shear and SSC on floc size in his conceptual diagram (fig. 1.7). An increase of SSC increases floc sizes, while an increase of shear stress only initially increases floc size due to an increased collision frequency of the suspended particles. Further increase of shear stress however causes flocs to break and decreases floc diameter.

A measure of turbulence intensity in the water column is the root mean square velocity gradient G, defined as the square root of the energy dissipation $\varepsilon$ divided by the kinematic viscosity $\nu$ of the fluid (Van Leussen 1994):

$$G = \sqrt{\frac{\varepsilon}{\nu}}$$  \hspace{1cm} (3.1)

It’s reasonable to assume that the turbulent energy dissipation $\varepsilon$ equals the turbulent energy production $P$ (Van Leussen 1994):

$$\varepsilon = P = \frac{\tau}{\rho} \frac{dU}{dz}$$  \hspace{1cm} (3.2)

In case of a logarithmic velocity profile:

$$\frac{dU}{dz} = \frac{u_*}{\kappa z}$$  \hspace{1cm} (3.3)

and assuming that the maximum shear $\tau$ at the bed decreases linearly to zero at the surface:

$$\frac{\tau(z)}{\rho} = u_*^2 \left[ 1 - \frac{z}{h} \right]$$  \hspace{1cm} (3.4)

Then:

$$G(z) = \sqrt{\frac{u_*^3 \left[ 1 - \frac{z}{h} \right]}{\nu \kappa z}}$$  \hspace{1cm} (3.5)
Where:
\[ G(z) = \text{root mean square velocity gradient at level } z \ (s^{-1}). \]
\[ z = \text{level above the bed (m)}. \]
\[ \varepsilon = \text{turbulent energy dissipation (m}^2\text{s}^{-3}). \]
\[ P = \text{turbulent energy production (m}^2\text{s}^{-3}). \]
\[ \nu = \text{kinematic viscosity (m}^2\text{s}). \]
\[ \tau(z) = \text{shear stress at level } z \ (\text{N/m}^2). \]
\[ \rho = \text{water density (kg/m}^3). \]
\[ U = \text{current velocity (m/s)}. \]
\[ u^* = \text{friction velocity (m/s)}. \]
\[ \kappa = \text{Von Karman constant} \approx 0.4. \]
\[ h = \text{water depth (m)}. \]

For the determination of \( G(z) \), \( u^* \) needs to be determined from velocity measurements.

In case of a logarithmic velocity profile:

\[
U(z) = \frac{u^*}{\kappa} \ln \left( \frac{z}{0.033k_s} \right) \tag{3.6}
\]

Where:
\[ k_s = \text{bed roughness (m)}. \]

### 3.3 Field experiment

The research was carried out in the Dollard estuary, which was described in chapter 2. This chapter will describe the results of floc size and settling velocity measurements throughout several tides in the tidal channel ‘Het Groote Gat’ and the tidal flat ‘Heringenplaat’ in the Dollard estuary (fig 2.1) with the VIS, Cilas and Owen tube as described in Chapter 2. The channel measurements with the VIS were conducted from a drifting vessel, which prevented floc breakup by current shear around the instrument. It also minimised the effect of horizontal advection on the measurement. Changes in suspended sediment concentration or floc sizes were therefore the result of local erosion/sedimentation or flocculation/break-up and not due to horizontal advection. The tidal excursion of the VIS measurements is shown in figure 2.1. Note that the presented Cilas and Owen tube measurements only provide a relative measure of floc size or settling velocity, as was explained in chapter 2. Besides floc measurements, current velocities and suspended sediment concentrations were also measured as was described in chapter 2.

### 3.4 Measurements of fluid shear

Fluid shear or \( G \) experienced by the mud flocs needed to be calculated from the friction velocity \( u^* \) with equation 3.5. In case of a stationary, uniform current and very accurate measurements of velocity at well defined levels above the bed, the friction velocity \( u^* \) and
bed roughness $k_s$ can be derived from a logarithmic fit on the velocity data (equation 3.6). In an estuary, however, the current is not uniform and not stationary which limits the logarithmic velocity profile to the near bed region. In practice the measured velocities and especially the measured levels above the bed in the Dollard were not accurate enough to calculate both $u^*$ and $k_s$ from the data. This was mainly caused by the movement of the research vessel on the waves in the channel and the low current velocities on the tidal flat. Bed roughness in the channel varied between $7\times10^{-7}$ m and $5.3$ m which are totally unrealistic. The median bed roughness $k_s$ however was $0.03$ m which is a more realistic value. For realistic calculations of $u^*$ and $G$, a bed roughness $k_s$ had to be estimated and $u^*$ was calculated from the current velocity at one level above the bed assuming a near bed logarithmic velocity profile and zero velocity at $z=z_0=0.033k_s$.

The bed roughness can also be expressed as a drag coefficient $C_d$ where:

$$C_d = \left(\frac{k_s}{\ln\left(\frac{z_0}{0.033k_s}\right)}\right)$$  \hspace{1cm} (3.7)

Drag coefficients were deduced from measurements in several estuaries by different authors. Lewis & Lewis (1987) found drag coefficients ranging from 0.0019 to 0.0131 on an ebb tide and $C_d$ lying between 0.002 and 0.0053 on the flood in the Tees estuary. A drag coefficient of $C_d = 0.003$ at $z = 1$ m seems to be a reasonable estimate for estuarine studies according to Van Leussen (1994) and Sternberg (1968). This corresponds to a $k_s$ of $0.02$ m, which agrees quite well with the median $k_s$ of $0.03$ m found from the logarithmic fits. Therefore, $k_s = 0.02$ m was used for the calculation of current related friction velocities in the channel as well as on the tidal flat. Current velocities were measured at $1.1$ m above the bed in the channel and at $0.079$ m above the bed on the tidal flat. From $k_s = 0.02$ m and the measured current velocities, $u^*$ was calculated with equation 3.6 and $G$ was calculated with equation 3.5. While the uncertainties in estimating $k_s$ are large, the impact of a 100% increase in $k_s$ results in only 16% increase in $G$ in the channel and a 26% increase in $G$ above the tidal flat. The percentages differ because the velocity was measured at $1.1$ m above the bed in the channel and at $0.079$ m above the bed on the tidal flat.

On the tidal flat waves also needed to be taken into account. Outside the wave boundary layer, the velocity profile under waves is different from a velocity profile without waves. This can be expressed by using an apparent roughness $k_a$ due to waves instead of a $k_s$ in equation 3.6. Based on analysis of experimental data from flumes with rippled beds, Van Rijn (1993) found:

$$\frac{k_a}{k_s} = e^{\frac{\gamma_a}{u}}$$  \hspace{1cm} (3.8)

Where:

$k_a$ = apparent roughness due to waves (m).
$$k_s = \text{current related bed roughness (m)}.$$  
$$\hat{U}_d = \text{peak orbital velocity near bed (m/s)}.$$  
$$U = \text{mean current velocity (m/s)}.$$  
$$\gamma = 0.8 + \phi - 0.3 \phi^2.$$  
$$\phi = \text{angle between current and wave direction (in radians between 0 and } \pi).$$  
$$\hat{U}_d \text{ and } U \text{ were measured with an electromagnetic current meter that sampled at a 2Hz frequency at 0.079 m above the bed on the tidal flat.}$$

### 3.5 Results

First the data collected with the VIS in the tidal channel will be presented. The VIS measurements of 11 October 1995, during spring tide, will be presented in detail as this measurement is representative for the general trend of floc size variations throughout the tide in the “Groote Gat”. The measurement of 19 October 1995, one week later and during neap tide, showed similar results. Other VIS measurements conducted throughout 1996 showed the same general trend as on 11 October 1995. This proves that the presented findings are not only valid for one day.

#### 3.5.1 Tidal Channel data: results of the Video In Situ system.

**Floc sizes**

The results of the floc size measurements in the tidal channel are shown in figure 3.1abc. Figure 3.1a shows the tidal elevation and the bed level referenced to Dutch ordnance datum (N.A.P.). The bed level varies along the track of the VIS. The measurements started at low water at a deeper part of the estuary towards Delfzijl (fig. 2.1). Then the VIS floated into the estuary until high water slack where it reached shallower water. After HW the VIS floated back to approximately its original position at low tide in deeper water again. Figure 3.1b is an area chart that shows the measured floc size distributions. (Note that descending lines between the size classes mean increasing floc sizes and vice-versa). Figure 3.1c presents the depth-averaged velocity and the suspended sediment concentration in the settling tube of the VIS during the measurements. Measured floc sizes ranged from 85 µm (detection limit) to 660 µm. Peaks in floc size appeared at about one hour after maximum flood velocity and at maximum ebb velocity. At these moments approximately 20% volume percentage of the flocs was larger than 300 µm. The peaks in floc sizes correlate well with the peaks in SSC. This corresponds with the conceptual model of Dyer (1989). There is no evidence of shear stresses disrupting the larger flocs. While this does not mean that floc break-up does not occur, it implies that SSC seems to dominate the flocculation process.
Figure 3.1 VIS measurements, Dollard, 11 October 1995. a) Water level and bed level against time b) Floc size distribution against time c) Depth averaged velocity and Suspended sediment concentration in the VIS against time
Figure 3.2  VIS measurements, Dollard, 11 October 1995. a) Floc size distribution against time b) Normalized velocity profiles (contours) and SSC profiles (gray-scales) against time
As the VIS is suspended at 2.9 m below the water surface and floating with the current, its relative position to the bed changes throughout the tide. In figure 3.1 it seems that the smallest flocs occur in the shallowest water. This is however coincidental, as correlation between bed level and floc size was not observed in other VIS measurements. For example, in the measurements of 19 October 1995 (fig 4.3; chapter 4) relatively small flocs also occurred in deep water in the mouth of the Dollard near Delfzijl at low water. Some of the measured floc size variation may be due to the proximity of the VIS to the bed. But such an effect was not observed in the measurements and it does not dominate the floc size variation. The floc size variation is related to the SSC.

In figure 3.2ab the floc size distribution and the velocity and concentration profiles are plotted. At the start of the measurements, after slack water, increasing current velocities resuspended mud into the water column. This mud was quickly mixed through the water column, so no vertical concentration gradient developed. As the SSC increased the floc size also increased. This may be caused by, either flocculation of smaller flocs, or resuspension of larger flocs or both. This mixing process continued towards maximum flood velocity. When the flood current velocity started to decrease, immediately a vertical concentration gradient developed. The current was no longer capable of keeping the larger flocs into suspension and therefore settling started. The maximum floc sizes appeared about one hour after maximum flood velocity, when the larger flocs were already settling and the SSC at the surface was decreasing. However, the SSC at the level of the VIS peaked at this moment (fig. 3.1bc). Differential settling may also have enhanced floc size at this time. With further decreasing current velocities the larger flocs kept settling, a lutocline developed and the floc sizes at the level of the VIS decreased again because the larger flocs had already passed towards the bed. At high water slack the settling sediment near the bed was deposited on the bed and the vertical concentration gradient disappeared. After high water slack a similar process occurred but now due to the ebb current. During ebb the maximum floc sizes appeared simultaneously with the maximum ebb current velocity (fig. 3.2bc), when the SSC in the VIS also reached its maximum value.

Eisma and Li (1993) also measured floc sizes in the Dollard estuary, at three fixed stations (Eulerian measurements). They also found a correlation between maximum floc size and SSC comparable with the present measurements. On the flood however they found increasing floc sizes also after the SSC maximum had occurred. They attributed this to the decreasing turbulence during flood as a result of the increasing water depth. In the present Lagrangean (floating with the current) measurements such increasing floc sizes after maximum SSC during flood were not observed. Maybe the increasing floc sizes towards high water as observed by Eisma and Li (1993) were caused by horizontal advection of flocs from upstream areas. In these areas, towards the mouth of the estuary, the current velocities are larger and could have resuspended more large flocs. The present measurements were floating measurements that were not affected by horizontal advection, and they do not show increasing floc sizes after maximum SSC.
Floc settling velocities

Floc settling velocities were not determined for each VIS measurement. They were obtained for only two VIS measurements on each measurement day. For that reason all settling velocity data collected from October 1995 until December 1996 was normalized relative to high water time and is plotted in figure 3.3. In this way it was possible to show the average tidal variation of floc settling velocities. Since the data was taken throughout a year, some of the floc size variation could also result from seasonal floc size variations. In chapter 5 (fig. 5.4) will however be shown that there is hardly any seasonal variation in the floc settling velocities in the Dollard. The floc size variations shown in figure 3.3 are therefore mainly tidal variations.

Each presented settling velocity is a mass weighted average settling velocity calculated from the data of a VIS measurement. A more extensive description of these settling velocity calculations will be given in Chapter 5. Figure 3.3 also shows the settling velocities of mud flocs in the “Ranselgat, EMS-Dollard” (fig 2.1) obtained by Van Leussen (1994) with the VIS and with a field settling tube. It is clear that the VIS measurements, as well as in the Ranselgat in 1990 as in the Groote Gat in 1996 show a strong increase in the floc settling velocity around or shortly after maximum current velocities. In both the Ranselgat and the Groote Gat maximum current velocities occur about 3.5 hours before and after high water. Slack tide occurs around high water.
The Ranselgat measurements by Van Leussen, 1994 show the settling velocities of the largest flocs that were observed. The Groote Gat measurements show mass weighted average settling velocities of all flocs. Obviously the settling velocities measured in the Groote Gat are therefore smaller than the settling velocities measured in the Ranselgat. Minimum settling velocities were observed around slack tide in the Ranselgat and about 1.5 hours after slack tide in the Groote Gat. This is probably also a result of the different measurement method, since in the Ranselgat only the largest fastest settling flocs were measured whereas in the Groote Gat the average settling velocity was obtained. It is logical that the fast flocs settle earlier after slack water than the average flocs.

Around and right after slack tide flocs generally fell slower, just as the smallest flocs were observed around and just after slack water in figure 3.1. Figure 3.3 and 3.1 show that the tidal variation in settling velocity is comparable to the tidal variation in floc size. The tidal variation observed from the “Groote Gat” results also agrees with the tidal variation observed by Van Leussen (1994) in the “Ranselgat”, except for the 1.5 hour time lag which presumably resulted from the measurement method, as was explained above. Van Leussen also conducted measurements with a field settling tube in the Ranselgat (fig. 3.3). Due to the different methodologies, the settling tube results and the VIS results cannot be compared quantitatively. Qualitatively however, the results suggest that the strong increase of floc settling velocities is not observed by the field settling tube. Van Leussen (1994) suggested that flocs are broken by the field settling tube, which is conceivable when the fragile nature of the flocs is taken into account.

3.5.2 Tidal flat data: results of the Cilas laser particle sizer and the Owen tube.

Floc sizes (Cilas laser particle sizer)

Floc sizes on the tidal flat were measured with the Cilas laser particle sizer. As already stated above, the floc sizes measured by the Cilas are uncalibrated. Note that the Cilas was deployed at a fixed location so horizontal advection may have influenced the measurements. The floc size distribution, the water level and wave height and the current velocity and SSC are presented in fig. 3.4abc respectively. Only the high water period is shown since during low water the flat is emerged.

About half an hour after immersion, the flocs were relatively small and the flood velocity and SSC reached their maximum value. The second peak in SSC at about 11:45h coincided with the concentration peak in the channel (fig. 3.1c) and may be due to advection of sediment from the channel but may also be a coincidental event. Towards high water the current velocity and SSC decreased, but the floc sizes increased. During ebb the current increased to a maximum velocity of 0.36 m/s together with a small increase in SSC. The peak of SSC however occurred just before emersion when the water was very shallow and waves (fig 3.4b) stirred up the bed. The floc sizes decreased again towards the end of the ebb tide.
Figure 3.4  Cilas measurements, Dollard, 11 October 1995. a) Floc size distribution against time (data from: M. Ebben, RIKZ) b) Water level and significant wave height against time c) Current velocity and SSC against time
**Floc settling velocities (Owen tube)**

In 1997 a large number of Owen tube measurements were conducted at three locations above the Dollard tidal flats. Figure 3.5 shows a sequence of 4 Owen tube measurements throughout the immersion period of the Heringsplaat on 12 June 1997.

![Owen tube, Heringsplaat 12 June 1997](image)

**Figure 3.5**  Tidal sequence of the floc settling velocity distribution above the Heringsplaat on 12 June 1997
The first three measurements describe the rising tide in the afternoon and the fourth measurement was taken during ebb of the preceding tide in the morning. The measurements were placed in this order to give an indication of the successive events occurring throughout the immersion period of the tidal flat. Note that the settling velocities in figure 3.5 are not the settling velocities as they would occur in situ, because of the shortcomings of the Owen tube described in chapter 2.

In figure 3.5, the settling velocity of the suspended sediment increases towards high water. This is in accordance with the observations from the Cilas (fig. 3.4), that showed the same behaviour for the floc sizes above the tidal flat. The results presented in figure 3.5 are however not consistent. Other measurements showed decreasing settling velocities towards high water, and positive relations between SSC and settling velocity as will be shown in figure 3.6.

For all Owen tube measurement that were taken in the Dollard during 1997, the median settling velocity was calculated. The accompanying times were normalised relative to the time of high water. These results are plotted in figure 3.6. It shows a very large scatter throughout the data. No consistent tidal variation can be observed. The data was also analysed for a seasonal variation but a relation between seasons and settling velocity variations could not be found.

Even though the Owen tube measurements were all conducted with the same sampling protocol, the results are inconsistent. Because of the inconsistency of the data it is difficult to draw conclusions from this data. Only a few indications can be derived from figure 3.6:

- The observed median settling velocities are between 0 and 1 mm/s, which is comparable to field settling tube data from other authors.
- During the flood, settling velocities are generally higher than during the ebb. During the flood, water from the tidal channel is also advected onto the tidal flat. Since maximum floc settling velocities in the tidal channel occur around maximum current velocities (fig 3.3), fast settling flocs may have advected from the tidal channel onto the tidal flat. This occurrence of larger settling velocities above the tidal flats during the flood than during the ebb may promote a residual sediment flux onto the tidal flats.
- Towards the end of the immersion period when the ebb current increases, the settling velocities increase again. Probably the ebb current resuspends some of the faster settling material. But Cilas measurements do not show a simultaneous increase in floc sizes towards the emergence of the flat. Possibly the ebb current resuspends some sand. This sand is detected as fast settling material by the Owen tube, but does not lead to the observation of larger particles by the Cilas.

Floc settling velocity measurements with the Owen tube were inconsistent. Therefore they cannot be trusted to be correct. The observations from the Owen tube may be instrument induced errors, due to floc breakup, reflocculation, hindered settling, water circulations inside the tube etc.
Figure 3.6  

a) Median settling velocities of the suspended sediment throughout the tidal cycle. Based on Owen tube measurements taken throughout 1997 on three tidal flats in the Dollard estuary

b) Representative current velocities above the tidal flats
In contrast with the Owen tube results, floc size variations measured above the tidal flat with the Cilas laser particle sizer did show consistent results. Floc sizes increase towards high water, and decrease again through the ebb. As the Cilas data seems much more reliable than the Owen tube data, the Cilas results will be mainly used in the discussion.

3.6 Discussion

In the tidal channel, both the floc size and floc settling velocity data showed a positive relation between SSC and floc size/settling velocity. Above the tidal flat there is a negative relation between SSC and floc size. The floc settling velocity data collected above the flat is inconsistent and will not be used. Above the tidal flat, large turbulence intensity due to currents and waves seems to inhibit the development of large flocs during flood and ebb tide. Larger flocs occurred only around high water slack, with low current velocities, larger water depth and therefore low relative wave height. This may have been caused by a decrease in turbulence intensity. Differential settling may also have played a role but this is unlikely. Firstly because of the shallow water (maximum 1.5 m) above the tidal flat. And secondly because Stolzenbach and Elimelech (1994) inferred that the effect of differential settling on aggregation in marine environments is small, since smaller particles that are overtaken by larger ones are deflected around the large particle instead of being scavenged by it. In the tidal channel floc sizes are affected by the SSC whereas above the tidal flat floc sizes seem to be dominated by the shear stresses.

In figure 3.7a the current velocity in the channel and the gradient G at the level of the VIS are plotted. In the channel obviously G depends on the current velocity. G ranged from 0.9 s\(^{-1}\) at slack tide to 11.2 s\(^{-1}\) at 17.25 h during maximum ebb current when the water was quite shallow (about 5 m depth) and the VIS was relatively close to, but still 2.1 m above, the bed. In figure 3.7b current velocity, wave height and G above the tidal flat are plotted. A distinction was made for G due to the current and G due to current and waves combined. G due to current and waves was calculated with equation 3.5 and 3.6 but instead of the bed roughness \(k_s\), an apparent roughness \(k_a\) (equation 3.8) was used that corrects for the changes in the velocity profile due to waves. For the data on 11 October 1996 \(k_a\) varied between 0.022 m and 0.075 m. G was calculated at the level of the Cilas at 30 cm above the bed. Since there were only small waves, the waves do not contribute very much to the gradient. Only at 13:50h a peak in wave generated shear appears but this is probably due to a measurement error in the orbital velocities because the peak does not appear in the wave height data. Above the tidal flat G ranged from 1 s\(^{-1}\) to 14.8 s\(^{-1}\) this is about the same range as measured in the tidal channel. The ranges of SSC are also comparable in both tidal channel and above the tidal flat. The Cilas data above the flat (fig. 3.4a) however suggests that the decrease in floc size at maximum current velocity is caused by floc break-up due to large shear (G). Since G at the Cilas is not significantly larger than G near the VIS another explanation needs to be found.
Figure 3.7  G in the tidal channel and above the tidal flat, Dollard, 11 October 1995.  a) Depth averaged velocity and G in the tidal channel b) Current velocity, Wave height and G at 30 cm above the tidal flat c) G at 1.5 cm above the tidal flat
There are three hypotheses for the differences in floc size behaviour between the tidal flat and the tidal channel:

1. **Advection.**

   Horizontal advection of flocs may cause changes in floc size distribution. On the flood tide the water comes from the tidal channel. Since the tidal variation of floc sizes in the tidal channel do not correlate with the tidal variation of floc sizes above the tidal flat, it is not likely that the floc size variation above the tidal flat can be explained by advection of flocs from the tidal channel onto the tidal flats.

2. **Instrument induced turbulence.**

   The Cilas instrument is quite large in quite a large frame. Therefore the instrument itself generates turbulence that causes floc break-up during higher current intensity. In chapter 2 was shown that a current velocity increase of 1 m/s causes an average decrease in d90 floc size of 80µm. The maximum difference in current velocity above the Heringsplaat is 0.3 m/s. This could result in a 24µm decrease of the d90 floc size above the Heringsplaat due to instrument induced shear. But the observed changes in d90 amount to 100µm. So although instrument induced shear contributes to the observed decrease in floc size at larger current velocities it cannot explain the full amount of floc size variation.

3. **Near bed shear.**

   Near the bed the gradient G can be very large. As an example the gradient G at 1.5 cm above the tidal flat is plotted in fig. 3.7c. G ranges from 3 s⁻¹ at slack tide to 74 s⁻¹ at maximum ebb velocity. This very high near bed shear is almost certainly capable of floc break-up. Mehta and Partheniades (1975) stated that the strong shear and lift forces near the bed control the size distribution of the flocs in suspension. Van Leussen (1994) distinguished a number of turbulent zones in the water column. The flocs are continuously moving through these zones in a continuous process of flocculation and break-up resulting in the ultimate floc size. In the tidal channel the near bed shear is also very high, however the water is much deeper and therefore the frequency by which flocs move through the near bed region is lower. This might explain why shear seems to dominate floc sizes above the tidal flat and SSC seems to dominate floc sizes in the tidal channel.

   The floc sizes measured with the Cilas may have been influenced by instrument induced turbulence as well as near bed shear. Floc breakup due to instrument induced turbulence explains about 25% of the observed floc size variation. The other 75% is likely to result from floc breakup by near bed shear. These percentages are only estimates, but they indicate that floc breakup due to near bed shear causes most of the observed floc size variations above the tidal flat. Above the tidal flat the water is shallower than in the tidal channel, so the average proximity to the bed is much closer above the flat than in the channel. Therefore, the impact of near bed shear on the floc sizes throughout the water column on the tidal flat will be higher than in the channel.

   **In Summary:** gradients G at the level of VIS and Cilas were comparable. Near the bed G is much higher. Above the tidal flat the frequency by which flocs approach the bed is much higher than in the channel. Furthermore the measurements above the tidal flat were taken much closer to the bed. So probably breakup of flocs near the bed and resuspension into
the water column has a large influence on floc sizes above the tidal flat and causes smaller flocs at high current velocities. Floc breakup near the bed is also likely to occur in the tidal channel but with much less impact on the whole water column because the water in the tidal channel is much deeper. So the residence time of the flocs in water with relatively low turbulent shear is much longer in the tidal channel than above the tidal flat. This allows for the development of large flocs in the tidal channel, during ebb and flood. It seems that SSC dominates the floc size as long as turbulence and the floc size itself are below a certain limit. The channel measurements show that SSC dominates floc sizes when \( G < 12 \text{ s}^{-1} \). Very large flocs may however be so fragile that they will break under this fluid shear intensity. Near the bed the shear is so high that it may also cause break-up of smaller flocs. This is very important for the sedimentation of mud in estuaries because flocculation could produce large flocs that settle to the region near the bed. These flocs may break and may be resuspended in the water column, which inhibits deposition. This may cause large SSC near the bed as can be seen in figure 3.2b. Only at slack tide, when the near bed shear is much lower, actual sedimentation occurs. Van der Ham (1999) conducted measurements of the turbulent diffusive sediment flux in the near bed zone of the Groote Gat. From these experiments he estimated settling velocities of approximately 0.5 mm/s in the near bed zone. Figure 3.3 showed settling velocities measured by the VIS in the Groote Gat ranging from 1.5 to 3.5 mm/s measured at about half the water depth. Even though the methodologies used to determine the settling velocities differ, this data indicates a smaller floc settling velocity in the near bed zone than higher in the water column. This also indicates that floc breakup in the near bed zone is likely to occur.

### 3.7 Conclusions

In October 1995 strong variations of floc sizes in the Dollard occurred within the tidal cycle. In the channel these variations correlated directly with the SSC and indirectly with the current velocity. Increasing current velocities caused increasing SSC, increasing floc sizes and good vertical mixing. Decreasing current velocities coincided with settling of larger flocs and the development of a vertical concentration gradient. It is possible that the high shear near the bed disrupted the large flocs and inhibited sedimentation. Deposition of mud to the bed was only observed with further decreasing current velocities. Above the tidal flat the fluid shear instead of SSC seemed to dominate the floc sizes. Only at high water slack, fluid shear did not inhibit floc growth. The measured fluid shear and SSC above the tidal flat were however comparable to SSC and fluid shear in the tidal channel. The close proximity of the bed above the tidal flat, with high fluid shear along this boundary, may have caused floc breakup and resuspension of the broken flocs during ebb and flood tides, which explains the smaller flocs above the tidal flat during high current velocities. This is in contrast with the tidal channel where the water is deeper and the frequency by which flocs approach the bed is much lower, which explains why SSC is able to dominate floc sizes in the tidal channel.